



**ANNUAL
REPORT
JAHRES
BERICHT**



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Editorial

Vorwort

Bundling forces and ensuring growth – true to this motto, the Ferdinand-Braun-Institut has followed its continuous growth path of recent years: With the increasing number of ambitious projects, we have been able to recruit further highly qualified employees. At the same time, our institute is pooling its forces with complementary partners – among other things within the new research area Integrated Quantum Technology, in joint labs with universities and in cooperative alliances. In combination with the excellent research equipment that we are currently expanding, FBH is securing its position as a strong R&D partner for industry and research.

Once again, FBH has achieved outstanding research results – in exploratory work as well as in its application-oriented developments. Gallium oxide power transistors, for example, achieved record values of 155 megawatts output power per square centimeter. The novel semiconductor material is highly attractive for future applications in mobile communications and artificial intelligence. Two UVC LED systems developed by the FBH are already undergoing practical testing. These irradiation systems aim to kill multi-resistant pathogens without using antibiotics. The Charité is currently investigating the effectiveness of irradiation with our short-wave LEDs on skin and skin models, and the University Medicine Center Greifswald is determining the optimal dosage.

The FBH is one of the world's leading institutes for laser diodes and micro-integrated laser modules. We develop customized laser modules for various applications based on the institute's unique microintegration technology. This technology is used, among other things, to build compact and robust laser modules with ultra-narrowband emission, which have repeatedly proven their capability in experiments in space. Currently, such laser modules are being developed and manufactured for the joint DLR and NASA project BECCAL, which aims at investigating fundamental physics questions with ultra-cold atoms on the international space station ISS. The new research area Integrated Quantum Technology also builds on this micro-integration know-how, covering the entire value-added chain – from the initial concept through technology development to the final components and subsystems.



FBH relies on strategic partnerships not only when it comes to its eight joint labs. For example, it is part of the Research Fab Microelectronics Germany (FMD), the largest cross-site R&D alliance for microelectronics in Europe. In this framework, we are currently expanding our technological infrastructure with state-of-the-art facilities that are presently being put into operation in an additional cleanroom at FBH. This excellent technological equipment is the basis for the joint technology offerings and services of the 13 partner institutes, which markets FMD as a one-stop-shop for industry and scientific institutions.

In the Innovation Campus Electronics and Microsensor Technology Cottbus – iCampus – we bundle our know-how in laser sensor technology as well as in microwave and terahertz electronics with the BTU Cottbus-Senftenberg. This way we support the structural change in the Lusatia region. In addition, we contribute our expertise to joint projects and interdisciplinary consortia. These include the "Advanced UV for Life" initiative led by the FBH, a consortium of almost 50 companies and research institutions dedicated to the development and application of UV LEDs.

I thank our co-workers who support the manifold activities of our institute with their expertise and commitment and who are indispensable for the further successful development. My thanks also go to our customers from industry and research for the many years of trustful cooperation, and I look forward to further exciting projects. I gratefully acknowledge the excellent cooperation and generous support provided by our sponsors, the State of Berlin and the Federal Government, backing our future-oriented activities.

We have summarized the results and events of the past year in this report. We wish you an inspiring reading,

Günther Tränkle

Kräfte bündeln und Wachstum sichern – getreu dieser Devise hat das Ferdinand-Braun-Institut seinen kontinuierlichen Wachstumspfad der vergangenen Jahre fortgesetzt: Mit der steigenden Anzahl anspruchsvoller Projekte konnten wir weitere hochqualifizierte Mitarbeiterinnen und Mitarbeiter gewinnen. Zugleich bündelt unser Institut seine Kräfte mit komplementären Partnern – unter anderem im Rahmen des neuen Forschungsbereichs Integrierte Quantentechnologie, in Joint Labs mit Universitäten und in kooperativen Verbänden. In Verbindung mit der exzellenten Forschungsausstattung, die wir zurzeit ausbauen, sichert das FBH seine Position als leistungsfähiger F&E-Partner für Industrie und Forschung.

Erneut hat das FBH wegweisende Forschungsergebnisse erzielt – bei explorativen Arbeiten ebenso wie bei seinen anwendungsorientierten Entwicklungen. So erreichten Galliumoxid-Leistungstransistoren Rekordwerte von 155 Megawatt Ausgangsleistung pro Quadratcentimeter. Das neuartige Halbleitermaterial ist hochattraktiv für künftige Anwendungen in der mobilen Kommunikation und der künstlichen Intelligenz. Bereits im Praxistest befinden sich zwei UVC-LED-Strahler des FBH, mit denen in Zukunft multiresistente Erreger ohne Antibiotika bekämpft werden sollen. Die Charité untersucht derzeit die Effektivität der Bestrahlung mit unseren kurzweiligen LEDs an Haut und Hautmodellen und die Uniklinik Greifswald ermittelt die optimale Dosierung.

Mit seinen Laserdioden und mikrointegrierten Lasermodulen zählt das FBH zu den weltweit führenden Instituten. Maßgeschneiderte Lasermodule entwickeln wir für verschiedenste Anwendungen. Basis dafür ist die am Institut entwickelte einzigartige Mikrointegrationstechnologie. Sie wird unter anderem für kompakte und robuste Lasermodule mit ultra-schmalbandiger Emission genutzt, die ihre Leistungsfähigkeit bei Experimenten im Weltraum mehrfach belegt haben. Aktuell werden derartige Lasermodule für das gemeinsame DLR- und NASA-Projekt BECCAL entwickelt und gefertigt, mit dem auf der internationalen Raumstation ISS künftig fundamental-physikalische Fragestellungen mit ultrakalten Atomen untersucht werden sollen. Auf dem Mikrointegrations-Know-how baut auch der neue Forschungsbereich Integrierte Quantentechnologie auf, der hierbei die gesamte Wertschöpfungskette abdeckt – von der Konzeption über die Technologieentwicklung bis hin zu den fertigen Komponenten und Subsystemen.

Nicht nur bei seinen mittlerweile acht Joint Labs, setzt das FBH auf strategische Partnerschaften. So ist es Teil der Forschungsfabrik Mikroelektronik Deutschland (FMD), dem größten standortübergreifenden F&E-Zusammenschluss für die Mikroelektronik in Europa. In diesem Zusammenhang bauen wir derzeit unsere technologische Infrastruktur aus. State-of-the-Art-Anlagen werden aktuell in einem zusätzlichen Reinraumlabor am FBH in Betrieb genommen. Diese exzellente technologische Ausstattung ist die Basis für die gemeinsamen Technologieangebote und Services der 13 Partnerinstitute, die die FMD als One-Stop-Shop für Wirtschaft und Wissenschaft anbietet.

Im Innovationscampus Elektronik und Mikrosensorik Cottbus – iCampus – bündeln wir unser Know-how in der Lasersensorik sowie der Mikrowellen- und Terahertz-Elektronik mit der BTU Cottbus-Senftenberg. Damit unterstützen wir den Strukturwandel in der Lausitz-Region. Darüber hinaus bringen wir unsere Kompetenzen in Verbundprojekte und interdisziplinäre Konsortien ein. Dazu zählt auch das vom FBH geleitete „Advanced UV for Life“-Bündnis aus fast 50 Unternehmen und Forschungseinrichtungen, das sich der Entwicklung und Anwendung von UV-LEDs widmet.

Ich danke den Kolleginnen und Kollegen, die mit ihrem Fachwissen und Engagement die vielfältigen Aktivitäten unseres Instituts tragen und unverzichtbar für die weitere erfolgreiche Entwicklung sind. Unseren Kunden aus Industrie und Forschung danke ich für die langjährige, vertrauensvolle Zusammenarbeit und freue mich auf weitere spannende Projekte. Mein Dank gilt auch unseren Zuwendungsgebern des Landes Berlin und des Bundes für die ausgezeichnete Zusammenarbeit und großzügige Unterstützung unserer zukunftsorientierten Vorhaben.

Die Ergebnisse und Ereignisse aus dem letzten Jahr haben wir hier zusammengefasst. Eine anregende Lektüre wünscht Ihnen

Günther Tränkle

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Who we are – FBH at a glance

Wer wir sind – das FBH im Profil

The Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoehstfrequenztechnik (FBH) researches electronic and optical components, modules and systems based on compound semiconductors. These devices are key enablers that address the needs of today's society in fields like communications, energy, health, and mobility.



Specifically, FBH develops light sources from the visible to the ultra-violet spectral range: high-power diode lasers with excellent beam quality, UV light sources, and hybrid laser modules. Applications range from medical technology, high-precision metrology and sensors to optical communications in space and integrated quantum technology. In the field of microwaves, FBH develops high-efficiency multi-functional power amplifiers and millimeter wave frontends targeting energy-efficient mobile communications, industrial sensing and imaging, as well as car safety systems. In addition, the institute fabricates laser drivers and compact atmospheric microwave plasma sources operating with energy-efficient low-voltage drivers for use in a variety of applications.

The FBH is a center of competence for III-V compound semiconductors covering the full range of capabilities, from design through fabrication to device characterization. Within Research Fab Microelectronics Germany (Forschungsfabrik Mikroelektronik Deutschland), FBH joins forces with 12 other German research institutes, thus offering the complete micro and nanoelectronics value chain as a one-stop-shop.



Das Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) erforscht elektronische und optische Komponenten, Module und Systeme auf der Basis von Verbindungshalbleitern. Diese sind Schlüsselbausteine für Innovationen in den gesellschaftlichen Bedarfsfeldern Kommunikation, Energie, Gesundheit und Mobilität.

Leistungsstarke und hochbrillante Diodenlaser, UV-Leuchtdioden und hybride Lasersysteme entwickelt das Institut vom sichtbaren bis zum ultravioletten Spektralbereich. Die Anwendungsfelder reichen von der Medizintechnik, Präzisionsmesstechnik und Sensorik bis hin zur optischen Satellitenkommunikation und integrierten Quantentechnologie. In der Mikrowellentechnik realisiert das FBH hoch-effiziente, multifunktionale Verstärker und Schaltungen, unter anderem für energie-effiziente Mobilfunksysteme, für die industrielle Sensorik sowie Komponenten zur Erhöhung der Kfz-Fahrsicherheit. Darüber hinaus entwickelt es Lasertreiber sowie kompakte atmosphärische Mikrowellenplasmaquellen mit Niederspannungsversorgung für vielfältige Anwendungen.

Das FBH ist ein international anerkanntes Zentrum für III/V-Verbindungshalbleiter mit allen Kompetenzen: vom Entwurf, über die Fertigung bis hin zur Charakterisierung von Bauelementen. In der Forschungsfabrik Mikroelektronik Deutschland (FMD) bündelt es sein Know-how und seine Ressourcen mit 12 weiteren Forschungseinrichtungen in Deutschland – die FMD bietet damit die komplette Wertschöpfungskette in der Mikro- und Nanoelektronik aus einer Hand.



What we do – research topics & competencies

The FBH develops high-value products and services for its partners in the research community and industry which are tailored precisely to fit individual needs. With its Prototype Engineering Lab, the institute strengthens its cooperation with customers in industry by turning excellent research results into market-oriented products, processes, and services. The institute thereby offers its international customer base complete solutions and know-how as a one-stop agency – from design to ready-to-use modules and prototypes.

Photonics

- high-power diode lasers: broad area & bars
- high-brightness & narrowband diode lasers
- hybrid laser modules (cw & pulsed): from NIR to UV spectral range, e.g. for biophotonics, laser sensors, ...
- nitride laser diodes for the blue & UV spectral range
- short-wave UV LEDs, e.g. for sensors, disinfection, medical & production technology, ...

Integrated Quantum Technology

- electro-optical components & hybrid micro-integrated modules
- integrated quantum sensors based on atomic gases
- nanostructured diamond systems & materials
- quantum emitters & nanofabricated optical waveguide chips

III-V Electronics

- GaN microwave transistors & MMICs
- advanced power amplifier concepts for the wireless infrastructure
- integrated circuits with InP HBTs for the 100... 500 GHz frequency range (THz electronics)
- fast drivers for laser diodes
- compact sources for microwave plasmas
- GaN power electronics

III-V Technology

- epitaxy (MOVPE) of GaAs- & GaN-based layer structures for devices
- (Al)GaN HVPE for bulk crystal growth
- *In situ* control techniques for MOVPE & HVPE
- complete process line 2" - 4" for GaAs, InP, SiC & GaN devices, including laser micro processing
- InP HBT technology for mm-wave & THz applications, hetero-integrated SiGe-BiCMOS/InP-HBT foundry with IHP
- mounting & assembling

Science Management

- technology transfer & marketing
- education & training management

Was wir tun – Forschungsthemen & Kompetenzbereiche

Für Partner aus Forschung und Industrie entwickelt das FBH hochwertige Produkte und Services, die exakt auf individuelle Anforderungen zugeschnitten sind. Mit seinem Entwicklungszentrum überführt das FBH exzellente Forschungsergebnisse in marktorientierte Produkte, Verfahren und Dienstleistungen und stärkt dadurch die Zusammenarbeit mit seinen Industriekunden. Das Institut bietet somit seinem internationalen Kundenstamm Know-how und Komplettlösungen aus einer Hand: vom Entwurf über gebrauchsfertige Module bis hin zu industrietauglichen Prototypen.

Photonik

- Hochleistungs-Diodenlaser: Breitstreifen & Barren
- Hochbrillante & spektral schmalbandige Diodenlaser
- Hybride Lasermodule (CW & gepulst): NIR bis UV-Spektralbereich, u.a. für Biophotonik, Lasersensorik, ...
- Nitrid-Laserdioden für den blauen & UV-Spektralbereich
- Kurzwellige UV-Leuchtdioden, u.a. für Sensorik, Desinfektion, Medizin- und Produktionstechnik, ...

Integrierte Quantentechnologie

- Elektrooptische Komponenten & hybrid mikointegrierte Module
- Integrierte Quantensensoren auf Basis atomarer Gase
- Nanostrukturierte Diamantsysteme und -materialien
- Quantenemitter & nanofabrizierte Lichtwellenleiterchips

III/V-Elektronik

- GaN-Mikrowellentransistoren & -MMICs
- Neue Leistungsverstärkerkonzepte für die drahtlose Infrastruktur
- Integrierte Schaltungen mit InP-HBTs für den Frequenzbereich 100...500 GHz (THz-Elektronik)
- Schnelle Treiber für Laserdioden
- Kompakte Quellen für Mikrowellenplasmen
- GaN-Leistungselektronik

III/V-Technologie

- Epitaxie (MOVPE) von GaAs- & GaN-basierten Schichtstrukturen für Bauelemente
- (Al)GaN-HVPE für Volumenkristalle
- In-situ Kontrolltechniken bei MOVPE & HVPE
- Komplette Prozesslinie 2" – 4" für GaAs-, InP-, SiC- & GaN-Bauelemente inklusive Lasermikrostrukturierung
- InP-HBT-Technologie für Millimeterwellen- & THz-Anwendungen, heterointegrierter SiGe-BiCMOS-/InP-HBT-Foundryprozess mit dem IHP
- Aufbau- & Verbindungstechnik

Wissenschaftsmanagement

- Technologietransfer & Marketing
- Bildungsmanagement

What we offer – technology transfer & services

The Ferdinand Braun Institute transfers its know-how and results in many different ways – and for an abundance of applications. The respective labs and departments develop sophisticated and tailor-made solutions for their customers in research and industry.

FBH's Prototype Engineering Lab complements the institute's scientific competence. Building on the institute's research results, it develops user-friendly prototypes based on systematic device engineering that can be tested in industrial applications. With its multifaceted approach, the institute ensures that research results are quickly transferred into market-oriented products, processes, and services.

Scientific Services

Based on its comprehensive know-how and state-of-the-art equipment, FBH offers a wide spectrum of scientific services for various applications. Services range from customer-specific epitaxial layer structures in excellent quality to the development of novel process steps and products such as tailor-made laser diodes or transistors. The customer portfolio comprises major companies as well as small and medium-sized enterprises (SMEs). For SMEs, in particular, the FBH is often an indispensable part in their own value-added chain, since running an elaborate infrastructure like a cleanroom is hardly economically viable for small companies.

Application Development

The Prototype Engineering Lab, created in 2014, develops and builds prototypes with which FBH demonstrates its research results in operational devices. The team of engineers and technicians works closely with all labs and departments of the institute. The Prototype Engineering Lab lends or sells the resulting prototypes to customers for testing in their own applications. In 2019, four new prototypes were built and in part jointly tested with cooperation partners. At trade fairs such as the Laser World of Photonics in Munich and Photonics West in San Francisco, for example, the pulsed laser source for LiDAR applications met with great interest.

Research Management & Transfer

The interdisciplinary team of FBH's Science Management Department supports not only the scientists of the institute, but also partners from science and industry in projects and R&D cooperations. It takes care of administrative and organizational work involved in applying for complex collaborative projects and international networks, subsequently coordinating, developing and managing the joint activities. For example, the team has been coordinating Advanced UV for Life for many years. The Twenty20 consortium of currently 49 partners researches and develops UV-LED technology along the entire value chain – from crystal to application in devices such as skin analysis.

Das bieten wir Ihnen – Technologietransfer & Services

Das Ferdinand-Braun-Institut transferiert sein Know-how und seine Ergebnisse in vielfältiger Weise – und für eine Fülle von Anwendungen. Die jeweiligen Labs und Departments entwickeln anspruchsvolle und maßgeschneiderte Lösungen für ihre Kunden in Forschung und Industrie.

Das Entwicklungszentrum ergänzt die wissenschaftliche Kompetenz des Instituts. Es entwickelt benutzerfreundliche Prototypen, die auf den Forschungsergebnissen basieren und dank der systematischen Geräteentwicklung unkompliziert in industriellen Anwendungen getestet werden können. Mit seinem breit gefächerten Ansatz stellt das Institut sicher, dass Forschungsergebnisse schnell in marktgerechte Produkte, Prozesse und Dienstleistungen umgesetzt werden.

Forschungsdienstleistungen

Auf Basis seines umfangreichen Know-hows und modernster Ausstattung bietet das FBH ein breites Spektrum an wissenschaftlichen Dienstleistungen für verschiedenste Anwendungen. Das Leistungsspektrum reicht von kundenspezifischen epitaktischen Schichtstrukturen in exzellenter Qualität bis hin zur Entwicklung neuer Prozessschritte und Produkte wie etwa maßgeschneiderte Laserdioden oder Transistoren. Das Kundenportfolio umfasst sowohl Großunternehmen als auch kleine und mittlere Unternehmen (KMU). Gerade für KMU ist das FBH oftmals unverzichtbar für die eigene Wertschöpfungskette, da der Betrieb einer aufwändigen Infrastruktur wie eines Reinraums für kleine Unternehmen kaum wirtschaftlich möglich ist.

Applikationsentwicklung

Das 2014 geschaffene Entwicklungszentrum entwickelt und baut Prototypen, mit denen das FBH seine Forschungsergebnisse in einsatzfähigen Geräten demonstriert. Das Team aus Ingenieuren und Technikern arbeitet dabei eng mit allen Labs und Departments des Instituts zusammen. Die hierbei entstehenden Prototypen verleiht oder verkauft das Entwicklungszentrum an Kunden für Tests in deren eigenen Anwendungen. So wurden 2019 vier neue Prototypen aufgebaut und teils gemeinsam mit Kooperationspartnern erprobt. Auf Fachmessen wie der Laser World of Photonics in München und der Photonics West in San Francisco stieß zum Beispiel die gepulste Laserquelle für LiDAR-Anwendungen auf großes Interesse.

Forschungsmanagement & Transfer

Das interdisziplinäre Team aus dem Wissenschaftsmanagement des FBH unterstützt nicht nur die Wissenschaftlerinnen und Wissenschaftler des Instituts, sondern auch Partner aus Wissenschaft und Industrie bei Projekten und F&E-Kooperationen. Es kümmert sich um administrative und organisatorische Arbeiten bei der Beantragung komplexer Verbundprojekte und internationaler Netzwerke. Zudem koordiniert, entwickelt und verwaltet es die gemeinsamen Aktivitäten. Dazu zählt beispielsweise seit vielen Jahren Advanced UV for Life. Das Zwanzig20-Konsortium mit derzeit 49 Partnern erforscht und entwickelt die UV-LED-Technologie entlang der gesamten Wertschöpfungskette – vom Kristall bis zur Anwendung, beispielsweise für Geräte zur Hautanalyse.

What is important is to us Was uns wichtig ist

Mission statement

... translating ideas into innovation

- We explore **cutting-edge technologies for innovative applications** in the fields of microwaves and optoelectronics. As a center of competence for III-V compound semiconductors, we are part of a worldwide network and achieve research results advancing the international state-of-the-art.
- We offer **complete solutions as a one-stop agency** – from design to ready-to-ship modules.
- We work **closely cross-linked** with the scientific community – including university cooperations (joint labs), strategic networks, and international projects.
- In **strategic partnerships with industry**, we transfer our research results into cutting-edge products and thus ensure German technological leadership in microwaves and optoelectronics. By means of spin-off companies, we bring innovative product ideas into the market.
- We provide **high-value products and services** for our customers in the research community and industry which are tailored to fit their individual needs.
- We offer our employees an **attractive and family-friendly working environment** with interesting tasks and career prospects. To maintain top-level expertise we guide, assist, and encourage young scientists and train our staff.
- We specifically aim at increasing the proportion of **female specialists and executive staff** in the technical and scientific area and actively assist **foreign colleagues** with their integration.
- Wir erforschen **Schlüsseltechnologien für innovative Anwendungen** in der Mikrowellentechnik und Optoelektronik. Als Kompetenzzentrum für Verbindungshalbleiter arbeiten wir weltweit vernetzt und erzielen Forschungsergebnisse auf internationalem Spitzenniveau.
- Wir bieten **Lösungen aus einer Hand**: vom Entwurf bis zum lieferfähigen Modul.
- Wir arbeiten **eng vernetzt** mit der Scientific Community: im Rahmen von Hochschulkooperationen (Joint Labs), strategischen Verbänden und in internationalen Projekten.
- Wir setzen unsere Forschung in **strategischen Partnerschaften mit der Industrie** in praktische Anwendungen um und sichern so die technologische Kompetenz Deutschlands in der Höchstfrequenztechnik. Innovative Produktideen transferieren wir erfolgreich durch Spin-offs.
- Wir offerieren **hochwertige Produkte und Services**, die exakt auf die Anforderungen unserer Kunden zugeschnitten sind.
- Wir bieten unseren Mitarbeitern ein stabiles, **attraktives und familienfreundliches Arbeitsumfeld** mit reizvollen Aufgabenstellungen und Entfaltungsmöglichkeiten. Unsere Zukunft sichern wir durch die gezielte Förderung des wissenschaftlichen Nachwuchses und die Ausbildung technischer Fachkräfte.
- Wir haben es uns zur Aufgabe gemacht, den Anteil **weiblicher Fach- und Führungskräfte** im technischen und naturwissenschaftlichen Bereich gezielt zu erhöhen sowie **ausländische Kolleginnen und Kollegen** aktiv bei der Integration zu unterstützen.



Hand in hand – making research utilizable

Hand in Hand – Forschung nutzbar machen

With its Prototype Engineering Lab, the FBH closely exchanges know-how with users. In close cooperation, the lab advances research results and technologies in a way that enables companies and research partners to use them in products and applications. This not only facilitates FBH technologies to be implemented quickly, but also opens the way for new developments.

Prototype Engineering Lab competencies Kompetenzen des Entwicklungszentrums

R&D results:

matching supply and demand

- establishing & intensifying industrial contacts
- exemplifying applications: FBH exhibits
- transfer: identifying topics and developing them further with the R&D teams

F&E-Ergebnisse:

Angebot und Nachfrage abgleichen

- Industriekontakte aufbauen und intensivieren
- Anwendungen veranschaulichen: FBH-Messeexponate
- Transfer: Themen identifizieren und mit den Fachabteilungen weiterentwickeln

Customized prototypes: concepts & construction

- demonstrators (within the scope of contracts & projects)
- system electronics & housing – tailored to the application
- special constructions

Passgenaue Prototypen: Konzeption & Bau

- Demonstratoren (im Rahmen von Aufträgen und Projekten)
- Systemelektronik & Gehäuse – abgestimmt auf die Anwendung
- Spezialbauten

Tests:

refining applications with partners

- aligning specifications with companies
- jointly advancing overall systems
- practical tests in the respective application

Tests:

Anwendungen mit Partnern weiterentwickeln

- Spezifikationen mit Unternehmen abstimmen
- Gesamtsysteme gemeinsam fortentwickeln
- Praxistests in der jeweiligen Anwendung

Exemplary – high-performance & compact turnkey systems for SERDS precision measurements

The research activities of the Laser Sensors Lab on Shifted Excitation Raman Difference Spectroscopy (SERDS) have led to close cooperation with partners in medicine and agriculture in recent years. In these fields, spectrally narrow-band, wavelength-stabilized laser systems are increasingly in demand.

Dual-wavelength diode lasers developed by the FBH deliver an output power of up to 200 milliwatts and efficiently separate Raman signals from disturbing background signals. This way, they yield a unique 'fingerprint' of the detected substances. In order to be able to operate these lasers stably and with maximum lifetime, the Prototype Engineering Lab has developed a miniaturized control system. This system is programmable on the computer; four different setups can be stored. Laser and control unit are integrated into a very compact housing, which offers up to 2 watts of heat dissipation. The turnkey system is portable, but can also be integrated into laboratory setups using a rod system. Laser operation can be triggered both internally and externally. This excitation light source is used for in-house research tasks as well as by FBH partners and can be completed with optical beam shaping to capture samples, detection unit and measurement evaluation to establish a Raman measurement system.

This system was further developed in 2019 to make it suitable for use in different laser combinations. It enables optical output powers of up to 1 watt, powers of up to 10 watts must be dissipated as heat. The system supplies the sections of a dual-wavelength laser with up to 750 milliamperes or 3 amperes, respectively. Switching between the two laser arms is performed at a frequency of up to 1 kilohertz. This speeds up the Raman measurement process and measurement accuracy, since many measurement points can be captured.

The suitable system for the respective application

Thanks to its modular design, the turnkey system can be flexibly adapted to different requirements. In addition, it is constantly being advanced at FBH. Both configurations of the system, the 200 milliwatt and the 1 watt version, are used by research partners and industrial customers at their sites to efficiently examine liquids and solids, but also special biological material by means of SERDS. The more powerful laser system has proven itself in more challenging measurement environments where the Raman signals to be measured are masked even more strongly by disturbing signals. It is used, for example, in medical technology (measurement of carotenoids on the skin), in the analysis of mixed substances (e.g. pharmaceuticals, plastics industry) and in agriculture (quality control of food and soil samples).



Dual-wavelength diode laser system for Raman measurements in operation. Zwei-Wellenlängen-Diodenlasersystem für Raman-Messungen im Betrieb.

Das FBH tauscht sich mit seinem Entwicklungszentrum eng mit Anwendern aus. Gemeinsam entwickelt es Forschungsergebnisse und Technologien so weiter, dass sie für Unternehmen und Partner aus der Forschung in Produkten und Applikationen nutzbar werden. Dadurch kommen nicht nur FBH-Technologien rasch in die Anwendung, es entstehen auch Ansätze für Neuentwicklungen.

Beispielhaft – leistungsstarke & kompakte Turnkey-Systeme für SERDS-Präzisionsmessungen

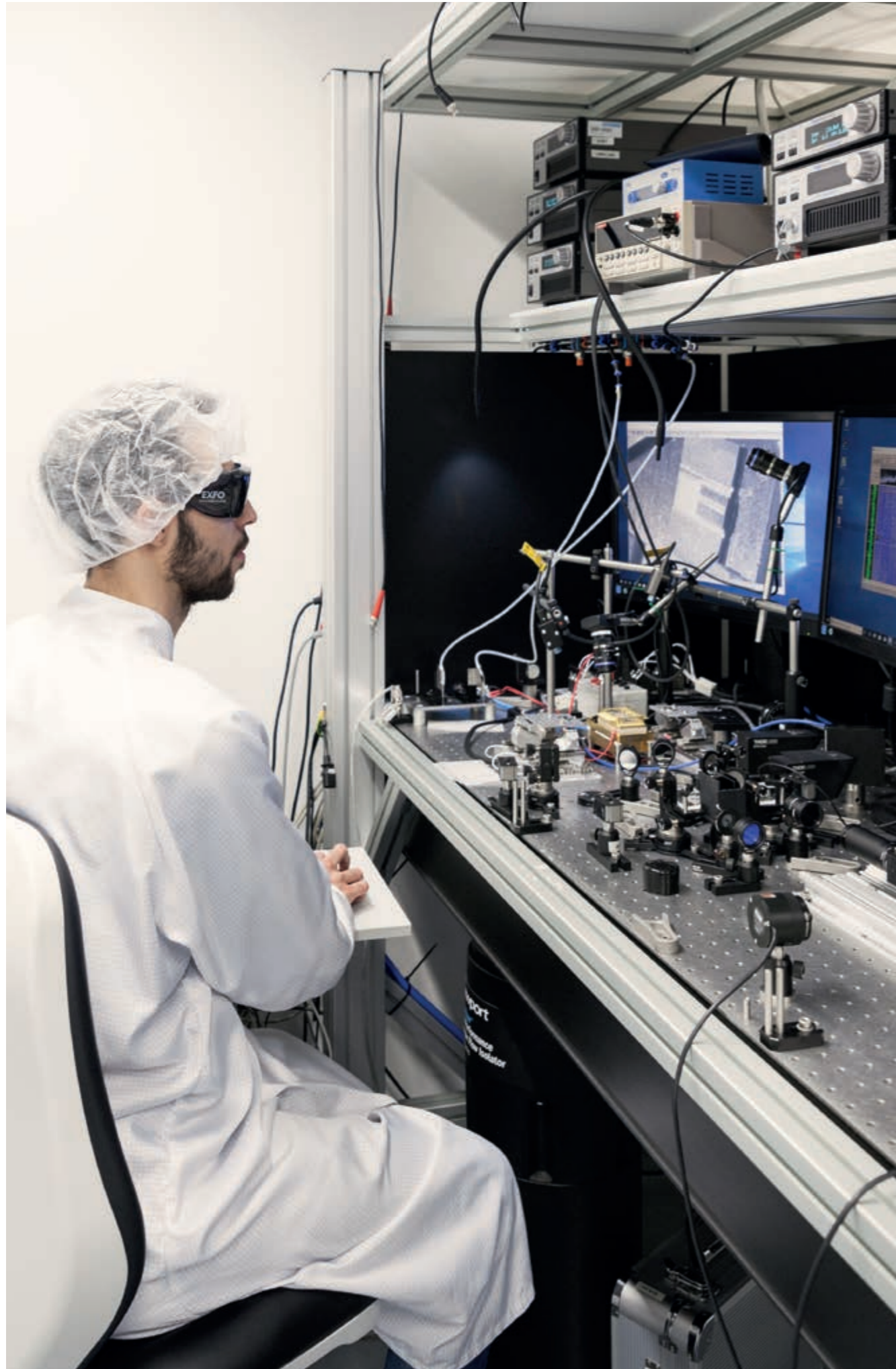
Die Forschungsarbeiten des Lasers Sensors Lab zur Shifted-Excitation-Raman-Difference-Spektroskopie (SERDS) haben in den letzten Jahren zu einer engen Zusammenarbeit mit Partnern in Medizin und Landwirtschaft geführt. Dort sind spektral schmalbandige, wellenlängestabilisierte Lasersysteme immer stärker gefragt.

Am FBH entwickelte Zwei-Wellenlängen-Diodenlaser liefern eine Leistung bis zu 200 Milliwatt und trennen Raman-Signale effizient von Störsignalen. Sie liefern dadurch einen eindeutigen „Fingerabdruck“ der erfassten Stoffe. Um diese Laser mit maximaler Lebensdauer stabil betreiben zu können, hat das Entwicklungszentrum eine miniaturisierte Ansteuerung entwickelt. Diese ist am Computer programmierbar; vier verschiedene Set-ups können gespeichert werden. Laser und Ansteuerung werden in ein sehr kompaktes Gehäuse integriert, das bis zu 2 Watt Wärmeabfuhr bietet. Das Turnkey-System ist tragbar, lässt sich mithilfe eines Stangensystems aber auch in Laboraufbauten integrieren. Der Laserbetrieb kann intern wie extern getriggert werden. Diese Anregungslichtquelle wird bei eigenen Forschungsaufgaben sowie bei Partnern des FBH eingesetzt und kann mit optischer Strahlformung zur Probenerfassung, Detektionseinheit und Mess-Auswertung zu einem Raman-Messsystem komplettiert werden. Dieses System wurde 2019 so weiterentwickelt, dass es in verschiedenen Laserkombinationen einsetzbar ist. Es ermöglicht optische Laserleistungen bis 1 Watt, Leistungen von bis zu 10 Watt müssen als Wärme abgeführt werden. Das System versorgt die Sektionen eines Zwei-Wellenlängen-Lasers mit bis zu 750 Milliampere beziehungsweise

3 Ampere. Das Umschalten zwischen beiden Laserarmen erfolgt mit einer Frequenz bis zu 1 Kilohertz. Dies beschleunigt den Ablauf einer Raman-Messung und die Messgenauigkeit, da viele Messpunkte aufgenommen werden können.

Das passende System zur Anwendung

Dank des modularen Aufbaus kann das Turnkey-System flexibel auf verschiedene Erfordernisse angepasst werden. Es wird zudem am FBH stetig weiterentwickelt. Beide Versionen des Systems, die 200-Milliwatt- und die 1-Watt-Variante, werden bei Forschungspartnern und Industriekunden vor Ort eingesetzt, um Flüssigkeiten und Festkörper, aber auch spezielles biologisches Material mittels SERDS effizient zu untersuchen. Das leistungsstärkere Lasersystem hat sich in schwierigeren Messumgebungen bewährt, bei denen die zu messenden Raman-Signale noch stärker von Störsignalen maskiert werden. Es kommt beispielsweise in der Medizintechnik (Messung von Carotinoiden auf der Haut), in der Analyse von Stoffgemischen (z.B. Pharmazie, Kunststoffindustrie) oder in der Landwirtschaft (zur Qualitätskontrolle von Lebensmitteln oder Bodenproben) zum Einsatz.



Skilled workers in high technology

Fachkräfte in der Hochtechnologie sichern

How to attract bright minds for research and development in high technology? For more than 25 years, the Ferdinand-Braun-Institut has been dedicated to promoting academic as well as vocational education and training.

The FBH is closely connected to universities and actively engaged in academic teaching and training. Eleven scientists of the institute currently teach at six different universities and universities of applied sciences. Furthermore, they train the next generation of scientists by supervising their bachelor, master and doctoral theses. There is also an intensive exchange of academic staff with postdocs and students, who conduct research both at FBH and at the respective partner university within the cooperation of currently eight Joint Labs. In the field of vocational education and training, FBH offers up to six apprenticeships per year in microtechnology. In addition, the institute provides training in two further professions: industrial mechanic and IT specialist for system integration.

Kluge Köpfe für Forschung und Entwicklung in der Hochtechnologie gewinnen! Seit mehr als 25 Jahren kümmert sich das Ferdinand-Braun-Institut um die Fachkräftesicherung im akademischen Bereich sowie in der beruflichen Aus- und Weiterbildung.

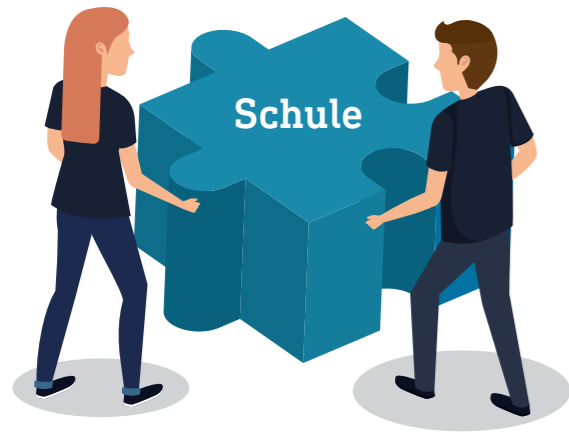
Das FBH beteiligt sich aktiv an der akademischen Lehre und Ausbildung und ist eng mit Hochschulen vernetzt. Elf Wissenschaftlerinnen und Wissenschaftler des Instituts lehren derzeit an sechs verschiedenen Universitäten und Hochschulen. Sie qualifizieren den wissenschaftlichen Nachwuchs zudem über Bachelor- und Masterarbeiten sowie Promotionen, die sie betreuen. Einen intensiven Austausch an akademischem Personal gibt es auch bei Postdocs und Studierenden, die im Rahmen der aktuell acht Joint Labs sowohl am FBH als auch an der jeweiligen Partnerhochschule forschen.

Im Bereich der klassischen Berufsausbildung bietet das FBH bis zu sechs Ausbildungsplätze pro Jahr in der Mikrotechnologie an. Darüber hinaus bildet das Institut in zwei weiteren Berufen aus: Industriemechaniker*in und Fachinformatiker*in für Systemintegration.

ANH Berlin – network for vocational and advanced training in high technology

ANH Berlin (Aus- und Weiterbildungsnetzwerk Hochtechnologie) was founded at the FBH in 2007. As a supplementary structure, the network promotes vocational education and training in STEM (science, technology, engineering, mathematics) far beyond the scope of the institute. At its core, the ANH Berlin team supports companies and research institutions within the Photonics Cluster to ensure their technical workforce.

Motivating suitable young people to consider vocational training within the high-tech sector remains a major challenge in this context. Many job profiles are scarcely known or even regarded as too 'cumbersome' or too 'demanding'. ANH Berlin makes technical occupations and promising career opportunities visible and gives young people an insight into real working conditions. Similar activities are addressing multipliers such as teachers, vocational counselors, and parents. The network thus helps to bridge the gap between school and working life.

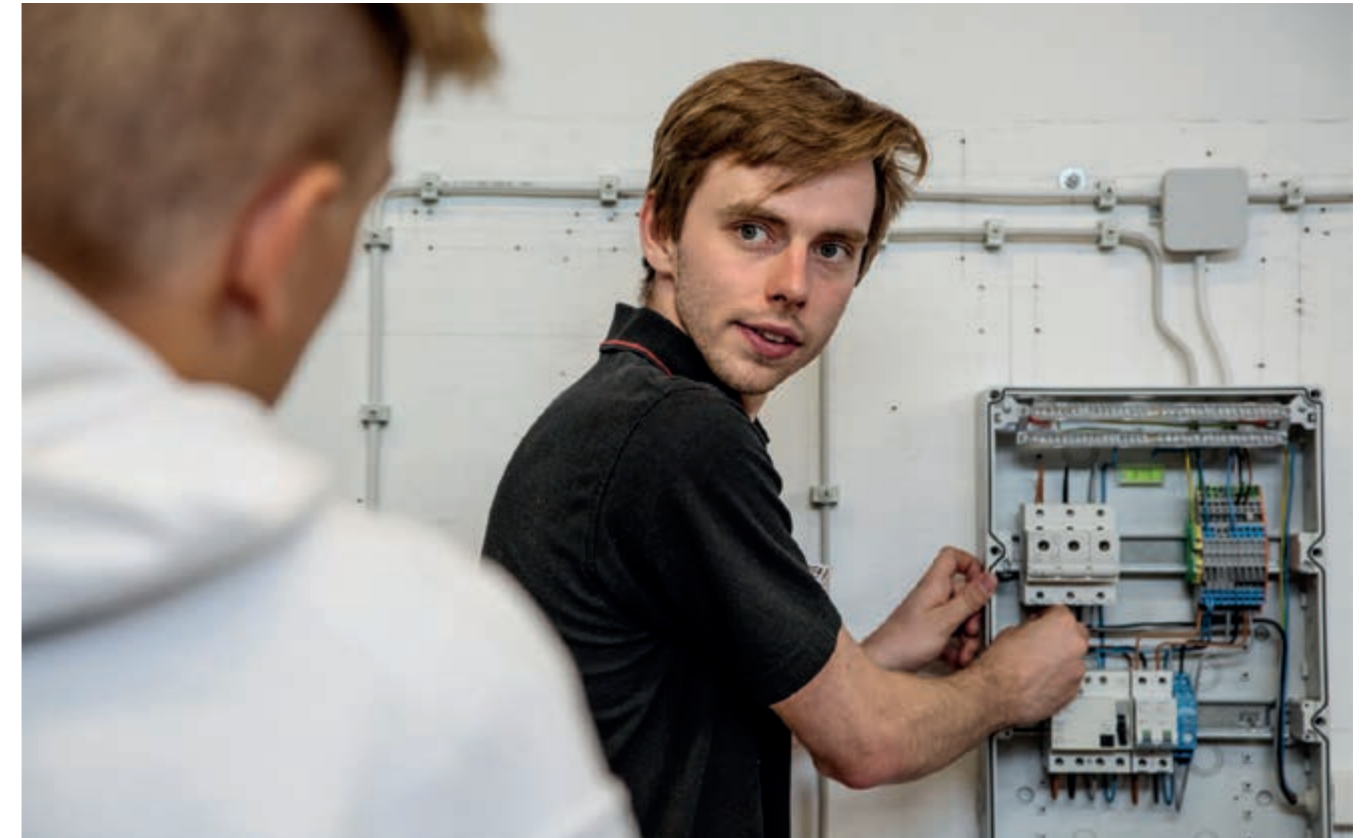


Aus- und Weiterbildungsnetzwerk Hochtechnologie – ANH Berlin

Mit dem 2007 am FBH gegründeten Aus- und Weiterbildungsnetzwerk Hochtechnologie (ANH Berlin) wurde eine Struktur geschaffen, die die berufliche Bildung weit über das Institut hinaus stärkt. Im Kern unterstützt das Team von ANH Berlin Unternehmen und Forschungseinrichtungen im Cluster Optik und Photonik bei der Sicherung des gewerblich-technischen Nachwuchses.

Geeignete Jugendliche für die duale Ausbildung im High-tech-Bereich zu begeistern, bleibt in diesem Zusammenhang eine große Herausforderung. Nach wie vor sind viele Berufsbilder zu wenig bekannt oder die Lehrinhalte werden als zu „trocken“ oder zu „anspruchsvoll“ eingeschätzt.

ANH Berlin macht zukunftsweisende Berufe greifbar und ermöglicht Jugendlichen Einblick in reale Arbeitswelten – parallele Angebote richten sich an Multiplikator*innen wie Lehrkräfte, Berufsberater*innen und Eltern. Das Netzwerk bildet eine wichtige Brücke am Übergang von der Schule ins Berufsleben.



🔗 Gaining insights into everyday working life – this student wants to know more about the profession of an electronics technician with focus on energy and building services engineering at Training Alliance Adlershof. Einblicke in den Berufsalltag – dieser Schüler interessiert sich für den Beruf Elektroniker – Energie und Gebäudetechnik bei der Ausbildungs-Allianz-Adlershof.

Activities offered by ANH Berlin for pupils

Finding the right job is not easy. Well, what can be done? Mostly, pupils do not know which professions exist, nor which tasks are associated with them. Getting to know the jobs on site is one solution! ANH Berlin organizes company tours for pupils. By talking directly to trainees and training managers, young people get a real feeling for professions they have never heard of before. They learn, for example, what a microtechnologist or industrial mechanic are actually working on.

- Get to know companies:**
- Training Alliance Adlershof
 - visits to the institute
 - parents on tour

Angebote von ANH Berlin für Schüler*innen

Den passenden Beruf zu finden, ist nicht leicht. Wie auch? Meist wissen Schüler*innen nicht, welche Berufe es gibt oder welche Aufgaben damit verbunden sind. Die Lösung: Arbeitsplätze vor Ort kennenlernen! ANH Berlin organisiert Betriebsbesichtigungen für Schüler*innen. Im Gespräch mit Azubis oder Ausbildungsleitung erfahren sie z.B., woran eine Mikrotechnologin oder ein Industriemechaniker genau arbeiten.

- Betriebe kennenlernen bei:**
- Ausbildungs-Allianz-Adlershof
 - Institutsbesichtigungen im FBH
 - Eltern auf Tour

ANH Berlin services for companies & research institutions

Starting vocational training – ANH Berlin guides companies step by step and

- provides support in choosing the appropriate training profile.
- informs about general requirements for vocational training (permission to be gained from the chamber of commerce, training content, funding options, ...).
- establishes contact to the relevant stakeholders such as vocational schools, training associations, and networks.

Attracting new apprentices – ANH Berlin supports the recruiting process of its partners and

- provides information at training fairs and at career days in schools.
- promotes vacancies on well-known online recruiting platforms for apprenticeships
- screens applications, preselects and recommends suitable candidates.

Services von ANH Berlin für Unternehmen & Forschungseinrichtungen

Einstieg in die duale Ausbildung – ANH Berlin begleitet Unternehmen Schritt für Schritt und

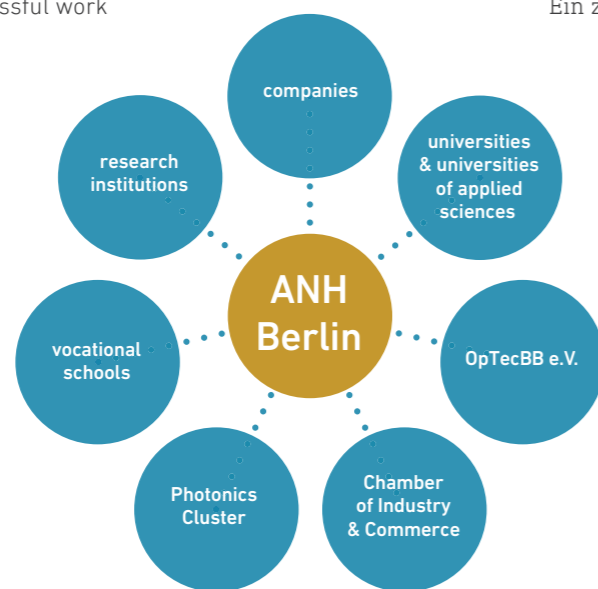
- unterstützt bei der Wahl des passenden Ausbildungsberufes
- informiert über Rahmenbedingungen der dualen Ausbildung (Anerkennung als Ausbildungsbetrieb, Ausbildungsinhalte, finanzielle Fördermöglichkeiten, ...)
- stellt Kontakte zu den relevanten Akteuren her (Kammern, Berufsschule, Kooperationsbetriebe)

Neue Auszubildende gewinnen – ANH Berlin unterstützt den Recruiting-Prozess seiner Partner und

- informiert auf Ausbildungsmessen und bei Karrieretagen in Schulen
- bewirbt offene Ausbildungsplätze auf großen Online-Ausbildungsplattformen
- sichtet Bewerbungen, übernimmt die Vorauswahl und leitet passende Kandidat*innen weiter

Benefiting from the network

A key factor of ANH Berlin's successful work is its very close and long-lasting cooperation with the relevant stakeholders in academic and vocational education and within the Photonics Cluster. The ANH Berlin team has established itself as an interface for all questions related to initial and further vocational training. Thus, the partners benefit from the extensive know-how and reliable contacts of the network. All services are made possible thanks to support from regional, national and European funding.



Vom Netzwerk profitieren

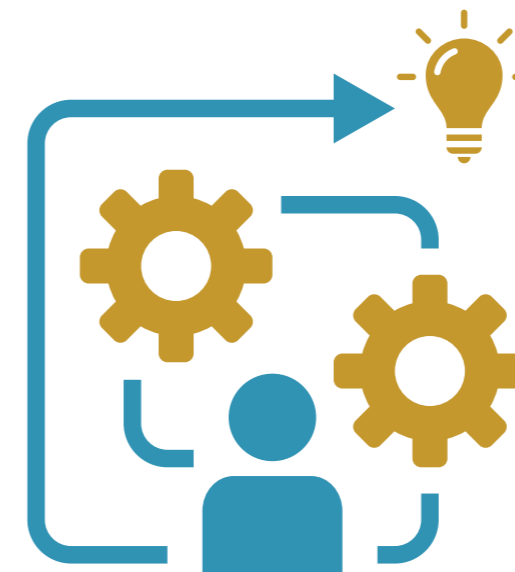
Ein zentraler Faktor für die erfolgreiche Arbeit von ANH Berlin ist die hervorragende Vernetzung mit den relevanten Akteuren aus der akademischen und beruflichen Bildung sowie innerhalb des Clusters Optik und Photonik. Das Team von ANH Berlin hat sich als Schnittstelle für alle Fragen rund um Ausbildung etabliert. Damit profitieren die Partner vom umfangreichen Know-how und von verlässlichen Kontakten des Netzwerks. Alle Dienstleistungen werden dank der Unterstützung durch regionale, nationale und europäische Fördermittel angeboten.

Highlight 2019 – ANH Berlin activities strengthened with new nonprofit association

General and human resources managers are having more and more difficulties to find suitable staff. Joining forces helps to meet those challenges. In addition to the proven formats, ANH Berlin has succeeded in structurally consolidating its activities. Initiated by the network, companies and research institutions founded the association proANH e.V. in May 2019. Apart from project funding, the network is now supported by membership fees from companies – for the first time since its foundation. Additional funding comes from the Senate Department for Economics, Energy and Public Enterprises to improve the regional economic structure.

Successfully completed projects in 2019

- **HAI** high-tech training in Berlin Brandenburg
- **beMINT**. Hands-on career opportunities
- **PHABLABS 4.0** Getting to know photonics in FabLabs



Project proposal in 2019

- **BM=x³** attractive vocational training in micro- and nanotechnology through excellent professions, excellent learning environment and excellent cooperation

Highlight 2019 – ANH Berlin-Aktivitäten mit neuem Verein verstetigt

Zusätzlich zu den bewährten Formaten ist es ANH Berlin gelungen, seine Aktivitäten strukturell zu verstetigen. Auf Initiative des Netzwerks gründeten Unternehmen und Forschungseinrichtungen im Mai 2019 den Verein proANH e.V., um Fachkräfte im Cluster Optik & Photonik zu sichern. Geschäftsführungen und Personalverantwortliche stehen unter immer größerem Druck geeignete Fachkräfte zu finden. Mit vereinten Kräften wollen sie dieser Herausforderung nun besser begegnen. Die Senatsverwaltung für Wirtschaft, Energie und Betriebe unterstützt den Verein mit Mitteln zur Verbesserung der regionalen Wirtschaftsstruktur (GRW). Zusätzlich zur Projektfinanzierung wird das Netzwerk erstmalig seit der Gründung auch über Mitgliedsbeiträge von Unternehmen gestützt.

Erfolgreich beendete Projekte in 2019

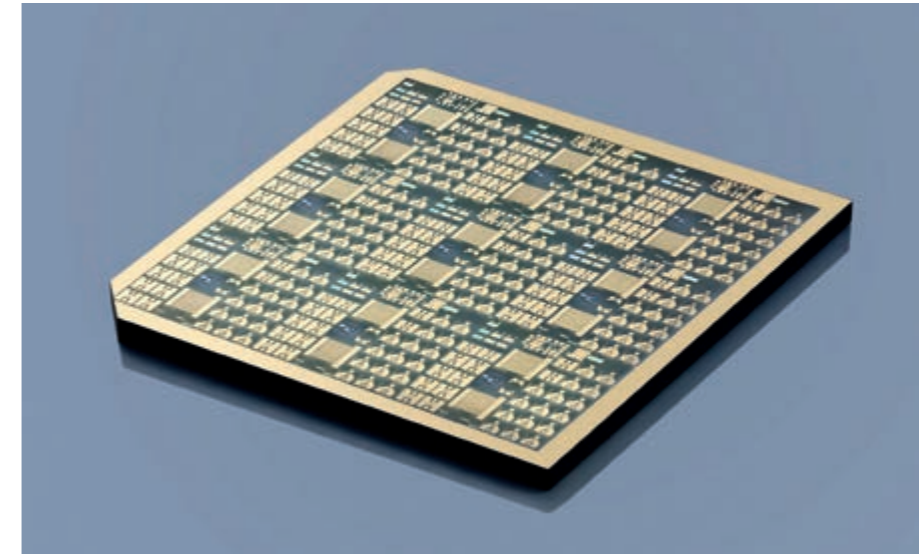
- **HAI** Hightech-Ausbildung in Berlin-Brandenburg
- **beMINT**. Berufsperspektiven zum Anfassen
- **PHABLABS 4.0** Photonik in FabLabs kennenlernen

Projekt in der Konzeptionsphase in 2019

- **BM=x³** attraktive berufliche Bildung in Mikro- und Nanotechnologie durch exzellente Berufe, exzellente Lernorte und exzellente Kooperationen



Highlights Schlaglichter



← Gallium oxide chip with transistor and measurement structures, produced at the FBH using projection lithography.
Galliumoxid-Chip mit Transistor- und Messstrukturen, hergestellt am FBH mittels Projektionsbelichtung.

New materials for communications of the future and digital transformation

FBH is constantly pushing the performance limits of established devices and is simultaneously investigating novel materials and components. The latter are indispensable for communications of the future, digital transformation of society, and applications of artificial intelligence. Power devices should be able to achieve ever higher power densities on the smallest possible area while consuming as little energy as possible, thus operating more efficiently. The material properties of the semiconductors beta-gallium oxide and aluminum nitride promise a high potential for realizing novel electronic power devices with outstanding efficiencies.

Gallium oxide – for next-generation power electronics

With a breakdown voltage of 1.8 kV and a record output power of 155 MW per square centimeter, beta-gallium oxide power transistors developed by the FBH have already achieved worldwide unparalleled key figures. With them, high voltages could be switched with considerably less material expenditure – the basis for more compact, high-performance systems. For this purpose, the FBH team improved layer structure and gate topology. Substrates from the Leibniz Institute for Crystal Growth (IKZ) with an optimized epitaxial layer structure provided the basis. Together with the IKZ and other partners, the high breakdown field strength of the material is to be used even more efficiently in the future through a vertical device structure within

the ForMikro-GoNext joint project – funded by the Federal Ministry of Education and Research (BMBF) with around 2 million euros over four years.

Aluminum nitride – developing the material for efficient power transistors

In the FBH-coordinated ForMikro-LeitBAN project, efficient power transistors based on aluminum nitride are to create the prerequisites for a variety of new applications – from e-mobility to artificial intelligence. The material will be tested in the project with suitable devices and qualified in systems for future applications. The semiconductor material aluminum nitride (AlN), which has been investigated only to a limited extent for electronic applications so far, offers up to 10,000 times less conduction loss as compared to silicon devices. It is also characterized by very high breakdown field strength and thermal conductivity – thus offering ideal prerequisites for power semiconductors with high power density and efficiency. Free-standing insulating AlN wafers will be used and qualified as the material basis. Compared to AlN epitaxy on foreign substrates such as silicon carbide, the dislocation density can be reduced by five orders of magnitude. This offers the potential for fast and efficient switching devices with simultaneously high reliability. ForMikro-LeitBAN is funded by the BMBF with 3.3 million euros until 2023.

Neue Materialien für die Kommunikation der Zukunft und den digitalen Wandel

Das FBH reizt die Leistungsgrenzen etablierter Bauelemente immer weiter aus und forscht zugleich an neuartigen Materialien und Bauelementen. Diese sind unerlässlich für die Kommunikation der Zukunft, für den digitalen Wandel der Gesellschaft und Anwendungen der künstlichen Intelligenz. Auf möglichst wenig Fläche sollen Leistungsbaulemente bei niedrigem Energieverbrauch immer höhere Leistungsdichten erreichen und damit effizienter arbeiten. Die Materialeigenschaften der Halbleiter Beta-Galliumoxid und Aluminiumnitrid versprechen hierbei ein hohes Potenzial, um neuartige elektronische Leistungsbaulemente mit herausragenden Wirkungsgraden zu realisieren.

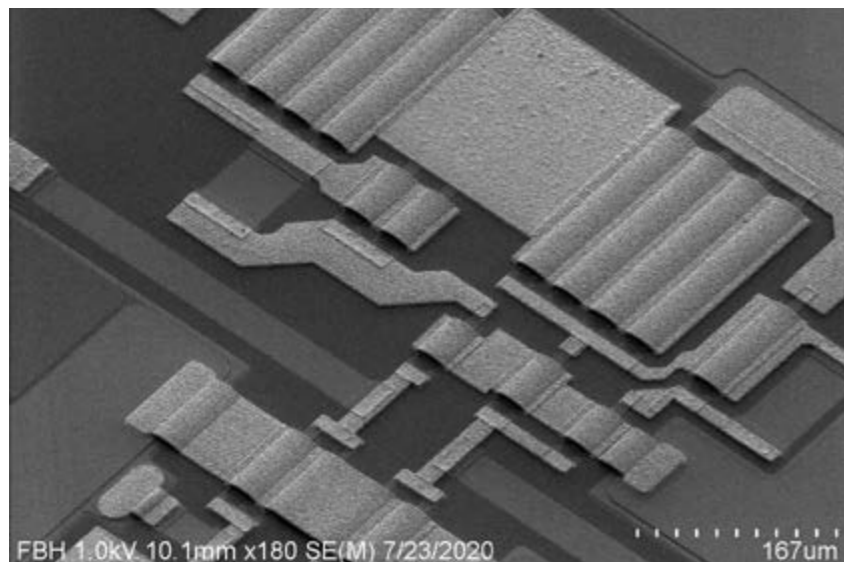
Galliumoxid – für die Leistungselektronik der nächsten Generation

Mit 1,8 kV Durchbruchspannung und einer Rekord-Leistung von 155 MW pro Quadratzentimeter erreichten am FBH entwickelte Beta-Galliumoxid-Leistungstransistoren bereits weltweit einzigartige Kennzahlen. Mit ihnen könnten hohe Spannungen mit deutlich geringerem Materialaufwand geschaltet werden – die Basis für kompaktere, leistungsfähige Systeme. Das FBH-Team verbesserte dazu Schichtstruktur und Gate-Topologie. Die Basis lieferten Substrate aus dem Leibniz-Institut für Kristallzüchtung (IKZ) mit einer optimierten epitaktischen Schichtstruktur. Gemeinsam mit dem IKZ und weiteren Partnern soll die hohe Durchbruchfeldstärke des Materials durch eine vertikale Bauelementstruktur im Verbundprojekt ForMikro-GoNext künftig noch effizienter genutzt werden – gefördert vom Bundesministerium für Bildung und Forschung (BMBF) mit rund 2 Millionen Euro über vier Jahre.

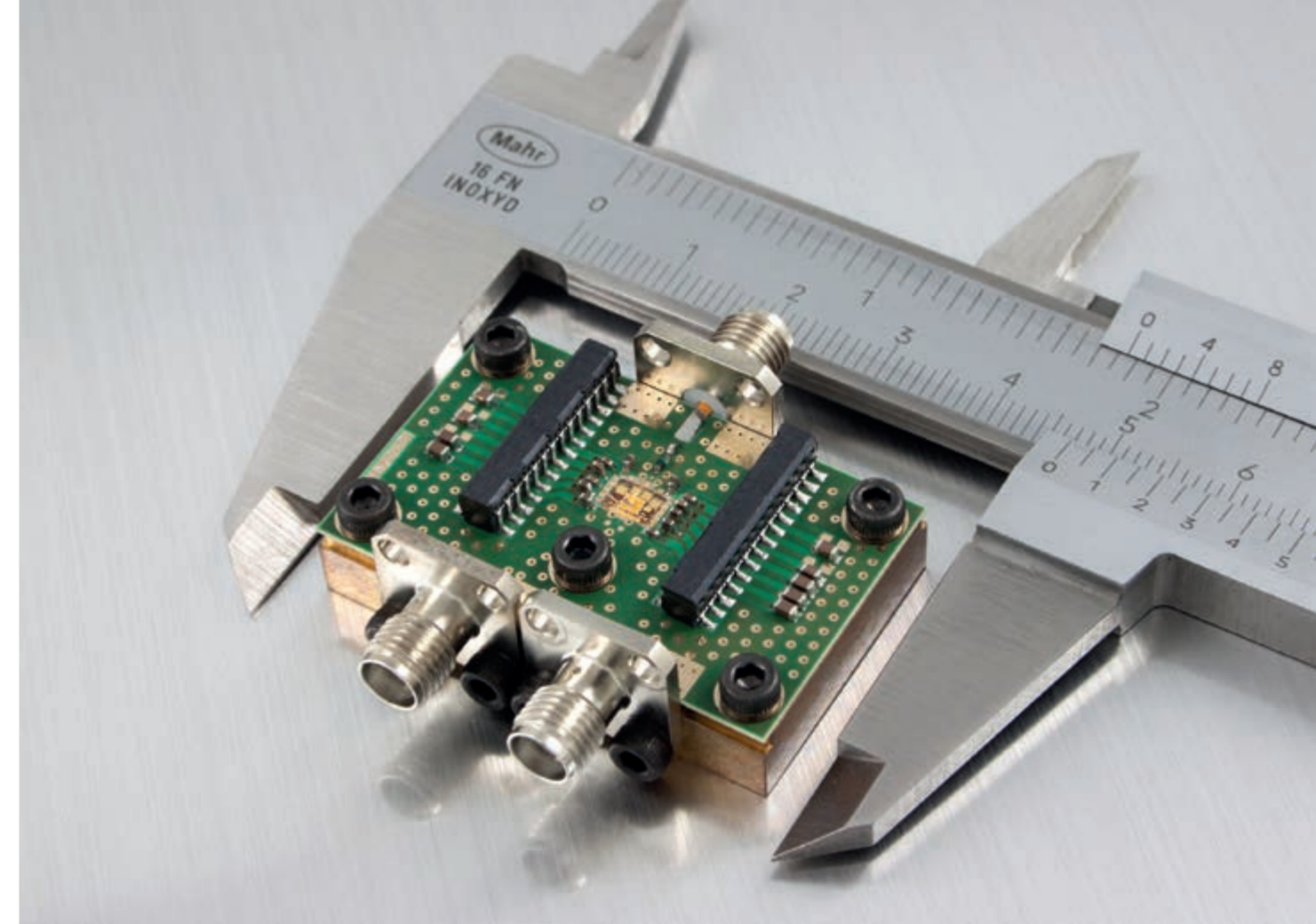
Aluminiumnitrid – das Material für effiziente Leistungstransistoren erschließen

In dem vom FBH koordinierten Vorhaben ForMikro-LeitBAN sollen effiziente Leistungstransistoren auf Basis von Aluminiumnitrid die Voraussetzungen für vielfältige neue Anwendungen schaffen – von der Elektromobilität bis hin zur künstlichen Intelligenz. Das Material soll im Projekt an geeigneten Bauelementen getestet und in Systemen für die zukünftigen Anwendungen qualifiziert werden. Das für elektronische Anwendungen bislang wenig erforschte Halbleitermaterial Aluminiumnitrid (AlN) bietet verglichen mit Silizium-Bauelementen einen bis zu 10.000-mal geringeren Durchlassverlust. Es zeichnet sich zudem durch eine sehr hohe Durchbruchspannungsfestigkeit und Wärmeleitfähigkeit aus – ideale Voraussetzungen für Leistungshalbleiter mit hoher Energiedichte und Effizienz. Freistehende isolierende AlN-Wafer sollen als Materialbasis eingesetzt und qualifiziert werden. Gegenüber einer AlN-Epitaxie auf Fremdsubstraten, wie etwa Siliziumkarbid, kann die Versetzungsdichte um fünf Größenordnungen reduziert werden. Das bietet das Potenzial für schnell und effizient schaltende Bauelemente bei gleichzeitig hoher Zuverlässigkeit. ForMikro-LeitBAN wird vom BMBF bis 2023 mit 3,3 Millionen Euro gefördert.

» Aluminiumnitrid bietet verglichen mit Silizium-Bauelementen einen bis zu 10.000-mal geringeren Durchlassverlust.



Power half bridge with gate drivers from an AlN-based 30 GHz MMIC. Leistungshalbbrücke mit Gatetreibern aus einem AlN-basierten 30 GHz MMIC.



Digital power amplifier for mobile communications. Digitaler Leistungsverstärker für die mobile Kommunikation.

Solutions for digitization and fast data transmission

Telecommunication providers are currently establishing the next standard in mobile communications: 5G promises super-fast data transmission in real time – with reduced energy consumption. This, however, is a paradox, since the extended technical possibilities will increase the consumption of electrical energy at first. According to a study conducted by energy supplier Eon, 5G will boost the energy demand of data centers alone by 3.8 billion kilowatt hours. This corresponds roughly to the annual power consumption of three major cities – and this does not even include the operation of the wireless infrastructure, the base stations and their interconnections.

In this context, the FBH systematically implements digitization down to the component level: Digital power amplifiers developed at FBH using efficient amplifier chips are ideally suited for broadband 5G applications. They are not only particularly capable, but also help to reduce the power consumption of modern information and communication technologies in terms of Green IT. Among other things, the institute has realized the first fully digital transmitter chain that successfully transmits broadband signals with highest efficiency and linearity (47 % at >52 dB ACLR). The compact digital transmitter is particularly

suitable for integration with antennas, which is interesting, for example, for multi-antenna systems (massive MIMO).

The FBH is also investigating energy-efficient amplifier concepts for higher signal widths in the sub-terahertz (THz) range above 100 GHz. Resource-friendly, high-frequency power amplifiers have a great potential to reduce power consumption and operating costs, since transmission amplifiers in communication systems often consume the largest share of energy.

Testing 5G components

To test 5G components, the FBH is currently setting up a worldwide unique measurement system for broadband multi-channel transmitters for 5G MIMO and space applications. This allows to characterize several MMIC amplifier channels simultaneously and thus to evaluate MIMO configurations, for example. It also enables further research in the field of broadband measurement techniques. This 5G-MIMO measurement system offers unique measurement capabilities not only to the FBH and its customers, but also the partner institutes that have joined forces within Research Fab Microelectronics Germany (FMD).

Lösungen für Digitalisierung und schnelle Datenübertragung

Telekommunikationsanbieter etablieren zurzeit den nächsten Standard im Mobilfunk: 5G verspricht superschnelle Datenübertragung in Echtzeit – bei reduziertem Energieverbrauch. Dies ist ein Widerspruch, denn die erweiterten technischen Möglichkeiten werden den Energieverbrauch zunächst steigern. Laut einer Studie des Energieanbieters Eon wird allein der Energiebedarf der Rechenzentren durch 5G um 3,8 Milliarden Kilowattstunden steigen. Das entspricht in etwa dem jährlichen Stromverbrauch von drei Großstädten – und hierbei ist der Betrieb der drahtlosen Infrastruktur, der Basisstationen und ihrer Vernetzung noch gar nicht berücksichtigt.

In diesem Zusammenhang setzt das FBH die Digitalisierung konsequent bis zur Komponentenebene um: Am FBH entwickelte digitale Leistungsverstärker mit effizienten Verstärker-Chips eignen sich ideal für breitbandige 5G-Anwendungen. Sie sind nicht nur besonders leistungsfähig, sondern helfen auch, den Stromverbrauch moderner Informations- und Kommunikationstechnologien im Sinne einer Green-IT zu reduzieren. Unter anderem hat das Institut die erste voll-digitale Transmitterkette realisiert, die breitbandige Signale mit höchster Effizienz und Linearität (47% bei >52 dB ACLR) erfolgreich überträgt. Der kompakte digitale Transmitter eignet

sich besonders für die Integration mit Antennen, was beispielsweise für Mehrantennensysteme (Massive MIMO) interessant ist.

Auch energieeffiziente Verstärkerkonzepte für höhere Signalbreiten im Sub-Terahertz (THz)-Bereich ab 100 GHz untersucht das FBH. Ressourcenschonende Hochfrequenz-Leistungsverstärker bieten großes Potenzial, Stromverbrauch und Betriebskosten zu senken, da Sende-Verstärker in Kommunikationssystemen in vielen Fällen den Großteil der Energie verbrauchen.

5G-Komponenten testen

Um 5G-Komponenten testen zu können, baut das FBH derzeit ein weltweit einzigartiges Messsystem für breitbandige Mehrkanal-Transmitter für 5G-MIMO- und Weltraumanwendungen auf. Damit können mehrere MMIC-Verstärker-Kanäle simultan charakterisiert und so zum Beispiel MIMO-Anordnungen evaluiert werden. Zudem ermöglicht es weitere Forschungen im Bereich von Breitband-Messtechniken. Dieses 5G-MIMO-Messsystem bietet nicht nur dem FBH und seinen Kunden einzigartige Messmöglichkeiten, sondern auch den Partnerinstituten, die sich in der Forschungsfabrik Mikroelektronik Deutschland (FMD) zusammengeschlossen haben.

Productive partnership – Research Fab Microelectronics Germany



Since April 2017, the Ferdinand Braun Institute has been a part of BMBF's Research Fab Microelectronics Germany (FMD) initiative – the largest R&D alliance for microelectronics and nanoelectronics in Europe comprising 13 members and over 2,000 scientists. Together with its partner institutes, the FBH is not only expanding its activities in the field of mobile communications of the future, but also in further topical fields such as sensor technology for autonomous driving and industry 4.0. In 2019, the FBH has presented its R&D results several times at trade fairs with joint FMD stands, for example at the MikroSystemTechnik Congress in Berlin and the European Microwave Week in Paris. FBH was also represented at the second FMD Innovation Day.

Creating synergies – through cross-site developments

The novel FMD concept for cross-site cooperation is proving to be successful. Joint projects, which were already launched in 2019, illustrate this. These include a LiDAR (Light Detection and Ranging) demonstrator produced by the start-up OQmented as part of the FMD Space program. The demonstrator consists of components from FBH and further FMD partner institutes and features a very large angular range compared to the state of the art. This feature is necessary to reliably detect objects in a wider surrounding in the future – and the prerequisite for permanent use of LiDAR technology in the field of autonomous driving. The demonstrator shows potential customers the development status of the components in actual applications. In particular, the advantages of wavelength-stabilized pulsed lasers with their narrow spectral linewidths can be demonstrated. Therefore, the LiDAR sensor can also be operated without temperature stabilization and achieves good signal-to-noise ratios despite strong solar irradiation.

»» The FBH systematically implements digitization down to the component level.



» The novel 5G-MIMO measurement system at FBH offers unique characterization capabilities.
Das neuartige 5G-MIMO-Messsystem am FBH bietet einzigartige Charakterisierungsmöglichkeiten.

Furthermore, the miniLiDAR project was launched at the end of 2019. Lead-managed by an industrial partner, FBH is developing a miniaturized LiDAR system for robotics together with the Fraunhofer Institutes IPMS, IZM and IMS. FBH designs and produces the required wavelength-stabilized pulsed lasers including the adapted pulse control electronics. The challenge for FBH is to significantly improve the beam quality of the laser chips in order to better focus the beam. This will allow to substantially increase the detection range.

To be able to control and monitor such processes, in which several partners are involved, even better in the future, the FMD institutes are currently implementing a uniform Manufacturing Execution System - MES (for details see subsequent text on digitization). With this system, plant and process data can be captured online and processed across different institutes.

Modernization of technology equipment is proceeding at top speed – new cleanroom at FBH

In the future, the Ferdinand-Braun-Institut will have about 1,000 square meters of additional space available for state-of-the-art technology development and fabrication. The newly procured large-scale facilities for the production of micro- and nanostructures for semiconductor devices are currently being installed and put into operation. These include a wafer stepper, an electron beam lithography system, and a high-temperature ion implanter as well as equipment for plasma etching, sputter coating, and electroplating. In addition, the equipment for RF measurement technology is also being updated and expanded. The Federal Ministry of Education and Research (BMBF) is supporting the idea of successfully conducting research and development across several locations with about 350 million euros until the end of 2020 – the FBH is investing about 34 million of this amount in the modernization of its R&D facilities.

Produktive Partnerschaft – Forschungsfabrik Mikroelektronik Deutschland

Das Ferdinand-Braun-Institut ist seit April 2017 Teil der BMBF-Initiative Forschungsfabrik Mikroelektronik Deutschland (FMD) – dem mit 13 Mitgliedern und über 2.000 Wissenschaftlerinnen und Wissenschaftlern größten F&E-Zusammenschluss für die Mikro- und Nanoelektronik in Europa. Gemeinsam mit den Partnerinstituten erweitert das FBH in diesem Rahmen nicht nur seine Aktivitäten zur mobilen Kommunikation der Zukunft, sondern auch zu weiteren Themenfeldern wie Sensorik für autonomes Fahren und Industrie 4.0. Auf Messen mit Gemeinschaftsständen der FMD hat das FBH 2019 mehrfach seine F&E-Ergebnisse präsentiert, etwa auf dem MikroSystemTechnik Kongress in Berlin und der European Microwave Week in Paris. Auch auf dem zweiten Innovation Day der FMD war das FBH vertreten.



FBH exhibits at the European Microwave Week 2019 in Paris. Exponate des FBH auf der European Microwave Week 2019 in Paris.

Synergien schaffen – durch standortübergreifende Entwicklungen

Das neuartige FMD-Konzept für die standortübergreifende Zusammenarbeit ist erfolgreich. Dies zeigen gemeinsame Projekte, die bereits 2019 gestartet sind. Dazu zählt ein LiDAR-Demonstrator (Light Detection and Ranging), der im Rahmen des FMD-Space-Programms von dem Start-up OQmented gefertigt wird. Der Demonstrator besteht aus Komponenten des FBH und weiteren FMD-Partnerinstituten und bietet einen sehr großen Winkelbereich verglichen mit dem Stand der Technik. Dieser ist notwendig, um Objekte künftig auch in einem größeren Umgebungsbereich sicher erfassen zu können – die Voraussetzung für den permanenten Einsatz der LiDAR-Technik im Bereich des autonomen Fahrens. Der

Demonstrator zeigt potenziellen Kunden den Entwicklungsstand der Komponenten in der realen Anwendung. Insbesondere können die Vorteile wellenlängenstabilisierter Puls laser mit ihren geringen spektralen Bandbreiten demonstriert werden. Dadurch kann der LiDAR-Sensor auch ohne Temperaturstabilisation betrieben werden und erzielt trotz starker Sonneneinstrahlung gute Signal-zu-Rauschverhältnisse.

Ende 2019 ist zudem das Projekt miniLiDAR gestartet. Unter Federführung eines Industriepartners entwickelt das FBH zusammen mit den Fraunhofer-Instituten IPMS, IZM und IMS ein miniaturisiertes LiDAR-System für die Robotik. Das FBH designt und realisiert die hierfür benötigten wellenlängenstabilisierten Puls laser inklusive der adaptierten Impulsansteuerelektronik. Die Herausforderung für das FBH besteht darin, die Strahlgröße der Laserchips wesentlich zu verbessern, um den Strahl besser fokussieren zu können. Dadurch lässt sich die Detektionsreichweite substantiell erhöhen.

Um derartige Prozesse, in die mehrere Partner eingebunden sind, künftig noch besser steuern und überwachen zu können, implementieren die FMD-Institute zurzeit ein einheitliches Manufacturing Execution System – MES (Details dazu im nachfolgenden Text zur Digitalisierung). Damit können Anlagen- und Prozessdaten online erfasst und institutsübergreifend verarbeitet werden.

Modernisierung der Anlagentechnik läuft auf Hochtouren – neuer Reinraum am FBH

Künftig stehen dem Ferdinand-Braun-Institut etwa 1.000 qm zusätzliche Fläche für die Technologieentwicklung und -fertigung auf dem neuesten Stand der Technik zur Verfügung. Die neu beschafften Großanlagen zum Erzeugen von Mikro- und Nanostrukturen für Halbleiterbauelemente werden derzeit installiert und in Betrieb genommen. Dazu zählen Waferstepper, Elektronenstrahlschreiber, Hochtemperatur-Ionenimplanter ebenso wie Anlagen zum Plasmaätzen oder zur Sputterbeschichtung und zur galvanischen Schichtabscheidung. Darüber hinaus wird auch das Equipment für die Hochfrequenz-Messtechnik upgedatet und erweitert. Die Idee, Forschung und Entwicklung über mehrere Standorte hinweg erfolgreich zu betreiben, unterstützt das Bundesministerium für Bildung und Forschung (BMBF) mit rund 350 Millionen Euro bis Ende 2020 – etwa 34 Millionen davon investiert das FBH in die Modernisierung seiner Forschungsausstattung.



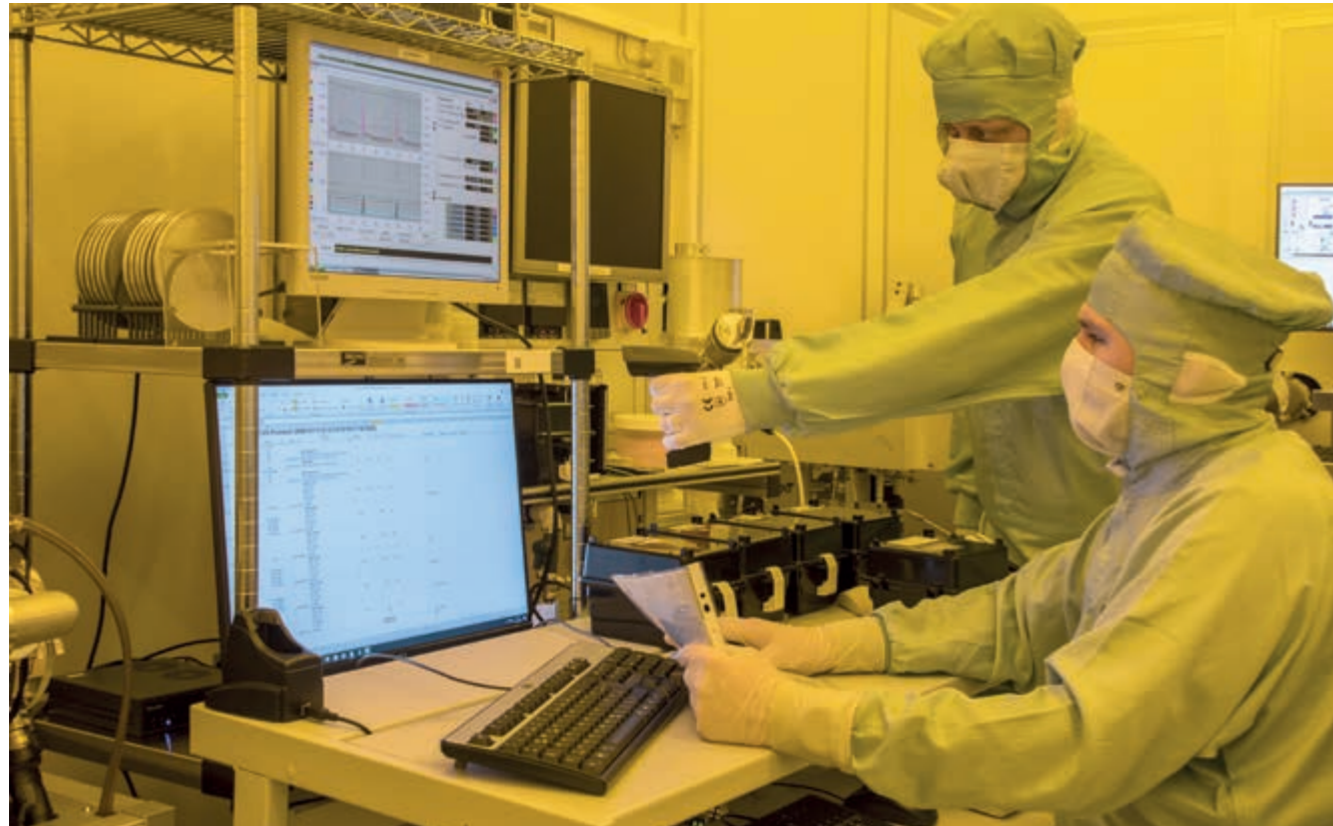
Single-emitter line scanner for automotive LiDAR – in the foreground one can see the vertical beam shaping of the pulsed diode laser source using a cylindrical lens. Einzelemittler-Linienscanner für Automotive LiDAR – vorne zu sehen ist die vertikale Strahlformung der gepulsten Diodenlaser-Quelle mittels einer Zylinderlinse.



At the beginning of 2020, the new equipment for electroplating and wet-chemical wafer processing for the new FBH cleanroom was delivered. Anfang 2020 wurden die neuen Anlagen zur galvanischen Schichtabscheidung und nass-chemischen Waferbearbeitung für den neuen FBH-Reinraum geliefert.



Delivery of the new electron beam lithography system in June 2020. Anlieferung des neuen Elektronenstrahlschreibers im Juni 2020.



Employees are testing a barcode scanner to capture plant data and accompanying process information.
Mitarbeiter erproben einen Barcode-Scanner zum Erfassen von Anlagendaten und Prozessbegleitinformationen.

The cleanroom becomes digital – seamless processes monitoring and quality control

Digitization and the Internet of Things (IoT) are currently revolutionizing processes in production halls and laboratories worldwide. According to the lab 4.0 model, FBH is currently transferring its production processes to a Manufacturing Execution System (MES) within the framework of Research Fab Microelectronics Germany (FMD). Production processes will then be mapped and controlled completely digitally, from wafer to component – and even across several FMD institutes. Product data can be traced back to the exact device, and processes can be monitored and optimized. Since potential sources of error – such as transmission mistakes caused by manual recording of process flows on paper – are eliminated, quality increases as well. Not least, customers benefit from this digitization, as they get pilot series and individual products with previously unattained efficiency and quality – digitally documented from start to end.

In the institute itself, resources can be planned more efficiently thanks to the MES, since information on plant capacities is available in one central location. Redundant capturing of process and plant data as previously carried out is thus no longer necessary. This saves time and helps to prevent errors. Since the corresponding data is stored centrally and metadata can

be assigned, processes can also be statistically evaluated and optimized. This opens up new prospects for correlating and analyzing data in order to gain new insights into tolerances and reciprocal effects of process steps. Handling of recipes for the individual process steps can be maintained centrally and can be tracked via version control. This feature is particularly advantageous with regard to stable device technologies, for example, if established manufacturing processes have to be reproduced and only slightly adapted. It is equally important for the research activities to allow sufficient flexibility in the MES for explorative work. With the extensive and constantly growing database, it must be possible to create new process sequences and recipe variants quickly and easily. The MES at FBH is therefore designed to meet both requirements explorative R&D on the one hand and application-oriented pilot production on the other.

iSensU – the smart solution for digital integration of legacy equipment

FBH pursues an all-encompassing digitization concept in manufacturing its electronic and optical components. This is why the FBH has developed iSensU (intelligent Sensor Unit) so that older equipment without embedded digital interface can also be

integrated. Thus, their data can also be acquired, processed and analyzed with the tool. This allows the FBH to digitally monitor the relevant equipment in its cleanrooms – an additional one is currently being put into operation. Moreover, iSensU provides an interface to the new MES; this is why the smart solution will also be implemented at the FMD partner institutes. Details about iSensU can be found on page 110.

FBH goes digital – an outstanding team effort

A task force has been established at FBH to acquire digital plant and process data efficiently. The interdisciplinary team comprises scientists, technical staff and IT specialists from almost all departments at FBH. It is planning and designing the framework conditions of the now digitized process flows. Thanks to the excellent team efforts, the project has been progressing rapidly under the project management of Dr. Til Bartel since July 2019.

FBH engineers have developed iSensU in this context. With the IoT tool, older plants can also be integrated into digital data acquisition – and can thus be digitally processed, evaluated and analyzed. The prerequisite for comprehensive digitization is an efficient and scalable IT infrastructure, which is provided by FBH's IT Services. The five-member team provides the accordingly configured hard- and software for the MES system and its databases as well as for the interfaces to the overall infrastructure.

Currently, group leaders, technology managers, and personnel responsible for sub-steps from the Process Technology Department are modelling exemplary wafer processing workflows. This involves assigning specific equipment and processing instructions to the wafers handled in the respective process flows and to collect process and equipment data. Moreover, new hardware, such as barcode scanners and tablets, is tested to automatically record logistical information.

The digitization of processes at the FBH is funded through the ERDF project "Application Laboratory III-V Components for Laser Technology and Electronics" and the BMBF project "Research Fab Microelectronics Germany".

» *FBH pursues an all-encompassing digitization concept in manufacturing its electronic and optical components.*

Der Reinraum wird digital – Prozesse lückenlos überwachen und Qualität sichern

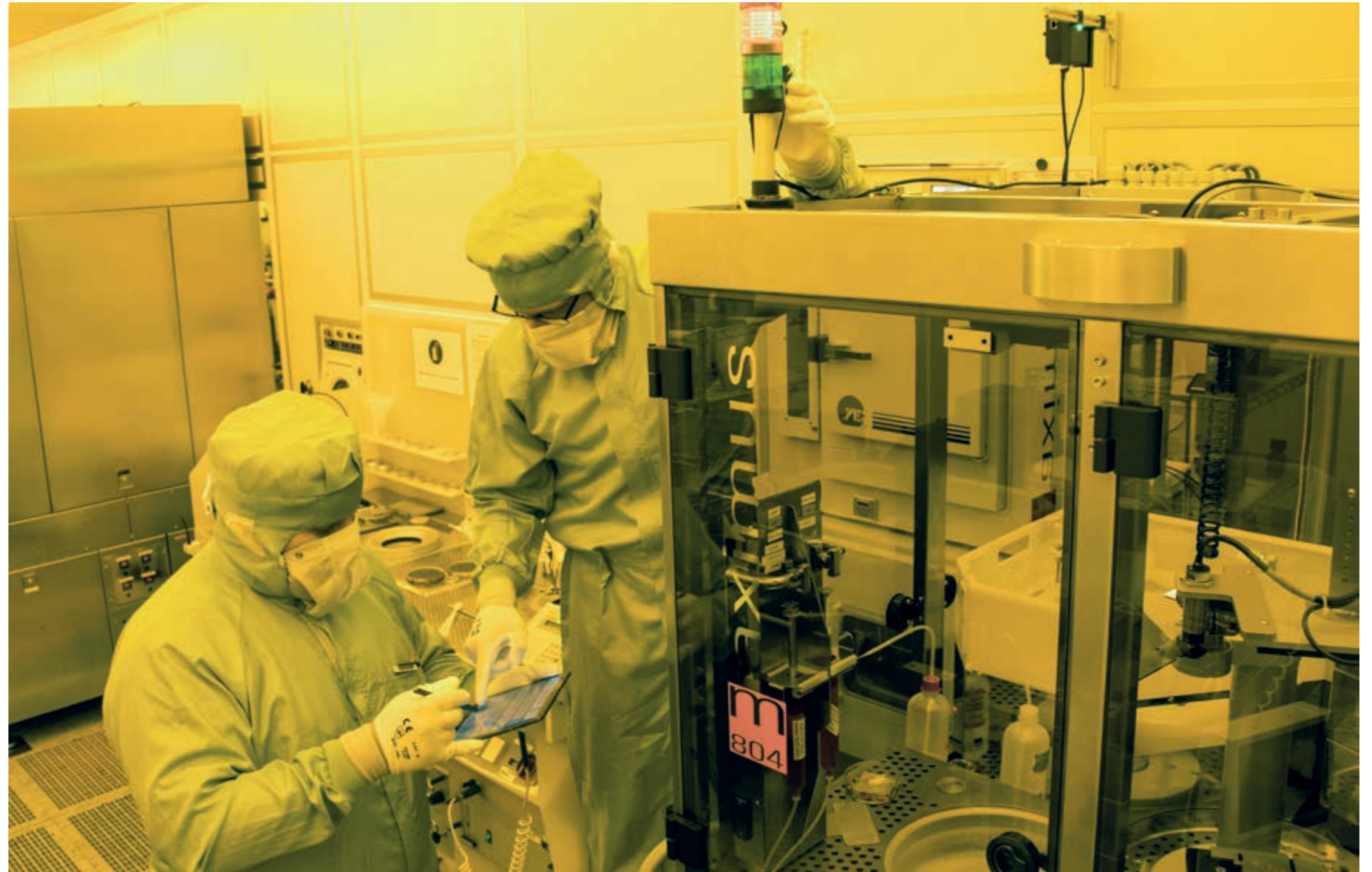
Digitalisierung und das Internet der Dinge (Internet of Things – IoT) revolutionieren derzeit weltweit die Prozesse in Produktionshallen und Laboren. Nach dem Leitbild des Lab 4.0 überführt das FBH im Rahmen der Forschungsfabrik Mikroelektronik Deutschland (FMD) seine Produktionsprozesse zurzeit in ein Manufacturing Execution System – MES. Fertigungsabläufe lassen sich so vom Wafer bis zum Bauelement vollständig digital abbilden und steuern – auch über mehrere Institute der FMD hinweg. Die Produktdaten können bauelementgenau zurückverfolgt sowie Prozesse überwacht und optimiert werden. Da Fehlerquellen – beispielsweise Übertragungsfehler durch manuelles Erfassen von Prozessabläufen auf Papier – entfallen, steigt auch die Qualität. Davon profitieren nicht zuletzt die Kunden, die Pilotserien oder Einzelprodukte in bisher unerreichter Effizienz und Qualität erhalten – digital dokumentiert von Anfang bis zum Ende.

Im Institut selbst lassen sich dank des MES Ressourcen besser planen, da Informationen zur Auslastung von Anlagen zentral

verfügbar werden. Dadurch entfällt das bisherige doppelte Erfassen von Prozess- und Anlagendaten. Das spart Zeit und hilft, Fehler zu vermeiden. Da die zugehörigen Daten zentral gespeichert und mit Metadaten versehen sind, lassen sich Prozesse zudem statistisch auswerten und optimieren. Es ergeben sich neue Möglichkeiten, Daten zueinander in Beziehung zu setzen und zu analysieren, um neue Erkenntnisse zu Toleranzen und Wechselwirkungen von Prozessschritten zu gewinnen. Die Bearbeitungsrezepturen der einzelnen Prozessschritte lassen sich zentral pflegen und sind über eine Versionskontrolle nachverfolgbar. Im Hinblick auf stabile Bauelementtechnologien ist dies besonders vorteilhaft, wenn etwa etablierte Fertigungsabläufe reproduziert und nur geringfügig angepasst werden müssen. Ebenso wichtig ist es für den Forschungsbetrieb, im MES genügend Flexibilität für explorative Arbeiten zu erlauben. Mit der umfangreichen und ständig wachsenden Datenbasis muss es möglich sein, schnell und einfach neue Prozessabläufe und Rezeptvarianten zu erstellen. Das MES am FBH wird daher so ausgelegt,



➊ Marco Spiesecke preparing a printed circuit board for integration into iSensU - with the IoT tool, data from older production plants without a digital interface can also be collected digitally.
Marco Spiesecke beim Vorbereiten einer Leiterplatte zum Einbau in iSensU – mit dem IoT-Tool können auch die Daten älterer Anlagen ohne digitale Schnittstelle digital erfasst werden.



➋ FBH colleagues are mounting a sensor for the trial operation of iSensU, which can be seen in the background at the top right of the wall. With this unit, operating conditions and other data of the coating system without integrated interface can also be collected digitally and analyzed using tablet or PC. FBH-Kollegen montieren einen Sensor für den Probetrieb von iSensU, der im Hintergrund oben rechts an der Wand zu sehen ist. Damit können Betriebszustände und weitere Daten der Belackungsanlage ohne integrierte Schnittstelle ebenfalls digital erfasst und auf Tablet oder PC ausgewertet werden.

dass es beiden Erfordernissen gerecht wird, der explorativen Forschung und Entwicklung einerseits und der industrienahen Pilotfertigung andererseits.

iSensU – die smarte Lösung, um ältere Anlagen digital einzubinden

Das FBH verfolgt ein allumfassendes Digitalisierungskonzept bei der Fertigung seiner elektronischen und optischen Bauelemente. Daher hat das FBH iSensU (intelligent Sensor Unit) entwickelt, um auch älteres Equipment ohne integrierte digitale Schnittstelle einbinden zu können. Das Tool ermöglicht es, auch deren Daten zu erfassen, zu verarbeiten und zu analysieren. Damit kann das FBH relevante Anlagen seiner Reinräume – ein weiterer wird zurzeit in Betrieb genommen – digital überwachen. iSensU bietet zudem eine Schnittstelle zum neuen MES, daher soll die smarte Lösung auch bei den Partnerinstituten der FMD eingeführt werden. Details zu iSensU gibt es auf Seite 110.

Das FBH wird digital – eine herausragende Teamleistung

Um digitale Anlagen- und Prozessdaten effizient zu erfassen, wurde am FBH eine Taskforce gegründet. Das interdisziplinäre Team besteht aus Wissenschaftlerinnen und Wissenschaftlern, technischen Mitarbeitenden und IT-Spezialisten aus nahezu allen Abteilungen des FBH. Es konzipiert und gestaltet die Rahmenbedingungen der nunmehr digitalisierten Prozessabläufe. Dank der exzellenten Teamleistung schreitet das Vorhaben unter der Projektleitung von Dr. Til Bartel seit Juli 2019 zügig voran.

In diesem Kontext haben Ingenieure des FBH iSensU entwickelt. Mit dem IoT-Tool lassen sich auch ältere Anlagen in die digitale Erfassung von Daten einbinden – und können so ebenfalls digital verarbeitet, ausgewertet und analysiert werden. Voraussetzung für die umfassende Digitalisierung ist eine leistungsfähige und skalierbare IT-Infrastruktur, die von den IT-Services am FBH bereitgestellt werden. Das fünfköpfige Team sorgt für die entsprechend konfigurierte Hard- und Software für das MES-System und dessen Datenbanken sowie für die Schnittstellen zur restlichen Infrastruktur.

Derzeit modellieren Gruppenleiter*innen, Teilschritt- und Technologieverantwortliche aus der Abteilung Prozesstechnologie beispielhaft die Abläufe bei der Waferbearbeitung. Hierbei werden den Wafern in Prozessflüssen, sogenannten „Flows“, bestimmte Anlagen und Bearbeitungsvorschriften zugeordnet sowie Prozess- und Anlagendaten erfasst. Parallel wird neue Hardware erprobt, wie etwa Barcode-Scanner und Tablets, um logistische Informationen automatisiert zu erfassen.

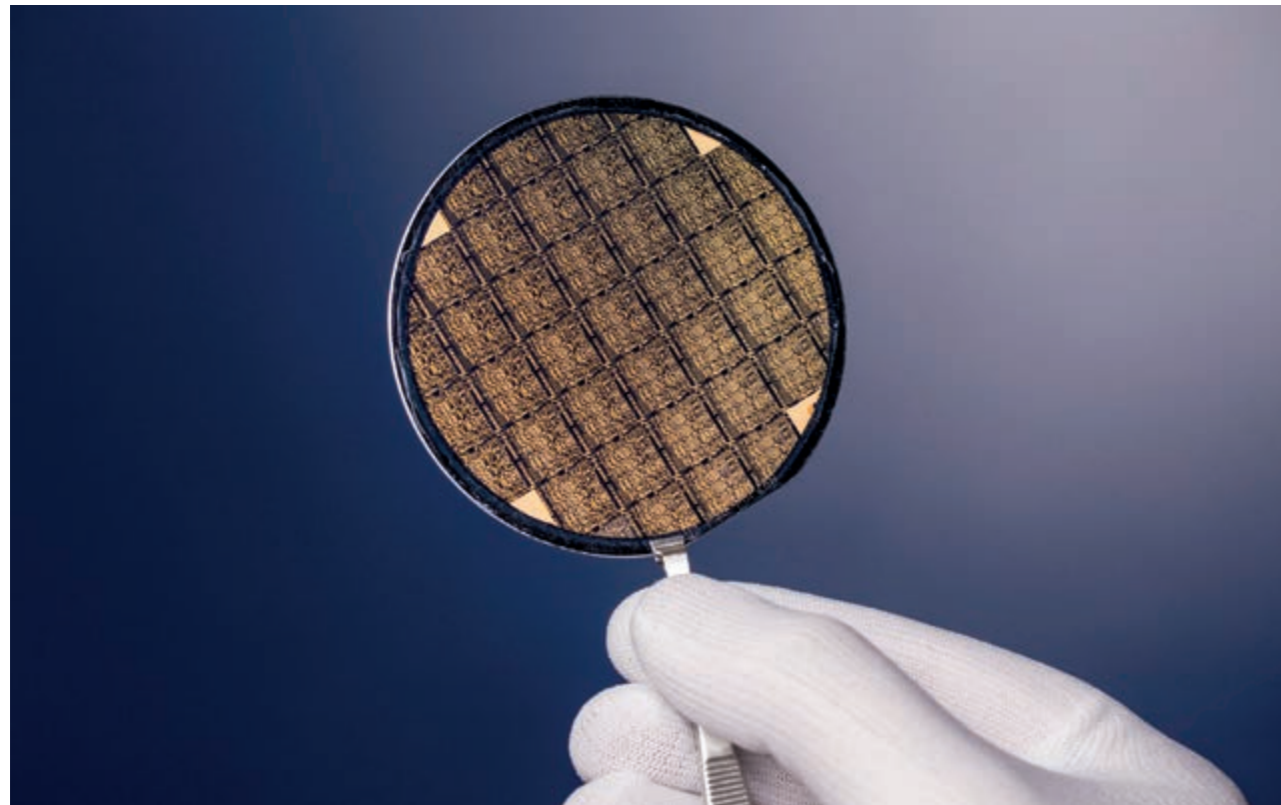
Die Digitalisierung der Prozesse am FBH wird finanziell gefördert durch das EFRE-Projekt „Applikationslabor III/V-Komponenten für Lasertechnik und Elektronik“ und durch das BMBF-Projekt „Forschungsfabrik Mikroelektronik Deutschland“.

New Joint Lab – indium phosphide based circuits for highest terahertz frequencies

In the field of III-V electronics, the FBH has established another Joint Lab - meanwhile the fourth in this research area. It combines the application-oriented activities of the InP Devices Lab at FBH, headed by Dr. Hady Yacoub, with the basic research conducted at the University of Duisburg-Essen (UDE). From the UDE side, the Joint Lab is coordinated by Prof. Nils Weimann, who is head of the Department of High Frequency Electronic Devices at UDE. The new Joint Lab InP Devices uses the complementary infrastructures of the FBH and UDE's Center for Semiconductor Technology and Optoelectronics (ZHO) and aims to transfer basic materials research into applied circuits and modules. The semiconductor material indium phosphide (InP), which is important for high-frequency applications, plays a crucial role here. With InP-based monolithic microwave integrated circuits (MMICs), the highest frequencies in the terahertz (THz) band can be achieved – currently only accessible on a laboratory scale with considerable effort – and thus new system applications can be implemented cost-effectively. Applications include non-destructive material testing, high-resolution medical imaging and broadband communication systems.

FBH's InP process technology is currently being considerably expanded within the framework of the German Federal Government's High-Tech Strategy. At ZHO, the crystal growth of InP semiconductor layers is being updated through an investment funded by the ForLab initiative of the Federal Ministry of Education and Research. In addition, a Terahertz Integration Center is being built at ZHO with ERDF funding from the government of North Rhine-Westphalia and the European Union to explore concepts for module integration of THz components.

» Mit InP-basierten monolithisch-integrierten Mikrowellenschaltkreisen lassen sich höchste Frequenzen im Terahertz-Band erreichen.



» Wafer with monolithically integrated InP transistor circuits. Wafer mit monolithisch-integrierten InP-Transistorschaltungen.

Neues Joint Lab – Indiumphosphid-basierte Schaltungen für höchste Terahertz-Frequenzen

In der III/V-Elektronik hat das FBH ein weiteres Joint Lab etabliert – das mittlerweile vierte in diesem Forschungsbereich. Es bündelt die bisherigen anwendungsbezogenen Aktivitäten des von Dr. Hady Yacoub geleiteten InP Devices Lab am FBH mit den grundlegenden Forschungsarbeiten der Universität Duisburg-Essen (UDE). Seitens der UDE wird das Joint Lab von Prof. Nils Weimann koordiniert, der dort das Fachgebiet Bauelemente der Höchstfrequenzelektronik leitet. Das neue Joint Lab InP Devices nutzt die komplementären Infrastrukturen des FBH und des Zentrums für Halbleitertechnik und Optoelektronik (ZHO) der UDE und will so grundlegende Materialforschung gezielt in angewandte Schaltkreise und Module umsetzen. Das für Höchstfrequenzanwendungen wichtige Halbleitermaterial Indiumphosphid (InP) spielt hierbei eine besondere Rolle. Mit InP-basierten monolithisch-integrierten Mikrowellenschaltkreisen (MMICs) lassen sich höchste Frequenzen im Terahertz-Band (THz) erreichen – dieses ist heute

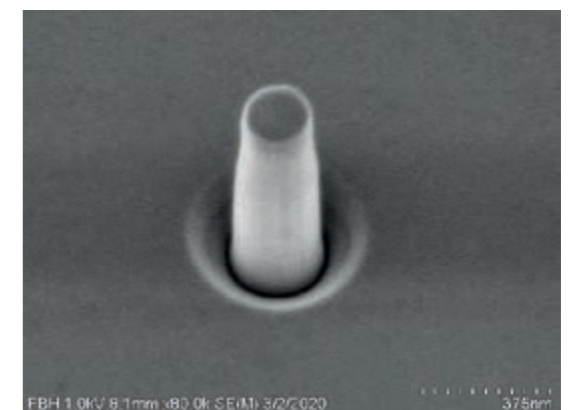
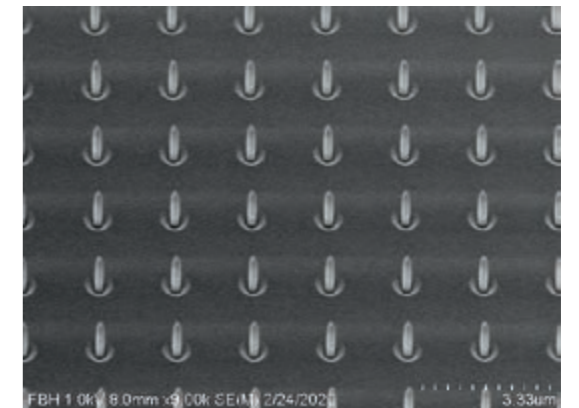
nur mit hohem Aufwand im Labormaßstab zugänglich – und somit neue Systemanwendungen kostengünstig realisieren. Die Applikationen liegen unter anderem in der zerstörungsfreien Materialprüfung, der hochauflösenden medizinischen Bildgebung sowie in Breitbandkommunikations-Systemen.

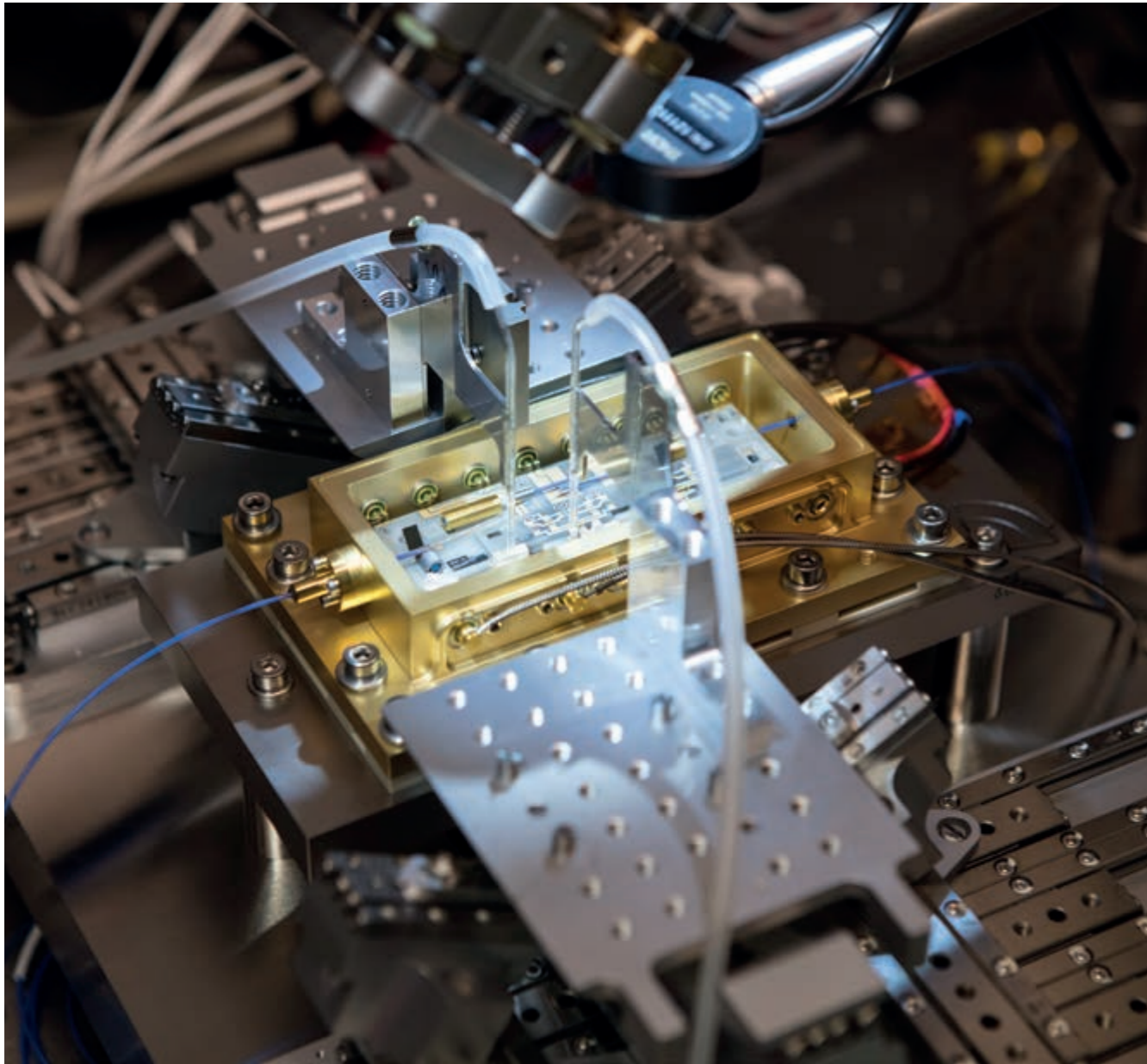
Die InP-Prozesstechnologie des FBH wird zurzeit in der Forschungsfabrik Mikroelektronik Deutschland im Rahmen der Hightech-Strategie der Bundesregierung erheblich ausgebaut. Im ZHO wird das Kristallwachstum von InP-Halbleiterschichten durch eine Investition im Rahmen der ForLab-Initiative des Bundesministeriums für Bildung und Forschung auf den neuesten Stand gebracht. Weiterhin entsteht am ZHO ein von der Landesregierung Nordrhein-Westfalen und der Europäischen Union mit EFRE-Mitteln gefördertes Terahertz-Integrationszentrum, um Konzepte zur Modulintegration von THz-Komponenten zu erforschen.

Transfer into industrial applications – new research area Integrated Quantum Technology

Since 2019, FBH has been establishing its new research area Integrated Quantum Technology, in which three Joint Labs with the Humboldt-Universität zu Berlin (HU Berlin) have meanwhile commenced their R&D activities. Currently, almost 30 colleagues are working in this research area at the Ferdinand-Braun-Institut. The partners cover the entire value chain – from concept development and demonstration to technology development and the final components and subsystems. The aim is to transfer proof-of-concept demonstrators of quantum technology (QT) from the laboratory into solutions suitable for industrial use. This will pave the way for the second quantum revolution into applications. Research is also being conducted into novel material

- » Array of diamond nanopillars (Ø approx. 250 nm, height 1.6 µm, lattice spacing 2 µm). Single nitrogen-vacancy defect centers are randomly incorporated in them and can be used as quantum memories (above). Nanopillar with flat top, which indicates a better process control (below). Array aus Diamant-Nanosäulen (Ø ca. 250 nm, Höhe 1,6 µm, Gitterabstand 2 µm). Einzelne Stickstoff-Fehlstelle-Defektzentren sind darin willkürlich eingebaut und können als Quantenspeicher genutzt werden (oben). Nanosäule mit flacher Oberseite, was auf eine bessere Prozesskontrolle schließen lässt (unten).





➤ Precision mounting of a hybrid-integrated laser module for space applications.
Präzisionsmontage eines hybrid-integrierten Lasermoduls für Weltraumanwendungen.

concepts with which light can be manipulated on the nano- and microscale.

Quantum technology uses the special properties of quantum mechanics and benefits from its specific effects and mechanisms, such as discrete energy levels, state superposition, quantum entanglement and the tunnel effect. Even minimal changes in environmental conditions significantly influence these states of quantum mechanics. Future quantum sensors, for example, which detect these changes in state, will therefore be much more sensitive than classical sensors.

Microintegration – key technology for space-suited laser modules with outstanding properties

Since 2008, FBH has been developing a unique microintegration technology especially designed for use in space. This know-how was developed within the framework of the first

Joint Lab with HU Berlin. Microintegration technology provides the basis for the compact and robust laser modules with ultra-narrowband emission, which are implemented as core components into the space-compatible systems of HU Berlin. These systems have already proven their capability several times in experiments in space.

In the coming years, more than 50 ultra-narrowband laser modules for the BECCAL (Bose-Einstein Condensate - Cold Atom Laboratory) apparatus will be developed, assembled and delivered. With BECCAL, the German Aerospace Center DLR and NASA intend to operate a research facility for quantum optical experiments with ultra-cold atoms on board the International Space Station ISS as of 2024. This will enable highly precise fundamental physics questions to be investigated with quantum objects close to absolute zero temperature (-273.15 °C).

In industrietaugliche Anwendungen überführen – neuer Forschungsbereich Integrierte Quantentechnologie

Seit 2019 baut das FBH seinen neuen Forschungsbereich Integrierte Quantentechnologie auf, in dem drei Joint Labs mit der Humboldt-Universität zu Berlin (HU Berlin) mittlerweile ihre F&E-Arbeiten aufgenommen haben. Derzeit arbeiten fast 30 Kolleginnen und Kollegen in diesem Forschungsbereich am Ferdinand-Braun-Institut. Dabei decken die Partner die gesamte Wertschöpfungskette ab – von der Konzeptentwicklung und Demonstration über die Technologieentwicklung bis hin zu den fertigen Komponenten und Subsystemen. Ziel ist es, Proof-of-Concept-Demonstratoren der Quantentechnologie (QT) aus dem Labor in industrietaugliche Lösungen zu überführen. Dies wird der zweiten Quantenrevolution den Weg in die Anwendungen ebnet. Erforscht werden zudem neuartige Materialkonzepte, mit denen Licht auf der Nano- und Mikroskala manipuliert werden kann.

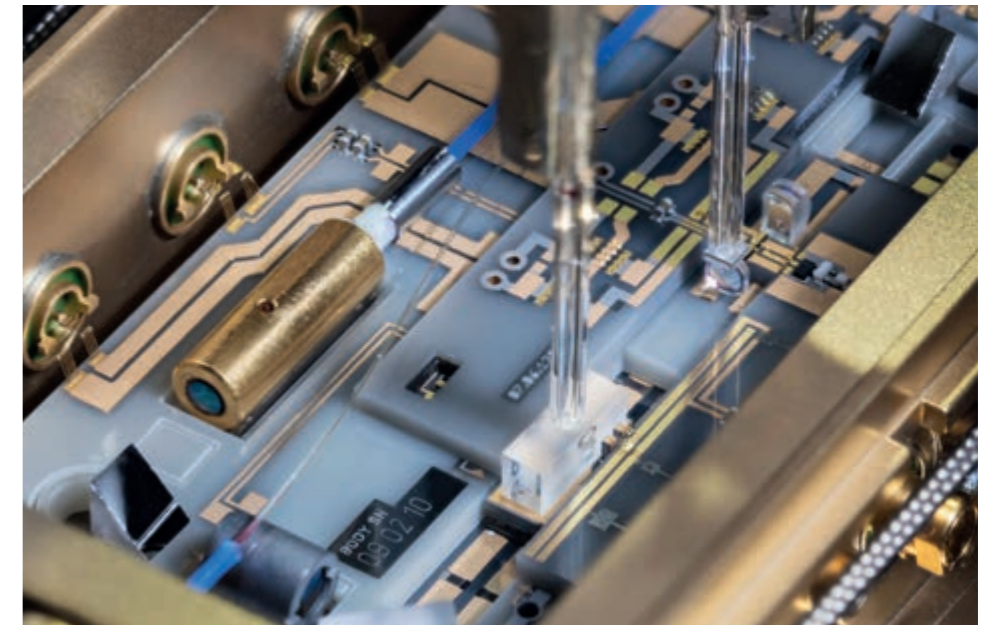
Die Quantentechnologie nutzt die besonderen Eigenschaften der Quantenmechanik und profitiert von deren spezifischen Effekten und Mechanismen: diskrete Energieniveaus, Zustandsüberlagerung, Quantenverschränkung oder der Tunneleffekt. Bereits minimale Änderungen der Umgebungsbedingungen beeinflussen diese Zustände der Quantenmechanik signifikant. Daher werden beispielsweise künftige Quantensensoren, die diese Zustandsänderungen detektieren, ungleich empfindlicher als klassische Sensoren sein.

Mikrointegration – Schlüsseltechnologie für weltraumtaugliche Lasermodule mit herausragenden Eigenschaften

Seit 2008 entwickelt das FBH eine einzigartige Mikrointegrationstechnologie, die insbesondere für den Einsatz im Weltraum entwickelt wurde. Dieses Know-how wurde im Rahmen des ersten Joint Labs mit der HU Berlin entwickelt. Die Mikrointegrationstechnologie liefert die Basis für die kompakten und robusten Lasermodule mit ultra-schmalbandiger Emission, die als Herzstücke in die weltraumtauglichen Systeme der HU Berlin implementiert werden. Bereits mehrfach haben diese Systeme ihre Leistungsfähigkeit bei Experimenten im Weltraum unter Beweis gestellt.

In den kommenden Jahren sollen mehr als 50 ultra-schmalbandige Lasermodule für die BECCAL-Apparatur (Bose-Einstein Condensate – Cold Atom Laboratory) entwickelt, aufgebaut und geliefert werden. Mit BECCAL wollen das Deutsche Zentrum für Luft- und Raumfahrt DLR und die NASA ab 2024 eine Forschungsanlage für quantenoptische Experimente mit ultrakalten Atomen an Bord der internationalen Raumstation ISS betreiben. Damit können hochgenau fundamentalphysikalische Fragestellungen mit Quantenobjekten nahe dem absoluten Temperaturnullpunkt (-273,15 °C) untersucht werden.

➤ Precision mounting of a grating (front) and a lens (rear) into a hybrid-integrated laser module – these components are used to precisely adjust the laser cavity.
Präzisionsmontage eines Gitters (vorne) und einer Linse (hinten) in einem hybrid-integrierten Lasermodul – mit diesen Komponenten wird der Laserresonator präzise justiert.



Competence in space – from optical communications over long distances to measurements of climate-relevant methane gas concentrations

The growing demand for optical communications between satellites is driving the development of space-suited diode-based laser systems. Large amounts of data need to be transmitted, for example, from earth exploration satellites. Also, optical networks are increasingly being installed in geostationary orbits. FBH has been developing laser diode benches (LDB) that are pumping solid-state lasers in space for many years. The Ferdinand-Braun-Institute's LDB technology is suitable for use in space. This is confirmed by comprehensive lifetime, irradiation and environmental testing including thermal cycling, mechanical vibrations and pyro shocks.

Coherent optical laser communication terminals (LCT) require extremely stable pump sources that operate at fixed wavelengths and with low noise in phase and amplitude over long mission periods of up to 15 years. These high requirements are also met by the pump module from the DLR-funded Radisat project. It was developed at FBH especially for use as transmitter and local oscillator in coherent inter-satellite communications over long distances (45,000 km). Centerpiece is a laser chip consisting of an array of ridge-waveguide lasers (RW) with monolithically integrated distributed Bragg reflectors (DBR-RW). The single-mode operation of each individual emitter in lateral and longitudinal direction ensures low-noise operation. Mode competition is eliminated, avoiding any bi-stability due to possible external feedback. The pump source, whose wavelength is stabilized at 808.5 nm, delivers an output power of 500 milliwatts in continuous wave operation at 45 °C. Further applications of the laser module are in space-based laser interferometry over long distances, space antennas for detecting gravitational waves, atmospheric trace gas measurement, light detection and distance measurement.



Robust laser technology for climate satellites

The Ferdinand-Braun-Institut has also developed and produced extremely reliable LDBs for MERLIN, the Franco-German climate satellite. MERLIN is due to be launched into space in 2025 to investigate the effect of the greenhouse gas methane on global warming. A radar-like laser system on the satellite will measure natural and man-made methane emissions: The Integrated Path Differential Absorption (IPDA) LiDAR sends laser beams to the Earth's surface and analyzes the backscattered signal.

Six of FBH's LDBs were recently integrated into three pump modules of the Fraunhofer ILT and delivered to the project partner ready for operation. The modules generate the necessary pump energy for the oscillator of a solid-state laser and

are integrated into the LiDAR system by ILT. With the laser diode benches, pump powers of more than 60 watts can be generated in double pulses with a repetition rate of 20 hertz and a pulse width of 150 microseconds. Thanks to the fast axis collimation lenses, the laser beam is coupled into an optical fiber with low loss. The laser diode benches were qualified after extensive internal testing by the European Space Research and Technology Centre ESTEC in the Netherlands. Their lifetime tests demonstrated that the power degrades only insignificantly even over a long operating time of more than four billion pulses. The scientists are therefore confident that the measuring system will function without failure even under space conditions.

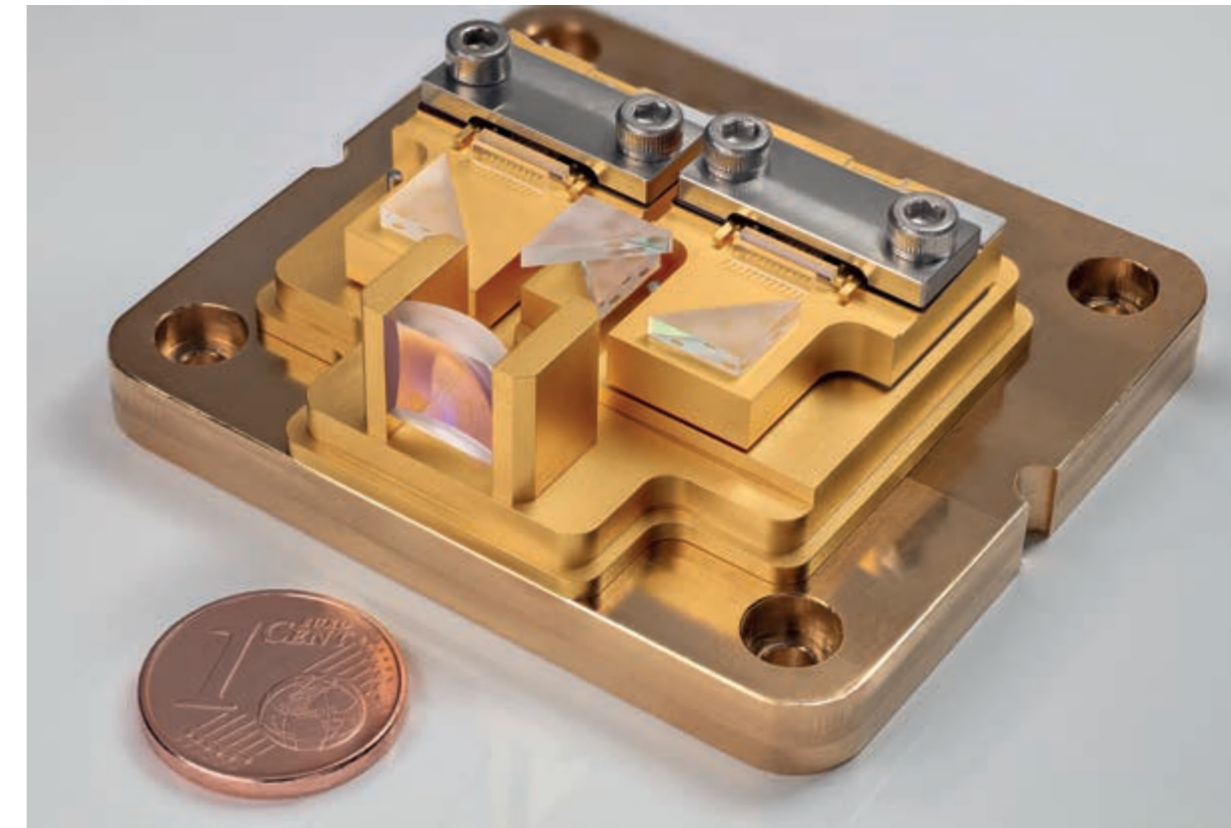
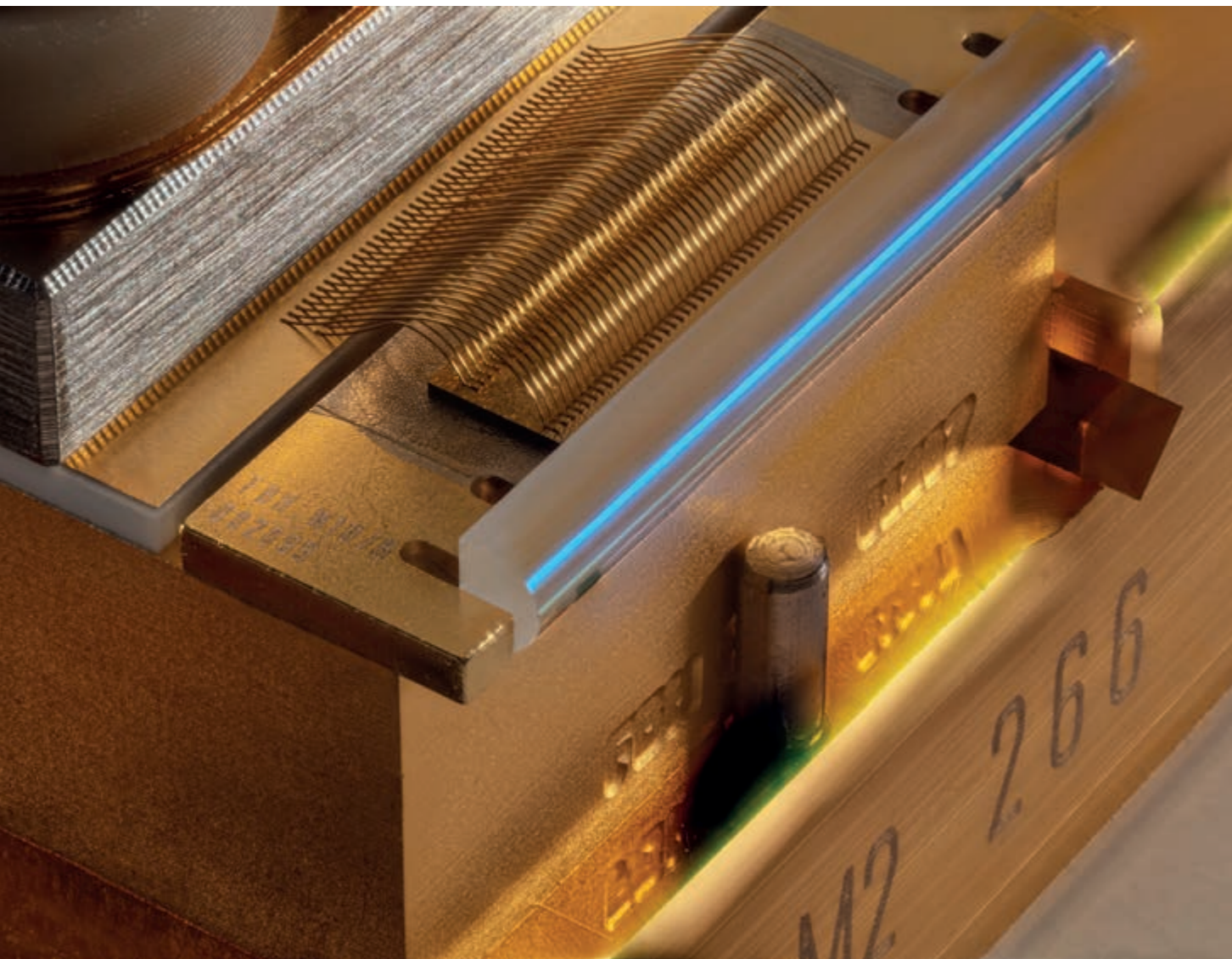


Illustration of the climate satellite MERLIN, which is designed to detect and monitor the greenhouse gas methane in the atmosphere. Illustration des Klimasatelliten MERLIN, der das Treibhausgas Methan in der Atmosphäre aufspüren und überwachen soll.

Radisat pump laser module on base plate – subsequently it is hermetically sealed and equipped with an optical fiber. Radisat-Pumplasermodul auf Basisplatte – anschließend wird es hermetisch versiegelt und mit einer optischen Faser versehen.

Kompetenz im Weltraum – von optischer Kommunikation über große Entfernungen bis zu Messungen klimarelevanter Konzentrationen von Methangas

Die steigende Nachfrage nach optischer Kommunikation zwischen Satelliten treibt die Entwicklung weltraumtauglicher diodenbasierter Lasersystemen an. So müssen beispielsweise große Datenmengen von Erkundungssatelliten übermittelt werden. Auch optische Netzwerke werden zunehmend bis in geostationäre Umlaufbahnen installiert. Seit vielen Jahren entwickelt das FBH Laserdiodenbänke (LDB) zum Pumpen von Festkörperlasern im Weltraum. Die LDB-Technologie am Ferdinand-Braun-Institut ist weltraumtauglich. Das bestätigen umfassende Lebensdauer-, Bestrahlungs- und Umwelttests einschließlich thermischer Wechselbeanspruchung, mechanischer Vibrationen und Pyroschocks.



🔗 Laser diode bench for the climate satellite MERLIN before integration into the pump module.
Laserdiodenbank für den Klimasatelliten MERLIN vor dem Einbau in das Pumpmodul.

» Seit vielen Jahren entwickelt das FBH Laserdiodenbänke (LDB) zum Pumpen von Festkörperlaser im Weltraum.

Kohärente optische Laserkommunikationsendgeräte (LCT) erfordern außerordentlich stabile Pumpquellen, die bei fester Wellenlänge und geringem Rauschen in Phase und Amplitude über lange Missionszeiten von bis zu 15 Jahren arbeiten. Diese hohen Anforderungen erfüllt auch das Pumpmodul aus dem DLR-geförderten Projekt Radisat. Es wurde am FBH speziell für den Einsatz als Sender und Lokoszillator in der kohärenten Intersatelliten-Kommunikation über große Entfernungen (45.000 km) entwickelt. Herzstück ist ein Laserchip, der aus einem Array von Rippenwellenleiterlasern (RW) mit monolithisch-integrierten, verteilten Bragg-Reflektoren (DBR-RW) besteht. Der Einzelmodenbetrieb jedes einzelnen Emitters in

lateral und longitudinaler Richtung sichert den rauscharmen Betrieb. Dabei wird die Modenkonzurrenz eliminiert, die jegliche Bi-Stabilität durch eventuelle externe Rückkopplung vermeidet. Die Pumpquelle, deren Wellenlänge auf 808,5 nm stabilisiert ist, liefert 500 Milliwatt Ausgangsleistung im Dauerstrichbetrieb bei 45 °C. Weitere Anwendungen des Lasermoduls liegen in der weltraumgestützten Laserinterferometrie über große Entfernungen, bei Weltraumantennen zur Detektion von Gravitationswellen, der atmosphärischen Spurengasmessung, Lichtdetektion und Entfernungsmessung.

Robuste Lasertechnik für Klimasatelliten

Auch für den deutsch-französischen Klimasatelliten MERLIN hat das Ferdinand-Braun-Institut extrem zuverlässige LDBs entwickelt und hergestellt. MERLIN soll 2025 ins All starten und die Wirkung des Klimagases Methan auf die Erderwärmung untersuchen. Auf dem Satellit misst ein radarähnliches Lasersystem natürliche und von Menschen verursachte Methanemissionen: Das Integrated Path Differential Absorption (IPDA)-LiDAR sendet dazu Laserstrahlen auf die Erdoberfläche und analysiert das zurückgestreute Signal.

Sechs der LDBs aus dem FBH wurden kürzlich in drei Pumpmodule des Fraunhofer-ILT integriert und einsatzbereit an den Projektpartner geliefert. Die Module erzeugen die notwendige Pumpenergie für den Oszillator eines Festkörperlaser und werden vom ILT in das LiDAR-System integriert. Mit den Laserdiodenbänken lassen sich Pumpleistungen von über 60 Watt in Doppelpulsen mit einer Wiederholrate von 20 Hertz und einer Pulsbreite von 150 Mikrosekunden erzeugen. Dank der Fast-Axis-Kollimationslinsen wird der Laserstrahl verlust-

arm in eine optische Faser einkoppelt. Die Laserdiodenbänke wurden nach umfassenden internen Tests vom europäischen Weltraumforschungs- und Technologiezentrum ESTEC in den Niederlanden qualifiziert. Deren Lebensdauertests zeigten, dass die Leistung selbst bei einer langen Betriebsdauer von über vier Milliarden Pulsen nur unwesentlich degradiert. Daher sind die Wissenschaftler zuversichtlich, dass das Messsystem auch unter Weltraumbedingungen ohne Ausfälle funktionieren wird.

Record values for high-power lasers – 1 kW output power at short wavelengths

With its diode lasers for high-power laser applications, FBH has been one of the internationally leading institutes for a long time. One focus is on the laser chips themselves, which the institute permanently optimizes in terms of output power, efficiency and beam quality with narrow spectral linewidth. In recent years, FBH has further developed diode laser bars for pumping pulsed solid-state laser systems in material processing in such a way that their peak output power in quasi-continuous operation could be increased up to fourfold while maintaining excellent efficiency. This reduces the costs in euro per watt – a central benchmark for industry. This enables more compact systems with higher performance (pumps with higher brilliance).

Diode laser bars with 1 cm stripe width in the wavelength range around 9xx nm have been successfully further developed at FBH in close cooperation with TRUMPF in recent years. In current studies, variations of the lateral structure have been investigated in particular. Thanks to a new structure consisting of eight 940 nm emitters, each with a width of 1093 µm and a fill factor of 87 %, the efficiency at 1 kW output was significantly increased from 61 % to 66 %. For another structure, the etching trenches of the reference structure were replaced by deep

implantation. Thus, the far-field angle was significantly reduced (95 % power content) by ~ 2° to 8.8° while maintaining the same efficiency.

In addition, bars emitting at 808 nm and 780 nm achieved an output of 1 kW for the first time. Such lasers are used to pump neodymium and thulium-doped solid-state crystals in industrial and experimental high-energy laser systems. However, the semiconductor materials required for this purpose exhibit a comparatively low power. Nevertheless, an FBH team succeeded in demonstrating a record output power of more than 1 kW in quasi-continuous wave operation in 2019. The laser bar prototypes were mounted on passive CCP heat sinks and were measured with 200 µs pulse duration and 10 Hz repetition rate.

In further work for future industrial systems, FBH has developed the world's first ridge waveguide laser diodes, which deliver a nearly diffraction-limited beam quality at up to 2.5 W output power with an efficiency of more than 55 %. Their brilliance and efficiency surpasses that of broad-area lasers. New approaches emerge from beam combination, in which FBH combines the emissions of more and more smaller lasers with good beam quality. As a result, they can even be used directly.



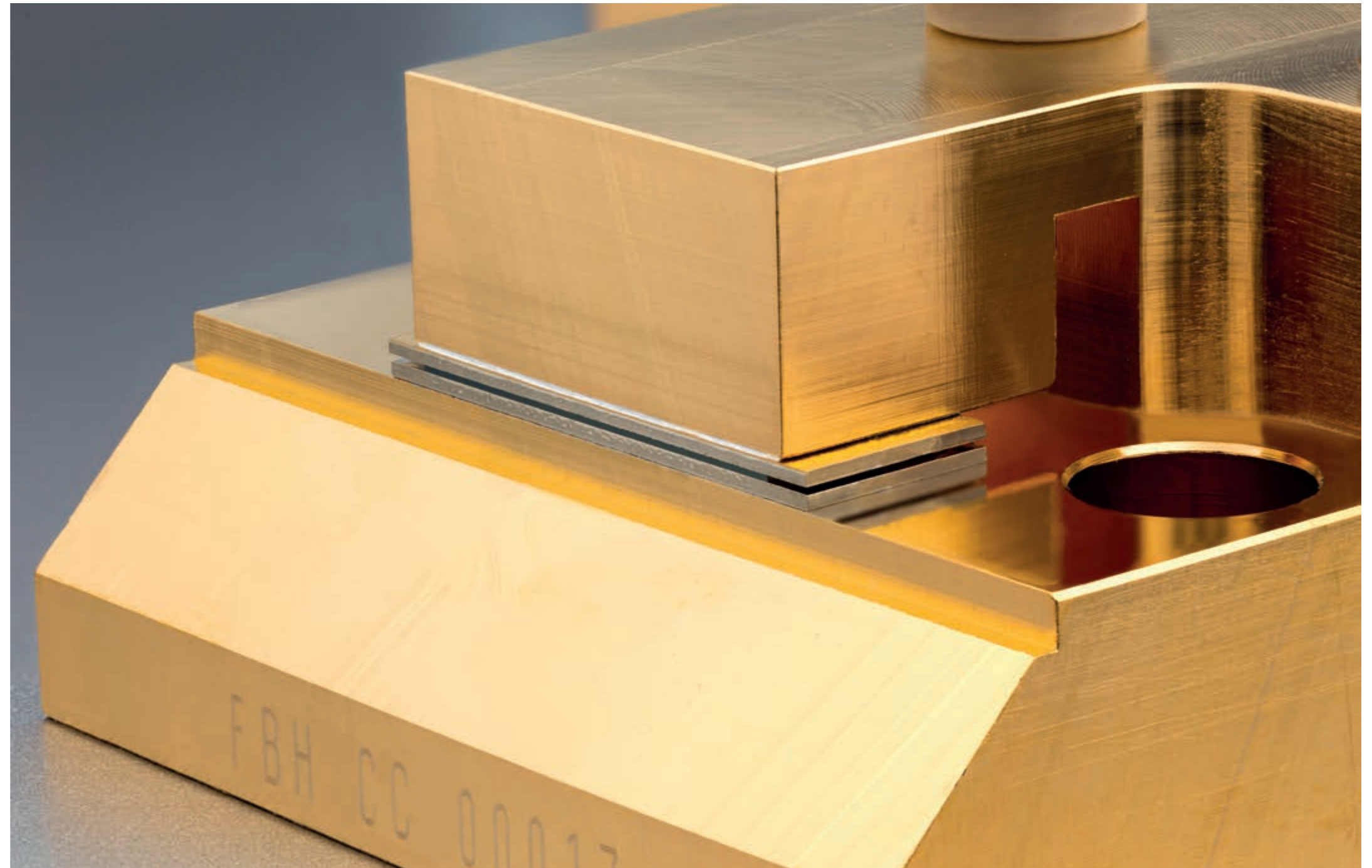
- High-brilliance single emitter before integration into a laser system that combines the beams of several diode lasers. Einzelemitter mit hoher Brillanz vor dem Einbau in ein Lasersystem, das die Strahlung von mehreren Diodenlasern kombiniert.

Rekordwerte bei Hochleistungslasern – 1 kW Ausgangsleistung bei kurzen Wellenlängen

Mit seinen Diodenlasern für Hochleistungs-Laseranwendungen gehört das FBH seit langem zu den international führenden Instituten. Ein Fokus liegt dabei auf den Laserchips selbst, die das Institut hinsichtlich Ausgangsleistung, Effizienz und Strahlgüte mit schmäler spektraler Linienbreite permanent optimiert. Für das Pumpen von gepulsten Festkörper-Lasersystemen in der Materialbearbeitung hat das FBH Diodenlaserbarren in den letzten Jahren so weiterentwickelt, dass deren Spitzenausgangsleistung im quasi-kontinuierlichen Betrieb bei zugleich exzellenter Effizienz bis zum Vierfachen gesteigert werden konnte. Dadurch sinken die Kosten in Euro pro Watt – eine zentrale Kenngröße für die Industrie. Das ermöglicht kompaktere Systeme mit zugleich höherer Leistungsfähigkeit (Pumpen mit höherer Brillanz).

Diodenlaser Barren mit 1 cm Streifenbreite im Wellenlängenbereich um 9xx nm wurden am FBH in den letzten Jahren in enger Zusammenarbeit mit TRUMPF erfolgreich weiterentwickelt. In aktuellen Arbeiten wurden vor allem Variationen der lateralen Struktur untersucht. So konnte dank einer neuen Struktur aus acht 940 nm Emittern mit je 1093 µm Breite und 87% Füllfaktor die Effizienz bei 1 kW Leistung signifikant von 61% auf 66% gesteigert werden. Bei einer anderen Struktur wurden die Ätzgräben der Referenzstruktur durch tiefe Implantation ersetzt. Damit reduzierte sich der Fernfeld-Winkel bei gleichbleibender Effizienz deutlich (95% Leistungsinhalt) um ~ 2° auf 8.8°.

»» *Dennoch ist es einem FBH-Team 2019 gelungen, einen Rekordwert von mehr als 1 kW Ausgangsleistung im Quasi-Dauerstrichbetrieb zu demonstrieren.*



- Kilowatt-class bar after mounting on a CCP heat sink. Barren der Kilowatt-Klasse nach Montage auf eine CCP-Wärmesenke.

Darüber hinaus erreichten Barren, die bei 808 nm und 780 nm emittieren, erstmalig Leistungen von 1 kW. Derartige Laser werden zum Pumpen von Neodym- und Thulium-dotierten Festkörperkristallen in industriellen und experimentellen Hochenergielaseranlagen eingesetzt. Jedoch bieten die dafür benötigten Halbleitermaterialien eine vergleichsweise geringere Leistung. Dennoch ist es einem FBH-Team 2019 gelungen, einen Rekordwert von mehr als 1 kW Ausgangsleistung im Quasi-Dauerstrichbetrieb zu demonstrieren. Die Laserbarren-Prototypen wurden auf passive CCP-Kühlkörper montiert und wurden mit 200 µs Pulsdauer und 10 Hz Wiederholrate gemessen.

In weiteren Arbeiten für zukünftige industrielle Systeme hat das FBH die weltweit ersten Rippenwellenleiter-Laserdioden entwickelt, die nahezu beugungsbegrenzte Strahlqualität bei bis zu 2,5 W Ausgangsleistung mit einer Effizienz von über 55% liefern. Sie erreichen eine Brillanz und Effizienz, die jene von Breitstreifenlasern übertrifft. Neue Ansätze eröffnen sich dabei mit der Strahlkombinierung, bei der das FBH die Emissionen von immer mehr kleineren Lasern mit guter Strahlqualität zusammenführt. Dadurch können sie sogar direkt eingesetzt werden.



Prototype UVC LED system – designed to kill microorganisms on the skin without side effects. Prototyp des UVC-LED-Strahlers – damit sollen Mikroorganismen auf der Haut ohne Nebenwirkungen abgetötet werden.

Prototypes in practical testing – fighting hospital germs with UVC-LED irradiation systems

According to the Robert Koch Institute, 400,000 to 600,000 infections with hospital germs occur in Germany every year – about 10,000 to 20,000 people die from them. Since multidrug resistant (MDR) pathogens often cannot be treated with antibiotics, alternative approaches are needed. One promising physical principle is irradiation with UVC light. Within the consortium Advanced UV for Life led by FBH, the Ferdinand-Braun-Institut and TU Berlin have developed LEDs in the far ultraviolet (UV) spectral range. They emit at wavelengths around 230 nm and provide more than one milliwatt output power. Such UVC LEDs are not yet commercially available worldwide due to technological challenges of the utilized material system aluminum-gallium nitride. Their light does not penetrate into the living layers of the skin because of their high degree of absorption. It is therefore expected that the skin – unlike with long-wave UVC radiation as emitted, for example, by mercury vapor lamps – will not be damaged at all or will be harmed so little that the natural repair mechanisms compensate for the effect.

Within the framework of the BMBF-funded VIMRE project (prevention of infection with multi-resistant pathogens via in-vivo UVC irradiation), FBH has developed and produced an irradiation system comprising an array of 118 of these LEDs on an area of 8 cm x 8 cm. It achieves a maximum irradiation power

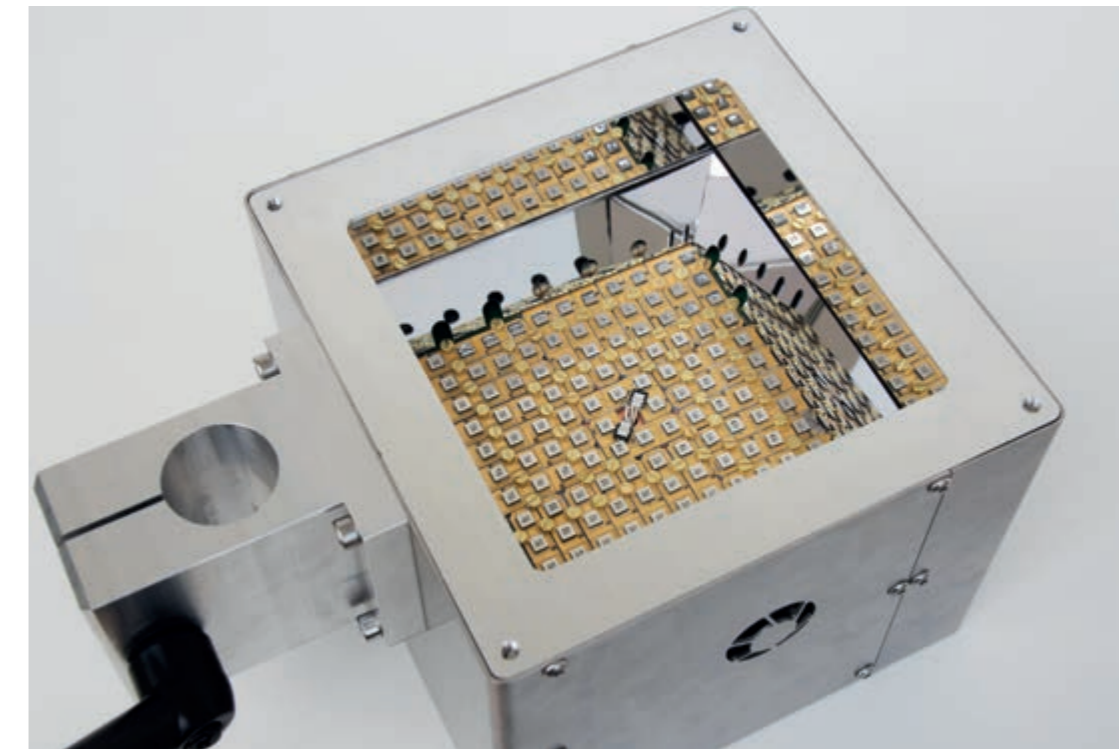
of 0.2 mW/cm² with more than 90 % uniformity over an area of 6 cm x 6 cm. In mid-2020, one prototype was delivered to the Department of Dermatology at Charité – Universitätsmedizin Berlin and one to the Institute for Hygiene and Environmental Medicine at Greifswald University Medicine. Tests of the two project partners with these devices are to show that UVC radiation is suitable for killing microorganisms and especially MDR. At the same time, it is to be demonstrated that it is safe for humans as long as certain exposure doses are observed. This will be verified using tissue samples of human skin as well as skin and mucosa models, since the preferred habitat of microorganisms such as MDR pathogens is the anterior nasal cavity and the pharynx. For this purpose, the Charité conducts dose-dependent investigations of potential DNA damage to irradiated skin. The Greifswald University Medical Center determines how effectively the UV LED irradiation system kills multidrug-resistant pathogens at 230 nm and compares the results with those of conventional UV lamps with emissions at 254 nm and 222 nm.



Prototypen im Praxistest – Krankenhauskeime mit UVC-LED-Strahlern bekämpfen

Laut Robert-Koch-Institut kommt es in Deutschland pro Jahr zu 400.000 bis 600.000 Infektionen mit Krankenhauskeimen – etwa 10.000 bis 20.000 Menschen sterben daran. Da multi-resistente Erreger (MRE) oft nicht mit Antibiotika behandelt werden können, sind alternative Ansätze gefragt. Ein aussichtsreiches physikalisches Wirkprinzip ist die Bestrahlung mit UVC-Licht. Damit lassen sich Mikroorganismen abtöten, ohne dass sich Resistenzen entwickeln können. Im Rahmen des vom FBH geleiteten Konsortiums Advanced UV for Life haben das Ferdinand-Braun-Institut und die TU Berlin LEDs im fernen ultravioletten (UV) Spektralbereich entwickelt. Sie emittieren bei Wellenlängen um 230 nm und liefern mehr als ein Milliwatt Ausgangsleistung. Derartige UVC-LEDs sind wegen der technologischen Herausforderungen des verwendeten Materialsystems Aluminium-Galliumnitrid bislang weltweit kommerziell nicht verfügbar. Ihr Licht dringt aufgrund der hohen Absorption nicht in die lebenden Schichten der Haut ein. Es wird daher erwartet, dass die Haut – anders als bei langwelliger UVC-Strahlung, wie sie etwa Quecksilberdampflampen emittieren – nicht oder so wenig geschädigt wird, dass die natürlichen Reparaturmechanismen die Einwirkung kompensieren.

Im Rahmen des BMBF-geförderten VIMRE-Projekts (Verhinderung der Infektion mit multiresistenten Erregern über in-vivo UVC-Bestrahlung) hat das FBH einen Strahler mit einem Array aus 118 dieser LEDs auf einer Fläche von 8 cm x 8 cm entwickelt und hergestellt. Er erreicht eine maximale Strahlungsleistung von 0,2 mW/cm² mit mehr als 90 % Uniformität über eine Fläche von 6 cm x 6 cm. Mitte 2020 wurde jeweils ein Prototyp an die Klinik für Dermatologie der Charité – Universitätsmedizin Berlin und das Institut für Hygiene und Umweltmedizin der Universitätsmedizin Greifswald geliefert. Tests der beiden Projektpartner mit diesen Geräten sollen zeigen, dass sich UVC-Strahlung eignet, um Mikroorganismen und insbesondere MRE abzutöten. Gleichzeitig soll nachgewiesen werden, dass diese für den Menschen unbedenklich ist, solange bestimmte Strahlendosen eingehalten werden. Dies wird anhand von Gewebeproben menschlicher Haut sowie an Haut- und Schleimhautmodellen überprüft, da der bevorzugte Lebensraum von Mikroorganismen wie MRE die vordere Nasenhöhle und der Rachenraum sind. Die Charité führt dazu dosisabhängige Untersuchungen möglicher DNS-Schäden an bestrahlter Haut durch. Die Universitätsmedizin Greifswald ermittelt, wie effektiv der UV-LED-Strahler multi-resistente Erreger bei 230 nm abtötet und vergleicht die Werte mit denen herkömmlicher UV-Lampen bei 254 nm und 222 nm.



Irradiation unit equipped with 118 UVC LEDs from the Ferdinand-Braun-Institut, which is integrated inside the prototype and emits downwards. Bestrahlungseinheit bestückt mit 118 UVC-LEDs aus dem Ferdinand-Braun-Institut, die im Prototyp integriert ist und nach unten abstrahlt.

iCampus – innovations for structural change in Lusatia

In November 2019, the Innovation Campus Electronics and Micro-sensor Technology Cottbus (iCampus) was launched at BTU Cottbus-Senftenberg. Within this framework, the Ferdinand-Braun-Institut is currently setting up a branch office in Cottbus; a joint lab with the university already exists. The focus of activities is on the field of sensor technology. Within iCampus, four non-university research institutions are pooling their expertise with those of the BTU at the joint location in Cottbus: FBH, Leibniz IHP and the two Fraunhofer Institutes IZM and IPMS. The aim is to create synergies and build an innovative, sustainable technology cluster that will support the structural change in Lusatia. iCampus is Brandenburg's first scientific project funded with 7.5 million euros in the BMBF's Immediate Action Program. FBH is involved in two of the five sub-projects:

Application laboratory μ -Spectrum

Lead-managed by FBH, the project partners in Cottbus are setting up the application laboratory μ -Spectrum. Novel spectroscopic measuring techniques will be developed at this lab for future real-world measurement systems. These rely on innovative diode-laser-based light sources, spectrometer-free reso-

nance Raman systems, novel MEMS-tunable grating filters, and germanium photodetectors with nanohole gratings.

The main focus at FBH is the spectrometer-free resonance Raman system, which is to be developed in cooperation with the Fraunhofer IPMS. This miniaturized overall system could replace complex and bulky spectrometers in the future. In addition, this system is expected to be much more cost-effective to manufacture. In principle, the measurement concept can be used for different substances. In a first step, however, it will be used for carotenoids, which play an important role both in plants and in medicine. Further applications are in industrial process control, for example in the food and pharmaceutical industries.

Ultra-low-power mobile radar for medical applications

Under BTU's management, a demonstrator of a mobile and compact radar system will be developed for cardiovascular monitoring at home. The contact-free system will be able to record cardiovascular parameters of patients and automatically transmit these data to their treating doctor via a secure interface.

iCampus – Innovationen für den Strukturwandel in der Lausitz

Im November 2019 ist der Innovationscampus Elektronik und Mikrosensorik Cottbus (iCampus) an der BTU Cottbus-Senftenberg gestartet. In diesem Rahmen baut das Ferdinand-Braun-Institut zurzeit eine Außenstelle in Cottbus auf, ein Joint Lab mit der Hochschule gibt es bereits. Der Schwerpunkt der Aktivitäten liegt auf dem Themenfeld Sensorik. In iCampus bündeln vier außeruniversitäre Forschungseinrichtungen ihre Kompetenzen mit denen der BTU am gemeinsamen Standort in Cottbus: Das FBH, das Leibniz IHP und die beiden Fraunhofer-Institute IZM und IPMS. So sollen Synergien entstehen und ein innovativer, nachhaltiger Technologiecluster aufgebaut werden, der den Strukturwandel in der Lausitz unterstützt. iCampus ist das erste wissenschaftliche Vorhaben Brandenburgs, das im Sofortprogramm des BMBF mit 7,5 Millionen Euro gefördert wird. Das FBH ist an zwei der insgesamt fünf Teilprojekte beteiligt:

Applikationslabor μ -Spektrum

Unter Federführung des FBH bauen die Projektpartner in Cottbus das Applikationslabor μ -Spektrum auf. Dort sollen neuartige spektroskopische Messverfahren für zukünftige Real-World-Messsysteme entwickelt werden. Diese basieren auf innovativen Diodenlaser-basierten Lichtquellen, spektrometerlosen Resonanz-Raman-Systemen, neuartigen durchstimmbaren MEMS-basierten Gitterfiltern und Germanium-Fotodetektoren mit Nanolochgittern.

Schwerpunkt am FBH ist das spektrometerlose Resonanz-Raman-System, das in Zusammenarbeit mit dem Fraunhofer IPMS entstehen soll. Dieses miniaturisierte Gesamtsystem könnte künftig komplexe und aufwändige Spektrometer ersetzen. Zudem soll dieses System deutlich kostengünstiger gefertigt werden können. Das Messkonzept ist prinzipiell für verschiedene Substanzen anwendbar, soll jedoch im ersten Schritt speziell bei Carotinoiden eingesetzt werden, die sowohl in Pflanzen als auch in der Medizin eine Rolle spielen. Weitere



➊ Raman handheld probe to measure carotenoids on the skin.
Raman-Optode zur Messung von Carotinoiden auf der Haut.

Anwendungen liegen in der industriellen Prozesskontrolle, etwa bei Lebensmitteln und im Bereich der Pharmazie.

Mobiles Ultra-Low-Power-Radar für Medizinanwendungen

Geleitet von der BTU soll der Demonstrator eines mobilen und kompakten Radarsystems zum Herzkreislauf-Monitoring für den Heimbereich entwickelt werden. Das System soll berührungslos Herz-Kreislauf-Parameter von Patientinnen und Patienten erfassen und diese Daten automatisiert über eine gesicherte Schnittstelle an den betreuenden Arzt übermitteln. Das FBH fokussiert sich dabei auf die technologische Weiterentwicklung des Radar-Detektors und den Modulaufbau.

➤➤ Dieses miniaturisierte Gesamtsystem könnte künftig komplexe und aufwändige Spektrometer ersetzen.

Photonics Photonik

Within its photonics research area, FBH covers a broad range of diode laser and light-emitting diodes (LED) developments that are tailored precisely to fit individual requirements. The portfolio ranges from research on basic issues to the development of ready-to-use modules and prototypes. It comprises gallium arsenide based diode lasers, emitting from the infrared to the UV spectral range, as well as laser diodes and LEDs based on gallium nitride with emission in the UV spectral range. The FBH currently focuses on the following topics:

- > **High-power diode lasers** – broad area lasers, laser bars, and stacks optimized for high output powers. They are used as pump lasers as well as for direct materials processing.
- > **Laser modules** – optics for beam shaping, external resonators, electronics, and crystals for frequency doubling are integrated into the miniaturized laser modules. Even subsequent coupling into glass fibers is possible. These light sources are ideally suited for applications including displays and medical technology.
- > **Laser sensors** – diode lasers that are customized for applications in sensors and analytics. They are employed, e.g., in miniaturized, portable laser measurement systems enabling to measure Raman spectra even in highly fluorescent environments.

- > **GaN optoelectronics** – FBH develops nitride laser diodes and UV LED especially for the UVB and UVC spectral range. Applications eligible for LEDs include surface treatment and plant illumination.

The required basic know-how for these developments is provided by the Optoelectronics Department. It designs, realizes, and characterizes the corresponding diode laser chips.

Im Forschungsbereich Photonik deckt das FBH ein breites Spektrum an Entwicklungen zu Diodenlasern und Leuchtdioden (LEDs) ab, die auf die jeweilige Anforderung zugeschnitten werden. Das Portfolio reicht von der Bearbeitung grundlagenorientierter Fragestellungen bis hin zur Entwicklung von einsatzfähigen Diodenlasermodulen und Prototypen. Es umfasst Galliumarsenid-basierte Diodenlaser, die vom infraroten bis zum ultravioletten Spektralbereich emittieren, sowie Laserdioden und LEDs auf Galliumnitrid-Basis, die im UV-Spektralbereich abstrahlen. Aktuell setzt das FBH die folgenden Schwerpunkte:

- > **Hochleistungs-Diodenlaser** – Breitstreifenlaser, Laserbarren und Stacks, optimiert auf hohe Ausgangsleistungen. Sie werden u.a. als Pumplaser und für die direkte Materialbearbeitung genutzt.
- > **Lasermodule** – in die miniaturisierten Module werden Optiken zur Strahlformung, externe Resonatoren, Elektronik und frequenzverdoppelnde Kristalle hochpräzise integriert. Auch die anschließende Kopplung in Glasfasern ist möglich. Sie eignen sich u.a. für den Einsatz in Displays oder der Medizintechnik.
- > **Lasersensorik** – Diodenlaser, die speziell auf Anwendungen in der Sensorik und der Analytik zugeschnitten sind. Sie kommen u.a. in miniaturisierten, portablen Lasermesssystemen zum Einsatz, die Messungen von Raman-Spektren auch in stark fluoreszierenden Umgebungen ermöglichen.

- > **GaN-Optoelektronik** – auf diesem Gebiet entwickelt das FBH Nitrid-Laserdioden und UV-Leuchtdioden, insbesondere für den UVB- und UVC-Spektralbereich. Die LEDs eignen sich u.a. für die Oberflächenbehandlung und die Pflanzenbeleuchtung.

Das erforderliche grundlegende Know-how hält das Department Optoelektronik bereit. Es entwirft, realisiert und charakterisiert die zugehörigen Diodenlaser-Chips.

Simulation-based design of compact tunable dual-wavelength diode lasers – attractive light sources with versatile applications

Compact lasers emitting coherent light featuring two slightly detuned wavelengths with excellent spatial beam characteristics are of great interest for various applications. These include Raman spectroscopy as well as the generation of tunable continuous wave THz radiation. Therefore, such light sources are subject of intensive research at the FBH, relying to a great extent on comprehensive simulations.

Dual-wavelength lasers can be realized by two coupled laser branches, each equipped with a spectrally detuned and highly reflective distributed Bragg reflector (DBR), as schematically shown in Fig. 1. Both branches are joined into one common front waveguide, resulting in a single light-emitting aperture. The lateral confinement of the optical wave inside the integrated waveguide components, such as straight and bent waveguides, are realized by etching parts of the chip surface and choosing appropriate contact layouts. The spectral fine-tuning of each laser arm is achieved by micro-heaters placed next to the DBRs.

In previous designs, the ridge waveguides were shallowly etched as shown in Fig. 2 (a), resulting in a 2000 μm long coupler section (see Fig. 1 (a)). To reduce the coupler dimensions, we theoretically investigated a new design based on two etch depths, see Figs. 2 (a) and (b). Here, regions where optical gain is supplied, namely the laser branches and the front section are shallowly etched to ensure fundamental lateral mode operation. In contrast, the coupler section is deeply etched to provide a higher refractive index contrast. This enables more compact coupler sections with reduced lengths of 700 μm and 1000 μm for the devices shown in Fig. 1 (b) and (c), respectively. The higher index contrast enables also using a multi-mode interference (MMI)

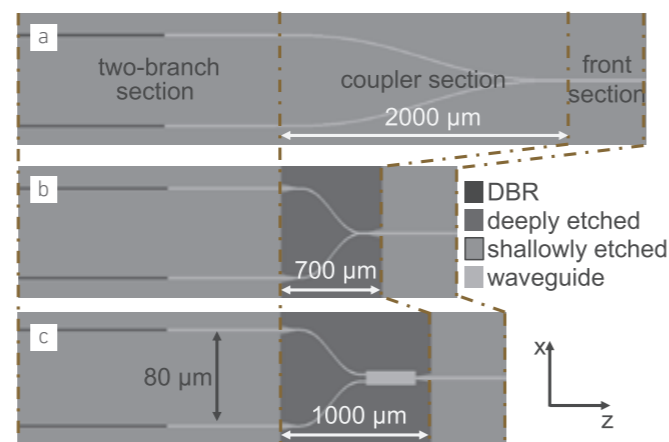


Fig. 1. Top view of different tunable dual-wavelength laser diode systems. (a) Reference Y-branch laser design with single etch depth, whereas designs (b) & (c) are based on two etch depths.

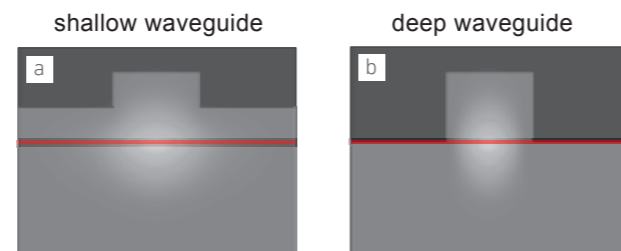
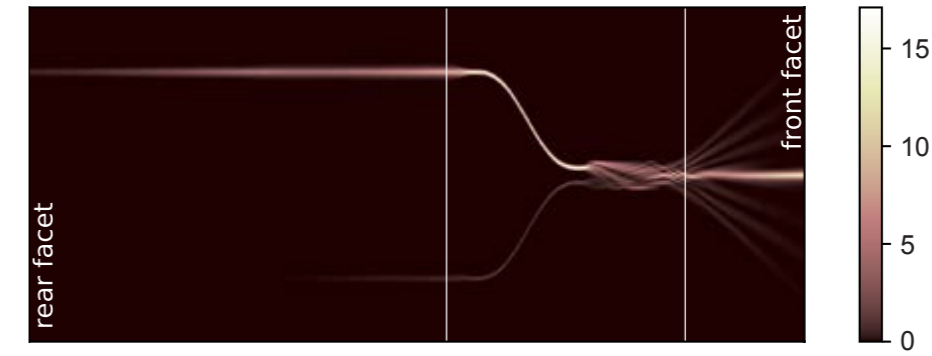


Fig. 2. Cross section of a shallowly (a) and a deeply (b) etched ridge waveguide. The resulting fundamental mode is shown as a grey-scale plot.

time averaged intensity distribution / $W \cdot \mu\text{m}^{-2}$



time averaged carrier density distribution / $10^{24} \cdot \text{m}^{-3}$

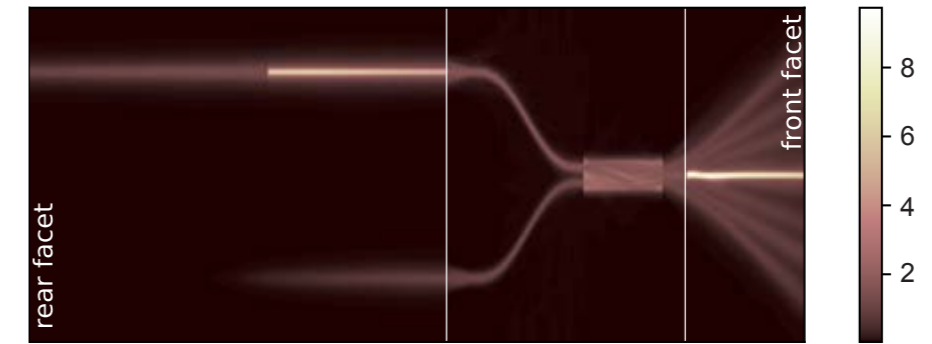


Fig. 3. Time-averaged intensity and carrier density distributions of a Y-branch laser featuring an MMI-coupler obtained by WIAS-BALaser simulations.

Kompakte Laserquellen, die Licht mit zwei leicht versetzten Wellenlängen aus einer Apertur emittieren, sind für verschiedene Applikationen interessant. Dazu zählen spektroskopische Anwendungen ebenso wie durchstimmbare Dauerstrich-THz-Strahlquellen. Derartige Zweiwellenlängen-Laserdioden werden daher am FBH stetig weiterentwickelt. In diesem Zusammenhang wurden neue Laserdesigns mithilfe von Simulationstools für passive Wellenleiter und aktive Laserresonatoren entworfen. Durch den Einsatz unterschiedlich tief geätzter Rippenwellenleiter konnte die Länge des Y-Kopplers, der beide Laserarme zusammenführt, stark reduziert werden. Die tief geätzten Bereiche ermöglichten zudem ein neues, auf MMI-Koppler basierendes Design. Zur Simulation der aktiven Laser wurde das Programm WIAS-BALaser verwendet, welches umfassende Einblicke in laserinterne Prozesse ermöglicht. Daraus lassen sich Erkenntnisse ziehen, die weder durch passive Wellenleiter-Simulationen noch durch Experimente gewonnen werden können.

coupler depicted in Fig. 1 (c) instead of the Y-couplers in Figs. 1 (a) and (b). In addition to favorable mode filter properties, meaning that higher order modes have a much lower transmission through the coupler than the fundamental mode, MMI-couplers are also more robust against fabrication fluctuations.

The device parameters of the integrated waveguide components, namely S-bend, coupler and spot size converter, were optimized using a numerically efficient and physically rigorous simulation tool for passive waveguides. This tool is based on eigenmode expansion, mode matching and bi-directional propagation. Subsequently, the entire active laser system was further analyzed, applying the sophisticated traveling-wave equation based tool WIAS-BALaser. Fig. 3 exemplarily shows the longitudinal-lateral (z, x) time-averaged intensity and carrier density distribution of the design shown in Fig. 1 (c) obtained by BALaser simulations. In this specific case, only the upper of two laser arms was electrically biased. It is visible that some of the forward traveling light gets radiated behind the waveguide coupler and that a part of the backward traveling wave is coupled into the lower unbiased laser arm. The full extent of those laser-internal effects are neither accessible by passive simulations nor by experiments.

Publication

J.-P. Koester, M. Radziunas, A. Zeghuzi, H. Wenzel and A. Knigge, "Simulation and design of a compact GaAs based tunable dual-wavelength diode laser system", Optical and Quantum Electronics 51(10), 334, (2019).

Raman spectroscopic investigations on soil using a 785 nm dual-wavelength diode laser

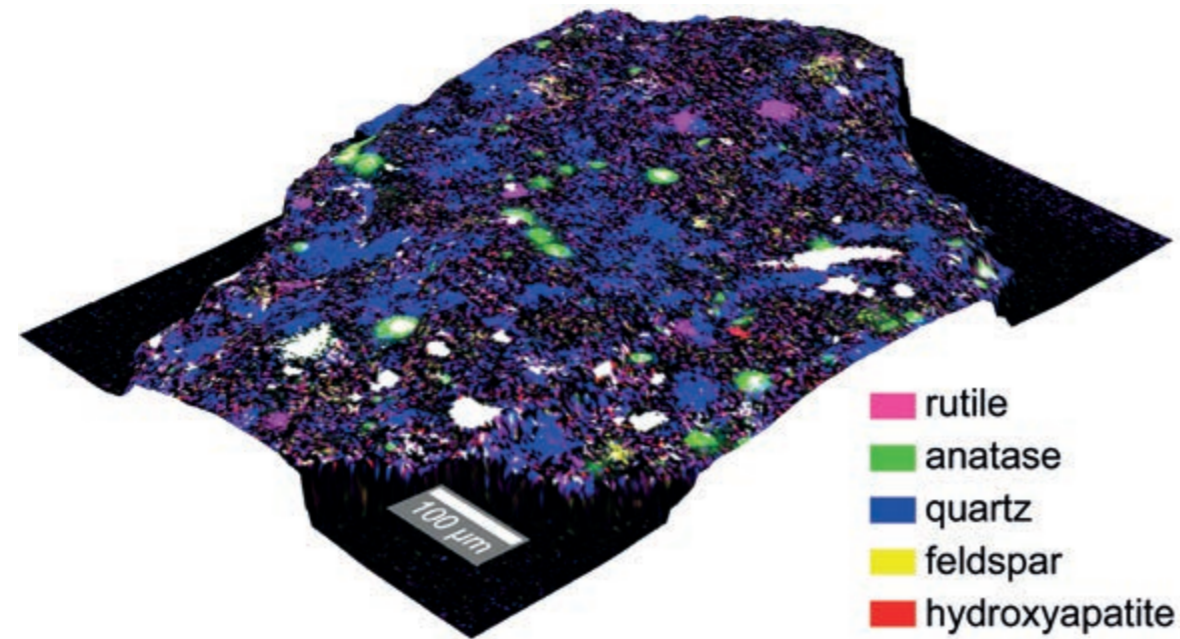


Fig. 1. 3D Raman microscopic image of soil sample. The different colors represent selected soil components as shown in the legend.

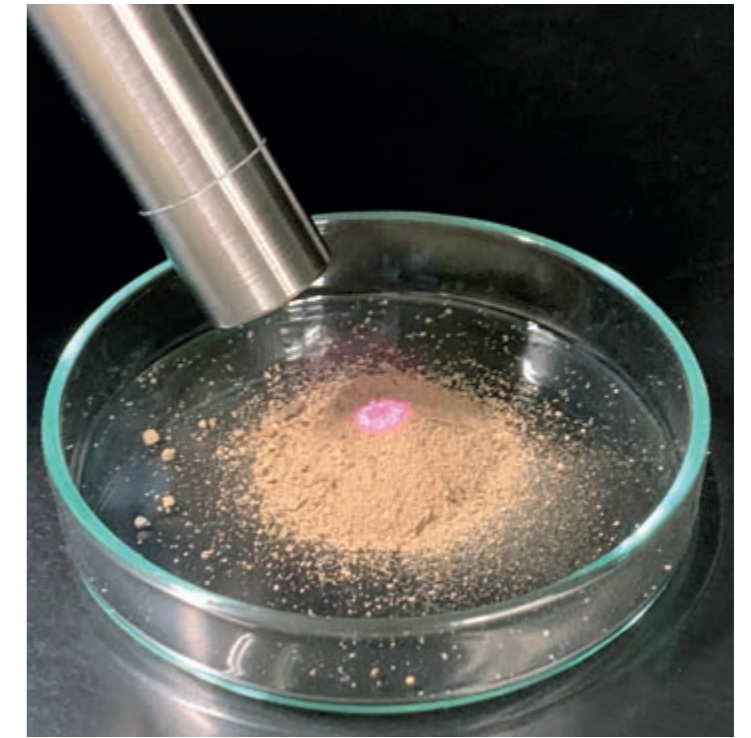
Precision agriculture is becoming increasingly important on a global level, for example in terms of meeting the food demand of a steadily increasing world population. Site-specific fertilizer application not only ensures the sustainable use of limited resources. It is, at the same time, crucial for environmental protection by avoiding excess fertilizer usage. With this goal in mind, the Ferdinand-Braun-Institut evaluates the potential of Raman spectroscopy. The non-destructive optical method can be used to characterize soil, thus paving the way for efficient nutrient management.

Shifted excitation Raman difference spectroscopy (SERDS) is applied to overcome interferences resulting e.g. from daylight or fluorescence and to extract the characteristic Raman signals. Such disturbing signals are common for a wide range of natural samples including soil. As SERDS requires an excitation light source with two distinct emission lines, an in-house developed Y-branch dual-wavelength 785 nm diode laser is used. The measurement principle has already been successfully demonstrated for *in situ* outdoor investigations in an apple orchard [1] and is now transferred to soil analysis.

To this end, confocal Raman microscopy measurements were performed in conjunction with our SERDS experiments to generate a better understanding of soil properties, e.g. the heterogeneous distribution of target substances. As the investigated area for each measured point is about $1 \mu\text{m}^2$, spatially resolved Raman spectra of individual soil constituents can be obtained. Fig. 1 shows a 3D false-color Raman image of the sample surface. Contributions of rutile, anatase, quartz, feldspar and our target analyte hydroxyapatite (a phosphate) can be seen.

For our SERDS investigations, the sample was initially excited at the first laser wavelength (784.47 nm) of the dual-wavelength diode laser [2], and the Raman spectrum was recorded (red curve in Fig. 2). Here, a larger excitation spot size (diameter approx. $20 \mu\text{m}$) was applied with respect to future field applications of portable Raman systems to obtain spectroscopic information from a larger, i.e. more representative area of the sample. The larger spot size also causes pronounced fluorescence interference and only one single Raman signal at 961 cm^{-1} is visible in this case. Subsequently, the sample was excited at the second laser wavelength (785.05 nm), the corresponding Raman spectrum is shown as green curve in Fig. 2. The spectrally narrow Raman signals shift with the shift in excitation wavelength, i.e. 10 cm^{-1} , while the spectrally broad

Weltweit werden in der Landwirtschaft zunehmend Sensor- und Messtechniken eingesetzt – etwa zur präzisen Düngung. Für ein effizientes Nährstoffmanagement, analysiert das Ferdinand-Braun-Institut Bodenproben mittels Laserlicht und nutzt dafür die Methode der Shifted Excitation Raman Difference Spectroscopy (SERDS). Vergleichende Messungen mit einem Raman-Mikroskop helfen, die heterogene Verteilung der einzelnen Bodenbestandteile besser zu verstehen. Als Anregungslichtquelle für SERDS verwendet das FBH einen speziell entwickelten Zwei-Wellenlängen-Diodenlaser, mit dem sich Raman-signale effektiv von Störeinflüssen trennen lassen. Spektroskopische Informationen einer repräsentativen Fläche der Bodenprobe können mithilfe einer geeigneten Messgeometrie ermittelt werden. Auf diese Weise wurden Quarz, Feldspat und die Zielsubstanz Hydroxylapatit (ein Phosphat) identifiziert. SERDS zeigt damit sein großes Potential für die Präzisions-Landwirtschaft, um Bodennährstoffe künftig noch genauer zu erfassen.



Probe tip of a SERDS measuring system developed at FBH for site-specific soil analysis. Excitation laser radiation is visible in the center of the soil sample.

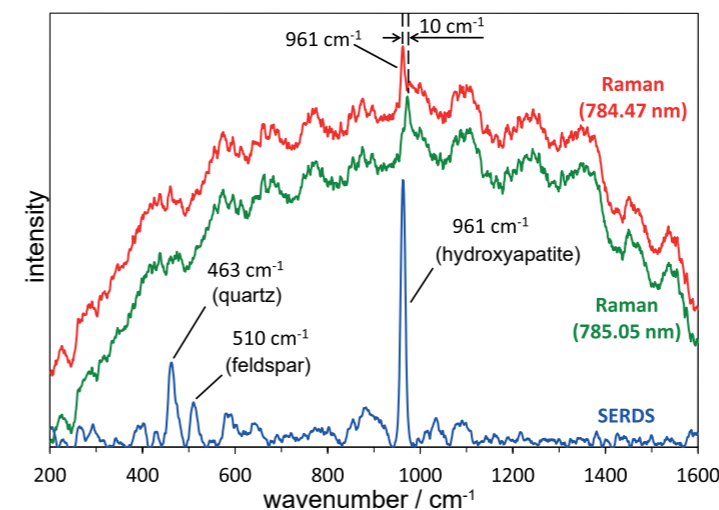


Fig. 2. Raman spectra excited at two slightly shifted wavelengths (red & green curve) and SERDS spectrum (blue curve) of soil sample measured with the FBH setup. SERDS allows identifying the soil components quartz, feldspar, and hydroxyapatite.

fluorescence remains unchanged. A subtraction of both spectra (and further mathematical processing) can therefore effectively separate the Raman signals from fluorescence interference as shown in the blue curve in Fig. 2. Due to the larger excitation spot size contributions from three individual soil components can be identified in the SERDS spectrum: quartz, feldspar and hydroxyapatite. These results highlight the large potential of SERDS as a promising tool for soil analysis in precision agriculture to improve soil nutrient management [3].

This study was funded by the Federal Ministry of Education and Research (BMBF) under contract 031A564C through the funding measure BonaRes (Soil as a Sustainable Resource for the Bioeconomy) within the consortium I4S (Intelligence for Soil).

Publications

[1] M. Maiwald, A. Müller, B. Sumpf, G. Tränkle, "A portable shifted excitation Raman difference spectroscopy system: device and field demonstration", *Journal of Raman Spectroscopy*, vol. 47, no. 10, pp. 1180-1184 (2016).

[2] M. Maiwald, B. Sumpf, G. Tränkle, "Rapid and adjustable shifted excitation Raman difference spectroscopy using a dual-wavelength diode laser at 785 nm", *Journal of Raman Spectroscopy*, vol. 49, no. 11, pp. 1765-1775 (2018).

[3] L. S. Theurer, M. Maiwald, B. Sumpf, "Shifted excitation Raman difference spectroscopy: A promising tool for the investigation of soil", *European Journal of Soil Science*, <https://doi.org/10.1111/ejss.12928> (2020).

Highest brightness for material processing from ridge waveguide laser diodes with industry-relevant efficiency

High output power is a key feature for laser material processing applications, especially high-volume applications such as laser cutting or additive manufacturing. However, not just the optical power from a laser is important but also how much of this power is delivered into a small spot. Both the lasing wavelength and its beam quality determine how small a laser spot can be produced. This can be parameterized using the beam parameter product (*BPP*), which is a function of the minimum beam width $W_{95\%}$ times minimum propagation angle $\Theta_{95\%}$, with $BPP = (1/4) \times W_{95\%} \times \Theta_{95\%}$. In high-power diode lasers, the largest limit to *BPP* is in the lateral direction (in the plane of the diode lasers), and one can benchmark laser diodes in terms of their linear lateral brightness B_{lat} , which gives the optical power, divided by the lateral *BPP*.

Formerly, only broad area lasers (BAL) could deliver the needed optical power and efficiency for many commercial applications. Due to their size, they have a limited beam quality, which is continuously improved but still insufficient for many applications. Thus, BAL are often used as efficient pump sources for solid-state lasers, transferring the power into a higher quality beam but losing power and efficiency in the process. Recent progress in beam combining methods (coherent and dense wavelength beam combing) allows merging the emission of more and more diode lasers into a single beam with increasing efficiency while keeping the same beam quality as for a single emitter. Higher performance single emitters are needed for these beam-combined systems. These single emitters should deliver the highest possible power with a much better quality beam than broad area lasers can achieve, with excellent conversion efficiency.

In 2019, the FBH has achieved strong progress in improving power and efficiency of just such high beam quality diode lasers. This work builds on more than 20 years of research and continuous improvement in highly efficient ridge waveguide (RW) lasers emitting around 970 nm, which show very good lateral beam quality. In recent studies, extreme-double-asymmetric epitaxial designs were used that suppress the onset of higher-order lateral modes and enable nearly diffraction-limited lateral beam quality at high power levels. To achieve this, the resonator length and the stripe width of the RWs had to be increased in order to lower electrical and thermal resistance, which enables higher efficiency at high powers. At the same time, designs were developed to further limit onset of higher order lateral modes. By implementing novel RW designs with broad front sections of 15 μm and narrow mode filters at the back side, we could significantly increase the maximum (nearly) diffraction-limited power from 1 W to 2.5 W. Thus, for the first time, with peak values of $B_{lat} = 7.5 \text{ W/mm}\cdot\text{mrad}$ (see Fig. 1), the maximum linear lateral brightness of an RW laser outperforms those of BAL. At the same time, an improved epitaxial design and a 1.5 times longer cavity enable efficiencies around 55% to be achieved at this power level (see Fig. 2). This exceeds previous best publications, which showed nearly diffraction-limited optical output power of < 2 W with an efficiency of less than 50% at 2.5 W. Lifetime of more than 1,000 hours was demonstrated at operating powers of more than 2 W.

We thank TRUMPF Laser GmbH, which supported parts of this work.

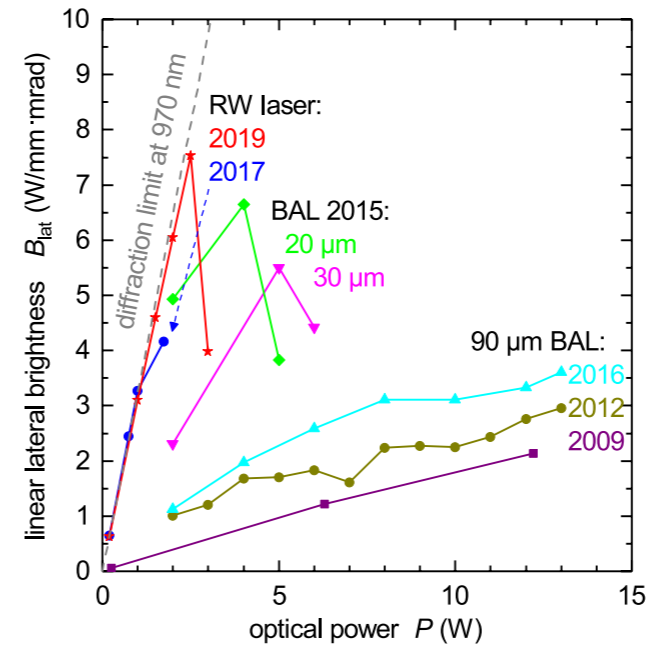


Fig. 1. Linear lateral brightness vs. current for BAL and RW lasers from the last few years.

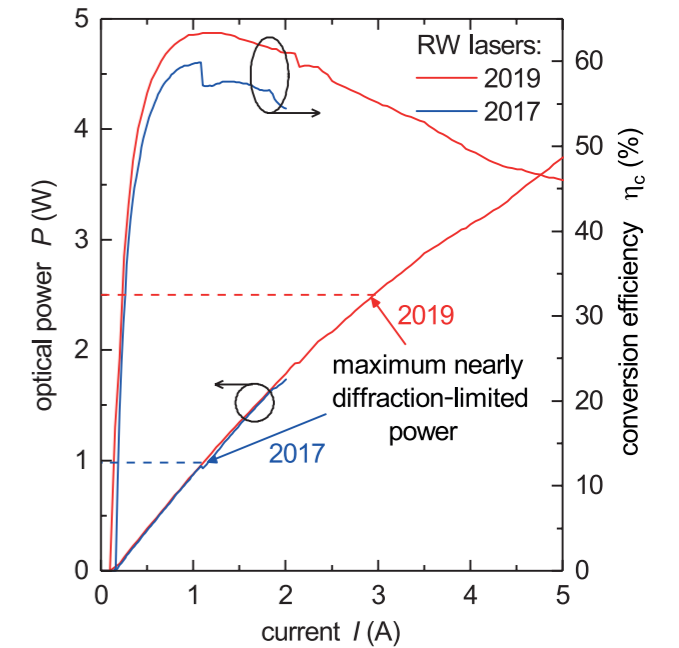


Fig. 2. Optical power and conversion efficiency vs. current of best RW lasers from 2017 and 2019.

Viele Anwendungen – speziell in der Materialbearbeitung – benötigen Lichtquellen mit einer hohen Leistung pro Fläche. Die mögliche Leistung einer Laserdiode pro Fläche lässt sich anhand der linearen lateralen Strahldichte B_{lat} bewerten. Bisher erzielten nur Breitstreifen-Laserdioden (BAL) die Leistungen und Effizienzen, die für derartig anspruchsvolle Anwendungen benötigt werden. Allerdings reicht deren Strahlqualität oft nicht aus. Deshalb werden BAL meist nur indirekt als Pumpquellen für Festkörperlaser verwendet, wobei optische Leistung und somit Effizienz verloren gehen. Jedoch lassen sich inzwischen durch Fortschritte in der Strahlkombinierung die Emissionen von immer mehr kleineren Lasern mit ausreichender Strahlqualität zusammenführen. Dadurch erreichen sie die benötigten Leistungen. Das FBH hat nun die weltweit ersten Rippenwellenleiter-Laserdioden entwickelt, die nahezu beugungsbegrenzte Strahlqualität bei bis zu 2,5 W Ausgangsleistung mit einer Effizienz von über 55% liefern. Damit übertreffen diese mit $B_{lat} = 7.5 \text{ W/mm}\cdot\text{mrad}$ erstmalig die maximale lineare laterale Strahldichte von BAL.

Publications

M. Wilkens, G. Erbert, H. Wenzel, A. Maaßdorf, J. Fricke, P. Ressel, A. Knigge, P. Crump, "Highly Efficient High-Brightness 970 nm Ridge Waveguide Lasers", IEEE Phot. Technol. Lett., vol. 32, no. 7, pp. 406-409, (2020).

M. Wilkens, G. Erbert, H. Wenzel, A. Maaßdorf, J. Fricke, P. Ressel, A. Knigge, P. Crump, "Efficient Narrow Stripe Ridge Waveguide Lasers for Single-Spatial Mode Operation up to 2.5 W", CLEO/Europe-EQEC 2019, Munich, Germany (2019).

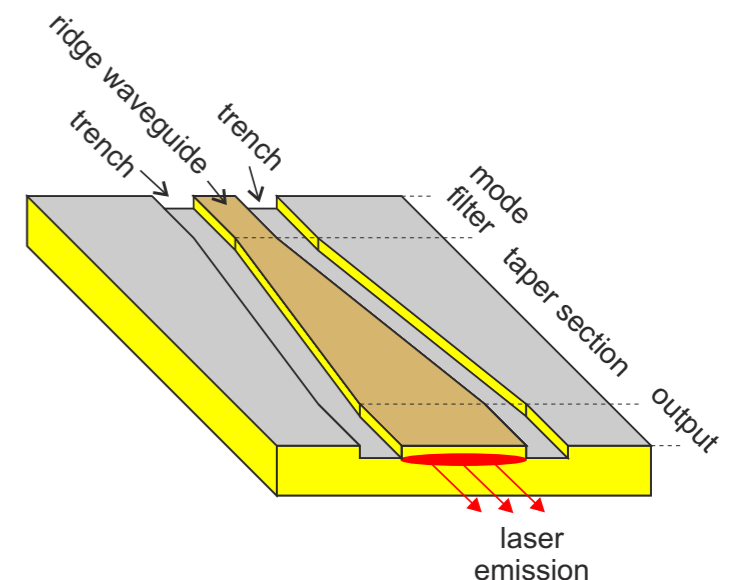


Fig. 3. 3D schematic depiction of a RW laser with integrated mode filter.

Record performance in kilowatt-class diode laser bars for industrial and scientific applications

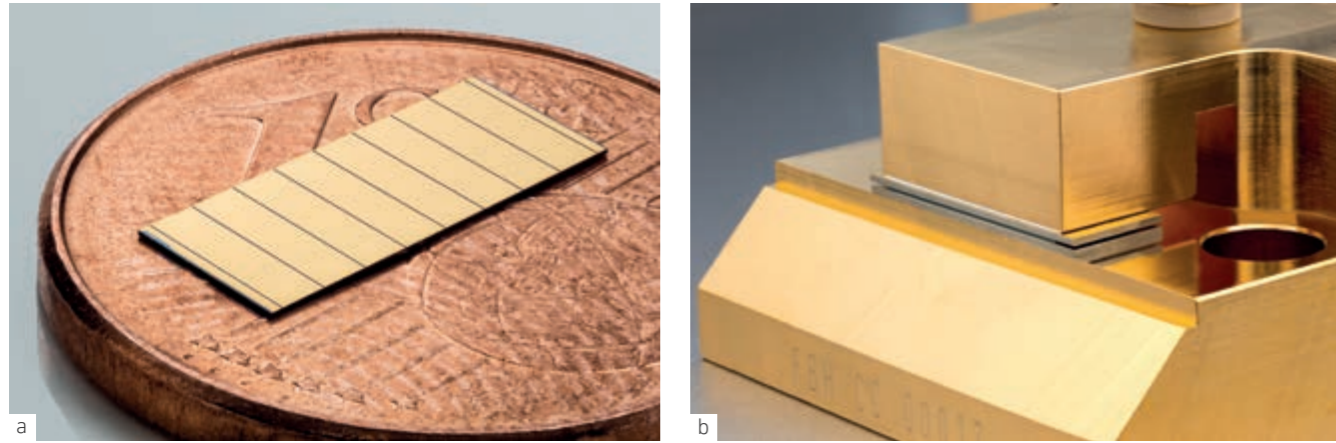


Fig. 1. Kilowatt-class laser bar, before (a) and after (b) mounting on a conductively cooled carrier.

1 cm wide diode laser bars are used as high-power light sources in a variety of industrial and scientific applications, with material processing (e.g. metal cutting and welding) being amongst the largest market segments. Specifically, the diode laser bars are used either directly or as pumps for solid-state and fiber lasers, and continuous improvement in performance is needed. FBH's ongoing diode laser bar research and technology development has enabled rapid progress, with recent work in the 9xx nm-range performed in close cooperation with TRUMPF. Examples at 940 nm include the first demonstration of output power $P_{\text{opt}} = 2$ kW per bar, the first bars with conversion efficiency $> 60\%$ at $P_{\text{opt}} = 1$ kW and the first demonstration of 1 kW continuous wave (CW) emission at 25 °C.

In new studies, FBH scientists have further improved both bar conversion efficiency η_E and bar lateral far field angle θ_{lat} , for 940 nm bars at the $P_{\text{opt}} = 1$ kW level, with details presented in [1-3]. The new research is focused on the impact of variation in the lateral structure on bars fabricated using established highly efficient epitaxial layer designs. The bars in all cases are 1 cm wide with a resonator length of 4 mm and a high fill factor $> 70\%$, mounted on passively cooled CCP heatsinks. Variations

in emitter number, emitter width and lateral guiding mechanism were assessed. For highest efficiency, FBH scientists made use of a novel lateral structure featuring 8 emitters, as shown in Fig. 1, each 1093 μm wide, pushing the filling factor up to 87%. Fig. 2 depicts the measured light-current-voltage characteristic (P_{opt}, I, V) of the new design compared to baseline material, in quasi-continuous wave (QCW) testing (200 μs pulses, 10 Hz repetition rate). Bars using the new design emit $P_{\text{opt}} = 1$ kW with the highest reported conversion efficiency $\eta_E = 66\%$, significantly increased over the baseline ($\eta_E = 61\%$). The use of wide stripes and resulting high fill factor were found to bring both lower series resistance and less power saturation, yielding higher efficiency at high power.

In parallel work, a second design was shown to reduce lateral far field angle θ_{lat} without compromising conversion efficiency. Newly developed bars omit etched grooves (baseline), instead using a deep implantation step to suppress lateral current spreading next to each stripe, maintaining high efficiency whilst narrowing lateral far field. The the new low far field design and the baseline structure hardly differ in their light-current-voltage characteristic. The lateral far field angle is, however,

reduced by $\sim 2^\circ$ to $\theta_{\text{lat}} = 8.8^\circ$ (at 95% power) at $P_{\text{opt}} = 1$ kW, the narrowest reported value, with results shown in Fig. 3.

In conclusion, research into lateral structuring of high fill factor diode laser bars has enabled FBH scientists to demonstrate new performance records for 940 nm at the operation point of $P_{\text{opt}} = 1$ kW. A design optimized for improved conversion efficiency pushed the efficiency up to $\eta_E = 66\%$, while a low far field design reduced the lateral divergence down to 8.8° , both at 1 kW emission power. In further recent work, it was also

possible to realize 1 kW power in QCW mode from a single bar at wavelengths of both 808 nm and 780 nm, for use as advanced pump sources for Nd- and Th-doped gain media [2]. These advances stress the suitability of FBH's diode laser bars for applications requiring highly efficient and low divergent emission at the kW-level.

We thank TRUMPF Laser GmbH, which supported parts of this work.

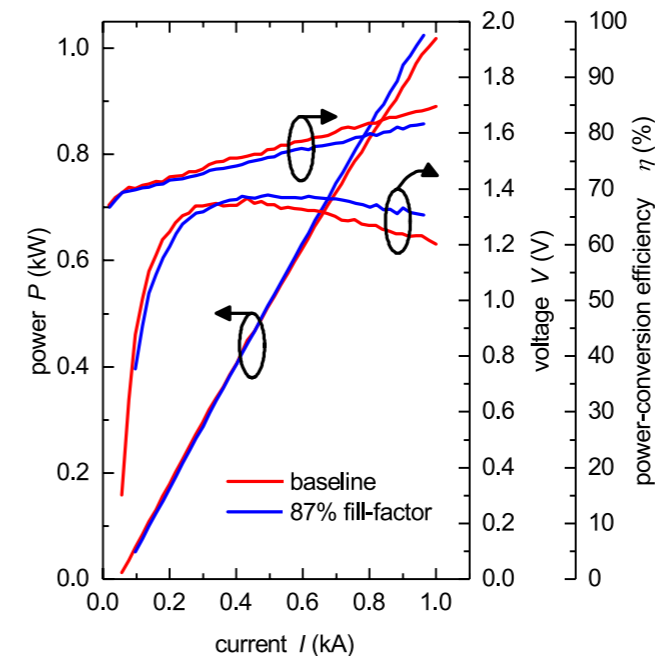


Fig. 2. Power, voltage and conversion efficiency of kW-class lasers, for baseline and high efficiency, high fill-factor designs.

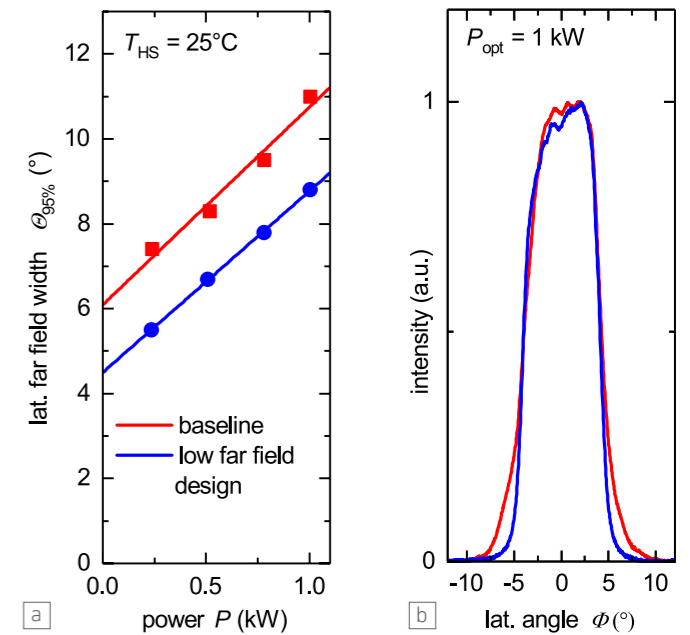


Fig. 3. Lateral far field of kW-class laser bars – baseline and bars with higher brightness (narrower far field). (a) Far field as function of operating power, (b) intensity as function of emission angle.

Diodenlaser Barren mit 1 cm Streifenbreite, die Ausgangsleistungen im Kilowatt-Bereich liefern, werden für viele Anwendungen benötigt und insbesondere in der Materialbearbeitung eingesetzt. Derartige Barren im Wellenlängenbereich um 9xx nm wurden am FBH in den letzten Jahren in enger Zusammenarbeit mit TRUMPF erfolgreich weiterentwickelt. In aktuellen Arbeiten wurden vor allem Variationen der lateralen Struktur untersucht. So konnte dank einer neuen Struktur aus 8 Emittern mit je 1093 μm Breite und 87% Füllfaktor die Effizienz bei 1 kW Leistung signifikant von 61% auf 66% gesteigert werden. Bei einer anderen Struktur wurden die Ätzgräben der Referenzstruktur durch tiefe Implantation ersetzt. Damit reduzierte sich der Fernfeld-Winkel bei gleichbleibender Effizienz deutlich (95% Leistungsinhalt) um $\sim 2^\circ$ auf 8.8° . Neben diesen Rekordwerten bei 940 nm erreichten Barren mit Wellenlängen von 808 nm und 780 nm zudem erstmalig Leistungen von 1 kW.

Publications

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- [2] P. Crump, G. Tränkle, "A brief history of kilowatt-class diode-laser bars", Proc SPIE 11301, 113011D (2020).
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FBH-made stack modules as pump sources for high-energy class applications

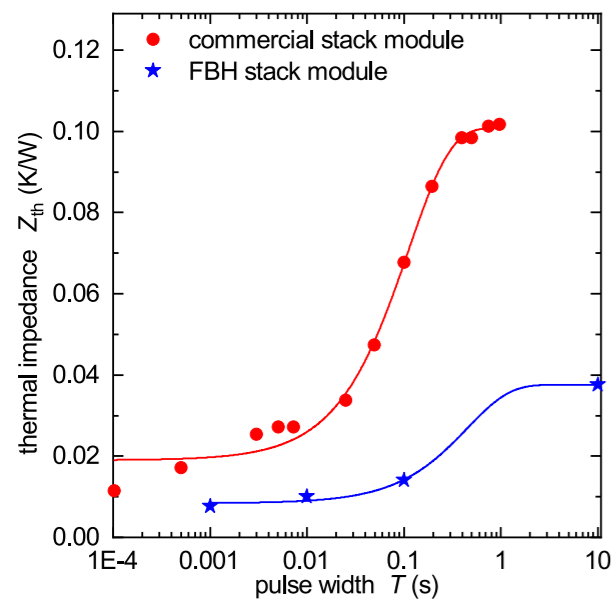


Fig. 1. Thermal impedance (whole module) vs. pulse width of a commercial and an FBH 3...4 kW pump module, both operating around a wavelength of 940 nm [1].

High-energy-class laser pulses are used in many applications, for example material processing, surgery, spectroscopy or to enable applications in basic science such as plasma accelerators. Efficient diode laser pump sources are key components in these laser systems, and produce all the initial photons. The performance of the systems is strongly dependent on the capability of the pump sources, thus they have to fulfill specific requirements and be continuously improved. Not just a high pump power, power density and efficiency are needed but also a high duty cycle, for more rapid processing. High optical pump power levels of many kilowatts are needed; and to achieve this, a large number of high-power diode lasers or laser bars are stacked on top of each other. Current commercially available stack modules were developed for low duty cycle applications. Such modules use low-cost passive cooling that extracts heat from the rear facet of the diode laser bars and therefore cannot be used in high duty cycle applications (or only with significant drop in performance). For higher duty cycles, micro-channel cooling is possible, but introduces much higher costs and is a reliability hazard. Hence, there is a significant gap in commercial availability of pumps with the performance required to address the needs of emerging high-energy pulsed laser applications.

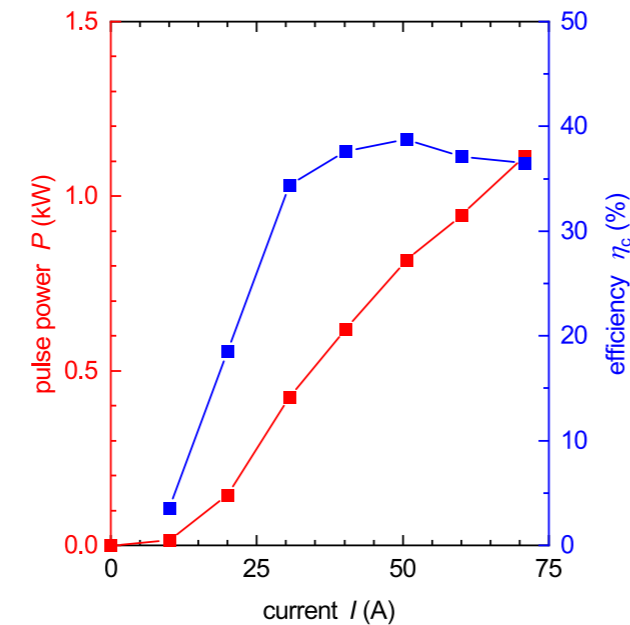


Fig. 2. Optical pulse power and conversion efficiency vs. current of first 780 nm pulsed pump prototype stack module (10 ms 10 Hz) [2].

Building on more than 10 years of ongoing research, the FBH has developed and produced stack modules that fill this gap. The institute develops novel emitters, packaging and cooling, with initial R&D focused on stacks operating at 940 nm for the pumping of Yb:YAG disk amplifiers. In summary, we build a stack of many large-area high-power single emitters and use a cost-efficient and reliable passive cooling on both sides of the stack, so that the heat is spread over a large area and efficiently removed. In 2019, the FBH team demonstrated that these novel designs lead to 3 - 4 kW stacks at an emission wavelength of 940 nm with a much lower dynamical thermal impedance than is possible in conventional bar-based stacks. This applies even for long pulses up to 100 ms and high duty cycles up to 20% (Fig. 1) [1].

In recent developments, we used our experience in 940 nm stack modules and transferred the wavelength to 780 nm, as reported in [2]. High energy, high duty cycle pump sources at 780 nm are essential for enabling high pulse energies in thulium-doped solid-state lasers, which are needed in future mid-infrared laser systems. The semiconductor materials needed to realize 780 nm diode lasers have lower performance compared to those used for 940 nm lasers, and this can compromise

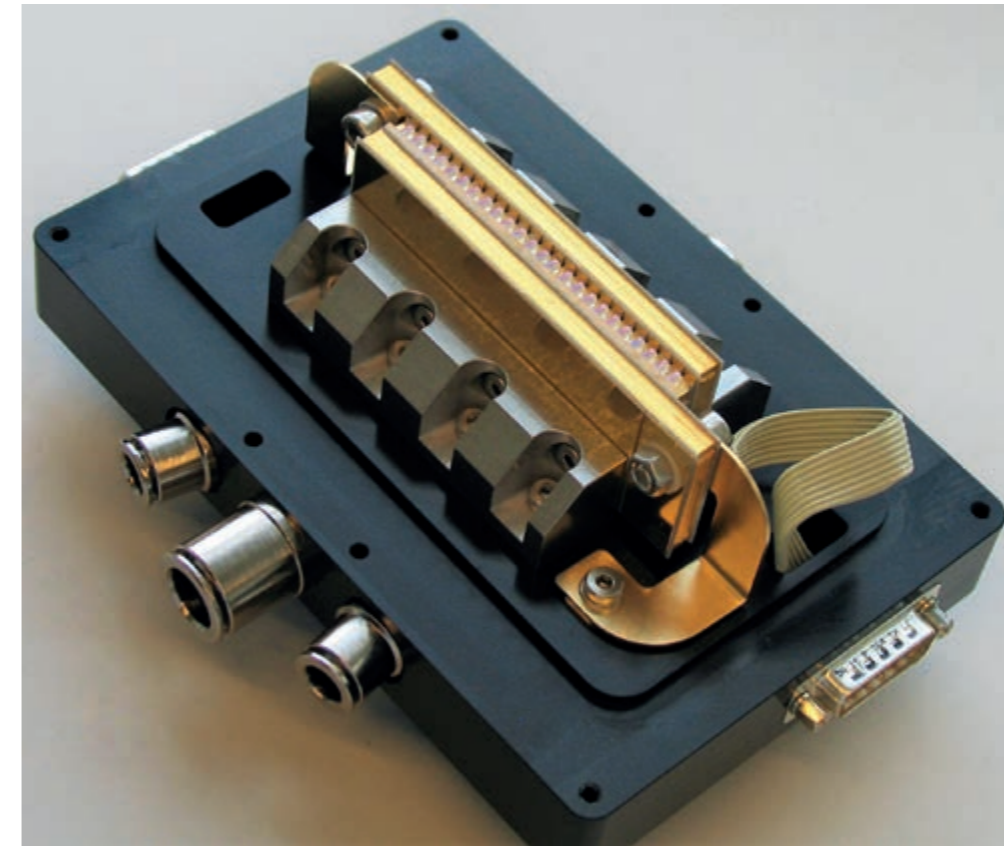


Fig. 3. Fully assembled and lensed FBH stack module.

reliability and efficiency. In spite of this limitation, the FBH team was able to build the first prototype stack that provides more than 1.1 kW at 780 nm with 10% duty cycle (10 ms pulse duration and 10 Hz repetition rate) (Fig. 2), without need for microchannel cooling. The 1.1 kW optical output (11 J pulses) was delivered close to 780 nm, with a spectral width of < 5 nm (with 95% power content, not shown). Promising first reliability data was also presented on single emitters. Further increases in power and efficiency are sought.

Fig. 3 shows the assembled stack module with power connectors fixed on the rear of the module and water connectors on the side. Each single stack element is fast axis-collimated, in order to enable an easy beam shaping of the module emission. Depending on the application, we can also optically combine two stack modules to double the optical power, provide a fiber coupling and housing or transfer it to further wavelengths, e.g. 808 nm or 980 nm, as discussed in [3].

Funding is from the German Federal Ministry for Education and Research (BMBF), within the KMU-NetC program (HECMIR: FKZ - 03VNE2068E).

Publications

[1] M. Hübner, I. Will, J. Körner, J. Reiter, M. Lenski, J. Tümmler, J. Hein, B. Eppich, A. Ginolas, P. Crump, "Novel High-Power, High Repetition Rate Laser Diode Pump Modules Suitable for High-Energy Class Laser Facilities", MDPI instruments, vol. 3, no. 3, pp. 34, (2019).

[2] P. Crump, M. Wilkens, M. Hübner, S. Arslan, M. Niemeyer, P. S. Basler, D. Martin, A. Maaßdorf, A. Ginolas, G. Tränkle, "Efficient, high power 780 nm pumps for high energy class mid-infrared solid state lasers", Proc. SPIE 11262, 1126204 (2020).

[3] M. Hübner, B. Eppich, A. Maaßdorf, D. Martin, A. Ginolas, P.S. Basler, M. Niemeyer, P. Crump, "High Duty Cycle, High Repetition Rate High Brightness Diode Laser Pulsed-Pump-Sources", Advanced Solid State Lasers Conference (ASSL 2019), Vienna, Austria, ISBN: 978-1-943580-68-2, paper JW2A.29 (2019).

Gepulste Laser der Hochenergie-Klasse werden vielfältig eingesetzt, unter anderem in der Materialbearbeitung. Pumpquellen für diese Systeme sind besonders anspruchsvoll, da die Laser neben einer hohen Leistung auch ein hohes Tastverhältnis benötigen. Diese Eigenschaften bieten kostengünstige kommerzielle Pumpmodule für gewöhnlich nicht, da sie nur über eine simple passive Kühlung verfügen. Module mit Mikrokanalkühlern hingegen sind sehr teuer und fehleranfällig. Die Lücke schließen Pumpmodule bei 940 nm, die das FBH seit einiger Zeit entwickelt und herstellt. Dank ihrer effizienten, doppelseitigen passiven Kühlung erreichen sie hohe Leistungen und Wiederholraten und sind gleichzeitig kostengünstig und zuverlässig. Unser Portfolio haben wir nun mit Modulen bei 780 nm erweitert, die auf unserem Know-how über Diodenlaser dieser Wellenlänge und bei der Herstellung von Pumpmodulen aufbauen. Der erste so hergestellte Prototyp liefert bereits weltweit einzigartige Kennzahlen mit Pulsleistungen von mehr als 1,1 kW bei einer Pulsbreite von 10 ms und einem Tastverhältnis von 10%.

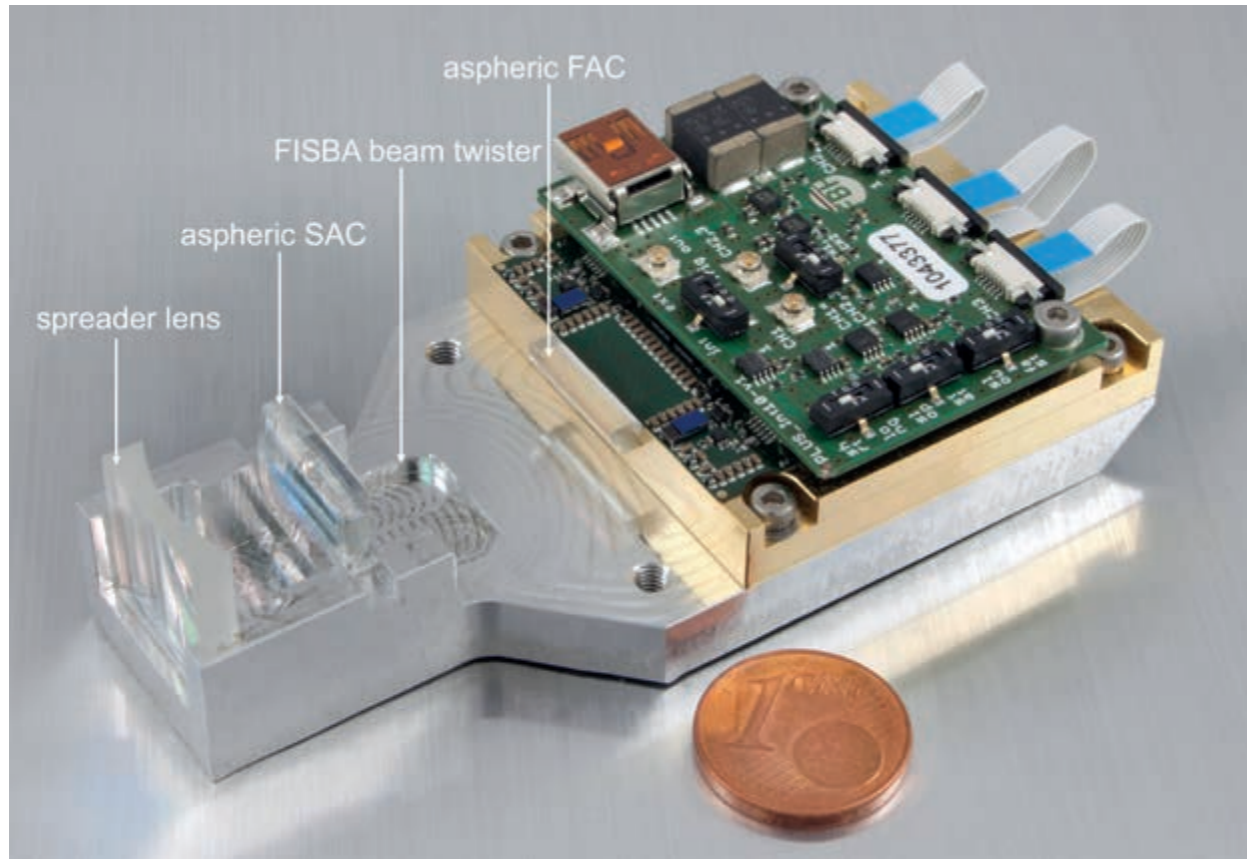


Fig. 1. 48 emitter DBR laser module hybridintegrated with beam forming optics.

600 W short pulse hybrid-integrated 48 emitter DBR laser module for 3D flash LiDAR

Diode lasers generating optical pulses with high peak power and pulse lengths in the pico- and nanosecond ranges are key components for systems like compact LiDAR (light detection and ranging) units. LiDAR systems provide the means to scan the local environment and measure the distance of objects by, for example, time-of-flight (ToF) measurements. To that end, 3D flash LiDARs (multibeam LiDARs) comprise, amongst others, a wide-angle source, a detector array, and wide-angle optics to focus the light reflected from one exposure area onto the detector.

For use in automotive LiDAR, short optical pulses (100 ps – 10 ns) with a peak optical power exceeding 100 W, a low temperature-dependent wavelength shift, and good beam quality are required. Shorter optical pulses provide a higher spatial resolution and are also beneficial with regard to eye safety. To avoid water vapor absorption under real-world atmospheric conditions, the emission wavelength has to be around 900 nm. The requirements can be fulfilled by means of integrating a wavelength-selective element like a Bragg grating into the laser.

For automotive 3D flash LiDAR, FBH has developed distributed Bragg reflector (DBR) board area laser bars comprising 48 single emitters on one chip with $\frac{1}{4}$ filling factor. The epitaxial layer structure features an InGaAs single quantum well embedded in an AlGaAs-based asymmetric waveguide and cladding. To allow for a cost-effective single-step epitaxial growth, 7th-order DBR grating is implemented into the surface of the layer structure. The laser bar is 4 mm long including the 1 mm long DBR grating. It is mounted p-side down on a CuW submount and sandwiched between an in-house developed electronic driver and a mount to minimize inductances, see Fig. 1. Thus, all 48 emitters are driven in parallel. The electronic driver features GaN-based transistors in the final stages due to their advantageous properties for high-speed high-current switching. Using four parallel final driver stages, the electronic driver provides 2 - 10 ns long, nearly rectangular-shaped current pulses with peak currents up to 1,000 A.

The dependence of the peak optical power on the pulse current of a 48 emitter DBR laser module is shown in Fig. 2 for a pulse width of 8 ns, a repetition rate of 10 kHz, and a temperature of 25 °C and 85 °C. A maximum peak optical power of about 640 W and still more than 400 W is achieved at a peak current of around 900 A at 25 °C and around 860 A at 85 °C, respectively. For both temperatures and for the respective maximum peak current, the corresponding optical spectra are depicted in the inset of Fig. 2. Both optical spectra feature a peak wavelength of around 900 nm and a spectral width of about 0.6 nm (95 % power content). A temperature-dependent wavelength shift of only about 60 pm/K ($\Delta\lambda = 3.8$ nm for $T = 25$ °C to 85 °C) can be determined. The horizontal power distribution (far field) of a hybrid-integrated 48 emitter DBR laser module (see Fig. 1) is shown in Fig. 3. The residual horizontal divergence angle of the homogeneous horizontal line is about 0.1 deg (full width at $1/e^2$ intensity). Thus, this hybrid-integrated laser module provides a horizontal beam diameter of about 17 cm in a distance of 100 m. In vertical direction, a divergence angle of about 24 deg is provided by a spreader lens.

This project was supported by the German Federal Ministry for Education and Research (BMBF) under grant no. 13N14023,26 within the funding initiative EffiLAS/PLUS and partly BMBF-funded within Research Fab Microelectronics Germany (FMD) under grant no. 16FMD02.

Fig. 3. Horizontal power distribution (far field) of 48 emitter DBR laser bar module shown in Fig. 1. The color-plot of the power distribution is not to scale.

Diodenlaser, die kurze optische Pulse mit hoher optischer Spitzenleistung emittieren, sind Schlüsselkomponenten in kompakten LiDAR-Systemen. Mit ihnen kann die Entfernung von Objekten durch Laufzeitmessung der Laserpulse bestimmt werden. Für LiDAR-Systeme in Automobilen werden 100 ps bis 10 ns lange Pulse mit mehr als 100 W Spitzenleistung bei Wellenlängen um 900 nm benötigt. Zudem dürfen Temperaturschwankungen nur einen geringen Einfluss haben. Für Linienscanner in Automobilen wurden am FBH DBR-Laserbarren mit 48 Emitttern sowie spezielle Treiberschaltungen entwickelt. Damit können Pulse im Nanosekundenbereich mit Spitzenleistungen von mehr als 600 W und schmalen optischen Spektrum um 905 nm erzeugt werden. Durch ein in den Laser integriertes Bragg-Gitter verschiebt sich die Wellenlänge mit der Temperatur um nur 60 pm/K. Zusammen mit Strahlformungsoptiken wird das Modul hybrid integriert aufgebaut und liefert einen horizontalen Strahldurchmesser von etwa 17 cm in 100 m Entfernung. In vertikaler Richtung erreicht es einen Divergenzwinkel von etwa 24 Grad.

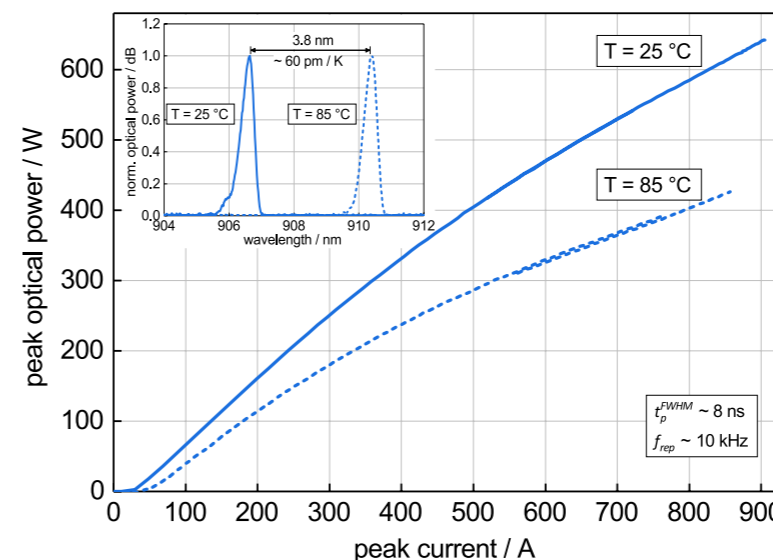
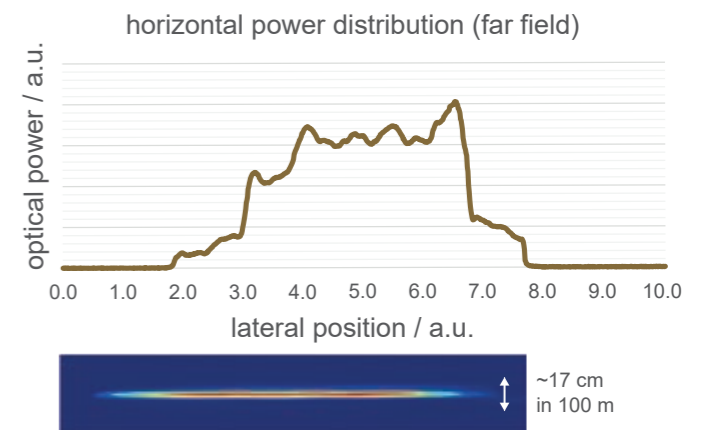


Fig. 2. Peak optical power and optical spectrum (inset) achieved for 8 ns long optical pulses with a repetition rate of 10 kHz at 25 °C and 85 °C.

Publications

A. Knigge, H. Christopher, A. Klehr, J. Fricke, A. Liero, T. Honig, E. Langenbach, H. Wenzel, G. Tränkle, "Wavelength stabilized high pulse power laser bars for line-flash automotive LiDAR", Proc. SPIE 11262, 11262-13 (2020).

H. Christopher, A. Klehr, J. Fricke, A. Liero, H. Wenzel, A. Knigge, G. Tränkle, "Investigation of 48 emitter DBR laser bars under nanosecond high peak current excitation", Proc. SPIE 11301, 11301-22 (2020).

A. Klehr, A. Liero, H. Christopher, H. Wenzel, A. Maaßdorf, P. Della Casa, J. Fricke, A. Ginolas, A. Knigge, "Wavelength stabilized high pulse power 48 emitter laser bars for automotive LiDAR application", Semicond. Sci. Technol., vol. 35, no. 06, pp. 065016, doi: 10.1088/1361-6641/ab8397 (2020).

H. Wenzel, A. Klehr, A. Liero, H. Christopher, J. Fricke, A. Maaßdorf, A. Zeghuzi, A. Knigge, "High pulse power wavelength stabilized 905 nm laser bars for automotive LiDAR", IEEE High Power Diode Lasers and Systems Conference (HPDL), pp. 7 – 8 (2019).

High-power micro-module for pumping of ultrafast solid state lasers

Reaching high optical output powers at excellent beam qualities has always been a challenging objective in diode laser development. FBH successfully processes Bragg-grating-stabilized tapered diode lasers with reliable output powers in the watt range at high beam qualities. In order to address applications in the ten watt scale and beyond, a laser system was developed which is capable of combining two laser beams almost loss-free. It is tailored to the needs of direct ultrafast solid-state laser pumping, as required for example in material processing and medical applications. The coupled radiation reaches optical output powers of more than 15 W in continuous wave mode at a wavelength of 980 nm (see Fig. 1). Furthermore, the high beam quality of the single emitters is maintained, achieving an output beam quality factor of $M^2 < 1.5$ in vertical as well as lateral dimension. The entire setup was micro-integrated into an FBH-developed butterfly housing with a footprint as small as $76 \times 54 \times 15 \text{ mm}^3$ (see Fig. 2.). The small size of the modules supports the compact integration into existing and newly developed systems. At the same time, the optical pumping geometries of solid-state lasers can be simplified. The high beam quality supports efficient pumping without the need for challenging beam shaping optics. By thermal manipulation of the Bragg gratings, the emitted wavelength can be precisely tuned in a range of more than 2 nm to meet the exact absorption characteristics of the pumped medium. This allows the setup to adapt to varying ambient conditions while maintaining the maximum possible overall efficiency.

To enable the high output power, the polarization characteristics of the tapered laser beams were utilized to couple the single laser beams inside the module. By rotating the polarization of one emitter, two beams can be combined using a thin film polarizer. The polarizer itself was adapted to withstand the high radiation intensities ($> 1 \text{ kW/cm}^2$) and enable maximum coupling efficiency at the given wavelength of 980 nm. To ensure undisturbed performance of the single emitters, thermal simulations of the complete module were carried out. Based on the results, the mechanic-optical setup was optimized in order to

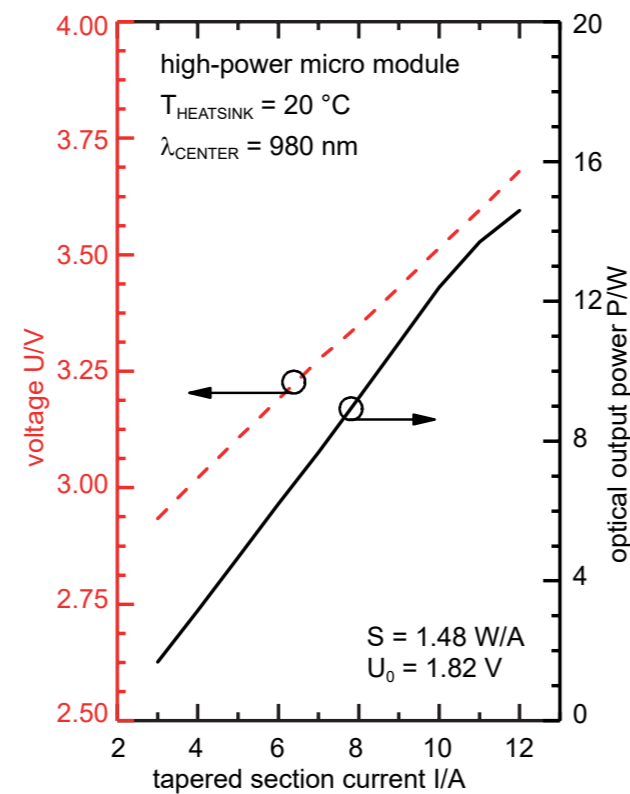


Fig 1. Power-current characteristics of the high-power micro module, yielding 15 W output power in CW mode while maintaining high beam quality.

avoid thermal crosstalk between the components while ensuring a minimal spatial footprint.

A key application for these laser modules is pumping of solid-state lasers for ultra-short pulses. The given high-performance optical output characteristics greatly depend on the setup accuracy. Therefore, specialized micromanipulators were used to ensure sub-micron positioning precision. An optimized adhesive ensures long-time steadiness of the setup as well as high dynamic stability under challenging physical conditions.

This concept is easily adaptable to tapered laser diodes of different wavelengths in the range between 780 nm and 1180 nm. The emerging optical output power can either be utilized both directly as collimated free beam and coupled to an optical fiber. In order to ensure maximum coupling efficiency, advanced optical simulations are utilized. Ray- and wave-optic simulations enable coupling even under challenging conditions for single-mode and low-order-mode fibers.

The high-power micro-module was developed within the MiFeM project, supported by the European Union in the Eurostars framework, EUROSTARS E! 11440 - MIFEM

Publication

P. Hildenstein, A. Sahn, D. Feise, M. Gorjan, S. Tacchini, K. Paschke, G. Tränkle, "High-power, high-beam quality miniaturized laser module for pumping of solid state lasers at 980 nm", Proc. SPIE 11262, 112620J (2020).

Diodenlaser werden seit langem erfolgreich zum Pumpen von Festkörperlasern und Verstärkern eingesetzt. Sie wandeln elektrische Leistung besonders effizient in optische Leistung um und ermöglichen so hohe Wirkungsgrade des Gesamtsystems. Um den Einsatzbereich dieser Laser zu erweitern, hat das FBH ein neuartiges Mikromodul entwickelt, das hohe Leistungen bei gleichzeitig hoher Strahlqualität bietet. Die Basis dafür sind optimierte, im Haus entwickelte Diodenlaser mit Trapezstruktur und integriertem Oberflächengitter (DBR-Trapezlasers). Dank ihrer exzellenten Leistungsparameter kann das Licht direkt und ohne aufwändige Strahlformungsoptiken genutzt werden. Zwei DBR-Trapezlasers wurden in das Hochleistungsmikromodul integriert, die sich durch Polarisationskopplung überlagern. Das 980 nm Lasermodul erreicht damit eine optische Ausgangsleistung von bis zu 15 Watt (CW) mit nahezu beugungsbegrenzter Strahlqualität. Diese Leistung kann sowohl direkt eingesetzt als auch in einen Lichtwellenleiter gekoppelt werden. Zusätzlich kann die Emissionswellenlänge über einen Bereich von bis zu 2 nm im Betrieb angepasst werden. Dank der geringen Abmessungen von nur $76 \times 54 \times 15 \text{ mm}^3$ eignet sich das Mikromodul für vielfältige Anwendungen.

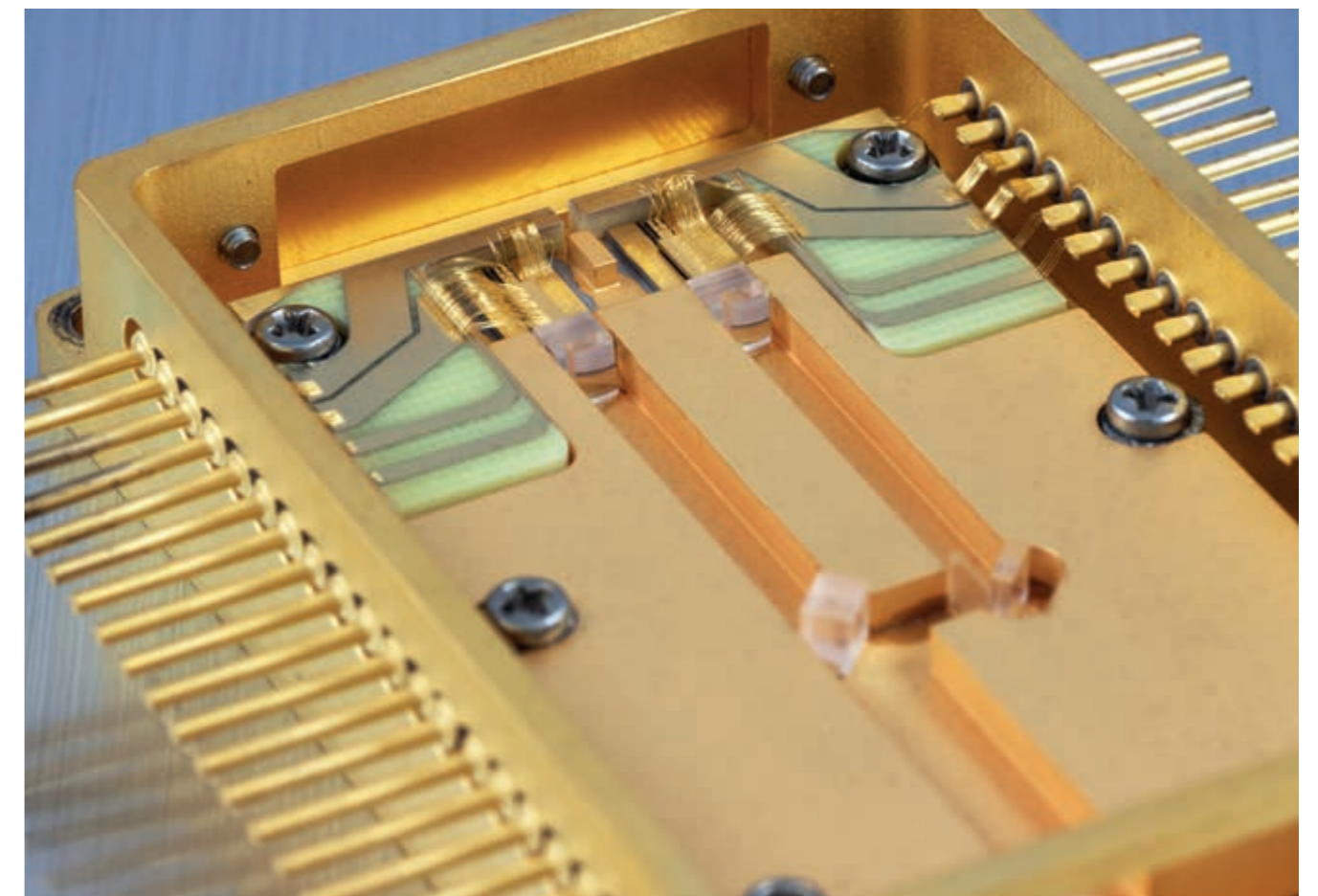
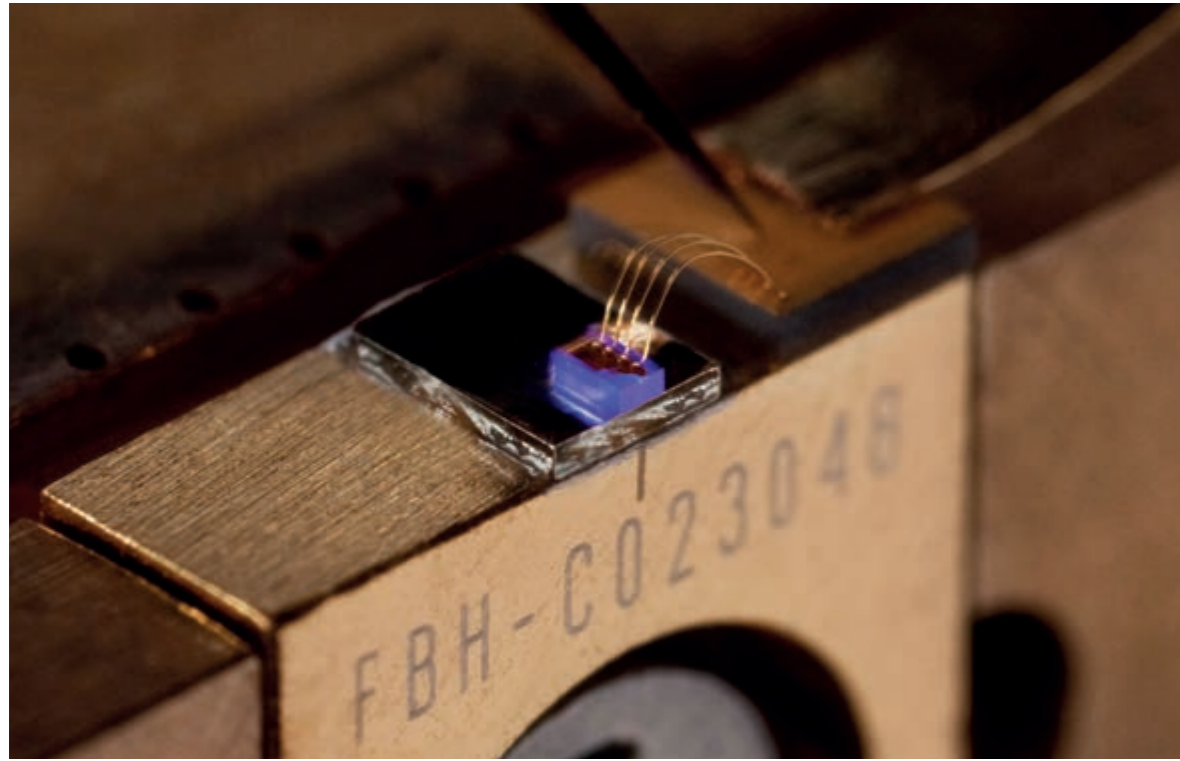


Fig. 2. Micro-integrated high-power diode laser module.



➊ GaN-based laser diode emitting in the blue-violet spectral range.

DFB laser diodes in the blue-violet spectral region for sensing and metrology

Single-mode laser sources emitting in the blue-violet spectral region are interesting light sources with applications in atom spectroscopy, atomic clocks, and medical diagnostics. Ideally, these devices are realized as compact distributed-feedback (DFB) laser diodes based on gallium nitride (GaN). However, since the current performance of DFB laser diodes is limited, their market launch is still some way off. Recently, FBH has considerably improved its technology for fabricating DFB laser diodes based on GaN using high-order surface Bragg gratings – a simple concept which does not require two-step epitaxy. As a result, single longitudinal and lateral mode DFB laser diodes emitting around 405 nm were demonstrated. The devices operate in continuous-wave (CW) mode and show a lower threshold current, higher slope efficiency and increased maximum optical power than previously reported devices with a similar design.

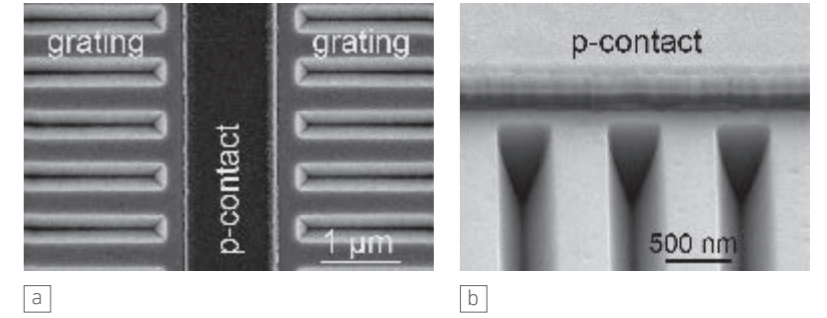
The group-III nitride laser heterostructure was deposited on 50 mm GaN (0001) substrates using metalorganic vapor phase epitaxy. The p-type conductivity in the Mg-doped layers was

activated by annealing the wafers in oxygen containing ambient, which is known to be critical to achieve reasonable device reliability. First, 1.5 μm-wide Pd/Pt p-contact stripes were fabricated. Second, 10th-order gratings with a period of either 802 nm or 812 nm were written in 0.25 μm distance along the p-contact stripes employing electron-beam lithography (see Fig. 1). Afterwards, the gratings were passivated using SiO₂. The optical mode is laterally confined in the 2 μm wide unetched region between the two grating regions. The opening angle and the depth of the V-shaped grooves of the grating were precisely adjusted in accordance to simulations to achieve a sufficiently high optical reflectivity of the grating. The rest of the chip process followed standard procedures. The final chips have a footprint of 400 μm x 600 μm, a high reflectivity coating on the back facet and an antireflection coating on the front facet. They were mounted p-side up on copper heatsinks.

The laser diodes were operated under CW conditions with up to 100 mW optical power (see Fig. 2). Threshold current and slope efficiency are typically in the range of 90 - 160 mA and

Publication

J. H. Kang, H. Wenzel, E. Freier, V. Hoffmann, O. Brox, J. Fricke, L. Sulmoni, M. Matala, C. Stölmacker, M. Kneissl, M. Weyers, S. Einfeldt, "Continuous-wave operation of DFB laser diodes based on GaN using 10th-order laterally coupled surface gratings", Opt. Lett., vol. 45, no. 4, pp. 935-938 (2020).



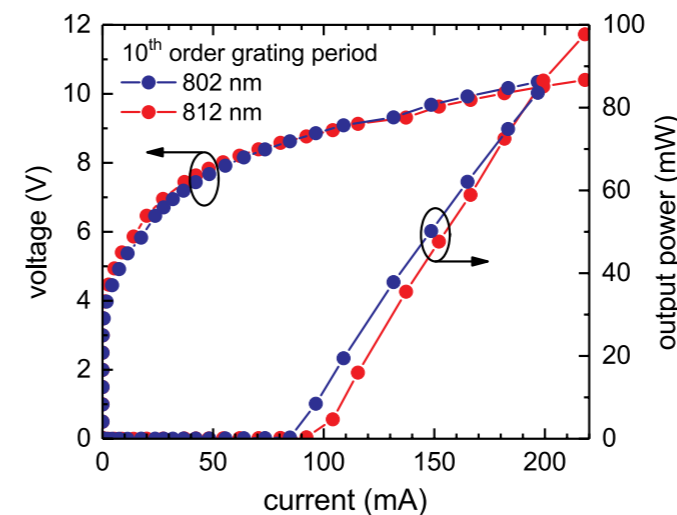
➋ Fig. 1. Scanning electron microscopy images of the surface gratings with V-shaped grooves fabricated alongside the p-contact stripe. The images are taken in plan view (a) and bird's eye view (b), respectively.

0.6 - 0.9 W/A, respectively. High-resolution emission spectra of the devices reveal single peak emission with a full width at half maximum of 0.02 nm and a side-mode suppression ratio beyond 26 dB. In agreement with the Bragg condition, the lasing peak shifts from 404.8 nm for a period of 802 nm to 408.5 nm for a period of 812 nm. Single longitudinal mode operation without mode hops is maintained from the threshold up to an optical output power of around 90 mW (see Fig. 3) and over a temperature range of 15 °C to 40 °C with a linear red-shift of the lasing wavelength of 0.018 nm/K.

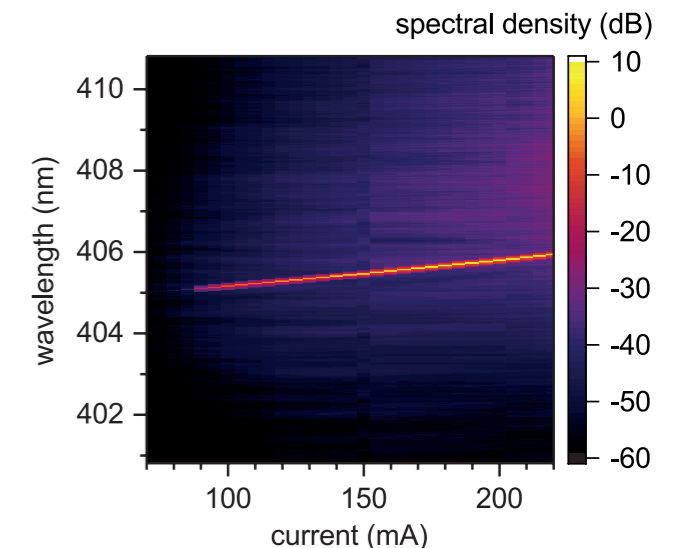
The data demonstrates feasibility to realize stable single longitudinal and lateral mode DFB laser diodes of various wavelengths in the blue-violet spectral region by properly designing and fabricating laterally coupled surface Bragg gratings of high order. The prospects are good that such DFB laser diodes can replace bulky, complex, and inefficient systems such as external cavity diode laser systems in the near future.

This work was supported by the European Fund for Regional Development of the European Union in the framework of the Berlin-Polish joint project "From UV to blue – Reliable laser sources for environmental monitoring (RelyLa)".

Blau-violett-emittierende Single-Mode-Laserdioden sind für Anwendungen wie Atomspektroskopie, Atomuhren und medizinische Diagnostik interessant. Um sie zur Marktreife zu bringen, müssen ihre Leistungsparameter jedoch noch deutlich verbessert werden. Kürzlich hat das FBH Laserdioden mit verteilter Rückkopplung (DFB-Laserdioden) auf der Basis von GaN demonstriert, die im Dauerstrichbetrieb longitudinal und lateral monomodig arbeiten. Dazu wurden Bragg-Oberflächengitter 10. Ordnung integriert, die lateral an die Mode unter einen 1,5 μm breiten p-Kontaktstreifen koppeln. Je nach verwendeter Gitterperiode konnte modensprungfreies Lasing bei 404,8 nm beziehungsweise 408,5 nm mit Leistungen bis zu 100 mW demonstriert werden. Mit einer Verschiebung der Laserwellenlänge von 0.018 nm/K sind die Laser relativ stabil gegen Temperaturänderungen. Die Aussichten sind gut, dass solche DFB-Laserdioden in naher Zukunft sperrige, komplexe und ineffiziente Systeme im blau-violetten Spektralbereich wie Diodenlasersysteme mit externem Resonator ersetzen können.



➌ Fig. 2. Continuous-wave optical power-current-voltage characteristics of DFB laser diodes with grating periods of 802 nm and 812 nm.



➍ Fig. 3. 2D color map of emission spectra of a DFB laser diode with a grating period of 802 nm operated in continuous-wave mode at different currents.

Far-UVC LEDs for medical and sensing applications

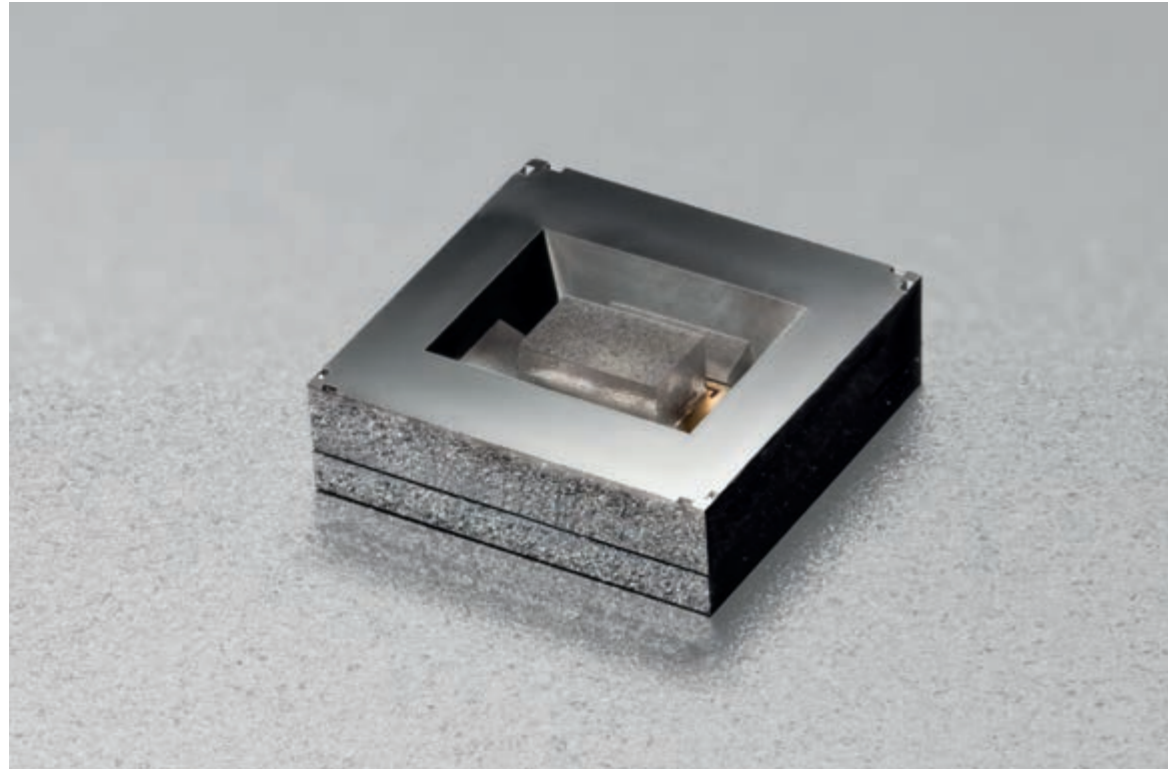


Fig. 1. Flip-chip mounted UV LED in a silicon-based package developed by CiS Forschungsinstitut für Mikrosensorik.

Research targeting far ultraviolet-C (far-UVC) light emitting diodes (LEDs) with emission wavelengths < 240 nm has increased in recent years, driven by applications like gas sensing, measurement of nitrate and skin antiseptics. In case of skin antiseptics, for example, irradiation of the skin with far-UVC radiation is believed to prevent infections by multi drug resistant (MDR) microorganisms without damaging healthy tissue. However, the performance of these LEDs is currently limited as the emission power is only a few milliwatts, the wall-plug efficiency is < 1 %, and the lifetime in the order of several ten to hundred hours of operation. The Joint Lab GaN Optoelectronics, operated jointly by FBH and Technische Universität Berlin, is addressing these issues and has recently improved the overall performance. Far-UVC LEDs could be optimized through several improvements along the fabrication chain, from epitaxial growth through chip processing to packaging.

Preparing proper metal-to-semiconductor contacts both at the p- and the n-side turned out to be critical to fabricate LEDs that can be operated at low voltages and have a high wall-plug efficiency. The high aluminum content in the AlGaIn heterostructure results in electrical contacts with non-linear characteristics and a high resistivity. Optimizations of the plasma etching process applied before metal deposition and thermal annealing of

the n-contact have reduced the voltage of the LEDs from (15.8 ± 0.8) V to (10.4 ± 0.8) V when operated at 20 mA.

In the last fabrication process, the LED chips are flip-chip mounted into silicon-based packages developed by CiS Forschungsinstitut für Mikrosensorik (see Fig. 1) which offer good heat dissipation and efficient light extraction via an integrated reflector. Driven at a current of 100 mA and actively cooled to 20 °C, the latest generation of such UVC LEDs shows an optical power of (1.9 ± 0.3) mW and a drive voltage of (around 13) V, respectively (see Fig. 2). The emission spectrum exhibits a single peak at (233 ± 1) nm (see inset Fig. 2) with negligible parasitic emission at longer wavelengths.

The impact of the operation conditions, particularly current and temperature, and the heterostructure design on the degradation behavior has been studied. The current density was found to have a strong impact on the reduction of the optical power. The lifetime of the LEDs scales with the cube of the current density. At the same time, no significant influence of temperature was found. Furthermore, raising the aluminum content in one part of the electron blocking heterostructure (EBH) increases the optical power and, at the same time, slows down the degradation. After 250 h of operation at a current of

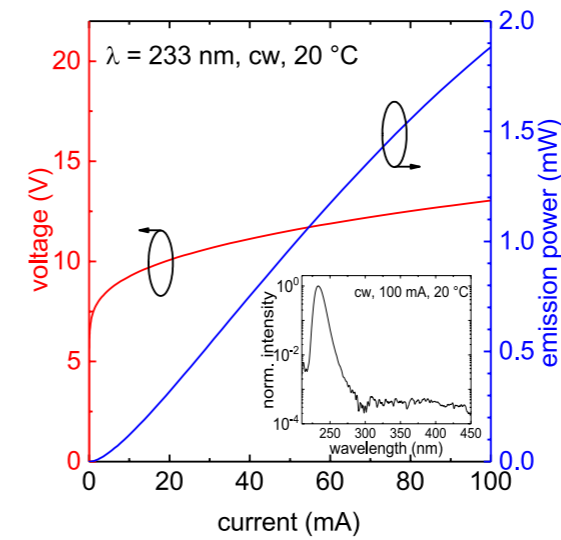


Fig. 2. Optical power and voltage as a function of current of a typical flip-chip mounted far-UVC LED. The inset shows the corresponding emission spectrum with a peak wavelength of 233 nm measured at 100 mA and 20 °C.

100 mA (current density = 67 A/cm²) and a heatsink temperature of 20 °C the optical power of LEDs with an aluminum content in the EBH of 65 % and 95 % decreased to 16 % and 32 %, respectively (see Fig. 3). After a 100 h burn-in period, the best currently available far-UVC LEDs exhibit extrapolated L50 lifetimes of >1,500 h. Extended heterostructure variations are planned to further improve the performance of the LEDs.

In parallel, FBH together with Charité Berlin and University of Greifswald has already begun with application development within the Advanced UV for Life project framework. The water-cooled UV radiation module for the antiseptics of living skin

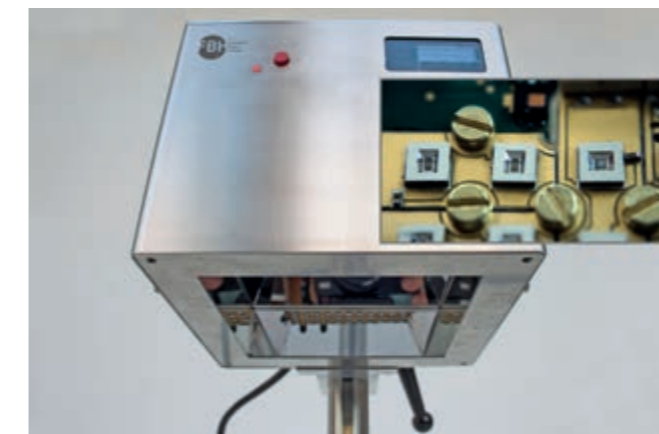


Fig. 4. Irradiation module containing 118 far-UVC LEDs emitting at around 233 nm. The module will be used for skin antiseptics experiments.

Publication

C. Stölmacker, N. Lobo Ploch, A. Thies, S. Hochheim, J. Rass, F. Schnieder, A. Mogilatenko, J. Ruschel, T. Kolbe, S. Knigge, S. Einfeldt, "Electroplated Gold Microstuds for Thermo-compression Bonding of UV LED Chips", IEEE Trans. Comp. Pack. Manuf. Technol., vol. 9, no. 12 (2019).

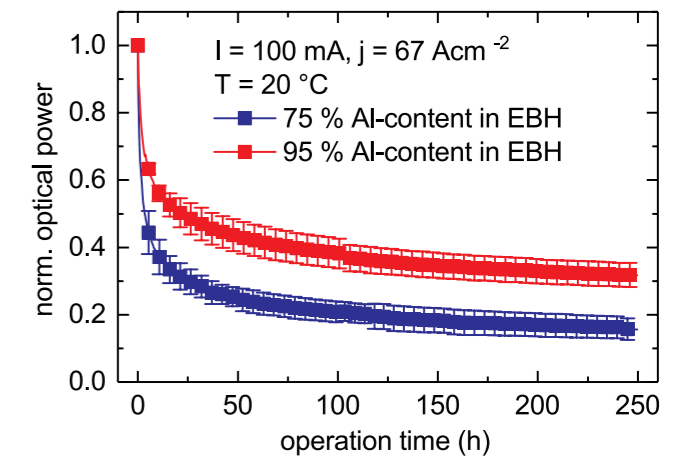


Fig. 3. Normalized optical power as a function of operation time for two batches of far-UVC LEDs with different aluminium content in the electron blocking heterostructure (EBH). The LEDs were operated at 100 mA and 20 °C.

(see Fig. 4) consists of 118 LEDs spread over an area of 8 cm x 8 cm. A two-part aluminum reflector minimizes radiation losses and ensures uniformity of the intensity beyond 90 % on a 6 cm x 6 cm area in 25 mm distance. This LED module will be used for skin irradiation experiments.

This work was partially supported by the German Federal Ministry of Education and Research (BMBF) under contract 03ZZ0146C within the Advanced UV for Life consortium. Further support was given by the Deutsche Forschungsgemeinschaft within the Collaborative Research Center Semiconductor NanoPhotonics" (CRC 787).

Leuchtdioden (LEDs), die im fernen UVC-Spektralbereich <240 nm emittieren, sind für Anwendungen wie etwa im Bereich der Gassensorik und der Medizintechnik hochinteressant. Da die Leistungsfähigkeit der LEDs derzeit noch begrenzt ist, optimieren das FBH und die TU Berlin parallel verschiedene Aspekte im Herstellungsprozess, vom Kristallwachstum bis zur Chipmontage in Gehäuse. Die Betriebsspannung wurde beispielsweise durch optimierte Fertigungsschritte des n-seitigen Metall-Halbleiter-Kontakts deutlich reduziert. Zudem zeigte sich, dass die Lebensdauer der LEDs im Dauerstrichbetrieb stark von der Stromdichte und vom Aluminiumgehalt eines Teils der Elektronenspererschicht abhängt. Die aktuelle UVC-LED-Generation zeigt nunmehr eine optische Leistung von etwa 1,9 mW und eine Betriebsspannung von 13 V bei 100 mA Betriebsstrom. Nach hundertstündigem Einbrennen zeigen diese LEDs eine extrapolierte L50-Lebensdauer von über 1.500 h. Gemeinsam mit der Charité Berlin und der Universität Greifswald hat das FBH mit der Applikationsentwicklung begonnen – ein LED-Modul wird künftig in Experimenten zur Bestrahlung von Haut getestet.

Improvements of UV LEDs due to better understanding the physics of degradation mechanisms

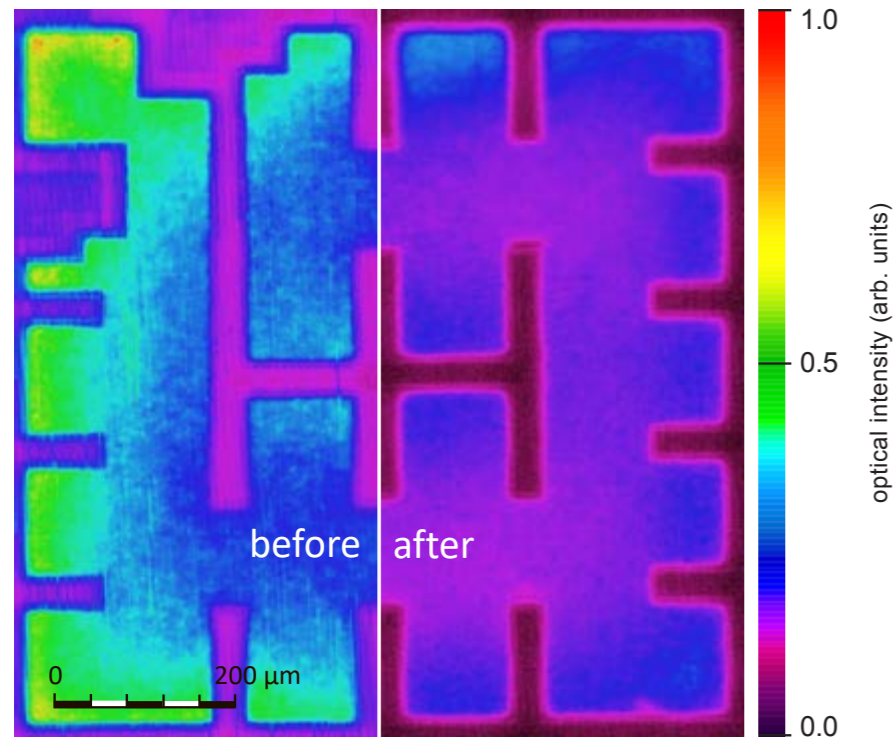


Fig. 1. Distribution of the electroluminescence intensity of a 1 mm x 1 mm UVC LED chip before and after 100 h operation hours at 350 mA at 20 °C.

AlInGaN-based ultraviolet light-emitting diodes (UV LEDs) with emission wavelengths below 320 nm are promising devices for a variety of applications such as sterilization, phototherapy, sensing, or plant growth lighting. Currently, the lifetime of those UV devices is still shorter than that of LEDs emitting in the UVA and blue spectral regions, i.e. their optical power decreases typically faster during operation. As a result, the applicability of the devices is limited. Therefore, an understanding of degradation processes that take place during operation is essential.

Localizing operation-induced changes within the device is one necessary step to narrow down possible processes which may cause degradation. For this reason, the lateral intensity distribution of the optical emission from the active region of UVB and UVC LEDs has been investigated before and after device operation (Fig. 1). It was found that the total optical power reduction results from a uniform decrease in emission intensity over the entire active area of the LED. Macroscopically isolated defects as well as leakage across the mesa edges could be

ruled out as degradation mechanisms, as they would lead to a local decrease in intensity. The results suggest that non-radiative recombination centers, such as point defects, are formed or activated during operation. These defects are uniformly distributed in the active region.

In search of these point defects, vertical depth profiles of hydrogen were recorded after different operation times. Hydrogen was found to migrate during operation from the p-side and near the active region to the n-side of the LED (Fig. 2). It is known that hydrogen results from the gas environment during epitaxial growth of the p-side of the LED. It passivates magnesium acceptors as well as other negatively charged point defects, such as group-III vacancies, by forming defect complexes. The findings indicate a degradation process in which bonds between hydrogen atoms and defects in the p-side and active region are broken. The detachment and migration of hydrogen likely leaves activated defects, which enhances non-radiative recombination in or near the active region. This effect would explain the operation-induced reduction in optical power.

Das FBH arbeitet intensiv daran, die optische Leistung und die Langzeitstabilität von UV-Leuchtdioden zu erhöhen. Dies erfordert ein tiefes physikalisches Verständnis der Mechanismen, die dazu führen, dass die optische Leistung während des Betriebs abnimmt. Mittels elektro-optischer und materialanalytischer Messverfahren konnten mögliche Mechanismen nunmehr stark eingegrenzt werden. UV-LEDs degradieren offensichtlich aufgrund von Defekten, die nahezu homogen verteilt in der aktiven Zone des Halbleiters entstehen und als nicht-strahlende Rekombinationszentren wirken. Die Migration von Wasserstoff spielt dabei eine entscheidende Rolle. Die Degradation zeigt zudem eine charakteristische Abhängigkeit vom Strom, die darauf hindeutet, dass energiereiche Ladungsträger aus Auger-Rekombinationen die nötige Energie für das Entstehen der Defekte liefern. Aus diesen Erkenntnissen lassen sich Ansätze ableiten, um UV-LEDs gezielt weiter zu optimieren.

Fig. 2. H and Al concentration depth profiles at different operation times determined by SIMS.

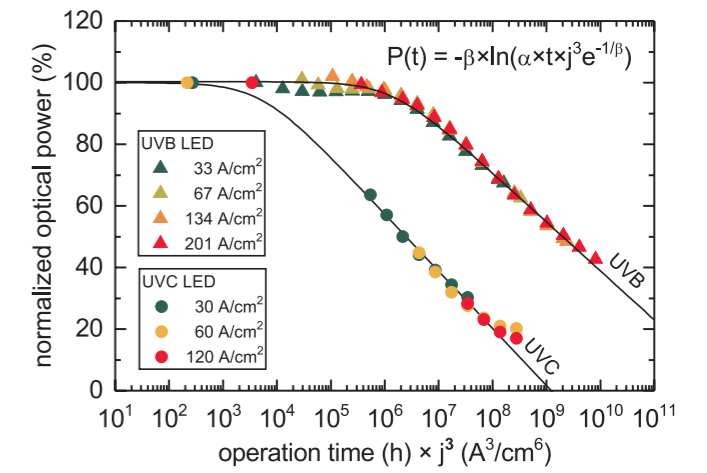
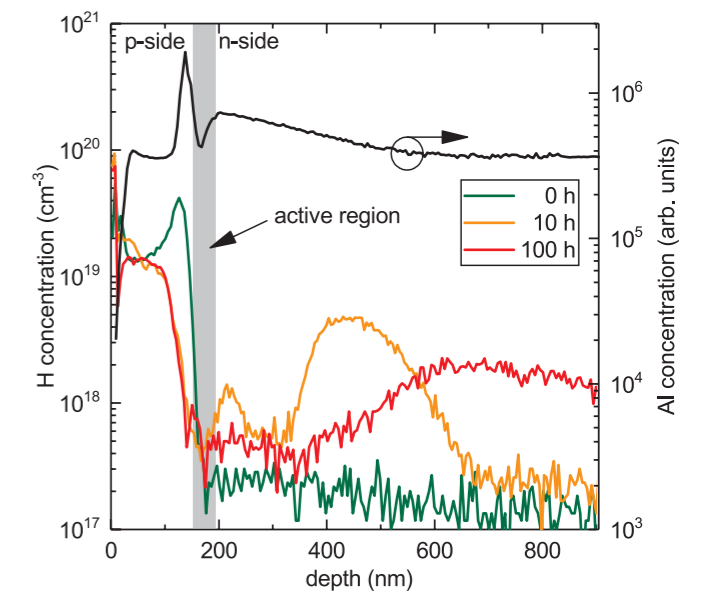


Fig. 3. Normalized optical power of UVB and UVC LEDs run at different current densities versus the operation time multiplied with the cube of current density.



The energy required to remove one hydrogen atom from a defect can be estimated to be at least 1 eV. This is considerably higher than the thermal energy of the lattice during device operation. Stress tests of UV LEDs under different operating conditions have indeed shown that degradation is not accelerated at elevated temperatures. In contrast, the current density was found to be the driving force for degradation as the device lifetime is inversely proportional to the cube of the current density. This relationship was verified for both UVB and UVC LEDs and can be clearly seen when the relative optical power is plotted accordingly (Fig. 3). It indicates that the injected charge carriers play an important role in the degradation process. Recent simulations have shown that the expected Auger recombination rate in the active region depends on the current density to a similar extent as the experimentally observed degradation rate. This suggests high energetic carriers from Auger recombination to be involved in degradation.

Consequently, the lifetime of the devices could be successfully increased by increasing the size of the active area, which would

reduce the current density. A reduction of the Auger recombination rate by band structure engineering and of the density of hydrogen-containing defect complexes are approaches that will be further pursued in the future to increase the lifetime.

This research was funded by the Federal Ministry of Education and Research (BMBF) (Advanced UV for Life, 03ZZ0130A); Deutsche Forschungsgemeinschaft (DFG) (CRC787).

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Integrated Quantum Technology

Integrierte Quantentechnologie

Within its research area integrated quantum technology, FBH carries out R&D activities that aim at bringing quantum technology (QT) from proof-of-concept demonstrators in a quantum optics lab to industry, so as to pave the way for the second quantum revolution to unfold its potential for tomorrow's society. Applications include quantum sensing, quantum communication, quantum simulation, and quantum computing, with operation in the field as well as in space. FBH research currently focuses on the following topics:

> **Quantum photonic components** – development of electro-optical components and hybrid micro-integrated modules providing coherent radiation required, e.g., for the implementation of quantum optical sensors or quantum computers based on cold ions or neutral atoms. Emphasis is on narrow and ultra-narrow linewidth diode lasers.

> **Integrated quantum sensors** – using high-precision spectroscopy techniques with atomic or molecular ensembles either at room temperature or, by laser cooling, near absolute zero. Realization of instruments for highly accurate measurements of physical quantities such as frequency, accelerations, electric or magnetic fields.

> **Diamond nanophotonics** – nanostructured diamond systems and materials targeting novel concepts for guiding, catching, and manipulating light on the nano- and microscale. Aim is to entangle single quantum memories with single photons, thus providing the basis for secure and versatile future quantum communication platforms.

In seinem Forschungsbereich Integrierte Quantentechnologie führt das FBH F&E-Aktivitäten durch, mit denen Proof-of-Concept Demonstratoren der Quantentechnologie (QT) aus dem Labor in industrietaugliche Lösungen überführt werden sollen. Dies wird der zweiten Quantenrevolution den Weg ebnen, sodass sie ihr Potenzial für die Gesellschaft von morgen entfalten kann. Zu den adressierten Anwendungen zählen die Quantensensorik, die Quantenkommunikation, die Quantensimulation und das Quanten-Computing – die außerhalb des Labors im Feld ebenso wie im Weltraum eingesetzt werden. Aktuell setzt das FBH die folgenden Schwerpunkte:

> **Quantenphotonische Komponenten** – Entwicklung von elektro-optischen Komponenten und hybrid-mikrointegrierten Modulen, die kohärente Strahlung für die Implementierung von quantenoptischen Sensoren oder Quantencomputern auf Basis von kalten Ionen oder neutralen Atomen erzeugen. Der Schwerpunkt liegt auf Lasern mit schmalen und ultra-schmalbandiger Emission.

> **Integrierte Quantensensoren** – Realisierung neuartiger Sensoren mittels hochpräziser Spektroskopiemethoden. Hierfür werden atomare oder molekulare Ensembles genutzt, die bei Raumtemperatur oder – lasergekühlt – nahe dem absoluten Nullpunkt untersucht werden. Dies erlaubt die Realisierung von Messgeräten, die physikalische Größen wie Frequenz, Beschleunigung, elektrische oder magnetische Felder mit höchster Präzision bestimmen können.

> **Diamant-Nanophotonik** – nanostrukturierte Diamantsysteme und -materialien für neuartige Konzepte zum Führen, Fangen und Manipulieren von Licht auf der Nano- und Mikroskala. Ziel ist es, einzelne Quantenspeicher mit einzelnen Photonen zu verschränken und damit die Grundlage für künftige Plattformen für die Quantenkommunikation zu schaffen, die sicherer und vielseitiger sind als bisherige Systeme.

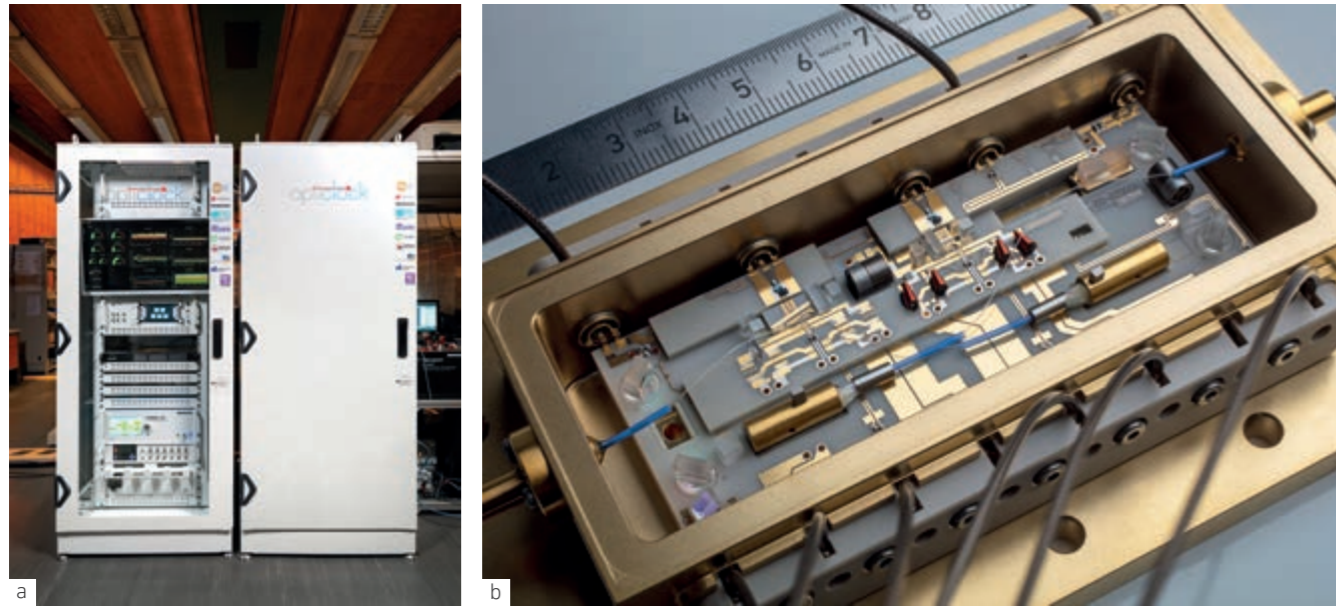


Fig. 1. (a) The transportable optical clock (double rack system) developed within the opticklock project; (b) a micro-integrated ECDL-MOPA laser.

Micro-integrated laser modules for optical frequency references and optical atomic clocks

Thanks to the second quantum revolution, the accuracy of time keeping has reached an unprecedented level. Today's optical atomic clocks would, when projected onto the age of the universe of 14 billion years, deviate from the 'true' elapsed time by only one second. This extraordinary precision opens the door for a wide range of applications including time keeping, synchronization of networks, geodesy, and deep space navigation. However, prototypes of the most accurate optical atomic clocks still have to be operated by experts inside specialized labs under well-defined conditions.

Therefore, opticklock – **optical single ion clock** (May 2017 – April 2020, www.opticklock.de) aims at developing a transportable, compact, robust, and user-friendly optical clock to be operated outside the lab. Thanks to opticklock team efforts, the laboratory construction of the single-ion $^{171}\text{Yb}^+$ optical clock at Physikalisch Technische Bundesanstalt (PTB), which normally covers the size of a medium-sized living room, could be shrunk to a transportable rack system, shown in Fig. 1 (a). Even a non-scientific user should be able to operate it. This transportable clock is supposed to demonstrate an accuracy of a few parts in 10^{15} , which should be better than any commercially available frequency standard. The clock itself is based on the $^2\text{S}_{1/2} - ^2\text{D}_{3/2}$ transition of a single $^{171}\text{Yb}^+$ ion at 436 nm.

Opticklock is one of three initially funded pilot projects addressing the strategy process of the German Federal Ministry of Education and Research (BMBF) in the field of quantum technologies. The consortium consists of ten partners both from academics (Universities of Siegen and Bonn, PTB, FBH) and industry (Toptica Photonics, Menlo Systems, QUBIG, Vacom, High Finesse, QuartiQ). FBH develops the required laser modules for the clock laser system; the radiation of which is used – after frequency doubling – for interrogation of the clock transition.

To this end, FBH realized a narrow-linewidth extended cavity diode laser (ECDL) operating at 871 nm. The module is based on the unique hybrid integration platform [2] that has been developed by the Joint Lab Quantum Photonic Components at FBH to provide robust and compact laser modules for quantum information and quantum sensing applications. The fiber-coupled output power of the ECDL is delivered to a second module, the power amplifier (PA), which provides more than 200 mW out of a single-mode polarization-maintaining optical fiber. Separation of the master oscillator (MO) and PA facilitates integration of a low insertion loss, high-isolation optical isolator between

Optische Atomuhren können bislang nur in einer gut kontrollierten Laborumgebung betrieben werden und müssen von Experten betreut werden. Diese Atomuhren sind zudem so groß, dass sie außerhalb optischer Labore nicht eingesetzt werden können. Damit Anwendungen künftig auch im Feld oder im Weltraum möglich sind, müssen unter anderem kompakte, robuste und energieeffiziente Halbleiter-Lasermodule verfügbar sein. Derzeit entwickelt das opticklock-Konsortium (www.opticklock.de) eine benutzerfreundliche, kompakte und robuste optische Atomuhr, deren Volumen erstmals von dem Volumen eines mittleren Wohnzimmers auf das eines transportablen Rack-Systems reduziert werden konnte. Das FBH hat die dafür benötigten Uhrenlasermodule als hybrid-mikrointegrierte Halbleiter-Lasermodule realisiert. Nach Integration in das Uhrenlasermodul wurden diese Module auf die optische Referenzkavität stabilisiert. Die Frequenzstabilität wurde mit einem hochstabilen Laser der PTB verglichen. Für Mittelungszeiten zwischen einer und 100 Sekunden wurde eine modifizierte Allan-Abweichung von weniger als $1,5 \times 10^{-15}$ nachgewiesen; die Anforderungen an das Uhrenlasermodul konnten damit erfüllt werden.

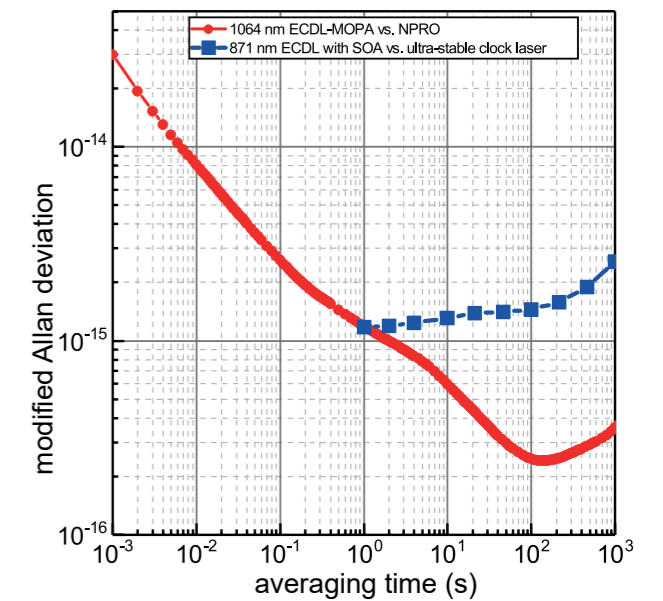


Fig. 2. Modified Allan deviation for the 871 nm laser modules locked to the opticklock reference cavity vs. PTB's ultra-stable reference laser and the 1064 nm ECDL-MOPA locked to ULE cavity at Humboldt-Universität zu Berlin vs. a YAG-based non-planar ring oscillator (NPRO) locked to the same cavity.

the two modules to protect the MO against optical feedback. The MO features a linewidth of < 50 kHz (1 ms).

To demonstrate suitability for operation of an optical atomic clock, both modules were integrated into Menlo Systems' clock laser system, and the ECDL module was frequency-locked to the clock's optical reference cavity. The frequency stability of the amplifier module output was compared against an ultra-stable reference laser at PTB via beat note measurements. A modified Allan deviation of less than $1,5 \times 10^{-15}$ was reached for averaging times between 1 - 100 s, see Fig. 2. The instability is considered to be dominated by the instability of the reference cavity.

The frequency stability of a similar laser module emitting at 1064 nm, which featured both the ECDL as well as the PA chip, was investigated by locking its frequency to an ultra-stable, high-finesse reference cavity at Humboldt-Universität zu Berlin. A beat note signal was created with a second laser that was stabilized to the same cavity so that instabilities of the cavity itself were suppressed. Here, a modified Allan deviation of less than 10^{-15} for an averaging time above 2 s was demonstrated, see Fig. 2. Work related to the 871 nm laser was supported with funds

provided by the BMBF within the funding program Photonics Research Germany under grant no. 13N14387. Work related to the 1064 nm laser was supported by DLR Space Administration with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant os. DLR 50 WM 1141, 50 WM 1545, and 50 WM 1646.

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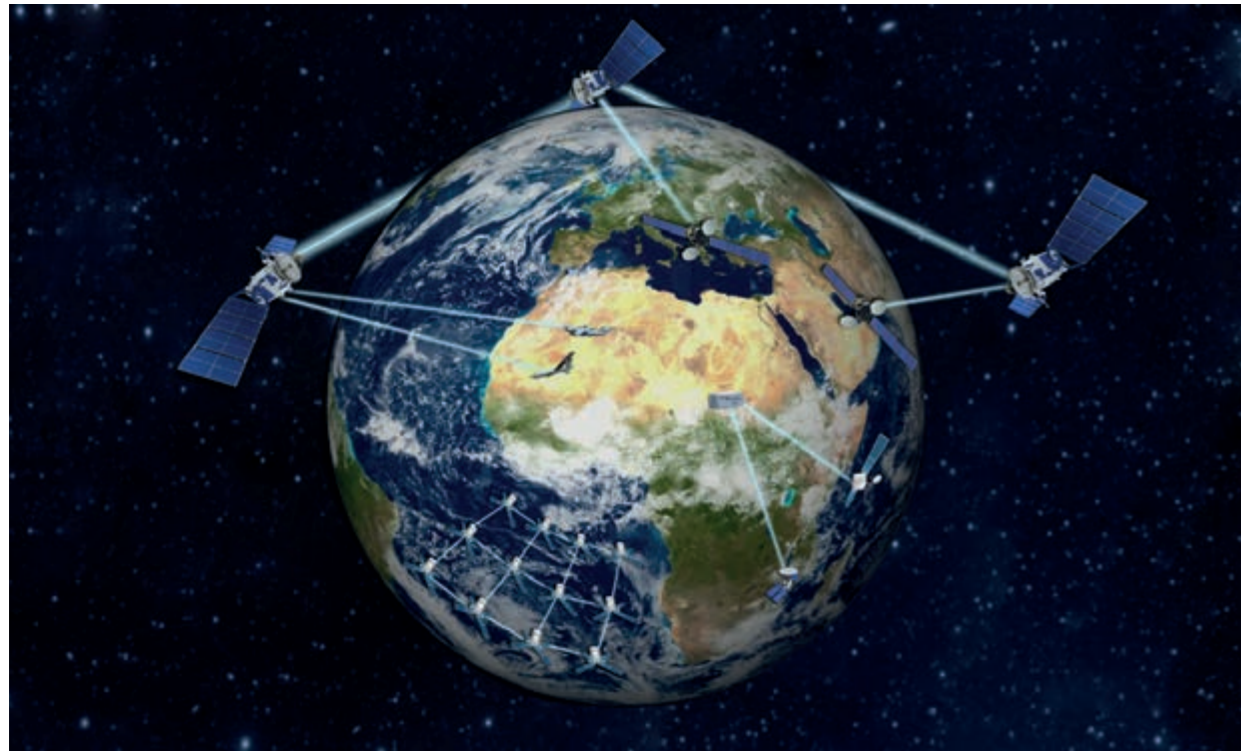
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Diode lasers for wavelength division multiplexing on optical communication satellites



Artist's impression of various free-space laser communication scenarios (© Tesat-Spacecom GmbH & Co.KG).

Optical communication systems are facing the continuous need for increased data rates. Employing wavelength division multiplexing (WDM), i.e. multiple spatially overlapped but spectrally shifted channels, is one way to boost the data rate of these systems. At the same time, this approach also increases the number of lasers, modulators, demodulators, and electronics. However, volume and mass in satellite communication terminals are limited. Small diode laser-based modules offer a way out. They feature a small size, low mass, and high intrinsic mechanical stability combined with a high electrical to optical conversion efficiency.

The smallest possible package could be achieved by utilizing monolithic diode lasers like distributed Bragg reflector (DBR) lasers. However, coherent optical communication systems require high spectral stability, i.e. the ability to establish relative phase stabilization between receiver (RX) laser and transmitter (TX) laser with a sufficiently small residual phase error. Hence, an appropriate ratio of the level of the frequency noise of these diode lasers and the achievable servo bandwidths

is required. Diode laser systems based on an extended cavity diode laser (ECDL) configuration are another option and have already demonstrated to be suited for phase stabilization in various applications. This proof has yet to be provided for DBR lasers.

FBH takes part in an ESA-funded activity to investigate the suitability of these two diode laser types for WDM in coherent optical communication terminals operating at 1064 nm. In the project, a proof of concept demonstrator (POCD) is set up and two channels are implemented – one based on ECDL lasers and the other on DBR lasers. Both channels utilize micro-integrated modules realized by means of FBH's micro-integration technology. While the RX lasers are either 'pure' ECDL or DBR lasers, each of the TX lasers includes an additional semiconductor optical amplifier to boost the output power in front of a shared fiber amplifier. Fig. 1 shows a micro-integrated DBR laser module on a mount with an external fiber coupler prior to integration into the POCD.

In a first step, the suitability of the two types of lasers, i.e. DBR and ECDL lasers, for coherent communication has been estimated with respect to the required phase stabilization. For this purpose, the frequency noise spectra of ECDL and DBR lasers were measured (see Fig. 2). The principle behavior of the linear spectral density (LSD) of the frequency noise, i.e. white noise at high Fourier frequencies and increasing noise towards lower Fourier frequencies is the same for both lasers except for the noise level. The DBR laser exhibits a white noise level of about 31 Hz/Hz^{1/2}, which corresponds to a Lorentzian linewidth of 3 kHz, whereas the ECDL exhibits a white noise level of about 14 Hz/Hz^{1/2}, which corresponds to a Lorentzian linewidth of 600 Hz. These measured data were compared to the theoretically estimated level of acceptable frequency noise. Fig. 2 shows such a comparison for a data rate of 1.8 Gbps and phase stabilization by means of a Dither loop. Here, the LSD of the ECDL's and the DBR laser's frequency noise is well below the requirement. Hence, not only ECDL but also DBR lasers are assumed to be suitable for coherent communication.

The micro-integrated laser modules for the POCD have already been set up and characterized individually. Currently, they are being integrated into the POCD to prepare for analyzing the performance of the two channels and hence to ultimately verify the lasers' suitability for coherent communication.

This work is supported by the European Space Agency (ESA) under contract no. 4000123552/18/UK/ND and by the Federal Ministry of Education and Research (BMBF) within the Research Fab Microelectronics Germany (FMD) framework under ref. 16FMD02.

Die Anforderungen an optische Kommunikationssysteme steigen – immer mehr Daten sollen immer schneller übertragen werden. Die Datenrate lässt sich beispielsweise durch Wavelength Division Multiplexing (WDM) erhöhen. Hierbei können mehrere Kanäle räumlich überlagert übertragen werden, wobei man sie spektral gegeneinander verschiebt. Jedoch werden dafür auch mehr Laser benötigt. Da der Platz auf Kommunikationssatelliten begrenzt ist, müssen die Lasersysteme sehr kompakt sein. Hierfür eignen sich Diodenlaser mit ihrer geringen Größe, niedrigen Masse und hohen mechanischen Stabilität besonders gut. Die kohärente Kommunikation erfordert darüber hinaus eine hohe spektrale Stabilität. Das FBH untersucht daher in einem ESA-Projekt zusammen mit Partnern die Eignung verschiedener Diodenlasertypen für die kohärente Kommunikation bei 1064 nm. Dazu baut das Institut mit den Partnern einen Demonstrator mit mikro-integrierten ECDL und DBR Lasern auf. Erste Untersuchungen legen nahe, dass nicht nur komplexe ECDL-Systeme, sondern auch monolithische DBR-Laser die Anforderungen erfüllen.

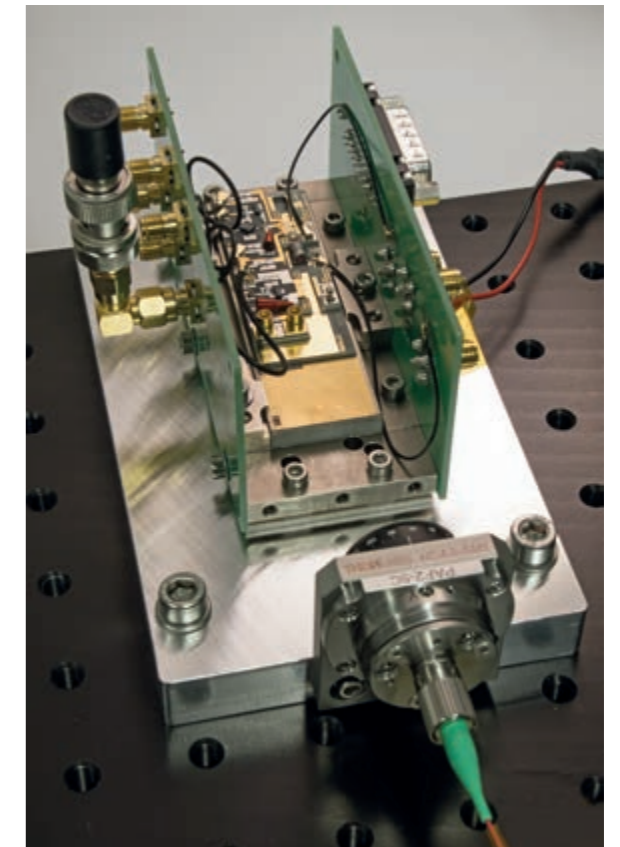


Fig. 1. Micro-integrated DBR laser module on a mount with an external fiber coupler prior to integration into the proof-of-concept demonstrator.

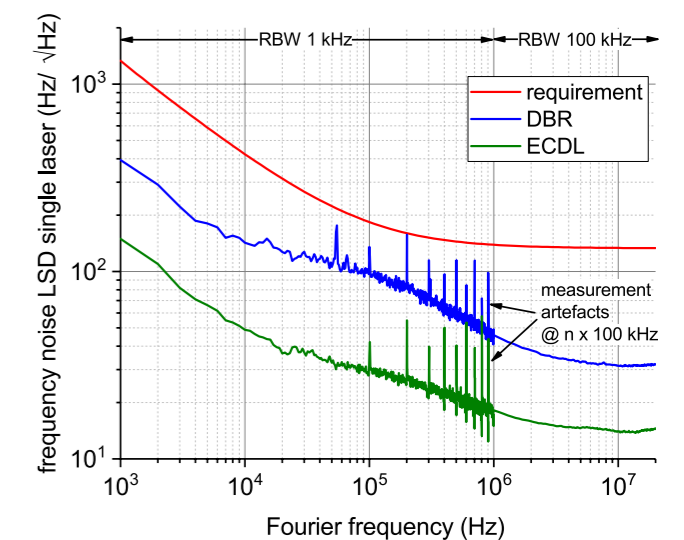


Fig. 2. Measured linear spectral densities (LSD) of frequency noise for single DBR and ECDL laser compared to a theoretically estimated requirement for a data rate of 1.8 Gbps and phase stabilization by means of a Dither loop.

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An optical clock based on an atomic strontium beam for future Global Navigation Satellite Systems

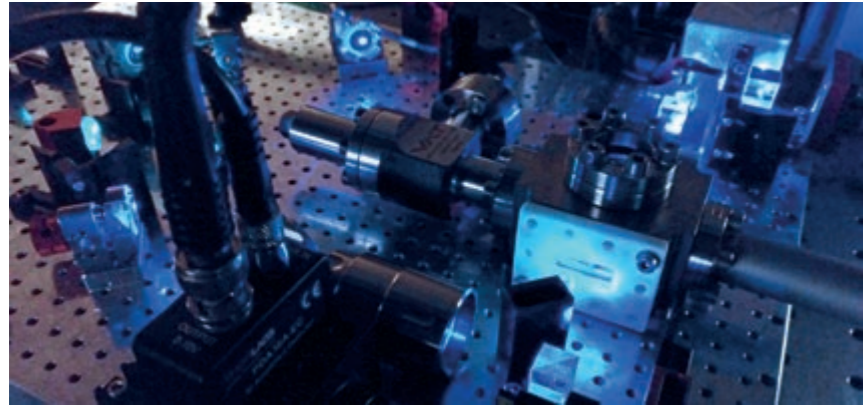


Fig. 1. Compact setup for spectroscopy of an atomic strontium beam.

The Joint Lab Integrated Quantum Sensors (IQS), which is operated by FBH and Humboldt-Universität zu Berlin, is developing an optical clock based on matter-wave interferometry of strontium atoms in a thermal beam configuration. This system offers excellent prospects for realizing compact and rugged optical frequency references whose frequency is stable to a few parts in 10^{16} . It receives great attention with respect to spaceborne operation. Optical clocks that are built around those references using frequency combs could address a variety of precision timing applications. For example, such a device and the underlying key technologies are candidates for next-generation Global Navigation Satellite System's (GNSS) core equipment.

In the OPUS project, four laser beams at 689 nm interrogate a narrow optical transition of the strontium atoms by splitting the atomic wave packet and recombining it. Fig. 2 shows a schematic of this operational principle as well as a reduced term scheme of strontium. The resulting interference depends on the detuning of the laser frequency from the optical transition, which enables to precisely stabilize the laser frequency. The interference is read out by interrogating a broader transition with a second laser emitting at 461 nm. As the quality of this signal strongly depends on the atomic flux, we investigate different atomic source concepts for the strontium beam. A picture of a dispenser-based atomic source is shown in Fig. 2, where blue light used for the readout transition is visible. As for implementing a first spaceborne demonstrator reaching a performance level relevant to GNSS, we are investigating trade-offs between different spectroscopy schemes and between cold and thermal beam sources.

We are closely cooperating with the Joint Lab Quantum Photonic Components (QPC). The QPC lab will build space-suitable hybrid micro-integrated laser modules which are specifically designed for the requirements of the beam optical clock. Existing semiconductor technology will be transferred to the wavelength of 689 nm, including the design of new emitter and amplifier structures. The laser modules will be designed based on an established master oscillator power amplifier (MOPA) concept, in which a narrow linewidth, optical grating-stabilized extended cavity diode laser (ECDL) acts as the master oscillator (MO), which is then amplified by a ridge-waveguide semiconductor chip (PA). Established integration concepts and designs of the QPC group will be transferred to the new wavelength range. An example of such a module is shown in Fig. 3. This clock laser at 689 nm is pre-stabilized to a high-finesse cavity, which enables high frequency stability at short timescales below 1 s. For longer timescales, the frequency stability stems from the atomic interrogation. An optical frequency comb will be optically locked to the strontium reference to transfer the frequency stability from the optical to the microwave regime, thus providing a usable clock signal.

In a measurement campaign with our project partner Menlo Systems, first spectroscopic measurements were performed at 689 nm in combination with an optical frequency comb. Here, a simpler spectroscopy method based on Doppler-free interrogation was employed. The next milestone is the setup of Ramsey-Bordé matter-wave interferometry, for which a first prototype is currently being built at HU Berlin.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number DLR 50WM1851-53.

Das Joint Lab Integrated Quantum Sensors entwickelt einen optischen Frequenzstandard, der auf Materiewellen-Interferometrie mit Strontium-Atomen in einem thermischen Atomstrahl basiert. Das System bietet beste Voraussetzungen, um eine kompakte und robuste Frequenzreferenz zu realisieren. Diese stabile optische Frequenz kann mithilfe eines Frequenzkammes in eine stabile Hochfrequenz umgewandelt werden und damit als Uhr genutzt werden. Eine derartige Uhr eignet sich für eine Vielzahl von Präzisionsanwendungen, beispielsweise für die nächste Generation eines globalen Satellitensystems zur Navigation. Für das geplante Setup werden zwei Laserquellen benötigt, die bei 689 nm und 461 nm emittieren. Das FBH entwickelt die kompakten Lasermodule für den Uhrenlaser bei 689 nm. An der HU Berlin werden momentan verschiedene Strontium-Atomquellen gebaut und getestet. Auch ein Aufbau zur Ramsey-Bordé-Interferometrie wird hier realisiert.

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Fig. 2. (a) Schematic of Ramsey-Bordé interferometry. The atoms interact with the clock laser beam four times, resulting in a frequency-dependent interference, which is then read out at another wavelength. (b) Simplified term scheme of strontium. The narrow transition at 689 nm is used as clock transition. The broad 461 nm transition is used to read out the atomic state after clock interrogation.

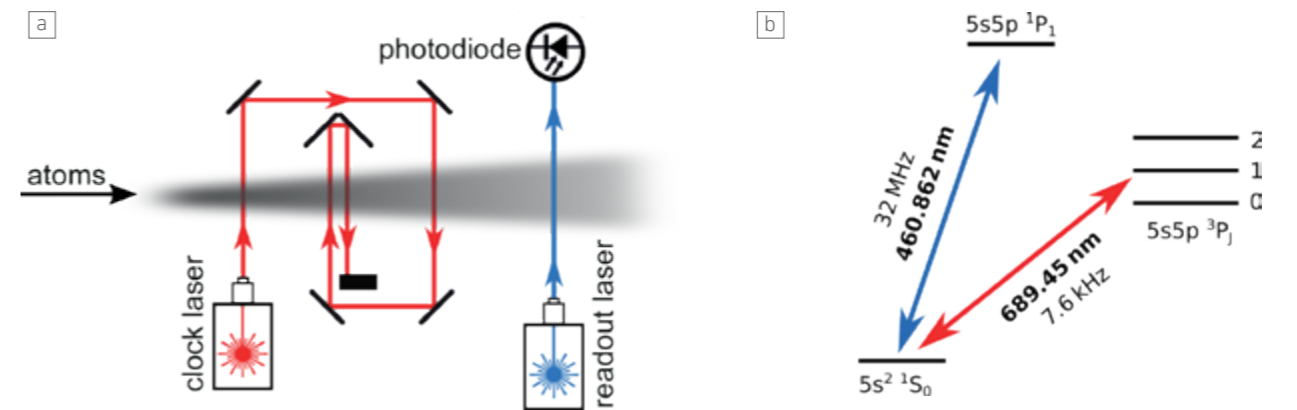


Fig. 3. Hybrid micro-integrated laser module (see p. 74), comprising a master oscillator power amplifier where a narrow-linewidth extended cavity diode laser acts as master oscillator. The emission is then amplified by a ridge-waveguide semiconductor chip.

Miniaturized, vacuum-compatible optical setups for cold atomic quantum sensor applications

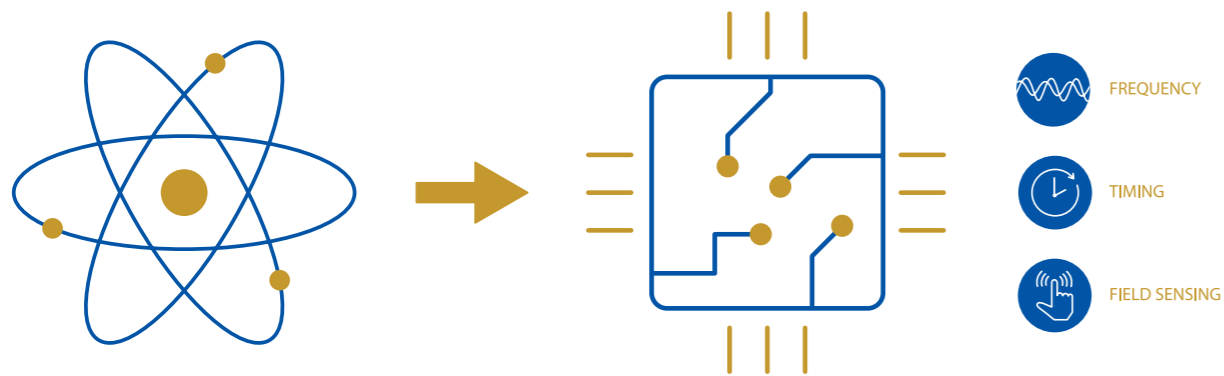


Fig. 1. Mission of the Joint Lab Integrated Quantum Sensors: Development of integrated atomic sensor systems for frequency, timing and field sensing.

Employing quantum sensors in field or in space allows for pioneering applications in the areas of timekeeping, optical communication, fundamental physics and sensing. Developments of the Joint Lab Integrated Quantum Sensors (IQS) target integrated atomic sensor systems for frequency, timing and field sensing, see Fig. 1. The IQS lab is operated jointly by FBH and Humboldt-Universität zu Berlin and pursues compact cold-atom based quantum sensors, enabling the transition of such devices from the lab to field-compatible devices. This implies meeting the challenging requirements regarding mechanical and thermal stability, size, weight, and power consumption of such quantum sensors.

Key components of our atomic quantum sensors are cold atom sources, which often incorporate atom chips. These chips are formed, for example, by copper circuits on a silicon wafer. They enable the fast generation and manipulation of ultra-cold atom ensembles by creating local magnetic fields, forming e.g. chip-based Ioffe-Pritchard traps. In the KACTUS and QCHIP project, we aim to achieve a further integration of the cold-atom sensors physics package. Furthermore, novel atom trapping configurations can be achieved by integrating miniaturized and micro-integrated electro-optical setups close to the atom chip.

Our KACTUS prototype design is depicted in Fig. 2, forming a crossed beam optical dipole trap within the atom chips center. After collimator and telescope, the beam of approximately 2 mm diameter is separated into two paths with equal intensity. These are focused down to a spot of approximately 20 μm radius in the crossing point. Such a configuration not only keeps the

compactness of an atom chip setup but also allows for transfer in purely optical or hybrid magneto-optical traps. To realize this, sub μm pointing stability and alignment accuracy have to be achieved. Since the lifetime of the cold atomic ensemble is dominated by collisions with residual atoms in the background, an ultra-high vacuum (UHV) environment and very low outgassing of chambers and components are mandatory.

To evaluate and qualify the UHV compatibility of all used electro-optical components and integration technologies, a versatile UHV qualification setup was designed and assembled. The setup, depicted in Fig. 2, is designed for measurement of gas rate and species down to $\sim 5 \times 10^{-10}$ mbar l/s. A sample transfer system allows for a quick exchange of samples sized up to 65 x 65 mm². To establish optimized integration processes, further capabilities and facilities to evaluate the cure-dependent outgassing, mechanical bond strength and shrinkage are built up. The mechanical properties are investigated by pull and shear strength tests of test samples in application-related geometries. Furthermore, adhesive aging is evaluated by thermal cycling and radiation exposure tests.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number DLR 50WM1648, 1949 and 50RK1978.

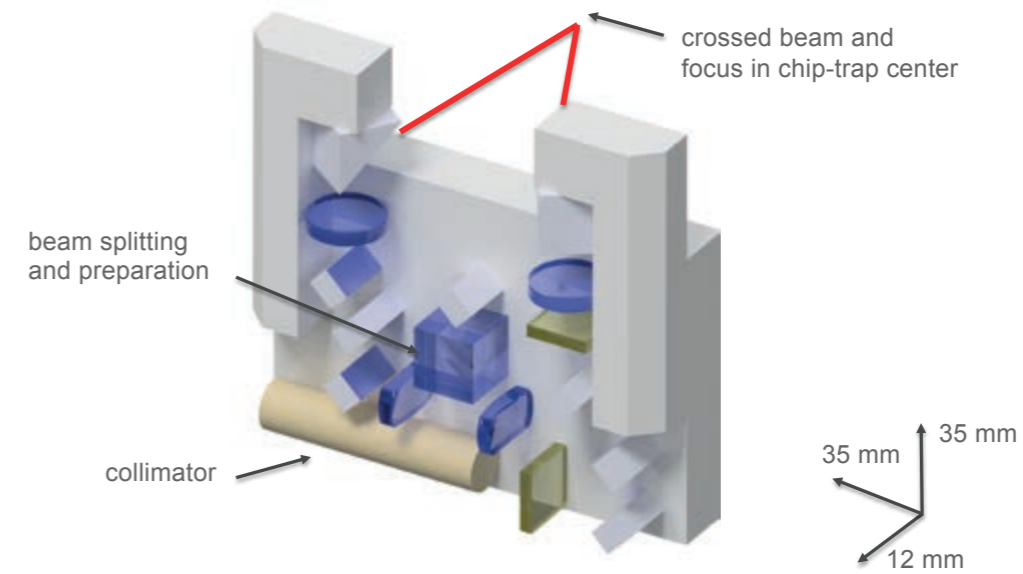


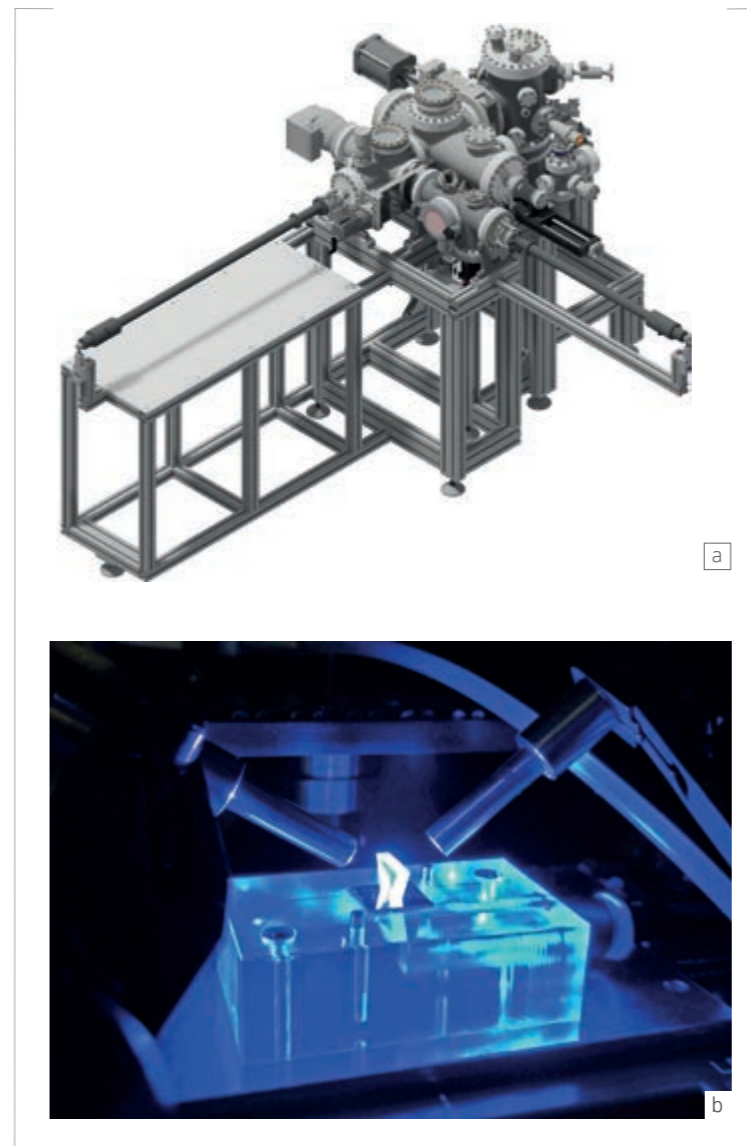
Fig. 2. Prototype design of an in-vacuum crossed beam optical dipole trap setup for integration with an atom chip system (not shown).

Publications

M. Christ, A. Kassner, R. Smol, A. Bawamia, H. Heine, W. Herr, A. Peters, M. Wurz, E. Rasel, A. Wicht, M. Krutzik, "Integrated atomic quantum technologies in demanding environments: development and qualification of miniaturized optical setups and integration technologies for UHV and space operation", CEAS Space Journal, 11(4), 561-566 (2019).

A. Kassner, M. Rechel, H. Heine, W. Herr, M. Christ, M. Krutzik, EM Rasel, MC Wurz, "Atom Chip technology for use under UHV conditions", Smart Systems Integration: 13th International Conference and Exhibition on Integration Issues of Miniaturized Systems, Barcelona, Spain, pp. 69-75, ISBN: 978-3-8007-4919-5 (2019).

M. Christ, A. Wicht, A., M. Krutzik, "Development and Qualification of Miniaturized, UHV-Compatible Optical Systems for Integrated Atomic Quantum Technologies", (CLEO/Europe-EQEC), Munich, Germany, ISBN: 978-1-7281-0469-0, ea-p.26 (2019).



Das Joint Lab Integrated Quantum Sensors entwickelt und realisiert kompakte Quantensensoren auf der Basis von kalten Atomen. Diese Sensoren sollen künftig nicht nur in Laborumgebungen für Grundlagenforschung, sondern auch als feldkompatible Systeme eingesetzt werden und neuartige Anwendungen in den Bereichen Zeitmessung und Sensorik ermöglichen. Das Herzstück des atomaren Quantensensors ist eine kalte Atomquelle, die oftmals auf einem Atomchip basiert. Im KACTUS-Projekt soll dieser Quantensensor weiter miniaturisiert und durch Integration eines optischen Systems im Ultra-hochvakuumssystem (UHV) funktional erweitert werden. Dies setzt voraus, dass sämtliche elektrooptische Komponenten und Fertigungstechnologien UHV-kompatibel sind. Zu deren Qualifikation wurde ein Teststand entworfen und aufgebaut. Darüber hinaus wird die mechanische Belastbarkeit der eingesetzten Integrationstechnologien in einer anwendungsbezogenen Probengeometrie nach der thermischen Alterung und Bestrahlung mit Gammastrahlen evaluiert.

Fig. 3. (a) UHV qualification setup for electro-optical components and integration technologies, allowing for gas rate and species determination. (b) UV curing of adhesive test samples for mechanical, thermal and radiation tests.

III-V Electronics

III/V-Elektronik

The overall target of FBH's research activities in the field of III-V electronics is to push the limits of electronic devices in terms of efficient power generation at high frequencies, high voltages, and short switching times. The frequency spectrum ranges from fast power electronics through the mobile communication bands in the lower GHz range to sub-millimeter waves. All activities are based on III-V semiconductor technology; they presently encompass the following major topics:

- > **Microwave power amplifiers based on GaN** for the use in base stations for mobile communications – the focus is on concepts improving energy efficiency (supply modulation/envelope tracking).
- > **Digital power amplifiers** – the FBH develops novel digital amplifier architectures for the wireless infrastructure. Long-term target is the complete digital transmitter.
- > **Terahertz components & systems** – the focus is on integrated circuits up to the 300 GHz band so far, using indium phosphide (InP) bipolar transistors (HBTs). A transferred-substrate process is applied including a wafer-scale InP-on-BiCMOS hetero-integration option. With these circuits, compact integrated frontend-modules for radar, sensor and communication systems can be realized.
- > **Using plasmonic effects for THz detection** – these detectors demonstrate device operation well beyond the classical frequency limits and thus open up possibilities for electronic components in the 1 THz range. We employ GaN as semiconductor for these developments.

- > **Lateral and vertical GaN-based switching transistors & Schottky diodes for high voltages** – for high-efficiency power converters with high clock speed, low weight, and volume. They are well-suited for a great variety of applications, e.g., in the field of electro-mobility.
- > **Laser drivers** – GaN transistors are also used to develop high-speed high-current drivers for laser diodes that are integrated with FBH laser diodes to realize pulse laser sources, e.g., for LiDAR applications
- > **Investigating transistors based on new wide-band-gap materials** such as AlN and Ga₂O₃ – for power electronics as well as microwave frequencies.

Besides the III-V semiconductor technologies, these research activities require the corresponding advanced simulation, modelling, circuit design, and measurement expertise.



Das übergreifende Ziel der Forschungsarbeiten des FBH im Bereich III/V-Elektronik ist, die Grenzen der elektronischen Bauteile hinsichtlich effizienter Leistungserzeugung bei hohen Frequenzen, hohen Spannungen und kurzen Schaltzeiten systematisch zu erweitern. Das Spektrum reicht von schneller Leistungselektronik über die Mobilfunkfrequenzen im unteren GHz-Bereich bis hin zu Sub-Millimeterwellen. Alle Aktivitäten basieren auf der III/V-Halbleitertechnologie. Sie umfassen derzeit hauptsächlich die folgenden Themen:

- > **HF-Leistungsmodule auf Basis von GaN** für den Einsatz in Mobilfunk-Basisstationen – der Schwerpunkt liegt auf Konzepten zur Verbesserung der Energieeffizienz (Versorgungsspannungsmodulation /Envelope Tracking).
- > **Digitale Leistungsverstärker** – das FBH entwickelt neue digitale Verstärkerarchitekturen für die drahtlose Infrastruktur, die Flexibilität mit Leistungseffizienz verbinden. Langfristiges Ziel ist der komplett digitale Transmitter.
- > **Terahertz-Komponenten & -Systeme** – der Schwerpunkt liegt auf integrierten Schaltungen mit Indiumphosphid (InP) Heterobipolartransistoren (HBTs), derzeit bis zum 300 GHz-Band. Dabei kommt ein Transfer-Substrat-Prozess zur Anwendung, der auch eine InP-auf-BiCMOS-Heterointegration auf Waferebene beinhaltet. Damit können kompakte integrierte Frontend-Module für Radar-, Sensor- und Kommunikationssysteme realisiert werden.
- > **Nutzung von plasmonischen Effekten für die Terahertz-Detektion** – diese Detektoren demonstrieren die Funktion von Transistorstrukturen weit oberhalb der klassischen Grenzfrequenzen im 1 THz-Bereich. Wir verwenden dazu die GaN-Technologie.

- > **Laterale und vertikale GaN-basierte Schalttransistoren & Schottkydioden für hohe Spannungen** – für hocheffiziente Leistungs-Umrichter mit hoher Taktrate, geringem Gewicht und Volumen. Damit eignen sie sich für vielfältige Anwendungen, u.a. im Bereich Elektromobilität.
- > **Lasertreiber** – GaN-Transistoren werden auch dazu eingesetzt, um schnelle Hoch-Strom-Treiber zu realisieren, die mit Laserdioden aus dem FBH zu Pulsquellen integriert werden, z.B. für LiDAR-Anwendungen.
- > **Transistoren auf Basis neuer Materialien mit großer Bandlücke** wie AlN und Ga₂O₃ – für Anwendungen von der Leistungselektronik bis zum Mikrowellenbereich

Neben der III/V-Halbleitertechnologie erfordern diese Forschungsarbeiten die entsprechende Expertise bei Simulation, Modellierung, Schaltungsdesign und Charakterisierung.

Dynamic current distribution in 600 W pulse laser diode sources for LiDAR

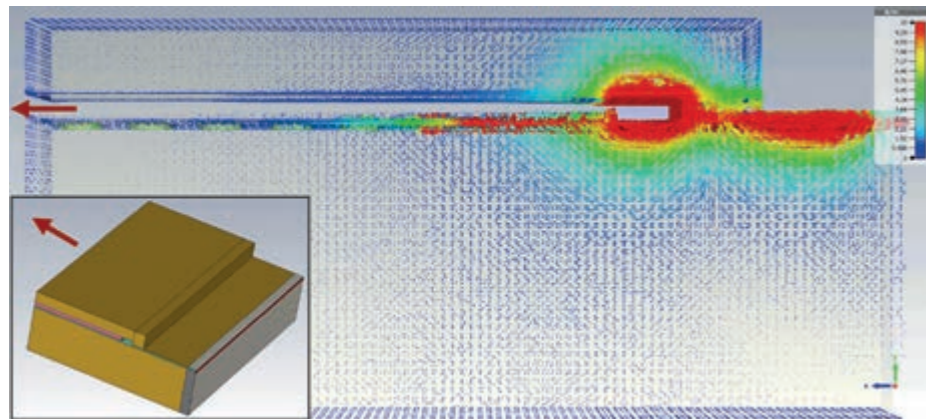


Fig. 1. Simulated current density with simplified geometry (structure see inset).

Laser diodes generating short optical pulses with high peak power are key components for compact LiDAR (Light Detection And Ranging) systems. These systems have a large scope of application for ranging and imaging of objects on earth, in air and space.

To reach a high spatial resolution very short optical pulses are needed, typically between 100 ps and 10 ns. The demand for a high operating range requires pulses with peak powers of about 100 W. Such power levels can only be generated by superposing several emitters of a laser diode bar. For pulse lengths in the ns range, the laser bar can no longer be regarded as a single lumped device. The distributed inductances and capacitances together with the spatial arrangement of the emitters have also to be considered.

To optimize current distribution within the laser diode bar, we perform 3-dimensional simulations of the current distribution within the laser structure using the "Low Frequency Time Domain Solver" (MQS) from CST. Fig. 1 presents the structure (inset) with the simulated current distribution. The results reveal particularly high current densities in the vicinity of the feeding points, caused, among others, by the skin effect. The geometry of the feeding structure and the laser assembly are designed to mitigate this current concentration. Minimizing the size of the inductive coupling loop and the right choice of the feeding point turned out to be extremely important. Fig. 2 shows the simulation of the current distribution of a ten millimeter wide laser bar with 48 single emitters. We found that the outer emitters are preferred because of the voltage drop along the inner

connections of the laser structure, which reduces the currents of the inner emitters. That is why detailed simulations of the feeding geometry are needed.

Each driver stage is described by an equivalent circuit according to Fig. 3, showing one of the four driver stages. We optimize the current feeding of each laser diode bar in order to reach a homogeneous current distribution over all the laser emitters. We developed SPICE (Simulation Program with Integrated Circuit Emphasis) models for the laser diodes, which consider both the geometrical structure of the laser diode bar and its parasitic resistances, inductances and capacitances. Fig. 4 presents the complete setup of the laser module attached with laser diode, driver circuits and interface board, which provides power supply and the trigger pulses for each driver separately.

Using this knowledge, a 48-emitter pulse laser source at 905 nm wavelength with a quadruple driver circuit was realized. An optical peak power of more than 600 W for pulse lengths from 4 to 10 ns is reached. This corresponds to maximum peak currents up to 1000 A (calculated from average current and duty cycle). Taking into account the maximum dissipated power, a repetition rate up to 150 kHz for 4 ns pulses is feasible.

This work was supported by the German Federal Ministry of Education and Research contract 13N14026 as part of the EffiLAS/PLuS project.

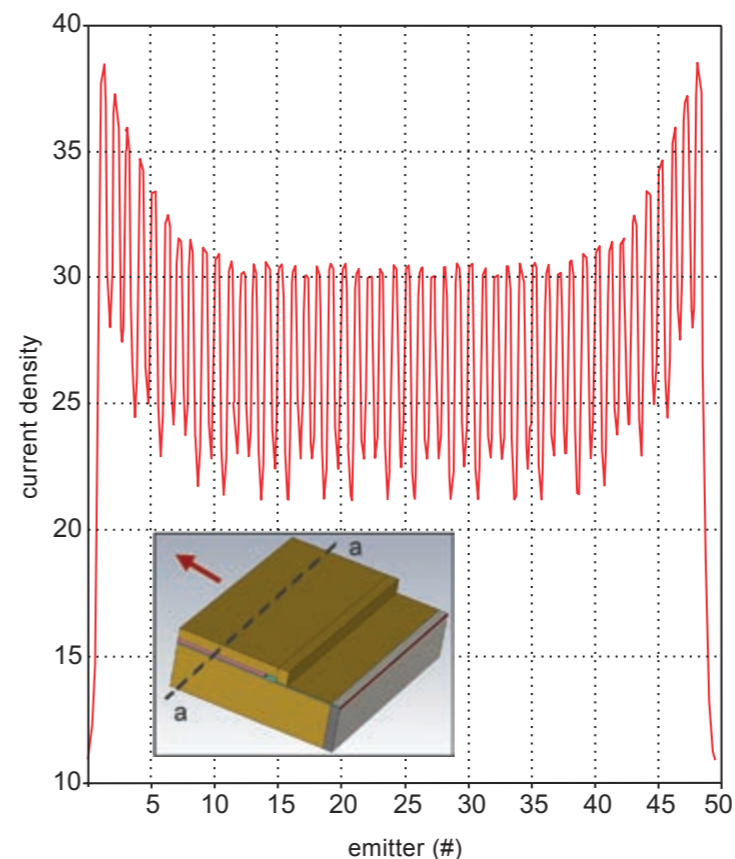


Fig. 2. Current density in feeding structure of a 10 mm wide laser diode consisting of 48 single emitters (in cross section a-a of the structure, orthogonal to the emitters at the center of the laser bar).

Halbleiter-Laserdioden, die kurze optische Pulse mit hoher Leistung erzeugen, sind Schlüsselkomponenten für kompakte LiDAR-Systeme. Diese werden unter anderem zur Ortung und Vermessung von Objekten auf der Erde, sowie in der Luft- und Raumfahrt eingesetzt. Dafür sind eine hohe Auflösung und somit sehr kurze optische Impulse im Bereich von 100 ps bis 10 ns notwendig. Hohe Reichweiten wiederum erfordern Pulse mit Spitzenleistungen im 100 W-Bereich. Derartige Leistungen können nur erzeugt werden, indem mehrere Emitters eines Laserbarrens parallel geschaltet werden. Bei den hierbei benötigten kurzen Strompulsen hoher Amplitude müssen die räumliche Anordnung der Einzelemitters und die resul-

tierenden Leitungsinduktivitäten und -kapazitäten beim Entwurf berücksichtigt werden. Für eine optimale Stromverteilung über den Diodenlaserbarren hinweg wurden 3-dimensionale Simulationen der Stromverteilung in der Laserstruktur durchgeführt. Entsprechend optimierte 48-Emitter-Laserbarren bei 905 nm mit einem Vierfach-Treiber wurden realisiert. Sie erreichen mindestens 600 W optische Spitzenleistung mit Pulsbreiten von 4 – 10 ns und Spitzenströme von bis zu 1000 A. Unter Beachtung der maximalen Verlustleistung wurden bei 4 ns Pulsbreite Wiederholfrequenzen bis 150 kHz realisiert.

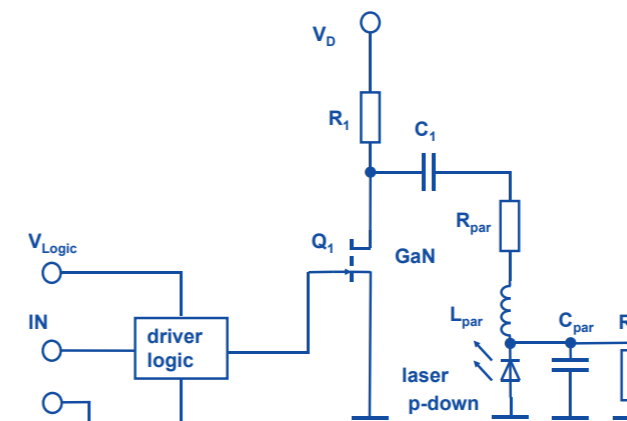


Fig. 3. Schematic of a driver final stage with GaN HEMT (4 of these stages are connected in parallel).



Fig. 4. Complete setup of the pulse laser module with laser diode, driver and interface circuit.

The floating-ground transistor – a key enabler for reverse-type envelope tracking systems for space applications and 5G

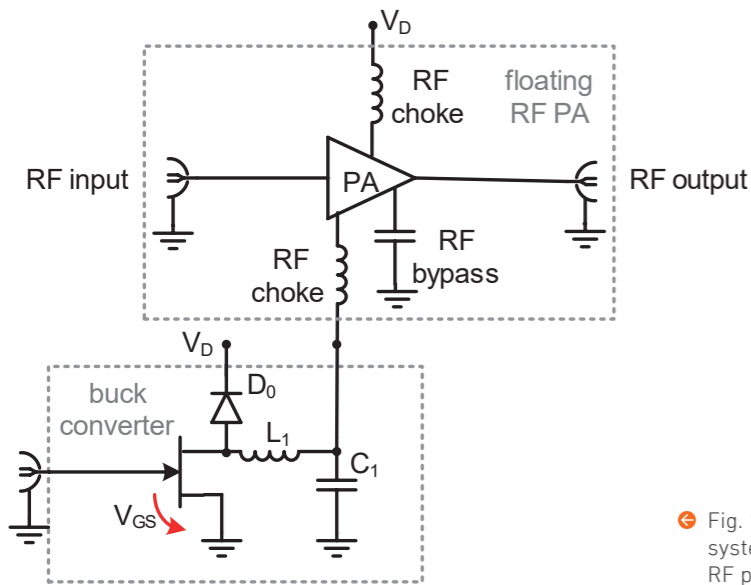


Fig. 1. Schematic of a reverse-type envelope tracking system with reverse buck converter and floating-ground RF power amplifier [3].

The unique properties of high electron mobility GaN transistors (GaN-HEMTs) – high power density and high operating voltage despite small dimensions – make them excellent devices not only for RF power amplifiers. They are also very suitable as switches in fast DC/DC converters and modulators for supply modulation (SM) techniques. These include envelope tracking (ET), where the RF power amplifier (PA) supply voltage is varied according to its instantaneous signal envelope. However, the excellent charge transport properties lie in the two-dimensional electron gas (2DEG) established in the heterojunction between the AlGaIn and the GaN layers. This 2DEG is only present in n-type GaN. Thus, no fast GaN p-type technology is available.

This makes modulator design for switch-based SM systems more difficult: the modulator with the fast switching GaN-HEMT is positioned on the high-voltage side, meaning that its source potential is continuously varying with the signal envelope. Hence, a galvanically isolated switch driver is required in the modulator, adding considerable parasitic capacitance to the switch. This reduces the possible switching frequency and thereby the achievable system bandwidth. In modern 5G telecommunication systems this is detrimental since the band-

width is very large and exceeds that of previous system generations by a factor of 10. A recently found workaround to overcome this shortcoming is to move the modulator to the low-voltage side and position the RF PA between the modulator and the high-voltage side. This is referred to as reverse-type ET system [1]. The corresponding schematic is shown in Fig. 1.

This approach simplifies the modulator design since the source of the switching transistor is connected to system ground, allowing the gate to be switched towards this fixed ground potential. In addition, it makes the galvanic isolation of the switch driver obsolete, reduces parasitic capacitances and thereby enables faster switching and a larger modulation bandwidth.

To position the RF PA on the high-voltage side means that its source potential is 'floating', i.e., it needs to be modulated in the DC and low-frequency (LF) domains, while system ground remains the RF ground. Hence, a ground separation for the different frequency domains is required at the transistor source. To assure broadband operation this separation has to be established as close as possible to the transistor with as little impact as possible on the RF performance.

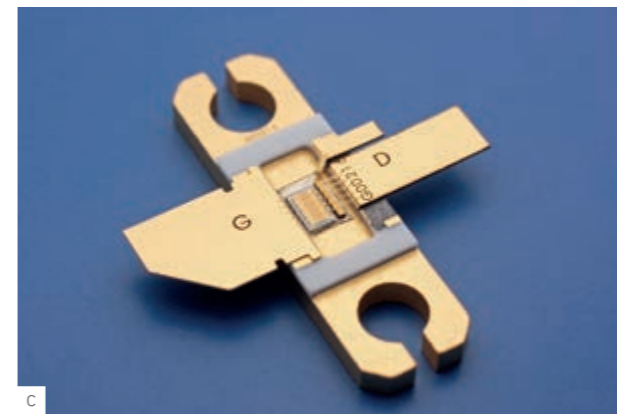
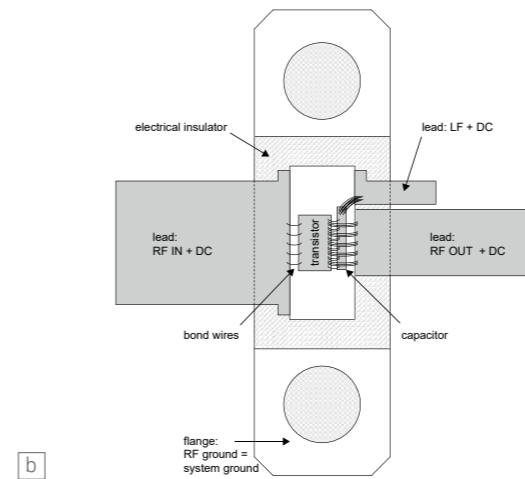
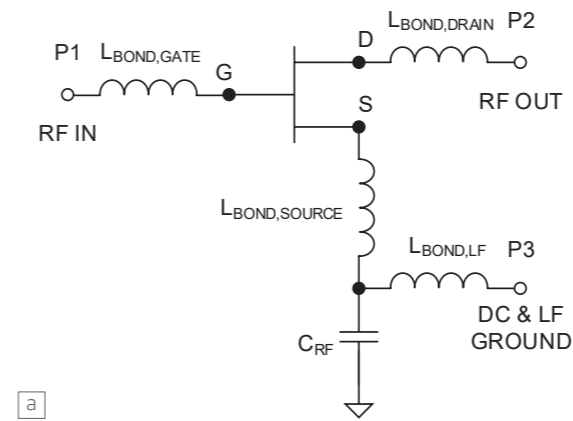


Fig. 2. Electrical schematic (a), physical drawing (b) and photo (c) of the packaged floating-ground transistor [2].

A novel patent-pending invention developed in the RF Power Lab at FBH is a packaged floating-ground RF power GaN-HEMT, facilitating RF PA design for floating operation. To achieve this, a capacitor to bypass the RF to system ground is placed inside the transistor package close to the transistor chip. A separate external connection is added where the DC and LF ground potential is applied. An electrical schematic, a physical drawing and a photo of the invented transistor are shown in Fig. 2a-c.

This novel device allows straightforward floating-ground RF PA designs, but also opens a whole new field of GaN based circuits that benefit from reverse operation. The main challenge is to achieve stability in the frequency region between the modulated LF band and the RF band where the PA system is operating. Devices using this topology are available as discrete packaged devices [2] and as MMICs [3] as seen in Fig. 3.

Die Modulationsbandbreite von Hochfrequenz- (HF) Verstärkersystemen mit Versorgungsspannungsmodulation lässt sich mithilfe von GaN-HEMT-basierten Schaltwandlern in Form von umgekehrten Abwärtswandlern signifikant verbessern. Anders als herkömmliche Modulatoren benötigen sie keinen galvanisch getrennten Schaltertreiber. Dies reduziert parasitäre Kapazitäten und ermöglicht somit eine größere Modulationsbandbreite. Allerdings ist ein HF-Leistungsverstärker mit „schwebender“ DC- und Niederfrequenz- (NF) Masse notwendig, der zwischen Modulator und Versorgungsspannung betrieben wird. Im RF Power Lab wurde ein neuartiger Transistor entwickelt, der in zwei Varianten verfügbar ist. Er trennt DC- und NF- beziehungsweise HF-Masse direkt im Transistorgehäuse oder auf dem MMIC-Chip mithilfe eines HF-Kurzschlusskondensators. Ein zusätzlich integrierter Anschluss ermöglicht die Modulation der DC- und NF-Masse.

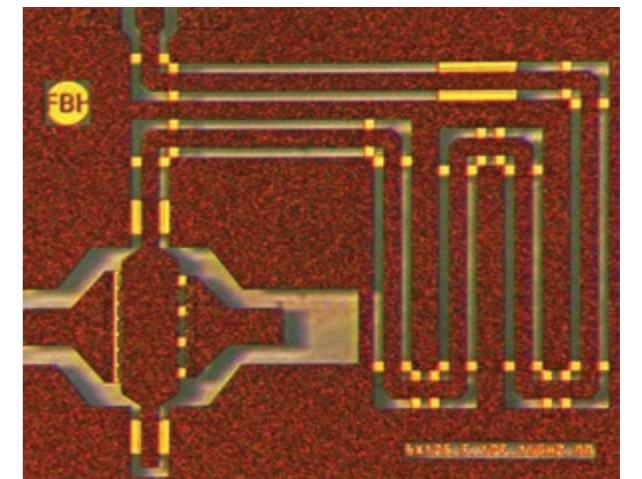
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[1] S. Paul, N. Wolff, C. Delepaut, V. Valenta, W. Heinrich, O. Bengtsson, "A 14 W wideband supply-modulated system with reverse buck converter and floating-ground RF power amplifier", IEEE MTT-S International Microwave Symposium (IMS), Honolulu, HI, pp. 936-939 (2017).

[2] S. Paul, G. N. Phung, W. Heinrich, O. Bengtsson, "Packaged Floating-Ground RF Power GaN-HEMT", 49th European Microwave Conference (EuMC), Paris, France, pp. 702-705 (2019).

[3] O. Bengtsson, S. Paul, W. Heinrich, "A GaN-HEMT with Floating LF Ground for Reverse Operation in Integrated RF Power Circuits", 14th European Microwave Integrated Circuits Conference (EuMIC), Paris, France, pp. 53-56 (2019).

Fig. 3. Floating-ground transistor as MMIC with integrated short-circuited $\lambda/4$ transformer for operation at around 10 GHz [3].



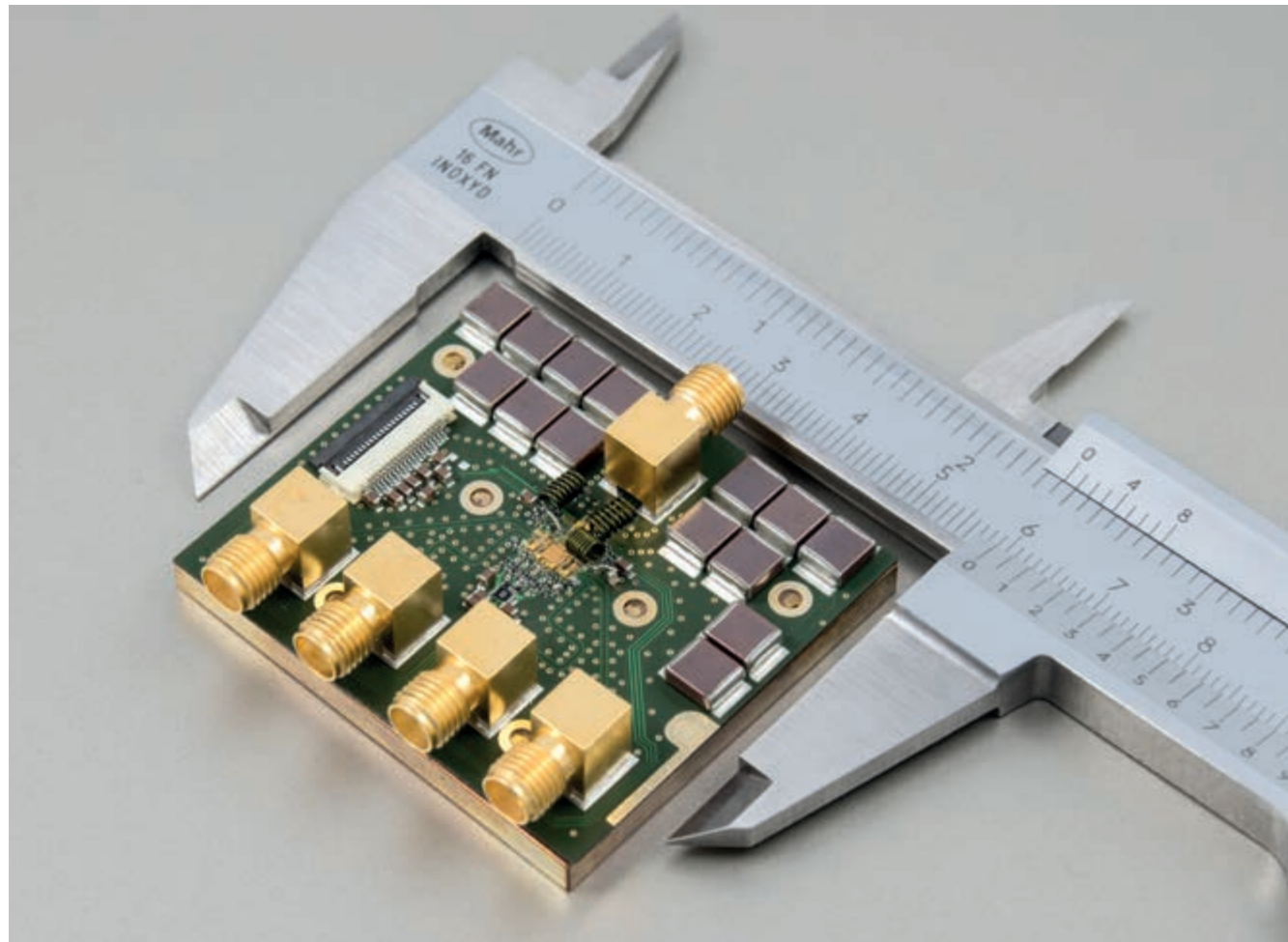


Fig. 1. Realized digital outphasing power amplifier module; size: 50 x 45 mm².

GaN digital outphasing power amplifier – targeting efficient 5G communications

The future mobile communications standard 5G is aimed at creating the prerequisites for transmitting more and more data at ever faster data rates. However, the mobile infrastructure must be adjusted to the demanding applications such as those required for Industry 4.0. Above all else, the next-generation wireless communication infrastructure demands for high flexibility, low cost and high efficiency. This goes along with the growing need for wideband, multi-band, and multi-standard features. In this context the all-digital transmitter chain represents the smartest solution.

Since several years, FBH is pursuing the digital power amplifier (PA) approach for mobile base stations. The analog output signal is encoded in a binary pulse sequence so that the only analog component left is a bandpass filter at the power amplifier output just before the antenna. As a consequence, the PA be-

comes a pure switch. Future wireless communication standards will be based on very broadband signals with high peak-to-average power ratios (PAPR) in the 10 – 12 dB range. These characteristics, however, are responsible for one of the most crucial problems of digital PAs up to now, the significant degradation of efficiency at high power back-off (PBO) values. The values achieved so far are not fully competitive to analog concepts like Doherty or envelope tracking. One promising solution to overcome these limits is the digital outphasing concept.

In 2019, FBH has presented a novel digital GaN-based outphasing PA module (Fig. 1) for the 800 MHz band. The very compact module includes two GaN amplifier MMICs (Fig. 2) and hybrid input as well as output circuitry for biasing, combining and filtering. The realized power amplifier applies different degrees

of resonant commutation (partly or full) with a novel output combiner for the voltage on the center output nodes, which is optimized for high efficiency in the PBO region. Furthermore, the amplifier uses novel high-side drivers for the push-pull final stages to ensure efficient driving.

In addition, a modulation scheme has been developed that is used to encode the baseband signal into a bitstream, suitable especially for digital outphasing amplification. The modulator includes features like dynamic back-scaling of the duty cycle and correction of system nonlinearities, which is indispensable for a modern communication system.

At the maximum module output power of 5.8 W, overall efficiency of the outphasing PA reaches 59% and decreases down to 25% at 10 dB PBO. The simulated final-stage drain efficiency peaks at 71% (0 dB PBO), drops down to 62% at 7 dB, and reaches 67% at 10 dB PBO. Additionally, the final stage efficiency stays above 50% even down to 15 dB PBO, which demonstrates the outphasing functionality. The total efficiency shows the potential of the proposed GaN-based digital outphasing approach.

This work was supported by the German Federal Ministry of Education and Research (BMBF) within the "Research Fab Microelectronics Germany (FMD)" framework under ref. 16FMD02.

Der künftige Mobilfunkstandard 5G soll die Voraussetzungen schaffen, damit immer mehr Daten immer schneller übertragen werden können. Jedoch muss die mobile Infrastruktur an die anspruchsvollen Anwendungen, wie sie etwa für Industrie 4.0 benötigt werden, angepasst sein. Da derzeit Signale noch teils analog verarbeitet werden, wäre die komplette Digitalisierung hierfür die ideale Lösung. Daher zielen Aktivitäten am FBH darauf ab, den digitalen Anteil an der Signalverarbeitung zu erhöhen. 2019 hat das FBH einen neuartigen, kompakten und effizienten Verstärker-Chip nach dem Outphasing-Prinzip realisiert, der auf dem hauseigenen 0,25 µm GaN-HEMT-Prozess basiert. Dafür wurde ein maßgeschneidertes Modulator-Konzept entwickelt, das auf einem patentierten FBH-Verfahren beruht. Mit diesem Chip wurde ein Modul realisiert, das mittels Outphasing und neuartiger Treiberkonzepte die Energieeffizienz der mobilen Infrastruktur steigert. Bei abnehmender Signaleingangsleistung sinkt – typisch für das Outphasing – die Effizienz des digitalen Transmitters für das 800 MHz-Band kaum.

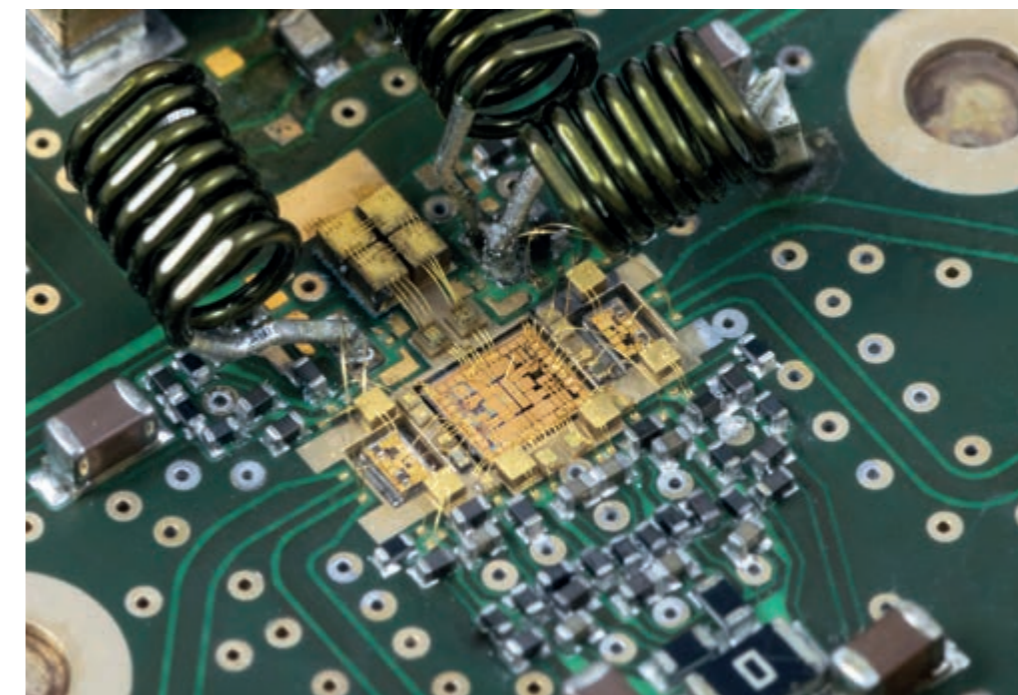


Fig. 2. Chip photograph of the realized GaN digital outphasing PA MMIC with connecting gold bond-wires; chip size: 2.1 x 1.9 mm².

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T. Hoffmann, A. Wentzel, T. Flisgen, F. Hühn, W. Heinrich, „GaN digital microwave outphasing PA“, International Journal of Microwave and Wireless Technologies, Special Issue EuMW 2019, pp. 1 – 11 (2020).

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Progress in mm-wave InP HBT circuits – a prerequisite for next-generation wireless and optical communications

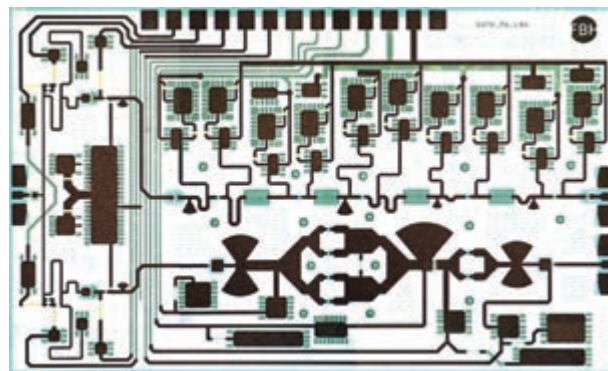


Fig. 1. Chip photograph of an integrated transceiver chip.

The development of electronic circuits for applications in the range from 100 GHz to 300 GHz is rapidly advancing, driven by next-generation high-resolution imaging and high-data-rate wireless communications. Also, integration of photonics with III-V based electronics for fiber optics is a hot topic. All of these applications need relatively high output power and large bandwidth. These requirements cannot be met by appropriate circuit design alone but demand for an advanced semiconductor process technology as well.

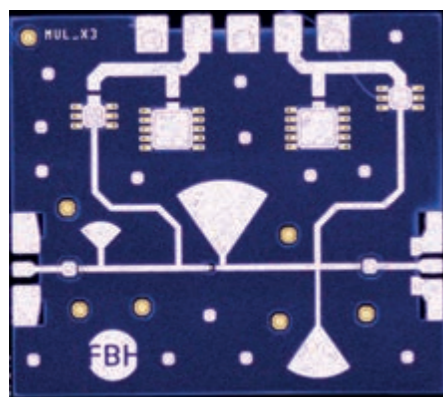
For this purpose, FBH is pursuing the development of an InP MMIC DHBT transferred-substrate process, which is well suited for high-power and ultra-wide bandwidth THz applications. This process offers higher cut-off frequencies as well as higher breakdown voltages as compared to a standard triple mesa process.

The FBH transferred substrate InP MMIC process has allowed the realization of state-of-the-art power amplifiers at D-band around 140 GHz and ultra-broadband circuits with bandwidth well in excess of 100 GHz. The complexity of the circuits has increased and full transceiver solutions in W-band and D-band have been demonstrated. In addition, signal sources based on fundamental and harmonic oscillator circuits and frequency multipliers were realized up to 500 GHz.

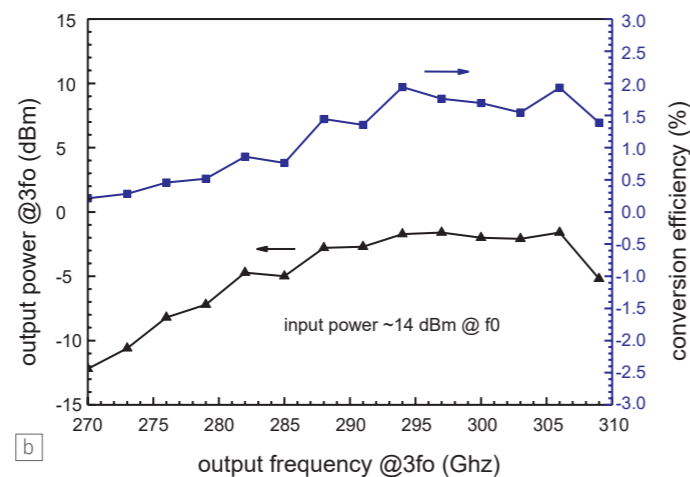
A few examples of recent circuits realized with this process are presented below.

W-band MMIC chip for future 5G communications

Realizing a mm-wave MMIC frontend for radar and communication applications on a single chip is attractive since it saves cumbersome interconnects, increases compactness, and reduces chip area. On the other hand, it is challenging because of crosstalk effects and process yield. FBH has realized a monolithically integrated transceiver chip, which includes an HBT-based switch, power amplifier and low-noise amplifier in W-band (75 – 110 GHz), as shown in Fig. 1, all operated from a single power supply interface [3,5]. The chip area is $2.5 \times 1.5 \text{ mm}^2$ only. The entire transceiver chip consumes a total of 280 mW DC power from a single positive power supply. It exhibits an output power of $> 13 \text{ dBm}$ and a noise figure of $< 8 \text{ dB}$.

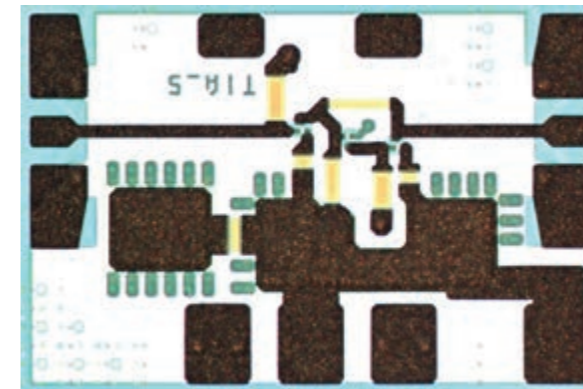


a



b

Fig. 2. Chip photograph of a tripler-based signal source (a) and measured output power and conversion efficiency against output frequency (b).



a

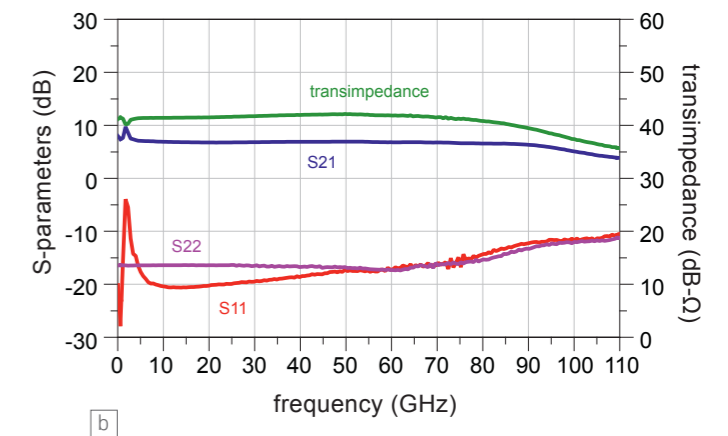
InP MMICs for next-generation imaging and high data rate optical communications

An efficient multiplier-based signal source has been designed, showing -1.6 dBm output power with 2 % conversion efficiency at 306 GHz [1]. The source offers more than 30 GHz bandwidth and exhibits very low unwanted harmonics. In addition, a 240 GHz active frequency source with -3 dBm output power was demonstrated [2]. The highest harmonic VCO signal source achieved so far in the process has obtained an output frequency of 480 GHz with an output power of -11 dBm [8].

Also, an ultra-wideband travelling-wave amplifier and transimpedance amplifier were implemented in the FBH process. A transimpedance gain of $> 40 \text{ dB-}\Omega$ with a 3 dB bandwidth from DC to 110 GHz has been achieved. The dimensions of the fabricated TIA chip are $0.4 \times 0.6 \text{ }\mu\text{m}^2$. The voltage gain (S21) is 7 dB within the 110 GHz of 3 dB bandwidth [6,7].

These achievements were realized within different national and international projects. Funding came from the European commission for the projects EU H2020 ULTRAWAVE and EU H2020 TERAWAY. This work was partly funded by the German BMBF within the "Research Fab Microelectronics Germany (FMD)" framework under ref. 16FMD02. The German Aerospace Agency funded the MMIC work of the DLR project MIMIRAWE II (ref. no. 50RA1910), while the national project SAW-2016-FBH: Electronic high performance components for applications between 500 and 1000 GHz provided finances for the technology advancement.

Zukünftige Kommunikationssysteme und hochauflösende Bildgebungssysteme benötigen hohe Ausgangsleistungen und große Bandbreiten. Diese lassen sich mit InP-MMIC-Schaltungen bei Frequenzen von 100 – 300 GHz erreichen. Zu diesem Zweck optimiert das FBH permanent seinen InP-MMIC-Transferred-Substrate-Prozess (TS-Prozess), der höhere Grenzfrequenzen und Durchbruchspannungen erzielt als vergleichbare Triple-Mesa-HBT-Prozesse. Mit diesem TS-Prozess wurden komplette Transceiver für den Frequenzbereich im W- und D-Band entwickelt und realisiert sowie



b

Fig. 3. Chip photograph of a transimpedance amplifier (a) and measured S-parameters and transimpedance as a function of frequency (b).

Publications

- [1] M. Hossain, S. Boppel, W. Heinrich, V. Krozer, "Efficient active multiplier-based signal source for $>300 \text{ GHz}$ system applications", *Electron. Lett.*, vol. 55, no. 23, pp. 1220-1221 (2019).
- [2] M. Hossain, S. Boppel, W. Heinrich, V. Krozer, "A 240 GHz Active Multiplier-Based Signal Source for Millimeter-Wave/Terahertz Applications", *44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, Paris, France, pp. 1-2 (2019).
- [3] M. Hossain, T. Shivan, M. Hrobak, T. Al-Sawaf, A. Rärner, W. Heinrich, V. Krozer, "Front-End Active Components for Millimeter-Wave and THz Communications in InP DHBT Technology", *8th ESA Workshop on Millimeter-Wave Technology and Applications, ESA/ESTEC, Noordwijk, Netherlands* (2018).
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- [5] T. Shivan, M. Hossain, R. Doerner, S. Schulz, T. Johansen, S. Boppel, W. Heinrich, V. Krozer, "Highly linear 90-170 GHz SPDT Switch with High Isolation for Fully Integrated InP Transceivers", *IEEE MTT-S International Microwave Symposium (IMS)*, Boston, USA, pp. 1011-1014 (2019).
- [6] T. Shivan, M. Hossain, R. Doerner, T. K. Johansen, H. Yacoub, S. Boppel, W. Heinrich, V. Krozer, "Performance Analysis of a Low-Noise, Highly Linear Distributed Amplifier in 500-nm InP/InGaAs DHBT Technology", *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 12, pp. 5139-5147 (2019).
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- [8] M. Hossain, N. Weimann, M. Brahm, O. Ostinelli, C. R. Bolognesi, W. Heinrich, V. Krozer, "A 0.5 THz Signal Source with -11 dBm Peak Output Power Based on InP DHBT", *49th European Microwave Conference (EuMIC)*, pp. 856-859 (2019).

Signalgeneratoren bis 500 GHz. So erzeugt der $2.5 \times 1.5 \text{ mm}^2$ große InP-DHBT-MMIC-Transceiver-Chip eine Ausgangsleistung von $> 13 \text{ dBm}$ mit einer Rauschzahl von $< 8 \text{ dB}$ bei einem Leistungsverbrauch von 280 mW. Der Transceiver-Chip verwendet zudem einen integrierten T/R-Schalter. Bei einer Spannungsverstärkung von 7 dB wurden breitbandige Schaltungen mit $> 100 \text{ GHz}$ Bandbreite und einer Transimpedanz von $40 \text{ dB-}\Omega$ realisiert.

AlN-based high-speed power cores for fast and efficient switching

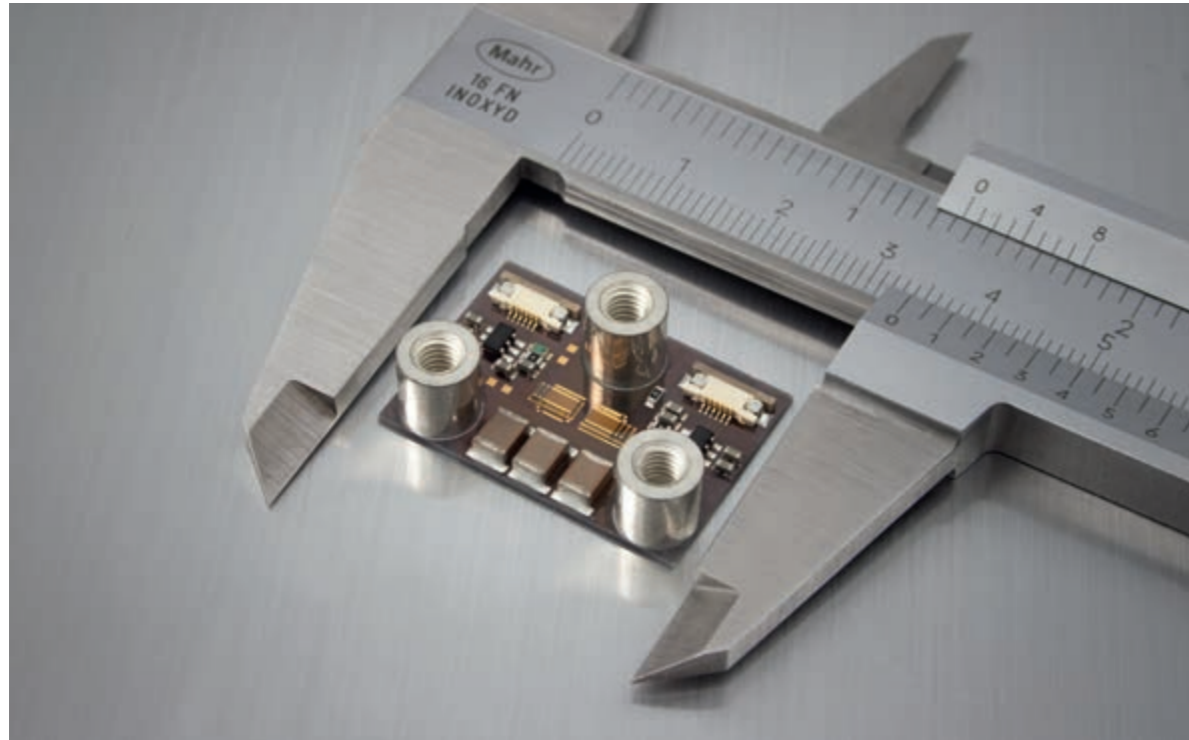


Fig. 1. 600 V/10 A half-bridge module with two 170 mΩ GaN transistor chips. The AlN substrate also supports the two gate drivers and the DC-link capacitors.

Increasing the power density of switch-mode power-electronic converters requires higher operation frequencies and thus switching transistors with high switching speed. GaN-based 650 V switching transistors feature a particularly low gate charge and a low output capacitance, which may result in 400 V switching transients of up to 200 V/ns slew rate. This is why GaN transistors demonstrate clear advantages in terms of switching speed over Si-based superjunction metal-oxide-semiconductor field-effect transistors (MOSFET) and even over SiC MOSFETs. These beneficial properties result in smaller and light-weight systems – which, in turn, reduces costs. Essential for gaining benefit from high-speed switching in a power converter system is the realization of a low-inductance environment for both gate and power loop. However, typical parasitic inductances from packaging and package inter-connects in the 10 nH range already generate ringing of switching transients in the 10 ns timescale. Increased switching losses and device over-voltage stress are the consequence, resulting in reduced power converter efficiency. Low-inductance designs with particularly small current loops are required for circuit board layout and for transistor packaging to take full benefit of the GaN transistor's inherently high switching speed.

As a hybrid integration approach, FBH has developed an AlN-based 600 V/10 A two-layer platform for high-speed power cores of compact converters. It enables a very compact assembly of the gate and power commutation loop for a GaN-based half bridge (Fig. 1). FBH uses its own established 600 V normally-off GaN transistor technology that is based on a p-GaN gate module for the two power switches. The AlN platform supports the die and wire bonding for the transistors as well as SMD soldering of gate driver ICs and DC-link capacitors. The two stacked metal layers allow for a particularly small power loop with only 3.0 nH parasitic stray inductance. The AlN substrate serves as electrically insulating heat sink with low thermal impedance.

Monolithic half bridge integration on one GaN chip is an additional approach to further reduce the size of current loops. Unlike for Si-based vertical MOSFETs of the 650 V class or SiC FETs, the GaN HFET lateral design makes source, gate and drain accessible from the chip top-side. Moreover, it offers the opportunity to laterally integrate different device functionalities on one die and to realize GaN-based integrated circuits. FBH combined two 600 V/170 mΩ GaN transistor structures on one chip as monolithically integrated half bridge and replaced the two discrete GaN transistor chips of the AlN-based

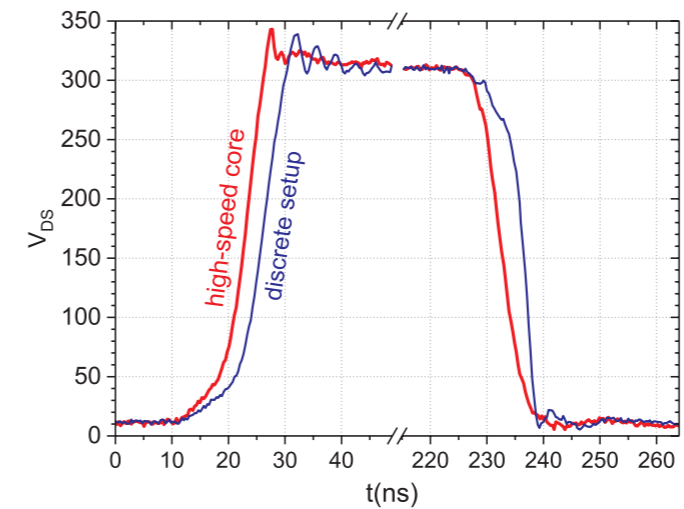


Fig. 3. 6 A, 300 V turn-off and turn-on voltage transients with the integrated half-bridge configuration of Fig. 2 (red), which is based on the high-speed core, compared to a conventional PCB-based packaging concept (blue).

high-speed core to further reduce the power commutation loop stray inductance to 2.4 nH (Fig. 2).

Comparing 6 A/300 V switching transients of the high-speed core with the ones of a conventional PCB-based setup reveals faster switching and less ringing for the high-speed core (Fig. 3). The faster turn-on is dedicated to the reduced power loop inductance, the smaller gate-driving inductance results in the faster turn-off transient.

This work was supported by the German Research Foundation (DFG) under contract WU172/5-1 and partly funded by the German Federal Ministry of Education and Research (BMBF) under project reference 16FMD02 (Research Fab Microelectronics Germany – FMD).

Galliumnitrid-basierte Transistoren bieten im Vergleich zu Silizium höhere Schaltgeschwindigkeiten, die zu kleineren und leichteren Systemen führen. Um diese Vorteile in leistungselektronischen Systemen nutzen zu können, müssen GaN-basierte Schaltzellen spezielle Anforderungen erfüllen: Sowohl der Leistungskreis als auch der Gateansteuerungskreis müssen extrem niederinduktiv ausgeführt werden. Typische platinenbasierte Aufbauten eignen sich wegen ihrer zu hohen Streuinduktivitäten im 10 nH-Bereich nicht. Sie erzeugen schädliche Schwingungen während der Schaltvorgänge, die den Wirkungsgrad des Konverters senken. Das FBH hat extrem kompakte und niederinduktive 600 V-Hochgeschwindigkeits-Schaltzellen mit exzellenter Entwärmung entwickelt, die auf AlN-Submounts mit zweilagiger Metallisierung basieren. Auf diesen Schaltzellen können Transistorchips aufgelötet und drahtgebondet werden. Auch SMD-Bauelemente, wie Gatetreiber ICs und Kondensatoren, lassen sich niederinduktiv integrieren. Mittels 6 A/300 V-Schalttransienten wurden für die neuen Schaltzellen sowohl schnellere Spannungsanstiegs- und Abfallzeiten als auch geringere Oszillationen nachgewiesen.

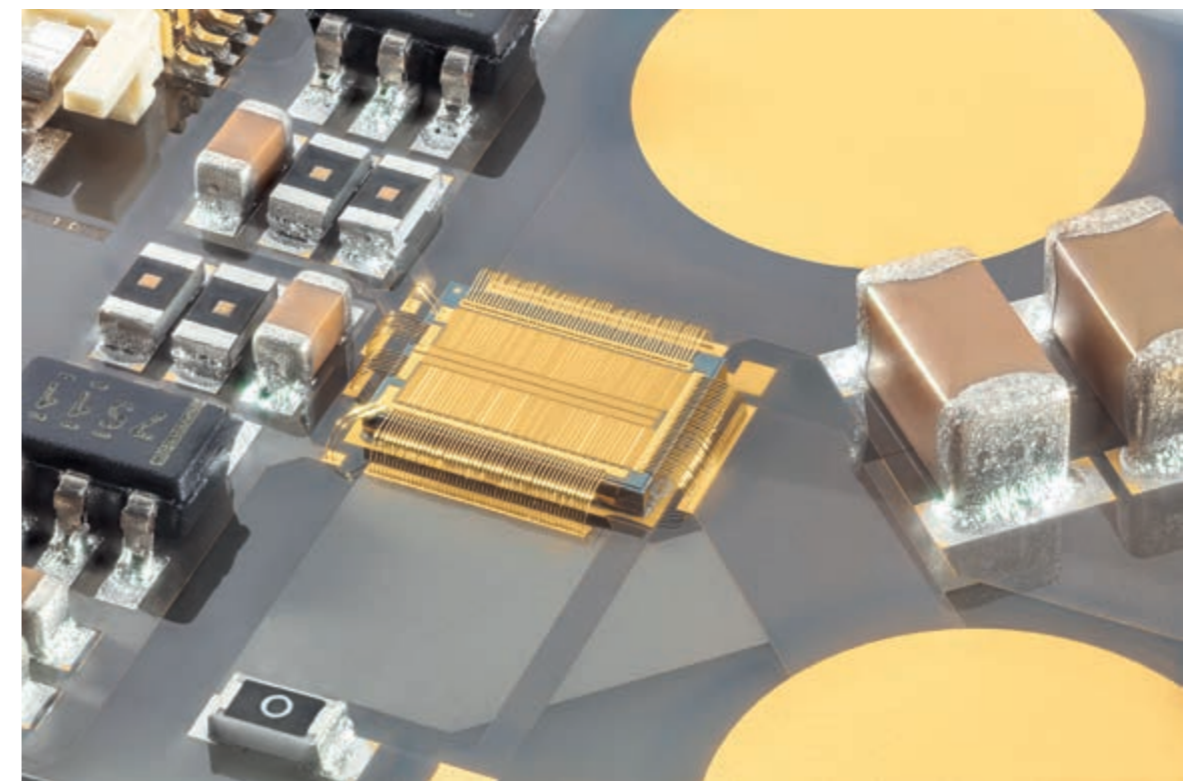
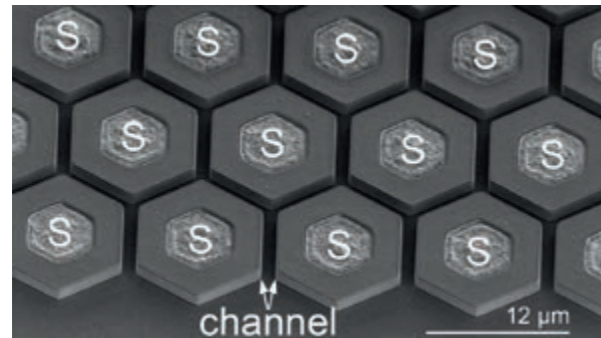


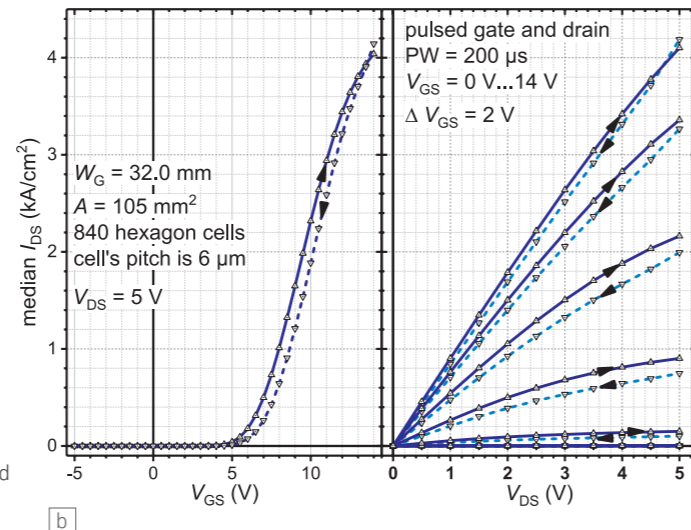
Fig. 2. Monolithically integrated 600 V/170 mΩ GaN half bridge mounted on the AlN-based high-speed core.

Large-scale vertical trench GaN MISFETs for power switching electronics



a

Fig. 1. SEM micrograph (a) from inline processing of a hexagonal trench transistor design with gate periphery density of approx. 300 mm/mm² and unit cell pitch of 6 µm. Transfer and output characteristics (b) of a vertical hexagonal design GaN trench MISFET.



b

Emerging GaN-based vertical trench MISFETs may outperform even SiC devices in terms of ON-state resistance, gate charge, parasitic capacitive loading and switching speed. This is due to the beneficial combination of larger breakdown fields, high bulk mobility and specific device geometry. At FBH, the development of vertical GaN trench MISFET technology currently focuses on pulsed laser driving applications with maximum voltages of less than 100 V. Drivers for pulsed lasers need to deliver very high currents in very short pulse lengths between 3 ns and 10 ns. Vertical GaN trench MISFETs are particularly suited for realizing the required steep current slopes due to their low output capacitance and gate charge figure of merits. Further, the vertical GaN transistor topology enables a compact assembly of the laser diode die directly on top of the vertical GaN transistor die, thus achieving an ultimately small current loop inductance in the laser drive circuit. Additionally, the vertical device concept allows aggressive device scaling and enables a high current density per unit area [1]. The technology towards highly conductive vertical GaN MISFETs grown on amonothermal GaN substrates has been developed with a strong focus on optimized design and manufacturing parameters. Using these devices, we demonstrated a high-speed laser drive circuit realized by chip-on-chip integration of GaAs diode lasers on top of large gate periphery vertical GaN MISFETs.

Reducing the area specific ON-state resistance is crucial to finally demonstrate competitive devices with current levels matching

the requirements of diode laser driving (around 50 A). Therefore, a major focus was set on scaling up the active device area and gate periphery. Since high-quality flat 50 mm GaN substrates became recently available, a high-resolution lithographic process using an industrial stepper is now possible. FBH's i-line stepper lithography enables a high resolution better than 0.5 µm and features an accurate overlay capability better than 0.2 µm, which translates into a compact 6 µm cell pitch design. In other words, depending on the specific design of the transistor cell, trench transistors with approximately 100 mm/mm² (gate periphery per mm² semiconductor area, i.e. mm/mm²) are feasible in more conventional finger-type architectures, whereas approximately 300 mm/mm² are realistic when using hexagonal cell designs. Fig. 1 (a) shows a SEM micrograph from of a hexagonal trench transistor design with a gate periphery density of approximately 300 mm/mm² and a unit cell pitch of 6 µm. Fig. 1 (b) depicts the electrical characteristics of such a hexagonal vertical GaN transistor manufactured on highly conductive amonothermal GaN substrates. The integrated devices demonstrate a low hysteresis ON-state conduction current up to 4000 A/cm² with a resistance of 1.1 mΩ/cm² and a forward bias gate leakage current less than 10⁻⁴ A/cm².

For electro-optical characterization a broad area DBR diode laser with an aperture of 50 µm and a cavity length of 3 mm was soldered p-side down on a CuW interposer. It was then mounted on top of a pre-characterized vertical GaN MISFET

placed on an AlN ceramic board. The selected GaN trench MISFET has an ON-state resistance of 300 mΩ and 142 mm gate periphery. The laser current aperture fits quite well to the active GaN transistor areas on the chip. To achieve minimum loop inductance, the ceramic block capacitors, temporarily delivering the energy for the short laser pulses, are placed close by on the same AlN board. This setup is coupled to an external pulse driver circuit located on an adjacent printed circuit board (Fig. 2). The whole arrangement has demonstrated 3.6 ns laser pulses at a repetition rate of 500 kHz at about 904 nm (Fig. 3). The peak optical power was calculated from the measured average power and repetition frequency to about 4 W at 6 V drain bias.

This work was supported by the European Fund for Regional Development (ERDF) in the frame of the German – Polish project "PioneerGaN" ref. 10157776 and partly funded by the German BMBF within the "Research Fab Microelectronics – FMD" framework under ref. 16FMD02.

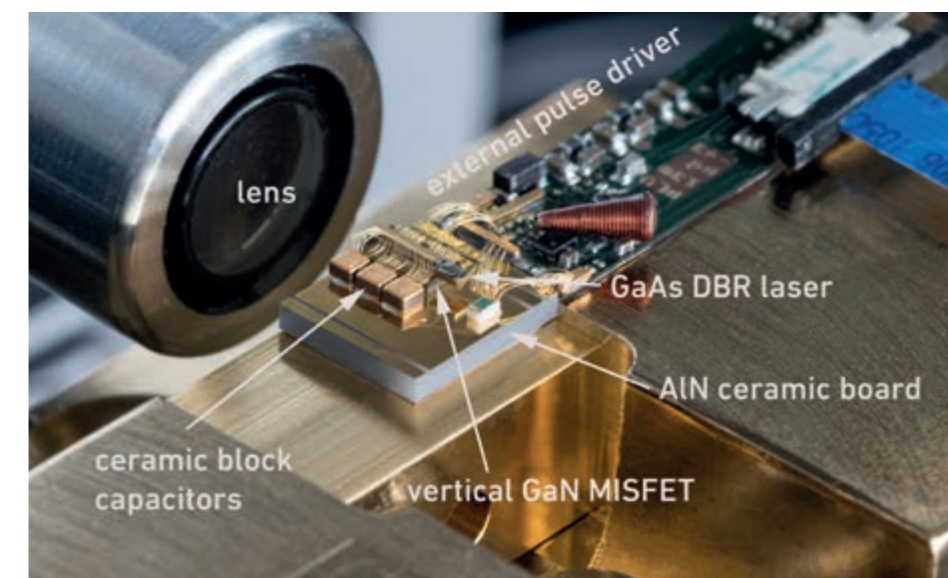


Fig. 2. Realized optical test bench with GaAs DBR laser, vertical GaN MISFET, ceramic block capacitors and electronic circuit.

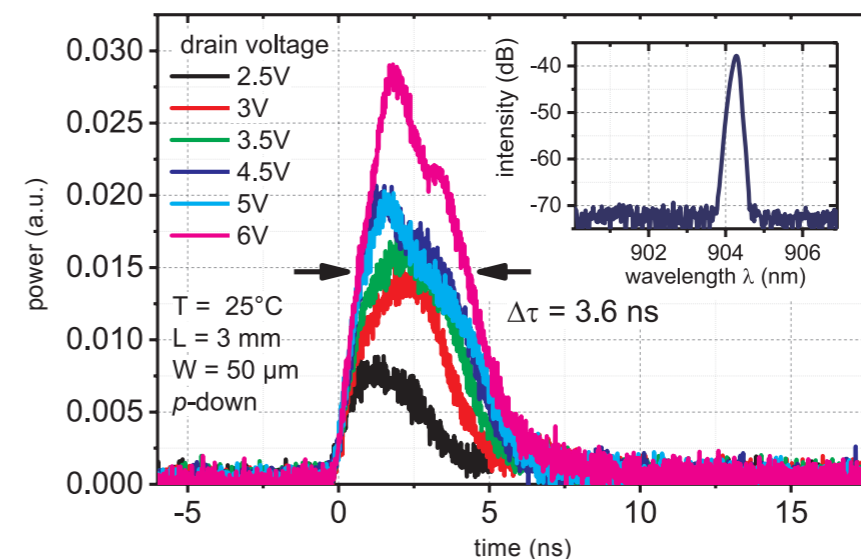


Fig. 3. Generated laser pulses with 3.6 ns optical width (FWHM) at 500 kHz at different excitation levels (drain bias), inset: emission wavelength of the generated pulse.

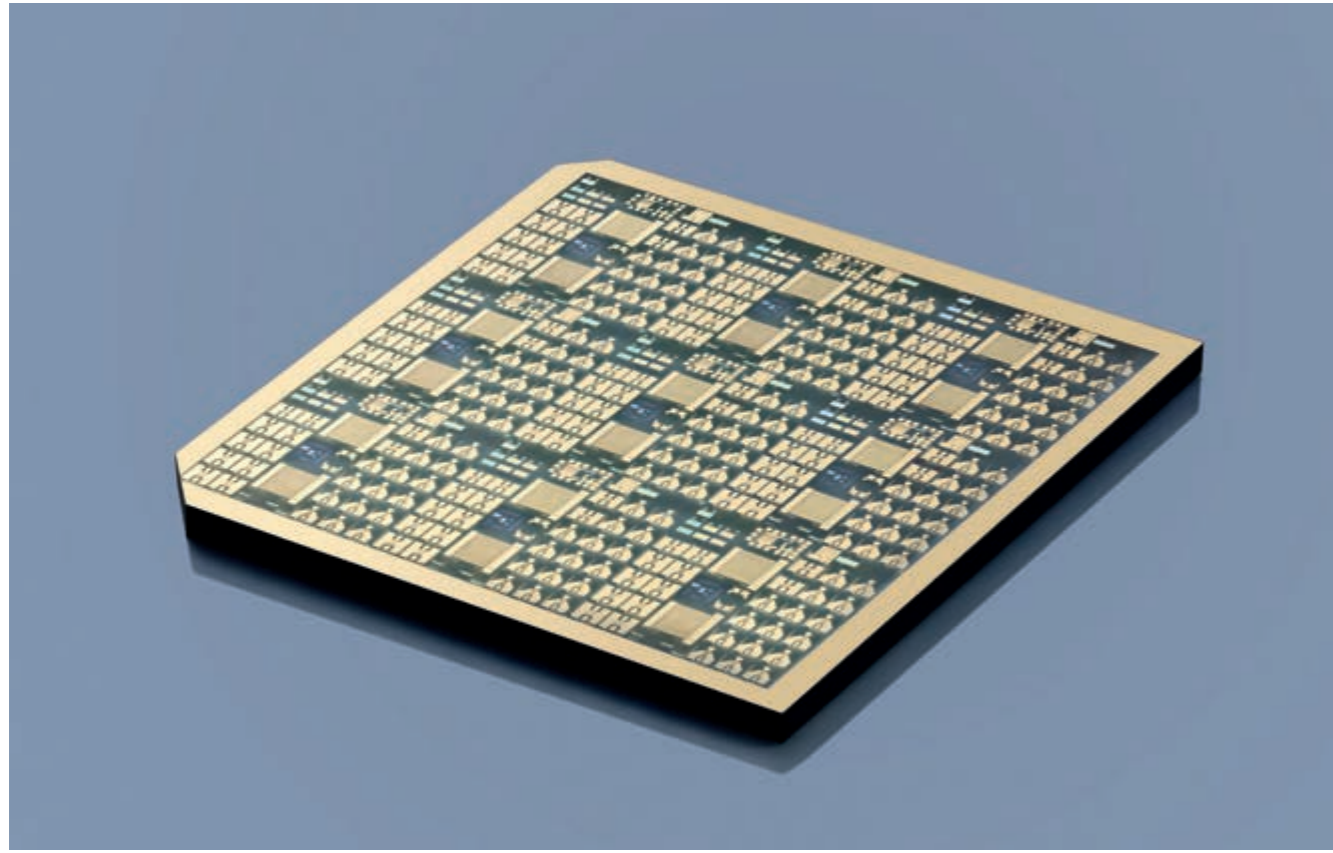
GaN-Schalttransistoren mit einer vertikalen Architektur sind für die Leistungselektronik hoch attraktiv. Dank der spezifischen Materialparameter von Galliumnitrid könnten sie sogar SiC-Bauelemente hinsichtlich Einschaltwiderstand und Schaltgeschwindigkeit übertreffen. Dazu muss jedoch die Transistorarchitektur entsprechend angepasst werden. Das FBH konzentriert sich derzeit auf vertikale GaN-Schalttransistoren für die direkte Chip-auf-Chip-Verbindung mit einem Diodenlaser. Diese Anordnung ermöglicht minimale parasitäre Induktivitäten und damit kürzeste Laserpulse. Zur Ansteuerung der Diodenlaser müssen die Transistoren auf Pulsströme von bis zu 50 A ausgelegt und an die Abmessungen der Diodenlaser angepasst werden. Um dieses zu erreichen, wurden verschiedene Skalierungskonzepte für die Transistorzellen entworfen und technologisch umgesetzt. Dabei konnte gezeigt werden, dass sich vertikale GaN-Transistoren durch Heterointegration mit einem Diodenlaser dafür eignen, Lichtpulse im unteren ns-Bereich zu erzeugen.

Publications

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Material with excellent properties – gallium oxide power transistors demonstrate ultra-high power density



Fully processed 10 mm x 10 mm $\beta\text{-Ga}_2\text{O}_3$ wafer.

Beta gallium oxide ($\beta\text{-Ga}_2\text{O}_3$) with its ultra-wide bandgap of 4.8 eV has emerged as a promising semiconducting material for next-generation power electronic devices. The estimated dielectric strength of 8 MV/cm along with the expected Baliga's figure of merit are important indicators to pave the way for power devices with even higher breakdown voltages and efficiencies than their SiC and GaN counterparts. Results on successfully fabricated power transistors based on $\beta\text{-Ga}_2\text{O}_3$ were published in several studies to date. However, the overall performances of those devices are far away from the theoretical limit for $\beta\text{-Ga}_2\text{O}_3$. The demonstrated power densities are still beneath the values for SiC or GaN devices and hover around the theoretical limit of Si-based devices. This is due to material- and/or device-related impairments. To overcome these issues, FBH in collaboration with the Leibniz Institute for Crystal Growth has started to significantly enhance the device perfor-

mance of $\beta\text{-Ga}_2\text{O}_3$ power transistors by combining optimized layer growth and improved process technology.

A first requirement to achieve high-performance power devices is substrate growth followed by epitaxial growth of high-quality semiconducting layers. Deposition of $\beta\text{-Ga}_2\text{O}_3$ layers by metal-organic vapor phase epitaxy on on-oriented (100) substrates leads to nucleation of two-dimensional islands with rotational domains, resulting in twin lamellae and a high defect density of the layers. Thus, substrates with vicinal surfaces were used for device fabrication. These vicinal surfaces were provided by (100) oriented substrates with a miscut in c direction. To achieve layers with a smooth step flow growth, direction and degree of the miscut are crucial. While substrates with a miscut towards [001] direction lead to highly defective epitaxial layers, using substrates with a miscut towards [00-1] results in

layers free of structural defects. Therefore, high-quality $\beta\text{-Ga}_2\text{O}_3$ layers with a very low defect density were homoepitaxially grown on 10 mm x 10 mm substrates with a miscut of 6° towards [00-1] direction.

Furthermore, applying a high-resolution process technology is mandatory for the fabrication of high-performing power devices with extremely precise submicron dimensions. Using wafer stepper lithography, it was possible to implement a more advanced recessed T-gate topology with a gate length down to 700 nm, as shown in Fig. 1. This technique allows reducing high electric fields emerging at the gate edge. It also paved the way for $\beta\text{-Ga}_2\text{O}_3$ transistors with breakdown voltages up to 1.8 kV at a gate-to-drain separation of 10 μm . At the same time, low on-state resistances were achieved owing to the high quality of the epitaxial layer, which yielded a record power figure of merit of 155 MW/cm^2 for these devices.

Benchmarking the results achieved at FBH with previously reported data on $\beta\text{-Ga}_2\text{O}_3$ power transistors verifies improved transistor performances with reduced DC conduction losses as can be seen in Fig. 2. The graph emphasizes that the combination of optimized layer growth and improved process technology leads to a significant performance shift closer to the theoretical limit for $\beta\text{-Ga}_2\text{O}_3$ power transistor devices.

This work was funded by the German Federal Ministry of Education and Research (BMBF) within the frame of the joint research project OXIKON, funding no. 03VP03711.

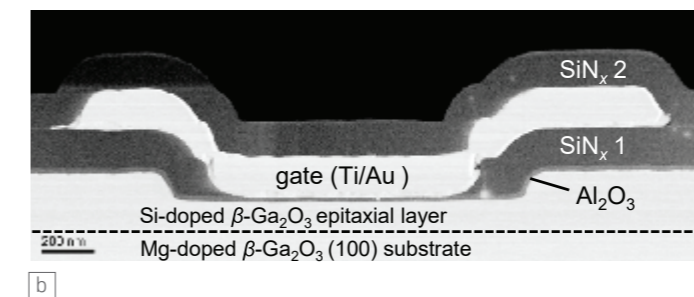
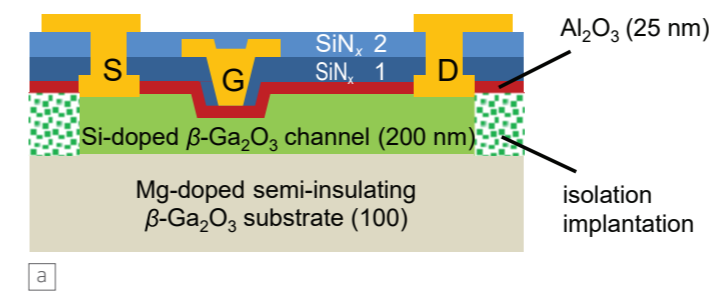
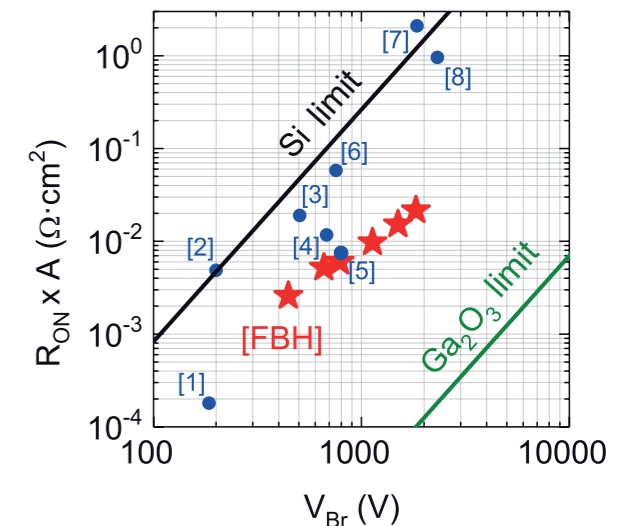


Fig. 1. Schematic cross section of the $\beta\text{-Ga}_2\text{O}_3$ power transistor devices (a) and TEM image showing the recessed gate topology of a processed $\beta\text{-Ga}_2\text{O}_3$ power transistor (b).

Der hohe Bandabstand von etwa 4,8 eV und die zu erwartende hohe Durchschlagsfestigkeit von 8 MV/cm machen das Halbleitermaterial Galliumoxid für leistungselektronische Systeme der nächsten Generation hochattraktiv. Jedoch konnten bislang nur flächenspezifische Einschaltwiderstände erreicht werden, die denen von Silizium-basierten Bauelementen entsprechen. Auch die Leistungsfähigkeit von Siliziumkarbid- oder Galliumnitrid-basierten Bauelementen erreichen sie – trotz der theoretisch besseren Werte – noch nicht. Dies hat sowohl material- als auch bauteilspezifische Gründe. Nun ist es dem FBH in Zusammenarbeit mit dem Leibniz IKZ gelungen die Leistungseigenschaften von Galliumoxid-Transistoren auf 10 mm x 10 mm großen Substraten maßgeblich zu verbessern; sie übertreffen damit die Leistungsdichte von Si-basierten Transistoren. Dazu wurde das Schichtwachstum optimiert und mit einer verbesserten, hochauflösenden Prozesstechnologie kombiniert. Die erzielten Transistorkennwerte belegen eine deutliche Verschiebung in Richtung des theoretischen Materiallimits von Galliumoxid.

Publication

K. Tetzner, E. Bahat Treidel, O. Hilt, A. Popp, S. Bin Anooz, G. Wagner, A. Thies, K. Ickert, H. Gargouri, J. Würfl, "Lateral 1.8 kV $\beta\text{-Ga}_2\text{O}_3$ MOSFET With 155 MW/cm^2 Power Figure of Merit", IEEE Electron Device Lett., vol. 40, no. 9, pp. 1503-1506 (2019).



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Fig. 2. Plot of the specific ON-resistance vs. breakdown voltage for benchmarking FBH's work (red stars) with recently published data on $\beta\text{-Ga}_2\text{O}_3$ (blue circles).

III-V Technology

III/V-Technologie

The research area III-V technology combines know-how and resources at FBH in materials and process technology as well as mounting and packaging. These competencies form the basis for the development of devices in the photonics, III-V electronics and integrated quantum technology research areas.

- > **Epitaxy nitrides** – heterostructures for UV LEDs, UV photodetectors, violet laser diodes, and GaN transistors. These heterostructures are the basis for the respective devices at FBH. Additionally, HVPE growth processes for AlN templates are developed.
- > **Epitaxy arsenides** – heterostructures for GaAs laser diodes over the whole wavelength range from 630 nm – 1200 nm for device development at FBH as well as for external customers. Also, SESAM structures for pulsed laser systems are fabricated.
- > **Process technology** – processes for a large variety of devices based on GaAs, InP, and GaN on wafers from 2" to 4" in diameter as well as on novel materials such as AlN, Ga₂O₃ and diamond. These are carried out and continuously improved on a process line that is compatible with industry standards, offering high flexibility at the same time.
- > **InP devices** – InP HBTs for THz frequencies form the basis for FBH THz systems. Monolithically integrated with Si BiCMOS circuits, this technology is also made available to external customers in cooperation with the Leibniz institute IHP.

- > **Mounting & assembly** – devices are mounted onto heat sinks or into packages to allow for integration into modules and systems.
- > **Materials analytics** – supports the development of epitaxial growth processes by characterization of heterostructures. These analysis techniques are also utilized for the development of processing and mounting steps as well as for the analysis of root causes for device failure.

We also make our technological infrastructure available to external partners, for whom we carry out process modules, develop fabrication technology, deliver epitaxial wafers or develop and build demonstrator systems

Im Forschungsbereich III/V-Technologie bündelt das FBH sein Know-how und seine Ressourcen in der Material- und Prozesstechnologie sowie in der Aufbau- und Verbindungstechnik. Diese bilden die Basis für die Entwicklung von Bauelementen in den Forschungsbereichen Photonik, III/V-Elektronik und Integrierte Quantentechnologie:

- > **Epitaxie Nitride** – Heterostrukturen für UV-LEDs, UV-Fotodetektoren, violette Laserdioden und GaN-Transistoren. Diese Heterostrukturen sind die Basis für die Entwicklung der entsprechenden Bauelemente am FBH. Weiterhin wird an HVPE-Prozessen für AlN-Templates geforscht.
- > **Epitaxie Arsenide** – Heterostrukturen für GaAs-Laserdioden im gesamten Wellenlängenbereich von 630 nm – 1200 nm sowohl für die Bauelemententwicklung am FBH als auch für externe Kunden. Darüber hinaus werden SESAM-Strukturen für gepulste Lasersysteme entwickelt.
- > **Prozesstechnologie** – Prozesse für eine Vielzahl von Bauelementen auf Basis von GaAs, InP und GaN auf Waferdurchmessern von 2" bis 4" wie auch auf den neuartigen Materialien Diamant, AlN und Ga₂O₃. Diese werden auf der industriekompatiblen und zugleich flexiblen Prozesslinie durchgeführt und beständig weiterentwickelt.
- > **InP Devices** – InP-HBTs für THz-Frequenzen, die die Basis für die THz-Systeme am FBH darstellen. Integriert mit Si-BiCMOS-Schaltkreisen wird diese Technologie in Kooperation mit dem Leibniz-Institut IHP auch für externe Kunden bereitgestellt.

- > **Aufbau- und Verbindungstechnik** – die Bauelemente werden auf Wärmesenken oder in Gehäuse eingebaut und damit für den Aufbau von Modulen und Systemen nutzbar gemacht.
- > **Materialanalytik** – unterstützt die Entwicklungen in der Epitaxie durch Charakterisierung der Eigenschaften der Halbleiterstrukturen. Diese Kompetenzen werden auch für die Entwicklung von Prozess- und Montageschritten sowie für die Analyse von Ausfallursachen der entwickelten Bauelemente eingesetzt.

Wir nutzen unsere technologische Infrastruktur auch für Aufträge von externen Partnern, indem wir z.B. Prozessmodule bereitstellen, Fertigungstechnologien entwickeln, Epitaxiestrukturen liefern oder Gerätedemonstratoren entwickeln und fertigen.

Paving the way towards high output power ultra-violet light emitting diodes



Fig. 1. Furnace for high-temperature annealing at FBH.

Light emitting diodes (LEDs) with wavelengths in the ultra-violet (UV) spectral range increasingly capture different fields of applications such as water disinfection, functional food, and medical treatment. Not least, such LEDs are environmentally friendly alternatives to mercury vapor lamps. High UV-light output power of the LEDs, which is required for many of these applications, is difficult to achieve and still an obstacle in exploiting their scientific and commercial potential.

As a prerequisite for high output power the aluminum gallium nitride (AlGaN) crystal layer, which forms the LED's basis, must have high material quality. Especially important is a low density of threading dislocations, since dislocations reduce the radiative recombination efficiency and thus light output. Therefore, the FBH developed production processes for AlGaN with low defect densities. One promising approach is the curing of material defects by high temperature treatment in a specially developed furnace (Fig. 1). In it, the crystalline layers can be heated at up to 1720 °C. With this approach we have already been able to reduce the defect density of aluminum nitride (AlN) layers by up to one order of magnitude in the past. This was the starting point to investigate whether this process could also be used to improve the crystalline quality of AlGaN. Therefore we heated 1 μm thick $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers with Al-mole fractions x between 0.50 and 0.80. The AlGaN layers had been grown by vapor deposition on 0.6 μm thick AlN on a 430 μm thick sapphire substrate, as illustrated in Fig. 2a. Threading dislocations in the resulting AlGaN layers can be made visible by etching to create etch pits on the surface. Fig. 2 exemplarily shows such etched surfaces of $\text{Al}_{0.75}\text{Ga}_{0.25}\text{N}$ without (Fig. 2b) and with (Fig. 2c) annealing at 1700 °C for one hour. Upon heating the AlGaN the etch pit density (EPD) is lowered by about 50 %, indicating a halved defect density.

Since UV LEDs emit through the substrate the AlGaN base layer has to be transparent. Unfortunately, the transparency of the

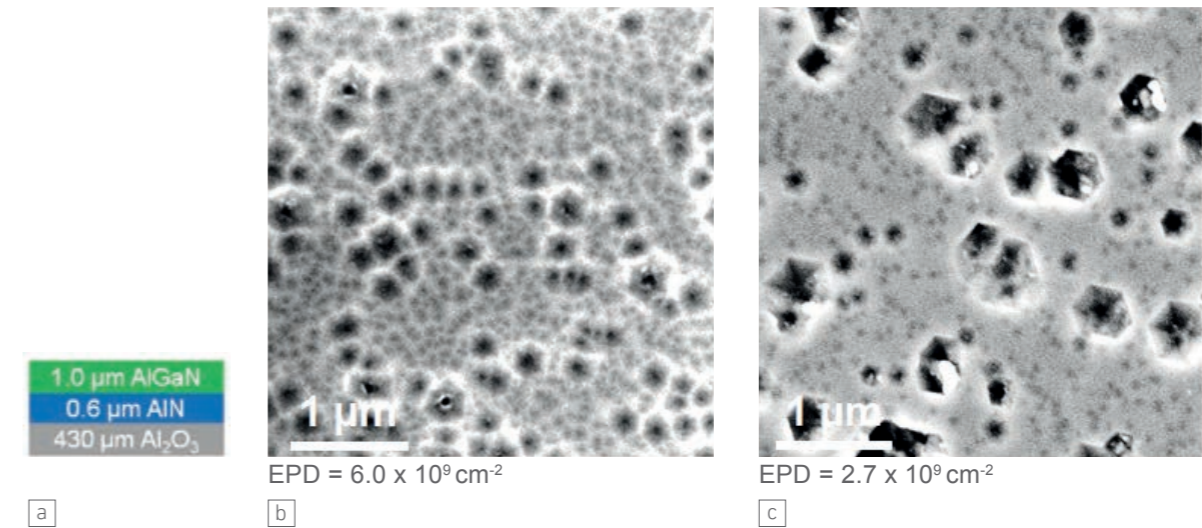


Fig. 2. Cross section of the AlGaN samples (a). Etched AlGaN surface without (b) and with annealing at 1700 °C (c). Surface etching was kindly provided by the Leibniz Institute for Crystal Growth.

AlGaN layers decreases with rising annealing temperature. This is already visible to the naked eye as brownish discoloration, as exemplarily shown for $\text{Al}_{0.50}\text{Ga}_{0.50}\text{N}$ with different annealing temperatures in Fig. 3. Absorption and luminescence spectra point to vacancies in the AlGaN crystal lattice as reason for decreasing transparency. The generation of these point defects can be controlled by environmental conditions close to the AlGaN surface during high-temperature treatment. Fig. 3 shows that the same annealing process at 1680 °C yields a transparent AlGaN layer, if sapphire instead of AlN is used to protect the AlGaN surface from decomposition.

These promising results pave the way towards AlGaN-based layers with low dislocation density, especially for LEDs emitting in the UVB spectral range.

This work was partially funded by the German Federal Ministry of Education and Research (BMBF) within the Advanced UV for Life project consortium (grant numbers: 03ZZ0112A&B, 03ZZ0134B&C, and 03ZZ0138A&B) and by the German Research Foundation (DFG) within the Collaborative Research Center "Semiconductor Nanophotonics" (CRC 787).

Publication

S. Hagedorn, S. Walde, A. Knauer, N. Susilo, D. Pacak, L. Cancellara, C. Netzel, A. Mogilatenko, C. Hartmann, T. Wernicke, M. Kneissl, M. Weyers, "Status and prospects of AlN templates on sapphire for UV LEDs", Phys. Stat. Sol. A, vol. 217, no. 14, special issue: ultraviolet materials and devices, pp. 1901022, DOI: 10.1002/pssa.201901022 (2020).

Leuchtdioden (LEDs) mit Wellenlängen im ultravioletten (UV) Spektralbereich werden zunehmend in Bereichen wie Wasserentkeimung, funktionale Lebensmittel und medizinische Behandlungen eingesetzt. Hohe UV-Lichtleistungen sind bei diesen LEDs jedoch schwer zu erreichen – und somit eine Hürde für die wissenschaftliche und kommerzielle Verwertung in einigen Anwendungen. Um eine hohe Ausgangsleistung zu erzielen, muss die Aluminium-Gallium-Nitrid (AlGaN)-Kristallschicht, die die Basis der LEDs bildet, eine niedrige Dichte an Fadenversetzungen aufweisen. Die Anzahl dieser Defekte konnte am FBH durch Erwärmen von AlGaN auf 1700 °C halbiert werden. Um gleichzeitig die notwendige Transparenz des AlGaN zu gewährleisten, wurden die Umgebungsbedingungen in der Nähe der AlGaN-Oberfläche während des Erhitzens optimiert. Das führte zu vielversprechenden Ergebnissen, die den Weg hin zu AlGaN-Basischichten für UVB-LEDs ebneten.

Fig. 3. AlGaN samples annealed at different temperatures. At 1680 °C, transparency can be maintained by improved stabilization during annealing.

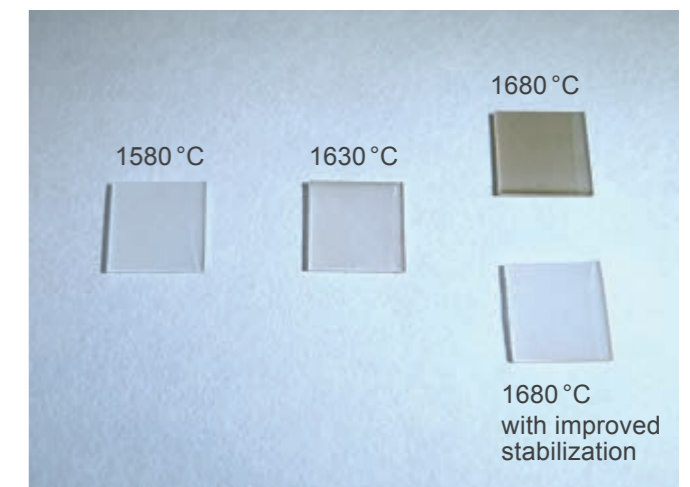




Fig. 1. Water disinfection module equipped with UV LEDs. Operation of the LEDs in the immediate vicinity of water recommends their protection by a hermetic package.

Application-based evaluation of different approaches to UV LED packages

UVB (280 nm - 315 nm) and UVC (< 280 nm) LEDs are used for several applications including water purification, gas sensing, plant lighting, and UV curing. For most of them, the UV LED needs to be packaged to protect the device from mechanical stress as well as ambient influences (Fig. 1). At FBH, UV LEDs are flip-chip mounted in AlN cavity packages and then sealed with a UV transparent quartz lid (Fig. 2). The sealing technology used depends on hermeticity requirements, influence on the device performance, e.g. output power and lifetime, and production costs. Three different technologies were investigated to seal UV LED packages with lids: (i) soldering with a gold-tin (AuSn) preform, (ii) gluing, and (iii) silver sintering. The influence on device performance as well as advantages and limitations of each technology were evaluated in detail.

FBH's standard technology for hermetic packaging of UV LEDs is fluxless AuSn soldering of the quartz lid at 320 °C. The lids can be attached in a batch process, and as it is a fluxless process no outgassing is expected. The bond between package

and lid is metallic, and hence anticipated to be UV stable. While AuSn soldering is known to form a hermetic bond, fine leak tests are still required to confirm the hermeticity of the LED package. The high price of AuSn preforms, however, greatly increases the total packaging cost. Thus, alternative inexpensive sealing technologies like silver sintering or gluing of the quartz lids to the LED package were investigated. For applications which do not require hermeticity, these technologies would provide cost-effective solutions, due to cheaper production and material costs. For the gluing process, quartz lids with epoxy glue attached were adhered to the LED packages by curing at 150 °C in a batch process. For silver sintering, a pressure-assisted paste was used to sinter the quartz lids to the LED packages. Silver paste was dispensed on the submount and then lids were sintered onto the submount at 250 °C. Outgassing normally occurs during both curing processes. Measurements of the output power of 310 nm LEDs however showed that no absorbing residues are deposited on the glass lids. Similar output powers were obtained for the LEDs both before

and after the lid mounting process. UV stability of the bond is important in applications like water disinfection where the devices are used in an array or circular arrangement, as irradiation from neighboring LEDs could lead to a degradation of the bond. While the sintered lids should be UV stable because of the silver layer, the glued samples have the tendency to degrade rapidly due to UV radiation. To check the UV stability of the glued lids, the LED packages were exposed to 254 nm UV radiation at 7 mW/cm² for 500 h. The stability of the bond was characterized using gross leak tests and measuring the change in the shear force after UV radiation stress. A minimum shear force of 100 N was defined as requirement for a stable bond for all applications. The packages successfully passed the gross leak test. A shear force decrease down to an average value of 56 N was observed after UV radiation, which is, however, still suitable for most applications.

The mechanical stability of the sealed lids using all three sealing technologies was studied using temperature cycle tests from -25 °C to +85 °C for 100 h (1 cycle = 1 h). Once again the stability of the bond was characterized using gross leak tests and measuring the change in the shear force. In all cases the packages successfully passed the gross leak tests and no considerable change in the shear force of the lids was observed.

In summary, FBH has qualified three technologies to seal a quartz lid onto a UV LED package. Based on the specifications of the application, the optimum packaging technology can be selected: For high-end applications with hermeticity requirements such as gas sensing, AuSn soldering or silver sintering would be a suitable option. For cost-driven applications, such as plant growth lighting, gluing of the quartz lids is recommended. Furthermore, the developed sealing processes are a technology platform that can also be used at FBH in connection with other devices.

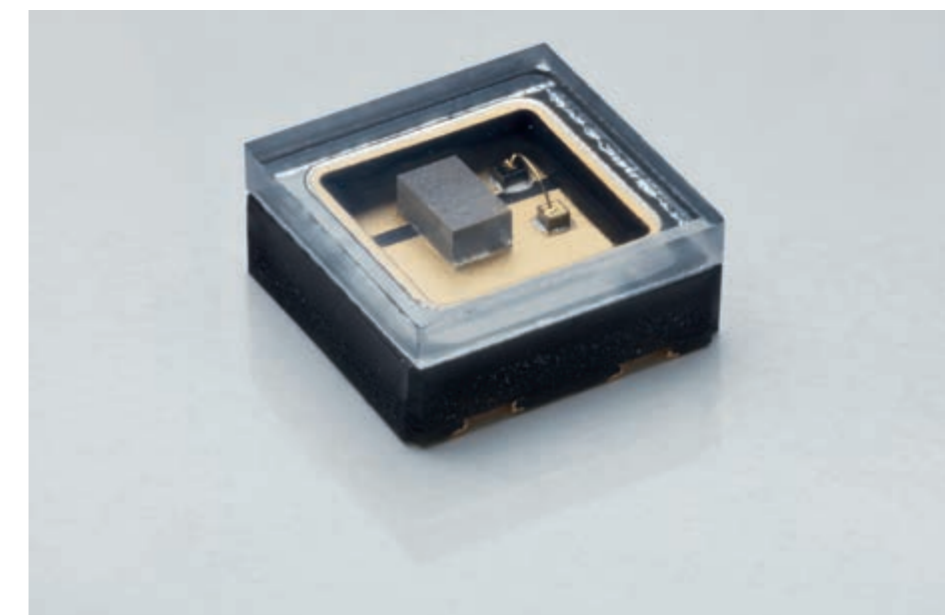


Fig. 2. Flip-chip mounted UV LED in a hermetic package.

UVB- (280 nm - 315 nm) und UVC- (< 280 nm) LEDs werden zur Wasserreinigung, in der Gassensorik, zur Pflanzenbeleuchtung oder zum Aushärten mit UV-Licht verwendet. Dabei müssen die Halbleiterchips durch geeignete Kapselung vor mechanischem Stress und Umwelteinflüssen geschützt werden. Mit welcher Technologie sie verpackt werden, hängt von der Anwendung, den Produktionskosten und der Verarbeitungstemperatur ab. Das FBH hat drei Methoden untersucht: (i) flussmittelfreies AuSn-Löten mit einer Preform sowie (ii) Kleben und (iii) Silbersintern als preisgünstigere Alternativen. Durch Tests wurden die Einflüsse der verschiedenen Fügetechnologien auf die Transparenz des Quarzdeckels (etwa durch Ausgasen des Klebstoffes oder der Sinterpaste) untersucht. Die UV-Stabilität der Kapselung wurde überprüft. Abschließend wurde der Einfluss von Temperaturwechseltests (-25 °C, +85 °C, 1 h/Zyklus, 100 h) auf die mechanische Stabilität der Kapselung betrachtet. Die Ergebnisse wurden mit Dichtigkeits-(Groblecktest) und mit Scher- tests bewertet. Es zeigte sich, dass für Anwendungen, die hohe Anforderungen an die hermetische Dichtigkeit stellen (z. B. Gassensorik), AuSn-Löten und Silbersintern passende Verpackungstechnologien sind. Kostengünstiger können die Quarzdeckel geklebt werden, sobald die Anforderungen an die hermetische Dichtigkeit geringer sind.

GaAs-based SESAMs for high peak power Q-switched pulse laser systems – to be used in materials processing

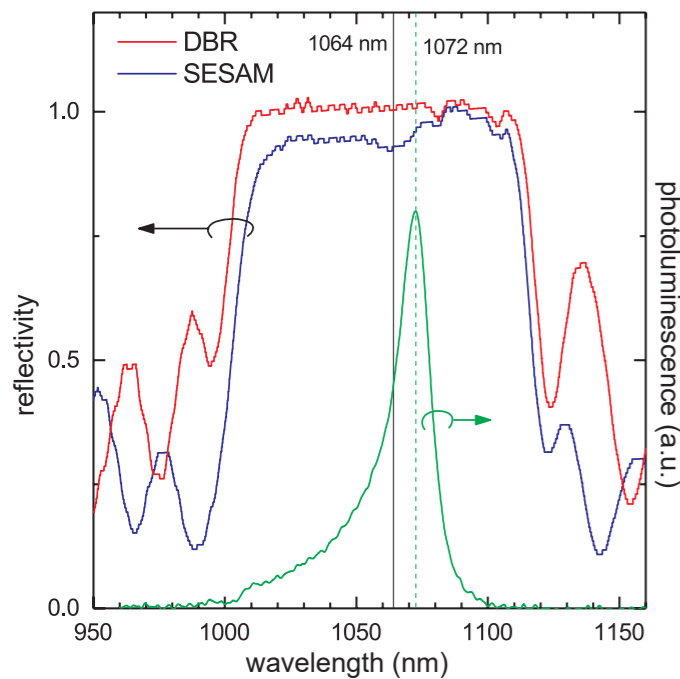


Fig. 1. Steady-state reflectivity of the as-grown DBR (red) and complete SESAM (black); Photoluminescence (green) of the MQW absorber.

Very short pulses in the ps range enable athermal removal of material required for a number of applications like cutting of stents or drilling of small holes with high precision. Semiconductor saturable absorber mirrors (SESAMs) are key components for ultrashort pulse laser systems enabling such short pulses with high peak power. Mode-locked systems with short pulses (< 10 ps) at high repetition rates (> 1 MHz) only have sufficient pulse energies after pulse selection and amplification, adding to system complexity and cost. In contrast, Q-switching

allows the realization of compact and cost-effective laser systems with high pulse energies at low repetition rates. However, current technology with pulse lengths in the range of some 100 ns to 500 ps is far away from the athermal range. Specifically designed SESAMs can close this gap. In contrast to SESAMs for mode locking with short (several ps) lifetime of the carriers excited by the laser pulse, SESAMs for Q-switching need long carrier lifetimes in order to build up sufficient inversion in the laser crystal.

The FBH developed such SESAMs consisting of an AlAs/GaAs distributed Bragg reflector (DBR) and an InGaAs multi quantum well (MQW) absorber. The steady-state reflectivity spectra of as-grown DBR and full SESAM (Fig. 1) reveal a pass band center at the operating wavelength of the laser crystal (1064 nm) and a somewhat longer photoluminescence peak at 1072 nm. Partners at Leibniz University Hannover (LUH) tested the laser-induced damage threshold (LIDT) until surface degradation for different coatings. The highest LIDT of 4 J/cm² was obtained for a combination of a thin SiN_x layer on the GaAs surface followed by 170 nm SiO₂. Characterization of such SESAMs at LUH yielded non-saturable losses R_{ns} below 0.5%, a modulation depth ΔR of approx. 13% and a saturation fluence F_{sat} of 12 $\mu\text{J}/\text{cm}^2$ (Fig. 2). Recovery times of about 600 ps to 700 ps were derived from pump-probe measurements. The low non-saturable loss and the long recovery time confirm the high quality of the SESAM heterostructure grown at FBH. Together with the high LIDT these devices thus fulfil all specifications. Finally, a SESAM was bonded to a Nd:YVO₄ laser crystal, the resulting microchip assembled into a seeder module and characterized at LUH. Continuously pumped at 808 nm this module generates light pulses of about 185 ps and a pulse energy of 300 nJ (200 kHz repetition rate) at a wavelength of 1064 nm (Fig. 3). Still; shorter

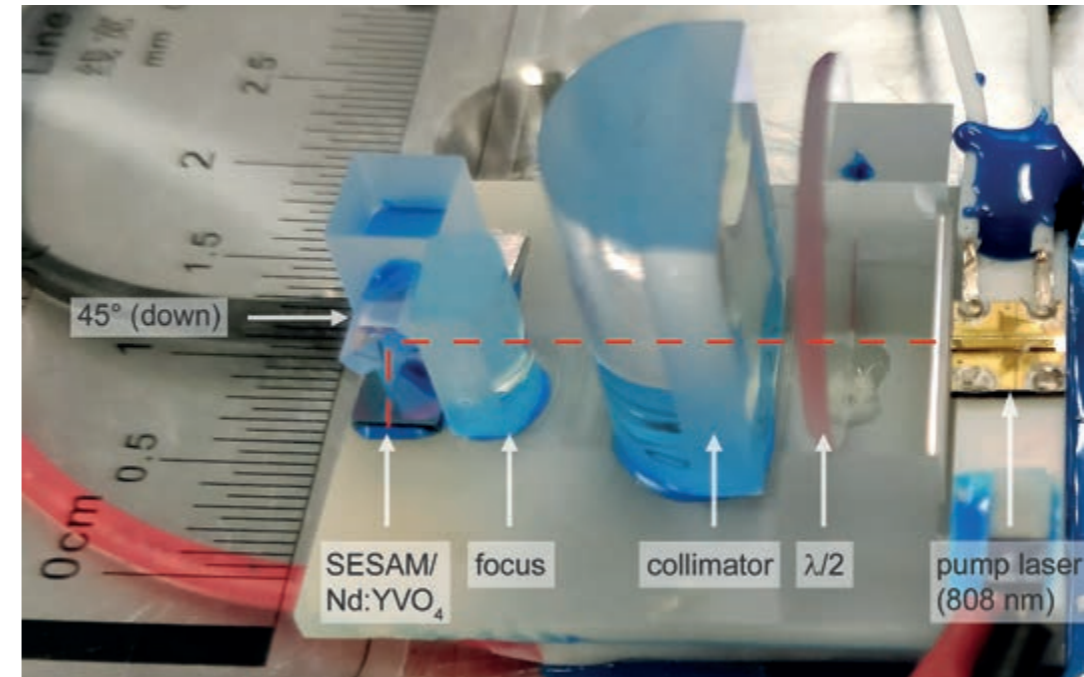


Fig. 3. Top-view photograph of the microchip laser module (seeder) developed by neoLase/LUH based on FBH's SESAMs – red dashed line gives guide to the eye. (© A. Marianovic, LUH)

pulse lengths (< 100 ps) are possible by a thinner Nd:YVO₄ crystal and thus a shorter cavity. Stable emission over more than 1000 h proves that the SESAMs not only have a high LIDT but also high long-term stability. This allows to use this compact module as oscillator for subsequent amplification to microjoule pulses.

In summary, the SESAMs developed at FBH have successfully been used for Q-switching operation with 185 ps pulses.

This work was supported by the Federal Ministry of Economics and Energy (BMWi) contract 16KN053029 as part of the Q-switched UKP Laser (QUKP) project.

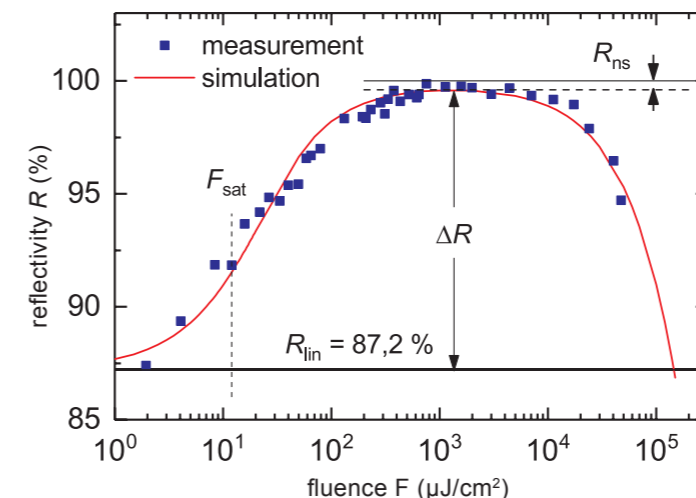


Fig. 2. Non-linear reflectivity of a SESAM (measured at LUH).

Ultrakurzpulslaser liefern Pulslängen im Piko- und Femtosekundenbereich und ermöglichen einen athermischen Materialabtrag. So lassen sich kleinste Strukturen besonders präzise bearbeiten. Schlüsselkomponenten sind hierbei halbleiterbasierte sättigbare Absorber (SESAMs) die eine passive Modenkopplung im Festkörperlaser ermöglichen. Diese Systeme sind allerdings aufwendig und teuer, da hohe Pulsraten zunächst heruntergetaktet und anschließend verstärkt werden müssen. Mit gütegeschalteten Systemen lassen sich höhere Pulsenergien bei geringeren Wiederholraten realisieren. Allerdings liegen die Pulslängen im Bereich von einigen 100 ns bis zu circa 500 ps und damit außerhalb des athermischen Bereichs. Das FBH hat langzeitstabile InAlGaAs-basierte SESAMs entwickelt, die zusammen mit einem 200 μm dünnen, bei 808 nm gepumpten Nd:YVO₄-Kristall Lichtpulse von etwa 185 ps bei einer Wellenlänge von 1064 nm erzeugen. Die Pulsenergie erreicht 300 nJ bei 200 kHz. Es wird erwartet, dass sich durch eine weitere Verkürzung des Resonators noch kürzere Pulse (< 100 ps) mit ausreichender Energie erzielen lassen.

Fabrication of optical micro-resonators and waveguides for quantum spectroscopy

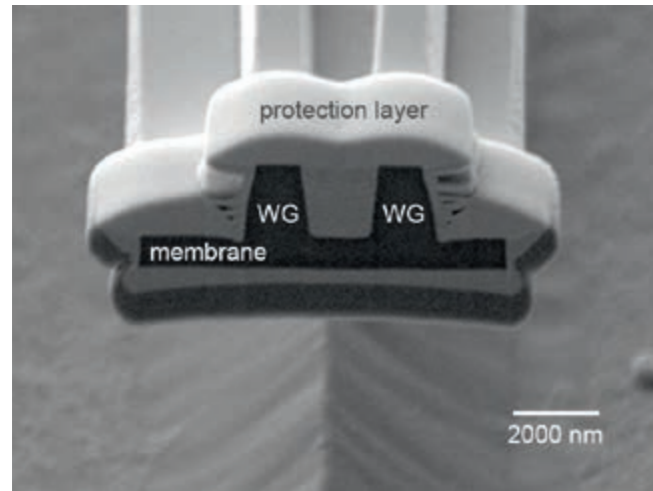


Fig. 1a. SEM picture of a cross-section of the coupling section of a ring resonator to a waveguide. Resonator and waveguide are connected by a membrane.

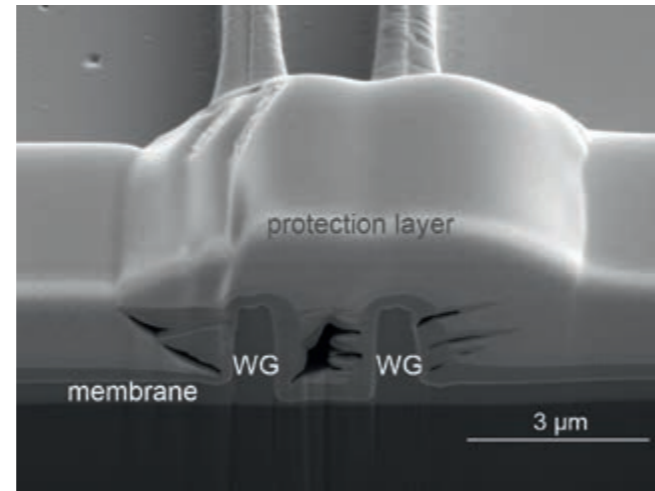


Fig. 1b. SEM picture of the same region after process optimization. The thickness of the membrane is significantly reduced.

The transmission of information by light in fiber-optic cables is the basis of modern, global communication technology – which is currently susceptible to eavesdropping and manipulation. An inherently secure communication technology would become possible by utilizing individual photons, since any change or even mere eavesdropping could be detected immediately. In order to bring a single photon-based communication technology to application level, numerous components still need to be further developed and investigated.

FBH has entered this highly topical field of research by contributing its expertise in manufacturing optical micro-resonators and waveguides to the three-year, EU-funded research project “Error-Proof Bell-State Analyzer (ErBeStA)”. This project tackles the challenging realization of an analyzer for Bell states. The technical implementation of the Bell-states concept, i.e. states of quantum entangled particle pairs that are connected without direct physical interaction, will yield a key component for optical quantum computers and quantum communication. It will evoke a wealth of new applications in the fields of computer science, sensor technology, simulation, and communications. A consortium consisting of seven European research institutes in Denmark, Great Britain, Austria and Germany is working on the realization of such a Bell-state analyzer by

combining single quantum emitters, nonlinear systems, and optical fibers.

In FBH's cleanroom, tiny light-guiding structures are manufactured using state-of-the-art semiconductor manufacturing processes. Lithography with ultraviolet light allows the fabrication of structures as small as 400 nm; electron beam lithography can be used for the generation of even smaller structures down to 50 nm in size. The structures initially created in a photoresist are then transferred into the desired material by etching processes. For applications in communication technology, many components often have to be connected in series. Therefore, materials with low losses at the wavelength used in the application are the focus of interest. One candidate material is silicon oxide, which has low attenuation and low fluorescence at the target wavelength of 635 nm. FBH has developed a multi-stage manufacturing technology which allows the fabrication of silicon oxide waveguides on a mechanically stable substrate. Due to the low refraction index of silicon oxide, the light will be guided in tiny waveguides and is not absorbed by the substrate. This is achieved by forming a thin silicon membrane on which the optical waveguide is embossed. Production technology for such structures was improved in the last year, such that the thickness of the membrane in the coupling area



Fig. 2a. Inclined SEM view of a $4 \times 4 \mu\text{m}^2$ intermittent waveguide with a gap of $12 \mu\text{m}$. The waveguides were manufactured with an optimized process, allowing the use of dielectric materials of up to $4 \mu\text{m}$ thickness.

between a ring resonator and an integrated waveguide can now be significantly reduced. (Figs. 1a and b). This is expected to further improve the quality of an optical resonant circuit with the current value of 10^6 . Such an optical resonant circuit can be used, e.g., as a bandpass. Sophisticated characterization will be carried out by the consortium partners.

Many applications in optical technologies require nonlinear building blocks. One of the systems under evaluation is based on the interaction between light and Rydberg atoms. These are highly excited single atoms in ultra-high vacuum. To interact with light they have to be brought in the vicinity of a waveguide. The FBH has designed and manufactured low-loss waveguides with a gap in which the atoms can be placed. Fig. 2a shows a SEM picture of such a waveguide and Fig. 2b the result of the optical characterization of such waveguides with gaps of various sizes. Only moderate additional losses due to the gaps are observed, making these structures promising candidates for wide spread applications.

Currently, the FBH is working with its partners on the challenging task of interfacing the miniature devices at low temperatures or in ultra-high vacuum.

Das FBH arbeitet gemeinsam mit sieben europäischen Forschungspartnern an einer Schlüsselkomponente für optische Quantencomputer und die Quantenkommunikation. Einzelquanten-Emitter, nichtlineare Systeme und optische Fasern werden hierzu im Rahmen des EU-geförderten Forschungsprojekts „Error-Proof Bell-State Analyzer“ miteinander kombiniert. Das FBH bringt seine Expertise in der Herstellung von optischen Mikroresonatoren und Wellenleitern ein. Deren Fertigungstechnologie wurde im letzten Jahr so verbessert, dass die Dicke der Membran im Kopplungsbereich zwischen einem Ringresonator und einem integrierten Wellenleiter deutlich reduziert werden kann. Damit soll sich die Güte eines optischen Schwingkreises vom aktuellen Wert von 10^6 weiter erhöhen. Abb. 2a zeigt das REM-Bild eines unterbrochenen Wellenleiters, in dessen Lücke Atome im Hochvakuum eingebracht werden können, um nichtlineare Bauelemente herzustellen. Das Ergebnis der optischen Charakterisierung solcher Wellenleiter mit unterschiedlich großen Lücken zeigt nur mäßige zusätzliche Verluste. Damit sind diese Strukturen vielversprechende Kandidaten für vielfältige Anwendungen.

This work was supported by the European Commission within the Horizon 2020 call under Grant Agreement 800642 ErBeStA.

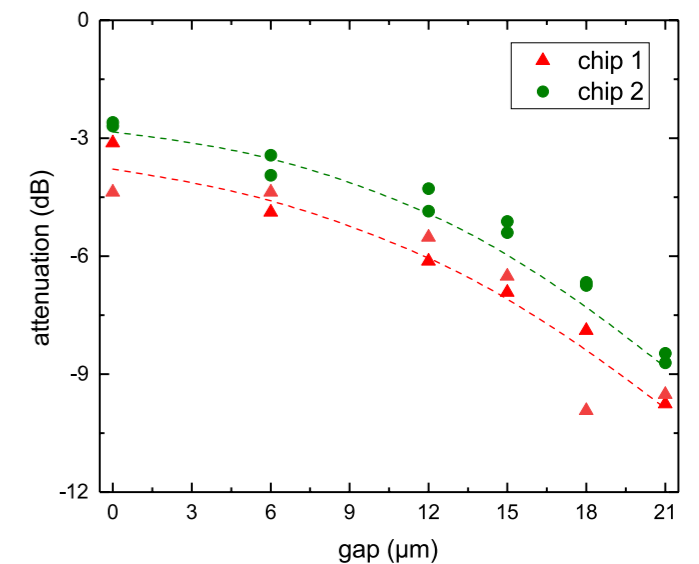


Fig. 2b. Optical characterization of intermittent waveguides at 780 nm wavelength, showing only low additional losses due to gaps of various sizes.

Process optimization and characterization of sub-500 nm InP HBTs for high-frequency integrated circuits

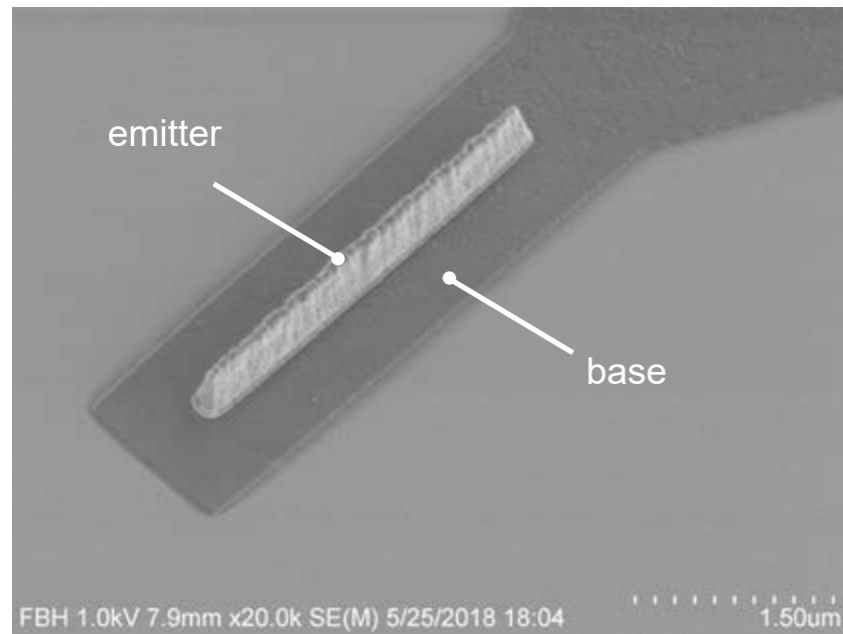


Fig. 1. SEM micrograph of a 250 nm DHBT before planarization with low-k dielectric. The refractory emitter and base electrodes are shown in this picture.

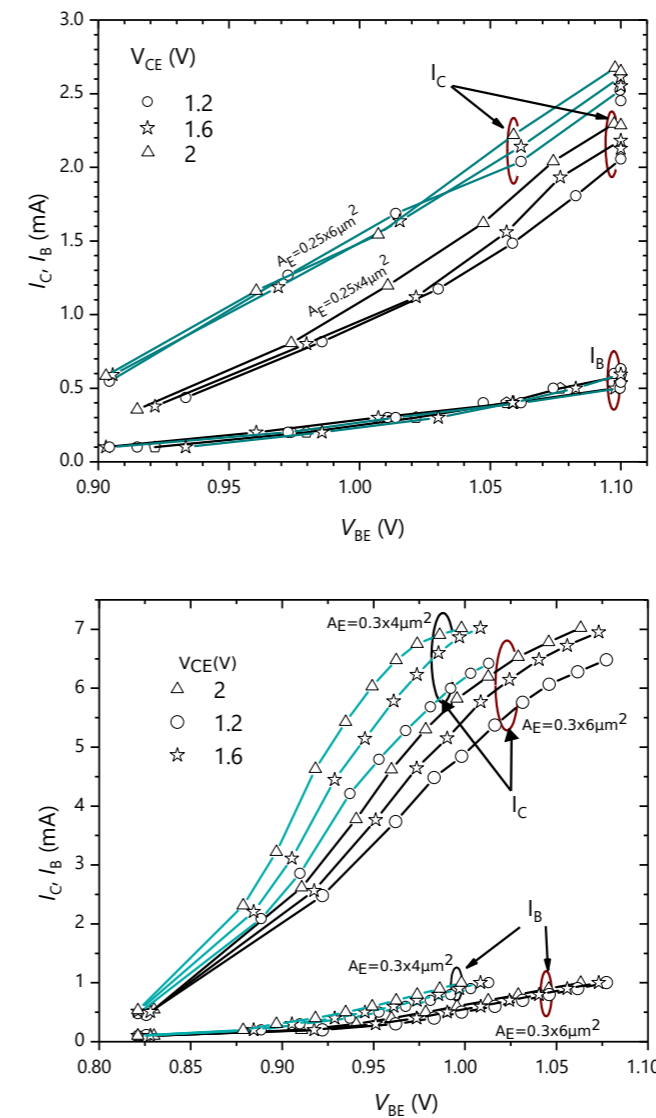
Indium phosphide (InP) based transistors offer the highest cut-off frequency for a given lithographic feature size than any other material system. This makes them particularly attractive for ultra-high speed applications such as optical integrated circuits, narrow beam radars, and future communication systems. The maximum cut-off frequency (f_t) of InP Double Heterojunction Bipolar Transistors (DHBT) is directly proportional to the electron transit time and the current density. Hence, there is a strong incentive to reduce epitaxial thickness and to optimize doping in order to achieve large bandwidths.

The FBH in-house transferred-substrate process was used to aggressively scale the extrinsic capacitances of the transistor by lithographically patterning both the front and back side of the device epitaxy. The process for forming the base, emitter and collector mesas has been transitioned from i-line projection to electron beam lithography (EBL). This was instrumental to fabricate deep submicron 250 and 300 nm emitter width junctions, with superior alignment resolution of sub-20 nm. EBL also enabled the patterning of highly symmetrical base contacts around the emitter, thus eliminating any parasitic capacitances and ensuring a seamless flow of electrons with no deterioration associated with current crowding. Moreover, the

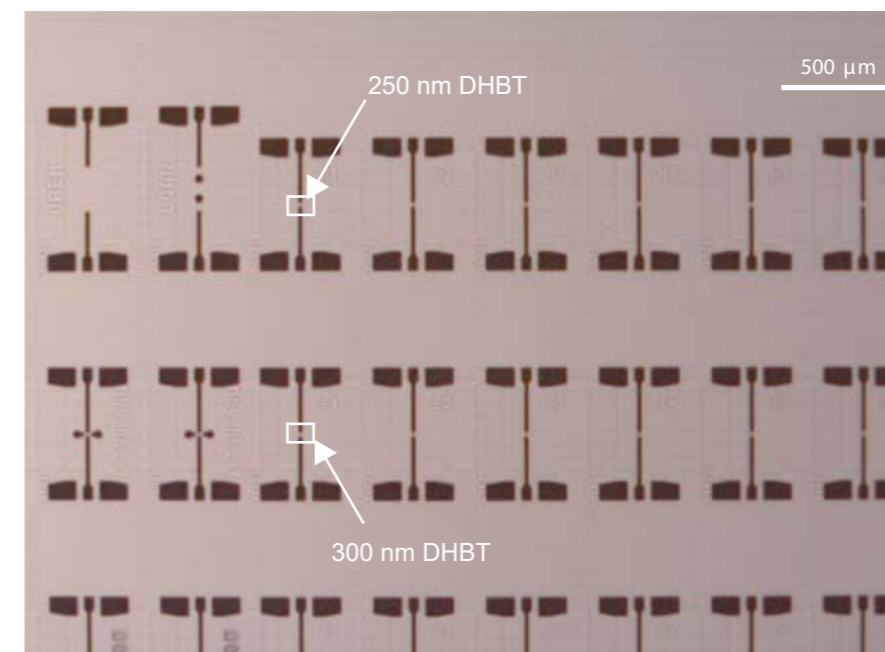
500 nm tall molybdenum-based emitters necessitate thick EBL resist for the formation of base electrodes and mesas, adding further complexity to the process. The ground plane was elevated by using a reinforcement gold layer designed to bring any coupling capacitance between the electroplated layers and the transistor to values below 2 pF.

Additionally, the device epitaxy has been tailored to support a submicron process, by significantly reducing the thickness of the InP and InGaAs layers, and by heavily doping the emitter and base to levels approaching the limit of carbon incorporation. Benefitting from a device thickness that is a fraction of our previous technology, 250 nm InP transistors could be realized for the first time without significantly altering process technology. Furthermore, the ultra-high doping in emitter and base provides enough free carriers to sustain high device current densities at elevated junction temperatures without substantial voltage drop across the space-charge region. Aligned wafer-to-wafer bonding was also achieved, enabling emitter-to-collector alignment of sub-250 nm structures.

During continuous maturing of the InP/InGaAs technology, our reliability studies have concluded that the thermal and mechanical



Figs. 2 and 3. The first DC results of the new transistors. Magnified gummel plots showing the base-collector IV curves. The $0.3 \times 4 \mu\text{m}^2$ exhibit a collector current density above $7 \text{ mA}/\mu\text{m}^2$, almost two times higher than the previous HBT generation.



Publication

[1] M. Brahm, A. Mogilatenco, D. Stoppel, D. Berger, S. Hochheim, D. Rentner, I. Ostermay, M. Reiner, S. Boppel, K. Nosaeva, N. Weimann, "Thermally stable iridium contacts to highly doped p-In_{0.53}Ga_{0.47}As for indium phosphide double heterojunction bipolar transistors", *Microelectron. Eng.*, vol. 215, pp. 111017 (2019).

Fig. 4. Final microstrip wiring structures as fabricated, which enable RF characterization of HBT devices. Open and short de-embedding structures are visible on the upper right corner of the micrograph.

stabilities of the platinum contacts are limited. A novel dual deposition base metallization process has been developed to evaporate the 20 nm iridium-based contact (Pt/Ir/Pt) and 150 nm electrode (Ti/Pt/Au), thus circumventing the limit of metal thickness imposed by the thinner emitter [1]. Additionally, the metal sheet resistance was greatly improved by using a composite refractory metal with an extremely low composite metal sheet resistance. ($0.15 \Omega/\square$)

These activities were funded by the Leibniz Association within the SAW project InP transistors for RF power applications above 300 GHz.

Indiumphosphid (InP)-basierte Transistoren bieten, verglichen mit anderen Materialsystemen, die höchste Grenzfrequenz für eine bestimmte lithografische Strukturgröße. Für derartige Transistoren nutzt das FBH seine Standard-Transfersubstrat-Technologie und verkleinert zugleich deren Abmessungen. Basis-, Emitter- (bis zu 250 nm Breite) und Kollektor-Mesas werden mittels Elektronenstrahl-Lithografie gefertigt. Zusätzlich wurde die Bauelementepitaxie so angepasst, dass sie einen Submikrometer-Prozess unterstützt. Die InP- und InGaAs-Schichtdicken wurden dazu erheblich reduziert sowie Emitter und Basis stärker dotiert. Darüber hinaus wurde ein neuartiges Dual-Deposition-Verfahren für die Basismetallisierung entwickelt. Die ersten DC-Ergebnisse des neuen $0,3 \times 4 \mu\text{m}^2$ großen Transistors zeigen, dass sich die Kollektorstromdichte auf über $7 \text{ mA}/\mu\text{m}^2$ verbessert hat. Dies entspricht fast dem Zweifachen der vorherigen HBT-Generation.

Digitization in cleanrooms – enabling tool connectivity to a Manufacturing Execution System



Fig. 1. Prototype of the iSensU IoT device with connectors for industrial light-tower read-out and additional 8 sensor inputs. Connectivity is achieved through WiFi, LAN (with PoE) or BLE.

Digitization, industry 4.0, and Internet of Things (IoT) will have a significant impact on our modern society, affecting everyday life as well as modern industrial production. Machines communicating with each other, interconnected processes, and data that are evaluated instantly will be standard. FBH is preparing for the future by digitizing its cleanroom infrastructure to optimize and evaluate the process steps in FBH's semiconductor research. Modern equipment with digital interfaces is used in parallel to established tools without a direct digital interconnection. Thus, machines with different automation levels are operated in one production facility. While today's state-of-the-art machinery and equipment usually offer electronic interfaces for data transfer, customized solutions are required to connect legacy tools to digital-based data acquisition.

Organizing, analyzing and evaluating these data requires advanced contextual information about the processes and products being executed in the cleanroom. A modern Manufacturing Execution System (MES) provides this context by mirroring every tool, object and process step in a virtual data object, a so-called digital twin. This way, it delivers relevant status information in real time and, ultimately, full sensory integration of all activities. The MES thus accompanies and guides processes to enable a new level of quality control both to technicians and scientists.

To unleash the full power of an MES it is mandatory to connect with the tools of the cleanroom. While this is easy with modern equipment that features standardized interfaces it becomes a

challenge for legacy tools. Older resources often miss a network connection or even any data acquisition interface all together. To master this challenge, FBH is currently developing an IoT device called iSensU (intelligent Sensor Unit, see Fig.) to connect the sensors directly to the network. It will deliver the data to the MES without sending them through the internet, where security or connection problems can be an issue. iSensU is currently able to read 8 high-precision analog voltage signals up to 12 V and additionally 4 ports to connect to a light tower.

The iSensU prototype is currently being tested at FBH and will shortly be made available to the altogether 13 research partners that joined forces within Research Fab Microelectronics Germany (FMD) – among them FBH. The FMD bundles the know-how and technological infrastructure as the largest cross-site R&D cooperation for micro- and nanoelectronics in Europe. The institutes within the FMD network operate more than 12,500 square meters of cleanroom facilities with over 2,000 tools, worth in excess of 1 billion euro. In order to efficiently use these cross-institutional resources, digital integration of the resources, their processes, and the associated technologies is required. FBH thus plays a key role in the digitalization of FMD fabrication processes, paving the way towards a lab with full sensory control. iSensU also provides an interface to the Manufacturing Execution System (MES) that is being rolled out within the FMD to process and analyze data for optimal processing results.

Weltweit revolutionieren Digitalisierung, Industrie 4.0 und das Internet der Dinge derzeit die Prozesse in Produktionshallen und Laboren. Sie ermöglichen es, Kleinstserien und sogar Einzelprodukte in bisher unerreichbarer Effizienz und Qualität herzustellen. Hierfür tauschen Produktionsanlagen kontinuierlich Daten mit einer Software zur Überwachung und Steuerung der Produktion (Manufacturing Execution System - MES) aus und können so Prozesse lückenlos überwachen. Das FBH verfolgt ein allumfassendes Digitalisierungskonzept in der Fertigung von elektronischen und optischen Bauelementen und wirkt hierzu in der Forschungsfabrik Mikroelektronik Deutschland (FMD) aktiv mit. Mit iSensU (intelligent Sensor Unit) entwickelt das FBH derzeit ein universelles IoT-Gerät, das Daten zwischen Anlagen und einem MES überträgt. In Kürze wird der Prototyp auch den anderen 12 Partnerinstituten der FMD zur Verfügung stehen. Damit treibt das FBH die institutsübergreifende Prozessdigitalisierung des größten standortübergreifenden FuE-Zusammenschlusses für die Mikroelektronik in Europa wesentlich voran.



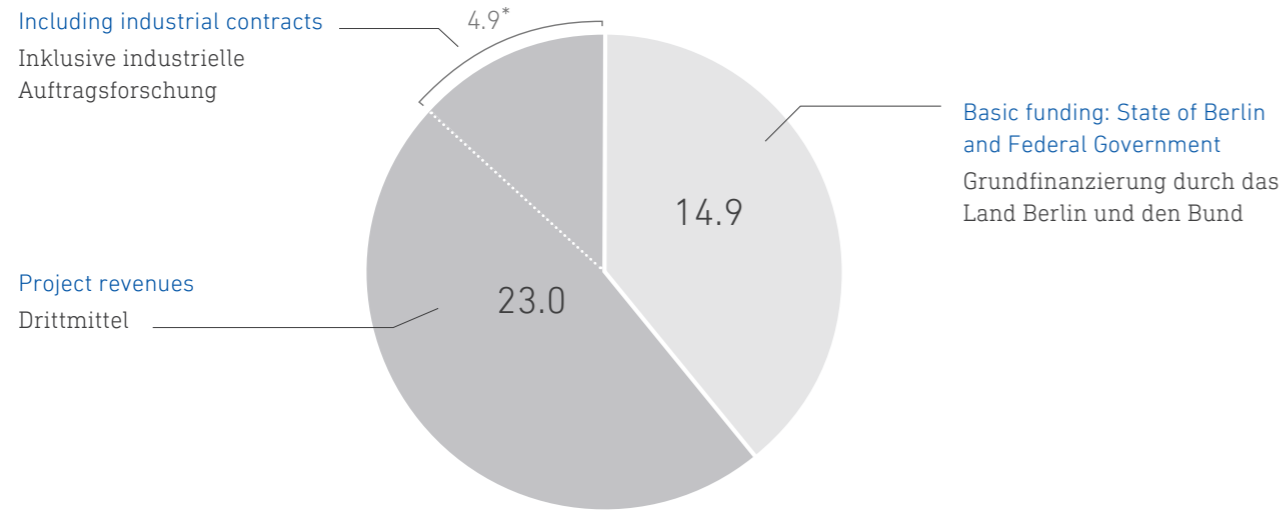
Annex Anhang

Facts & Figures

Zahlen & Fakten

Budget (in million Euros) | Umsatz (Mio. Euro)

2018



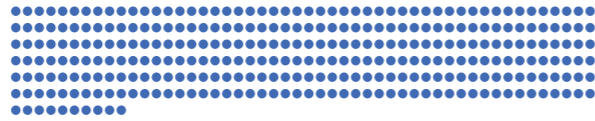
2018

2019

* 2018: income-based, €3.8 million on expenditure basis

Staff | Team

305 310



Scientists | Wissenschaftlerinnen & Wissenschaftler

111 110



PhD candidates | Promovierende

41 34



Student assistants & bachelor/master students | Studentische Hilfskräfte & Bachelor-/Masterstudierende

24 25

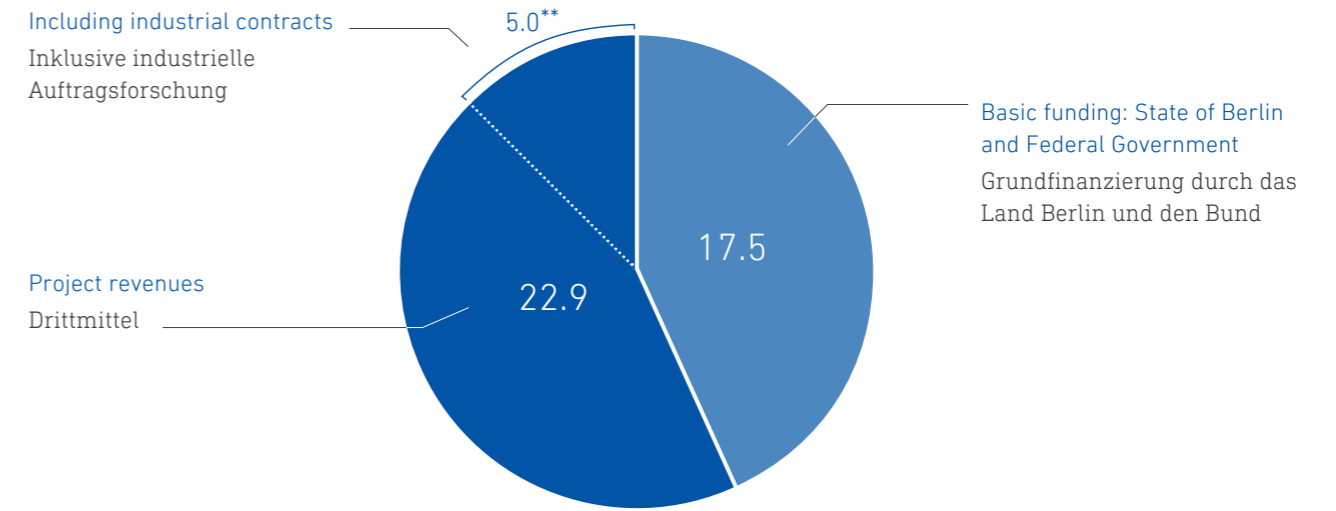


Trainees | Auszubildende

13 12



2019



2018

2019

** 2019: income-based, €2.5 million on expenditure basis

Projects | Laufende Projekte

233 243



Publications (peer reviewed) | Publikationen (referiert)

106 108



Patents | Patente

283 285



Talks (invited) | Vorträge (eingeladene)

152⁽¹⁵⁾ 147⁽²⁴⁾



Personnel & Awards

Personalia & Auszeichnungen

Markus Krutzik receives NASA Group Achievement Award

The prestigious award recognizes the achievements of the Cold Atom Laboratory (CAL) team at Jet Propulsion Laboratory (JPL), USA. As a postdoc, Krutzik contributed there to the development of an instrument that was used to successfully generate ultra-cold atoms on the International Space Station ISS. Cold atoms can be used in space in the future, for example to enable highly accurate and drift-free measurements of inertial forces for navigation. Markus Krutzik has been in charge of the Joint Lab Integrated Quantum Sensors of the Ferdinand-Braun-Institut (FBH) and Humboldt-Universität zu Berlin (HU Berlin) since January 2019.



Markus Krutzik mit NASA Group Achievement Award ausgezeichnet

Der prestigeträchtige Preis würdigt die Leistungen des Cold Atom Laboratory Teams am Jet Propulsion Laboratory (JPL) in den USA. Markus Krutzik war dort als PostDoc an der Entwicklung eines Instruments beteiligt, mit dem erfolgreich ultrakalte Atome auf der Internationalen Raumstation ISS erzeugt wurden. Kalte Atome können im Weltraum künftig eingesetzt werden, um beispielsweise hochgenaue und driftfreie Messungen inertialer Kräfte für die Navigation zu ermöglichen. Markus Krutzik leitet seit Januar 2019 das Joint Lab Integrated Quantum Sensors des Ferdinand-Braun-Instituts (FBH) und der Humboldt-Universität zu Berlin (HU Berlin).

Paul Rappaport Award an FBH-Autoren verliehen

Für die Publikation „Local 2DEG Density Control in Heterostructures of Piezoelectric Materials and Its Application in GaN HEMT Fabrication Technology“ wurden die Autoren Konstantin Osipov, Joachim Würfl, Ina Ostermay, Frank Brunner, Günther Tränkle und Maniteja Bodduluri mit dem renommierten Paul Rappaport Award ausgezeichnet. Damit würdigt die Electron Device Society (EDS) jährlich die beste Arbeit, die in den IEEE Transactions on Electron Devices im Vorjahr veröffentlicht wurde. Die Arbeit wurde aus mehr als 790 Artikeln ausgewählt, die 2018 veröffentlicht wurden. Ina Ostermay nahm den mit 2.500 \$ dotierten Preis stellvertretend für das Autorenteam am 9. Dezember 2019 in San Francisco entgegen.



🕒 Fernando Guarin (right), President of EDS, awards Maniteja Bodduluri and Ina Ostermay.

Fernando Guarin (rechts), Präsident der EDS, zeichnet Maniteja Bodduluri und Ina Ostermay aus.



Towards quantum internet – Tim Schröder receives ERC Starting Grant

Fast internet is still on the wish list in large parts of Germany. But Tim Schröder is already researching the next generation of fast, secure and future-compatible communication at the interface of integrated quantum optics, communication and new material

systems – towards the quantum internet. With the QUERP project “Quantum Repeater Architectures Based on Quantum Memories and Photonic Encoding”, he has been awarded an ERC Starting Grant in 2019 and will be funded for five years with €1.5 million. Tim Schröder is head of the Joint Lab Diamond Nanophotonics, operated by FBH together with HU Berlin.

Prize of the European Microwave Association 2019 awarded to Wolfgang Heinrich

Making microwave research visible and connecting the players in research and industry – this has been Wolfgang Heinrich’s driving force for many years. For his outstanding engagement, the head of the Microwave Department at Ferdinand-Braun-Institut has been awarded the “Distinguished Service Award” by the European Microwave Association (EuMA).

Prize-worthy vocational training – Dominik Sudau repeatedly awarded

In November, the microtechnologist Dominik Sudau was honored by the Leibniz Association for his excellent graduation with the apprentice award. This puts him among the top three of around 350 trainees educated within the research organization. Just before that, the Berlin Chamber of Industry and Commerce had awarded Dominik Sudau as the best microtechnology trainee in Berlin. He had completed the three-year training on February 1, 2019 – shortening it by six months due to the excellent educational and practical achievements.



Auf dem Weg zum Quanteninternet – Tim Schröder wirbt ERC Starting Grant ein

In weiten Teilen Deutschlands steht schnelles Internet noch auf dem Wunschzettel. Doch Tim Schröder forscht bereits an der nächsten Generation schneller, sicherer und zukunftscompatibler Kommunikation an der Schnittstelle von integrierter Quantenoptik, -kommunikation und neuen Materialsystemen – auf dem Weg zum Quanteninternet. Mit dem Projekt QUERP „Quantum Repeater Architectures Based on Quantum Memories and Photonic Encoding“ hat er 2019 erfolgreich einen ERC Starting Grant eingeworben und wird für fünf Jahre mit 1,5 Millionen Euro gefördert. Tim Schröder leitet das Joint Lab Diamond Nanophotonics, das das FBH gemeinsam mit der HU Berlin betreibt.

Preis der European Microwave Association 2019 an Wolfgang Heinrich verliehen

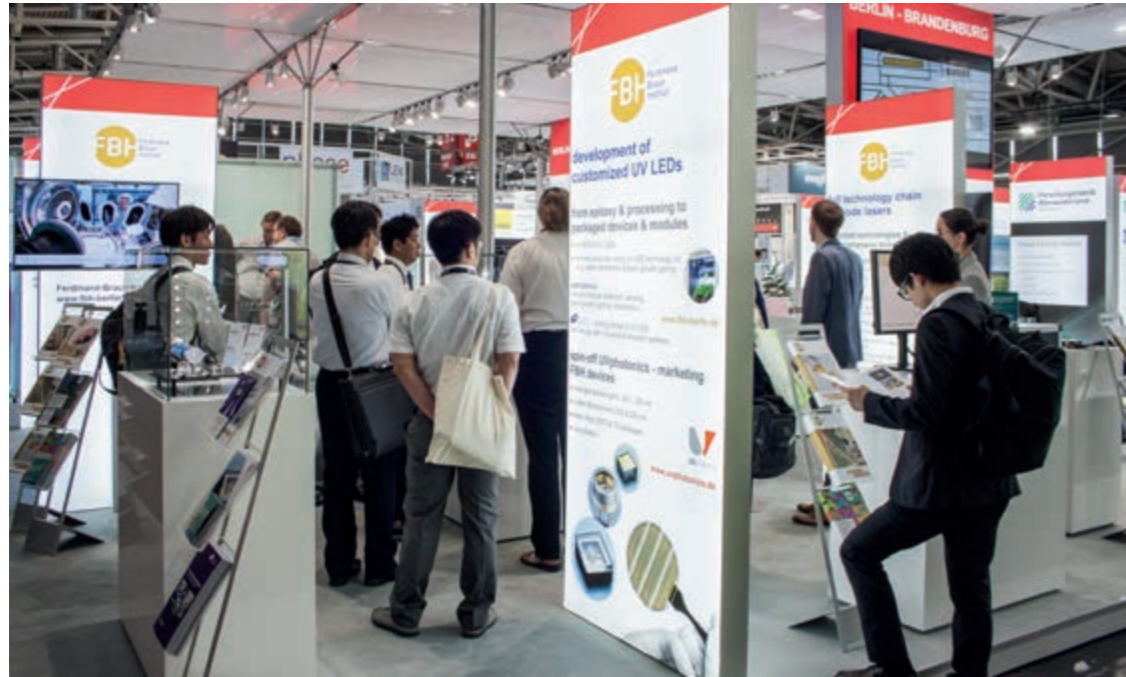
Mikrowellen-Forschung sichtbar machen und die Akteure in Forschung und Industrie vernetzen – dieses Anliegen treibt Wolfgang Heinrich seit vielen Jahren an. Für sein herausragendes Engagement wurde der Leiter der Abteilung Mikrowellentechnik am Ferdinand-Braun-Institut von der European Microwave Association (EuMA) mit dem „Distinguished Service Award“ ausgezeichnet.



Preiswürdige Ausbildung – Dominik Sudau mehrfach ausgezeichnet

Im November wurde der Mikrotechnologe Dominik Sudau von der Leibniz-Gemeinschaft für seinen exzellenten Abschluss mit dem Auszubildenden-Preis geehrt. Er zählt damit zu den besten drei von rund 350 Auszubildenden der Forschungsorganisation. Die IHK Berlin hatte Dominik Sudau kurz zuvor als besten Berliner Mikrotechnologie-Azubi ausgezeichnet. Die dreijährige Ausbildung hatte er zum 1. Februar 2019 abgeschlossen – aufgrund der exzellenten schulischen und praktischen Leistungen um ein halbes Jahr verkürzt.

🕒 Dominik Sudau at the IHK Berlin award ceremony. Dominik Sudau bei der Bestenehrung der IHK Berlin.



Booth of the Ferdinand-Braun-Institut at Laser World of Photonics in Munich.
Messestand des Ferdinand-Braun-Instituts auf der Laser World of Photonics in München.

Events for experts Veranstaltungen für das Fachpublikum

Once again, the Ferdinand-Braun-Institut presented its research results and developments at the key industry and scientific meetings, with contributions at more than 15 international conferences and workshops in 2019. Here is a selection of FBH presentations at trade fairs and conferences:

Already for the third time in a row, the FBH exhibited at **Photonics West** in the beginning of 2020 – the world's largest photonics trade fair in San Francisco, USA. This time, the institute was accompanied by its spin-offs UVphotonics and BeamXpert. As in previous years, the FBH was also prominently represented at the associated conferences with 20 scientific contributions.

At the European level, FBH made itself highly visible at 2019's **Laser World of Photonics** in Munich and the affiliated **CLEO Europe** – with 16 contributions to the conference. Exhibits at the joint Berlin-Brandenburg stand included a stand-alone, PC-controlled LiDAR demonstrator and a SERDS turnkey system for Raman spectroscopic measurements on site.

In November 2019, the FBH also started introducing its R&D for space applications to a wider audience from industry. For the first time, the institute presented its space-compatible, ultra-narrow linewidth diode laser modules and systems along with further III-V components for satellite applications at **Space Tech Expo Europe** in Bremen.

Erneut hat das Ferdinand-Braun-Institut seine Forschungsergebnisse auf den zentralen Branchentreffs vorgestellt und war 2019 auf mehr als 15 internationalen Fachkonferenzen und Workshops mit eigenen Beiträgen vertreten. Hier eine Auswahl von FBH-Auftritten auf Messen und Konferenzen:

Bereits zum dritten Mal in Folge stellte das FBH Anfang 2020 auf der **Photonics West** aus – der weltweit größten Photonik-Messe in San Francisco, USA. Dieses Mal wurde das Institut von seinen Spin-offs UVphotonics und BeamXpert begleitet. Wie in den Vorjahren auch war das FBH auf den begleitenden Konferenzen mit 20 wissenschaftlichen Beiträgen prominent vertreten.

Auf europäischer Ebene war das FBH auf der **Laser World of Photonics 2019** in München und der angegliederten **CLEO Europe** gut sichtbar – mit 16 Beiträgen zur Konferenz. Zu den Exponaten auf dem Berlin-Brandenburger Gemeinschaftsstand gehörten ein autonomer, PC-gesteuerter LiDAR-Demonstrator und ein SERDS-Turnkey-System für Raman-spektroskopische Messungen vor Ort.

Im November 2019 hat das FBH zudem begonnen, seine F&E-Ergebnisse für Weltraumanwendungen einem breiteren Publikum aus der Industrie vorzustellen. Erstmals präsentierte das Institut auf der **Space Tech Expo Europe** in Bremen seine weltraumtauglichen Diodenlasermodule und -systeme

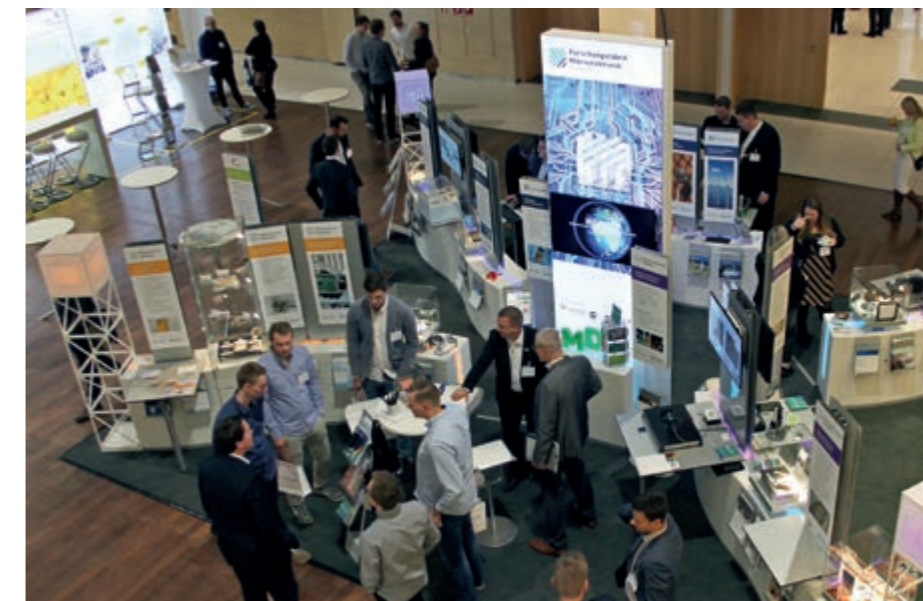
The **International Conference on Defects-Recognition, Imaging and Physics in Semiconductors – DRIP XVIII** in Berlin was co-organized by the FBH. 119 scientists from 17 countries met at DRIP in September 2019 to present and discuss correlations between crystal defects, device fabrication and degradation. Two junior prizes, the Best Student Poster Award (Jonas Weinrich) and the Best Student Oral Presentation Award (Norman Susilo), were presented by the international steering committee. The work of the two PhD students was carried out at or in cooperation with the Ferdinand-Braun-Institut.

In 2019, the FBH exhibited several times jointly with partner institutes from the Research Fab Microelectronics Germany (FMD). At the **Microsystems Technology Congress**, held in October 2019 in Berlin, the FBH displayed space-suited diode laser modules based on the institute's unique microintegration technology. Further hybrid-integrated components from microwave technology and terahertz electronics were presented. At the **European Microwave Week 2019** in Paris the FBH not only presented its developments from III-V electronics at the joint FMD booth, but also at the conference. Moreover, the FBH made its scientific results visible at the **International Microwave Symposium** in Boston, USA, the premier annual meeting for technologists involved in all aspects of microwave theory and practice.

mit extrem schmaler Linienbreite sowie weitere III/V-Komponenten für Satellitenanwendungen.

Die **International Conference on Defects-Recognition, Imaging and Physics in Semiconductors – DRIP XVIII** in Berlin wurde vom FBH mitorganisiert. Im September 2019 trafen sich auf der DRIP 119 Wissenschaftler aus 17 Ländern, um die Zusammenhänge von Kristalldefekten, Bauelementherstellung und Degradation vorzustellen und zu diskutieren. Der internationale Lenkungskreis verlieh zwei Nachwuchspreise, der Best Student Poster Award (Jonas Weinrich) und der Best Student Oral Presentation Award (Norman Susilo). Die Arbeiten beider Doktoranden wurden am oder in Zusammenarbeit mit dem Ferdinand-Braun-Institut durchgeführt.

2019 stellte das FBH mehrfach gemeinsam mit Partnerinstituten aus der Forschungsfabrik Mikroelektronik Deutschland (FMD) aus. Auf dem **Mikrosystemtechnik-Kongress**, der im Oktober 2019 in Berlin stattfand, zeigte das FBH weltraumtaugliche Diodenlasermodule, die auf der einzigartigen Mikrointegrationstechnologie des Instituts basieren. Zudem wurden hybrid-integrierte Komponenten aus der Mikrowellentechnik und der Terahertz-Elektronik vorgestellt. Auf der **European Microwave Week 2019** in Paris präsentierte das FBH seine Entwicklungen aus der III/V-Elektronik nicht nur auf dem Gemeinschaftsstand der FMD, sondern auch auf der Konferenz. Darüber hinaus machte das FBH seine wissenschaftlichen Ergebnisse auf dem **International Microwave Symposium** in Boston, USA, sichtbar, dem wichtigsten jährlichen Treffen für Technologen, die sich mit allen Aspekten rund um Mikrowellentheorie und -praxis beschäftigen.



Joint trade fair presentation of Research Fab Microelectronics at the Microsystems Technology Congress in Berlin.
Gemeinsamer Messeauftritt der Forschungsfabrik Mikroelektronik Deutschland auf dem Mikrosystemtechnik-Kongress in Berlin.

for the interested offspring für den interessierten Nachwuchs

FBH again opened its laboratories to inspire young people for a career in natural sciences. Visits at the institute included laboratory and cleanroom tours as well as hands-on experiments – as for example during **Girls' Day** and **Education Alliance Adlershof**.

With its ANH Berlin network, the FBH also promoted career options in technical professions like in microsystems technology at **several vocational training fairs** in the Berlin Brandenburg region. Further information related to securing young talents can be found on page 19.

Auch 2019 hat das FBH seine Labore für junge Menschen geöffnet, um sie für eine Karriere in den Naturwissenschaften zu begeistern. Zu den Institutsbesuchen gehörten Labor- und Reinraumführungen sowie Experimente zum Anfassen – wie zum Beispiel beim **Girls' Day** oder bei der **Ausbildungs-Allianz Adlershof**.

Mit seinem ANH Berlin-Netzwerk warb das FBH zudem auf mehreren **Ausbildungsmessen** in der Region Berlin-Brandenburg für Karrierechancen in technischen Berufen wie etwa in der Mikrosystemtechnik. Weitere Informationen zur Nachwuchssicherung gibt es auf Seite 19.

for ourselves – FBH also successful in sports für uns selbst –FBH auch sportlich erfolgreich

Once again, the proven FBH running team with Veit Hoffmann, Nicolas Hübener and Christoph Stölmacker won the 3 x 2,9 km **Adlershof Company Relay** in the men's category – with more than two minutes distance to the second-placed team.

Erneut gewann das bewährte FBH-Laufteam mit Veit Hoffmann, Nicolas Hübener und Christoph Stölmacker die 3 x 2,9 km **Adlershofer Firmenstaffel** bei den Männern – mit mehr als zwei Minuten Abstand zum zweitplatzierten Team.



Structure of the institute Institutstruktur

The Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenztechnik organizes its research activities in labs and departments within its four research areas: photonics, integrated quantum technology, III-V electronics and III-V technology. Here, FBH cooperates closely with universities in the framework of joint labs.

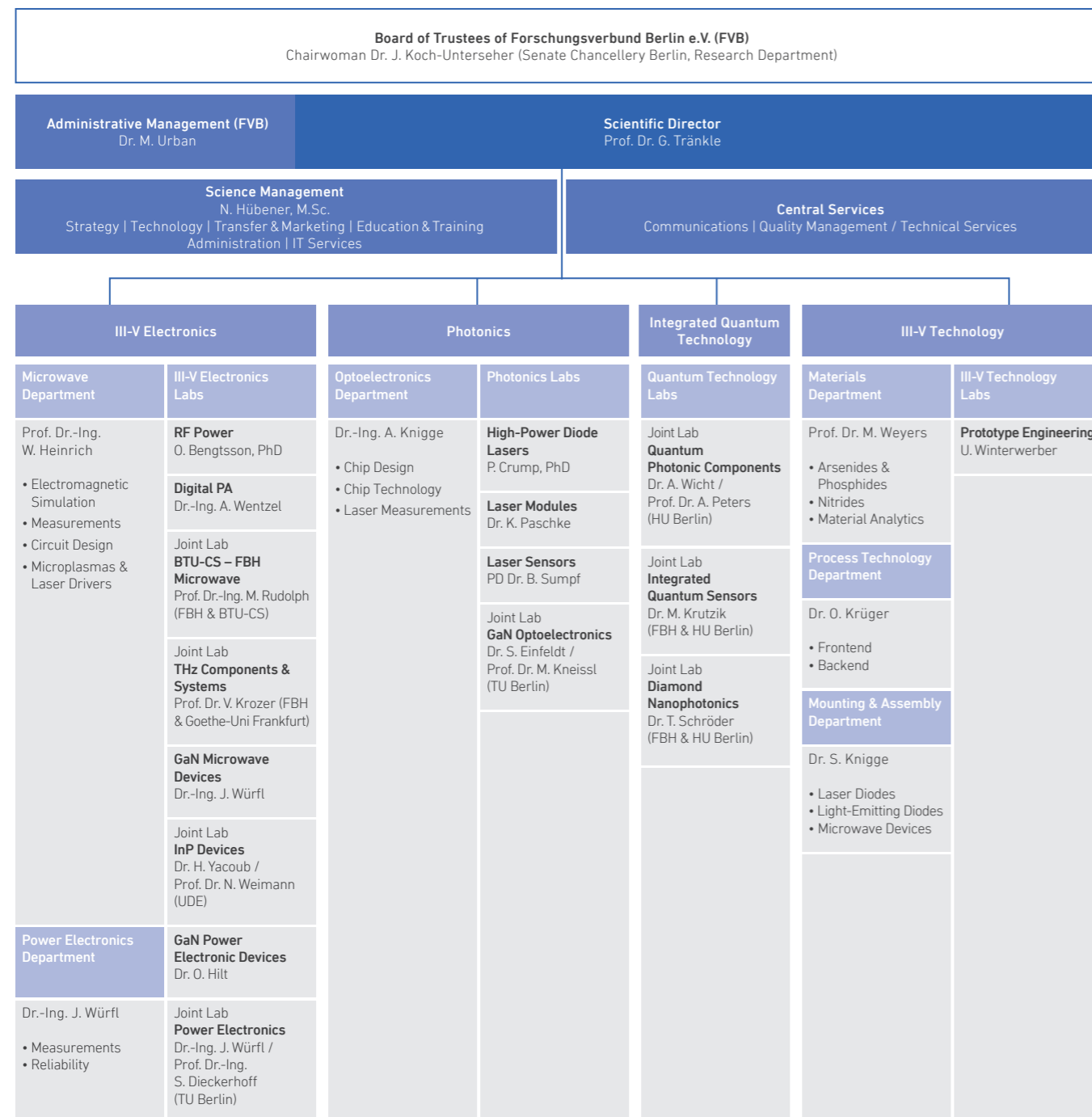
With its Science Management the institute provides an interface between science, industry and education/training. The department coordinates various networking projects in the high-tech field and is also responsible for administration and IT services. An efficient, process-oriented quality management system and the communication unit complement FBH competencies. The technical services team ensures the smooth operation of laboratories and cleanrooms.

Das Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik organisiert seine Forschungsaktivitäten in Labs und Departments in den vier Forschungsbereichen Photonik, integrierte Quantentechnologie, III/V-Elektronik und III/V-Technologie. Hierbei kooperiert das FBH im Rahmen von Joint Labs eng mit Universitäten.

Mit seinem Wissenschaftsmanagement verfügt das Institut über eine Schnittstelle zwischen Wissenschaft, Wirtschaft und Bildung. Hier werden verschiedene Vorhaben zur Vernetzung im Hochtechnologie-Bereich koordiniert; das Department ist zudem für Verwaltung und IT-Services zuständig. Der Stab wird ergänzt durch ein effizientes, prozessorientiertes Qualitätsmanagement und den Bereich Kommunikation. Für den reibungslosen Betrieb der Labore und Reinräume sorgt das Team der Technischen Dienste.

Organizational chart

Organigramm



Scientific advisory board

Wissenschaftlicher Beirat

Chair | Vorsitz

Dr. Patrick Scheele
HENSOLDT Sensors GmbH, Ulm

Members | Mitglieder

Prof. Dr.-Ing. Manfred Berroth
Universität Stuttgart

Dr. Kolja Nicklaus
Space Tech GmbH, Immenstaad

Prof. Dr.-Ing. Wolfgang Bösch
Technische Universität Graz (A)

Dr. Berthold Schmidt
TRUMPF Photonic Components GmbH, Ulm*

Dr. Franz Dielacher
Infineon Technologies Austria AG, Villach (A)

Dr. Ulrich Steegmüller
Microsoft Development Center Copenhagen, (DK)**

Prof. Dr. Ulrike Grossner
ETH Zürich (CH)

Prof. Dr.-Ing. Stephan Völker
Technische Universität Berlin

Dr. Siegbert Martin
Tesat-Spacecom GmbH & Co. KG, Backnang

Prof. Jelena Vuckovic
Stanford University (USA)

* – 12/2019: TRUMPF Lasertechnik GmbH, Ditzingen

** – 09/2019: Osram Opto Semiconductors GmbH, Regensburg



The Forschungsverbund Berlin e.V. (FVB) is Berlin's largest non-university research institution. It comprises eight institutes that conduct cutting-edge research in the fields of natural, life and environmental sciences – among them the Ferdinand-Braun-Institut. FVB provides its eight institutes with a joint administration (Head of FVB: Dr. Manuela Urban). All of these research institutes are members of the Leibniz Association and are funded jointly by the German federal and state governments. The Leibniz Association connects 96 independent research institutions. The associated institutes employ around 20,000 people, and the financial volume amounts 1.9 billion euros.

🌐 www.fv-berlin.de

🌐 www.leibniz-gemeinschaft.de

Der Forschungsverbund Berlin e.V. (FVB) ist die größte außeruniversitäre Forschungseinrichtung Berlins. Er besteht aus acht Instituten der Natur-, Lebens- und Umweltwissenschaften, die Spitzenforschung betreiben – darunter das Ferdinand-Braun-Institut. Der FVB bietet diesen Forschungseinrichtungen eine gemeinsame Verwaltung (Geschäftsführerin Dr. Manuela Urban). Alle FVB-Institute sind Mitglieder der Leibniz-Gemeinschaft und werden gemeinsam durch Bund und Länder finanziert. Die Leibniz-Gemeinschaft verbindet 96 selbständige Forschungseinrichtungen. Die zugehörigen Institute beschäftigen knapp 20.000 Personen und mit einem Finanzvolumen von 1,9 Milliarden Euro.

How to get in touch

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C. Ruß: p. 7

M. V. Trovato: pp. 8, 14, 18, 24, 112

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