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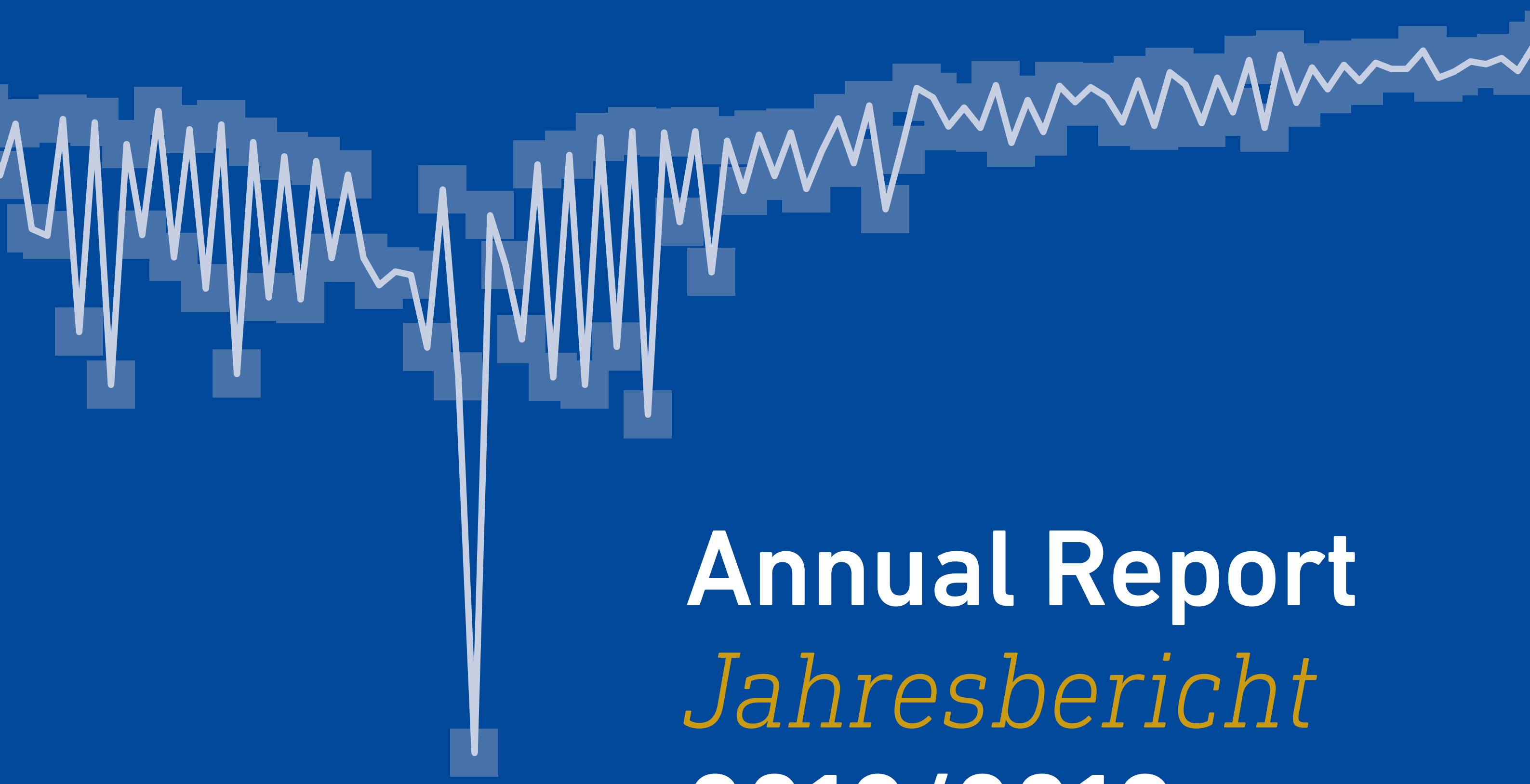

Annual Report
Jahresbericht
2018/2019

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Editorial
Vorwort

Taking advantage of opportunities and creating perspectives – with this in mind, the Ferdinand-Braun-Institut has set its course for the future. I would like to give you a brief insight:

Within the framework of "Research Fab Microelectronics Germany" (FMD), FBH has expanded its R&D activities targeting future-oriented topics such as 5G and sensor technology for autonomous driving. The first joint technology offerings with the 12 partner institutes were launched and presented at trade fairs and the first FMD Innovation Day 2018 in Berlin. At the same time, a new cleanroom with high-performance equipment is being established at FBH, enabling us to manufacture state-of-the-art electronic and optoelectronic components. It will be put into operation in 2020.

With its new research area "Integrated Quantum Technology" FBH sets another strong accent. Since 2008, the institute has been establishing a unique micro-integration technology in a Joint Lab with Humboldt-Universität zu Berlin that has been developed especially for space applications. Three further Joint Labs are currently being set up, thus promising many exciting R&D tasks: from novel material concepts capable of manipulating light on nano and micro scales to laser modules manufactured as small series for use in space. In the coming years, more than 50 ultra-narrowband laser modules for BECCAL (Bose-Einstein Condensate – Cold Atom Laboratory) are to be developed, assembled and supplied. With BECCAL, the German Aerospace Center and NASA intend to operate a multifunctional facility on board the International Space Station ISS from 2024 onwards. For the first time, it will be possible to investigate fundamental physical questions with highest precision that involve quantum objects and are carried out near absolute temperature zero (-273.15 °C).

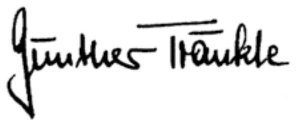
With Lausitz Strategy, the State of Brandenburg is supporting structural change in the region together with the Federal Government. Activities include innovative and sustainable technology clusters which are to be established. We are linking our activities in microwave and terahertz electronics as well as in laser sensor technology permanently via the BMBF project *iCampus*. This is the first step of our institute towards a branch office at BTU Cottbus-Senftenberg, with which we already maintain a Joint Lab.

Within recent years, FBH has established itself as a reliable technology partner for industrial customers. They employ our components, for example, for their R&D in the field of gallium nitride transistors and MMICs used for energy-efficient power electronics and communication technology. It is also planned to further pursue the development and manufacture of VCSELs for sensor applications.

With these comprehensive activities, we are well positioned for the future – both regionally and internationally. As a result, we offer our partners from research and industry ideal conditions for research projects and contracts.

I like to thank all our companions for the trusting and fruitful collaboration. My thanks also go to the staff at the Ferdinand-Braun-Institut, carrying out an ever increasing number of challenging projects at the highest level. I would like to thank our sponsors, the State of Berlin and the German Federal Government, for their excellent cooperation and the generous support that ensures the operation of our high-tech laboratories.

I am very much looking forward to the further cooperation with all of you. I hope you enjoy reading through the results and events from the past year.



Chancen nutzen und Perspektiven schaffen – in diesem Sinne hat das Ferdinand-Braun-Institut die Weichen mit Blick in die Zukunft gestellt. Ich möchte Ihnen dazu einen kurzen Einblick geben:

Im Rahmen der „Forschungsfabrik Mikroelektronik Deutschland" (FMD) hat das FBH seine F&E-Aktivitäten zu zukunftsorientierten Themenfeldern wie 5G und Sensorik für autonomes Fahren ausgebaut. Erste gemeinsame Technologieangebote mit den 12 Partnerinstituten wurden geschaffen, die auf Fachmessen und dem ersten Innovation Day der FMD 2018 in Berlin vorgestellt wurden. Parallel entsteht am FBH ein neuer Reinraum mit einer sehr leistungsfähigen Ausstattung, die es uns ermöglicht, elektronische und optoelektronische Bauelemente auf dem neuesten Stand der Technik zu fertigen. Er wird 2020 in Betrieb gehen.

Mit seinem neuen Forschungsbereich „Integrierte Quantentechnologie" setzt das FBH einen weiteren starken Akzent. Seit 2008 entwickelt es in einem Joint Lab mit der Humboldt-Universität zu Berlin eine einzigartige Mikrointegrationstechnologie, die insbesondere für den Einsatz im Weltraum entwickelt wurde. Drei weitere Joint Labs sind derzeit im Aufbau. Das verspricht viele spannende F&E-Aufgaben: von neuartigen Materialkonzepten, mit denen Licht auf der Nano- und Mikroskala manipuliert werden kann, bis hin zu Lasermodulen, die als Kleinserie für den Einsatz im Weltraum gefertigt werden. So sollen in den kommenden Jahren mehr als 50 ultra-schmalbandige Lasermodule für BECCAL (Bose-Einstein Condensate – Cold Atom Laboratory) entwickelt, aufgebaut und geliefert werden. Mit BECCAL wollen das Deutsche Zentrum für Luft- und Raumfahrt und die NASA ab 2024 eine Multifunktions-Anlage an Bord der internationalen Raumstation ISS betreiben. Damit können erstmals hochgenau fundamental-physikalische Fragestellungen mit Quantenobjekten nahe dem absoluten Temperaturnullpunkt (-273,15 °C) untersucht werden.

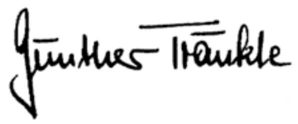
Mit der Lausitz-Strategie unterstützt das Land Brandenburg gemeinsam mit dem Bund den Strukturwandel in der Region. Unter anderem sollen innovative und nachhaltige Technologiecluster aufgebaut werden. Wir binden unsere Aktivitäten aus Mikrowellen- und Terahertz-Elektronik sowie aus der Laser-Sensorik über das BMBF-Projekt *iCampus* dauerhaft ein. Dies ist ein erster Schritt unseres Instituts hin zu einer Außenstelle an der BTU Cottbus-Senftenberg, mit der es bereits ein Joint Lab gibt.

In den letzten Jahren hat sich das FBH als zuverlässiger Technologiepartner für industrielle Kunden etabliert. Diese nutzen unsere Komponenten beispielsweise für ihre F&E im Bereich Galliumnitrid-Transistoren und -MMICs für die energieeffiziente Leistungselektronik und Kommunikationstechnik. Geplant ist zudem, die Entwicklung und Fertigung von VCSEL für Anwendungen in der Sensorik weiterzuführen.

Mit diesen umfassenden Aktivitäten positionieren wir uns für die Zukunft – sowohl regional als auch international. Unseren Partnern aus Forschung und Industrie bieten wir so beste Bedingungen für Forschungsprojekte und -aufträge.

Ich danke all unseren Wegbegleitern für die vertrauensvolle und gute Zusammenarbeit. Mein Dank geht auch an die Mitarbeiterinnen und Mitarbeiter am Ferdinand-Braun-Institut, die immer mehr anspruchsvolle Projekte auf höchstem Niveau durchführen. Unseren Zuwendungsgebern des Landes Berlin und des Bundes gilt mein Dank für die ausgezeichnete Kooperation und die sehr großzügige Unterstützung, die den Betrieb unserer Hightech-Labore sichert.

Ich freue mich auf die weitere Zusammenarbeit mit Ihnen allen. Eine anregende Lektüre der Ergebnisse und Ereignisse aus dem letzten Jahr wünscht Ihnen, Ihr



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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 Hoechstfrequenztechnik (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. 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. In der Mikrowellentechnik realisiert das FBH hocheffiziente, 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
Was wir tun – Forschungsthemen & Kompetenzbereiche

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 ultra-cold atoms
- 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

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 mikrointegrierte Module
- Integrierte Quantensensoren auf Basis ultrakalter Atome
- Nanostrukturierte Diamantsysteme & -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
Das bieten wir Ihnen – Technologietransfer & Services

The Ferdinand-Braun-Institut 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 FBH lends or sells the resulting prototypes to customers for testing in their own applications. In 2018, five new prototypes were built and partly tested together with cooperation partners. New developments like the ultra-compact microwave plasma source µPQ met with great interest at trade fairs such as the SEMICON Europa in Munich.

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 non-scientific 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 47 partners researches and develops UV-LED technology along the entire value chain – from crystal to application in devices such as for skin analysis.

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 FBH an Kunden für Tests in deren eigenen Anwendungen. So wurden 2018 fünf neue Prototypen aufgebaut und teils gemeinsam mit Kooperationspartnern erprobt. Auf Fachmessen wie der SEMICON Europa in München stießen Neuentwicklungen wie die ultrakompakte Mikrowellen-Plasmaquelle µPQ 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 nichtwissenschaftliche 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 47 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 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 Verbünden 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.

Prototype Engineering Lab – making research results applicable to industry

EntwicklungsZentrum – Forschungsergebnisse für die Industrie nutzbar machen

For five years now, the Prototype Engineering Lab at FBH has been supporting especially small and medium-sized enterprises (SMEs) with tailor-made prototypes, helping them to realize innovative product ideas. Thus, new products come into the market faster, since smaller companies often do not have the necessary personnel or equipment. Not uncommon that they shy away from development costs for prototypes or small-scale series.

Seit fünf Jahren unterstützt das EntwicklungsZentrum am FBH vor allem kleine und mittelständische Unternehmen (KMU) durch maßgeschneiderte Prototypen, um innovative Produktideen zu realisieren. Neue Produkte kommen so schneller auf den Markt, da gerade kleinere Firmen häufig nicht die nötigen personellen Ressourcen oder die entsprechende Ausstattung haben. Oft scheuen sie auch die Entwicklungskosten für Prototypen oder kleine Stückzahlen.

PLS flex - the system can be flexibly equipped with different pulsed diode lasers.
PLS flex – das System kann flexibel mit verschiedenen gepulsten Diodenlasern bestückt werden.

The Prototype Engineering Lab translates FBH technologies into functional devices that companies can then easily test in their applications. This has led to a series of prototypes and model series – from several UV LED irradiation modules used for plant growth lighting to the flexible PLS flex laser system. This "modular laser kit" is an example for FBH's transfer approach towards industrial customers: With one basic system, various pulsed FBH diode lasers can be optimally operated. For this purpose, components were modularized and standardized accordingly. With PLS flex, FBH can now respond more quickly and flexibly to demands for diode lasers with electronic control. In the future, know-how for specific applications is to be bundled even further in interdisciplinary teams and advanced jointly. These measures will be accompanied by systematic market and competition analyses and sustainable contact management.

The Prototype Engineering Lab has always worked closely with scientists from the institute's research departments. This enables the lab to identify research topics and results at an early stage that are suitable for transfer into industrial applications. The team is also involved in R&D projects right from the start. It actively participates in the development process and at the same time examines how results can be optimally utilized. This yields specialized and pragmatic solutions that are developed from the user's point of view and designed to meet their needs. One of the highlights in 2018 was the successful live demonstration of a compact atmospheric plasma source at SEMICON Europa. The source in the 2.45 GHz ISM band comprises a microwave power oscillator, a resonator for plasma excitation, and the control electronics, all integrated into a compact housing. Supply of the plasma

Das EntwicklungsZentrum überführt Technologien des FBH in funktionsfähige Geräte, die die Unternehmen dann unkompliziert in ihren Anwendung testen können. So sind eine Reihe von Prototypen und Modellreihen entstanden – von mehreren UV-LED-Bestrahlungsmodulen für die Pflanzenzucht bis hin zum flexibel bestückbaren Lasersystem PLS flex. Dieser „Laserbaukasten" steht exemplarisch für den Transferansatz des FBH in Richtung industrielle Anwender: Mit einem Grundsystem können verschiedene gepulste Diodenlaser des FBH optimal betrieben werden. Dazu wurden die Komponenten entsprechend modularisiert und vereinheitlicht. Mit der PLS flex kann das FBH nun Nachfragen nach Diodenlasern mit Steuerung schneller und flexibel bedienen. Künftig soll Know-how für konkrete Anwendungen noch stärker in abteilungsübergreifenden Teams gebündelt und gemeinsam weiterentwickelt werden. Begleitet werden diese Maßnahmen von systematischen Markt- und Wettbewerbsanalysen und einer nachhaltigen Kontaktpflege.

Das EntwicklungsZentrum arbeitet seit jeher eng mit den Wissenschaftlerinnen und Wissenschaftlern in den Fachabteilungen des Instituts zusammen. Dadurch identifiziert es frühzeitig Forschungsthemen und Ergebnisse, die sich für den Transfer in industrielle Anwendungen eignen. Auch in F&E-Projekte ist das Team von Anfang an eingebunden. Es bringt sich aktiv in den Entwicklungsprozess ein und prüft zugleich, wie Ergebnisse optimal verwertet werden können. Im Ergebnis entstehen ebenso spezialisierte wie pragmatische Lösungen, die aus Sicht von Anwendern entwickelt und für deren Bedürfnisse gedacht sind. Unter anderem wurde 2018 eine kompakte atmosphärische Plasmaquelle für Demonstrationszwecke auf der SEMICON Europa erfolgreich im Live-Betrieb gezeigt.

Atmospheric microwave plasma source µPQ - an easy way to activate surfaces.
Atmosphärische Mikrowellen-Plasmaquelle µPQ – damit lassen sich Oberflächen unkompliziert aktivieren.

medium (air, oxygen, argon, ...) and the cooling medium is so flexible that the source can be used both manually (e.g., in medicine) and implemented in production or process machines (e.g., printing industry, coating equipment).

Die Quelle im 2,45 GHz-ISM-Band besteht aus einem Mikrowellen-Leistungsoszillator, einem Resonator zur Plasma-Anregung und der Ansteuerelektronik, die gemeinsam in einem kompakten Gehäuse integriert sind. Die Zufuhr des Plasma-Mediums (Luft, Sauerstoff, Argon, ...) sowie des Kühlmediums ist so flexibel realisiert, dass die Quelle sowohl händisch (z.B. in der Medizin) wie auch in Produktions-oder Prozessmaschinen (z.B. Druckindustrie, Beschichtungsanlagen) integriert werden kann.

Ulrike Winterwerber (l.), head of the Prototype Engineering Lab, discusses the status of a prototype with her team.
Ulrike Winterwerber (li.), Leiterin des EntwicklungsZentrums, bespricht mit ihrem Team den Status eines Prototypen.

Expanded competencies – the institute's in-house workshop
Kompetenzen erweitert – die institutseigene Werkstatt

The institute's workshop has been part of the Prototype Engineering Lab since 2018 – which means that seven engineers and precision mechanics are now working together on developing prototypes and specialized systems. Moreover, the precision mechanics workshop continues to manufacture special constructions required for scientific projects or laboratory set-ups.

The workshop upgraded its technical equipment last year in order to be able to manufacture an even larger range of ever smaller components with highest precision. Computer-optimized processes also make it possible to produce more workpieces in less time, and a new five-axis CNC milling machine

Seit 2018 gehört die institutseigene Werkstatt zum EntwicklungsZentrum – damit arbeiten nun sieben Ingenieure und Feinwerktechniker gemeinsam an der Prototypen- und Geräteentwicklung. Auch Spezialanfertigungen, die für wissenschaftliche Projekte oder Laboraufbauten benötigt werden, stellt die feinmechanische Werkstatt weiterhin her.

Technisch hat die Werkstatt im letzten Jahr aufgerüstet, um eine noch größere Bandbreite an immer kleineren Bauteilen sehr präzise herstellen zu können. Durch computeroptimierte Prozesse lassen sich zudem mehr Bauteile in weniger Zeit fertigen und dank einer neuen fünfachsigen

Actively involved in vocational training – workshop manager Daniel Bandke (l.) explains microtechnology trainee Abdulhamid how workpieces are precisely manufactured and measured.
Aktiv in die Ausbildung eingebunden – Werkstattleiter Daniel Bandke (l.) erklärt Mikrotechnologie-Azubi Abdulhamid, wie Werkstücke präzise hergestellt und vermessen werden.

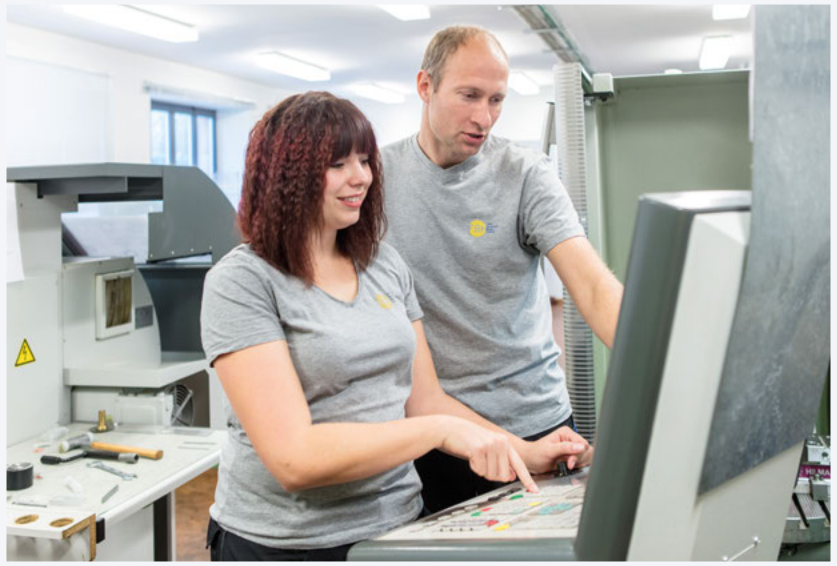
enables more complex components to be produced. At the same time, the workshops of other Adlershof research institutes have established a network. They pool their resources, for example by sharing special machines. As a result, fewer parts have to be manufactured externally.

The requirements are getting more demanding, therefore the workshop will move into new premises next year. At the neighboring Center for Microsystems Technology and Materials offers sufficient space for newly acquired equipment. In the future, further machinery will be replaced and new production technologies introduced.

CNC-Fräse sind komplexere Bauteile möglich. Parallel haben sich die Werkstätten anderer Forschungseinrichtungen am Standort Adlershof vernetzt. Sie bündeln ihre Ressourcen, indem sie etwa Spezialmaschinen gemeinsam nutzen. Dadurch müssen weniger Bauteile extern gefertigt werden.

Die Anforderungen steigen, daher wird die Werkstatt im kommenden Jahr neue Räumlichkeiten im benachbarten Zentrum für Mikrosysteme und Materialien beziehen, die ausreichend Platz für die neu beschafften Anlagen bieten. Perspektivisch werden weitere Maschinen erneuert und neue Fertigungstechnologien eingeführt.

A practiced team – industrial mechanic Michelle Schulz with workshop manager Daniel Bandke.
Ein eingespieltes Team – Industriemechanikerin Michelle Schulz mit Werkstattleiter Daniel Bandke.



Wanted! 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

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

Skilled personnel is always needed, no matter if they are physicists, electrical engineers or microtechnologists.
Fachkräfte werden immer gebraucht, ob Physiker*in, Elektrotechniker*in oder Mikrotechnolog*in.

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.

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 further training in high technology

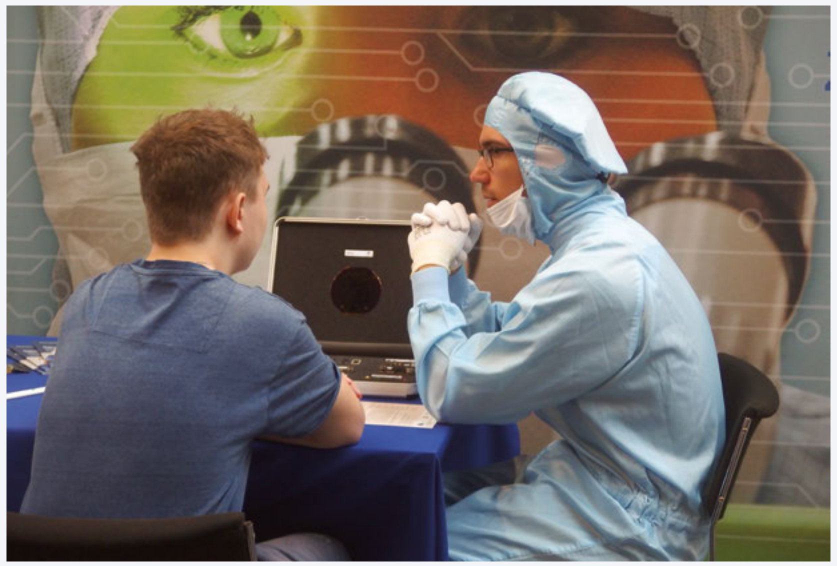
Aus- und Weiterbildungsnetzwerk Hochtechnologie – ANH Berlin

ANH Berlin (Aus- und Weiterbildungsnetzwerk Hochtechnologie) was founded at the FBH in 2007. As a supplementary structure, the network promotes vocational training in STEM (science, technology, engineering, mathematics) far beyond the scope of the institute. At its core, the ANH Berlin team supports research institutions and companies 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 "technical" or too "demanding". ANH Berlin makes technical occupations and promising career opportunities visible and provides young people with insights 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.

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 Forschungseinrichtungen und Unternehmen 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 „technisch" oder zu „anspruchsvoll" eingeschätzt. ANH Berlin macht technische Berufe sichtbar 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.



At vocatium, a career and study fair, a microtechnology trainee consults interested visitors at the ANH booth.
Am ANH-Stand berät ein Mikrotechnologie-Azubi Interessierte auf der vocatium, einer Fachmesse für Ausbildung und Studium.

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 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 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

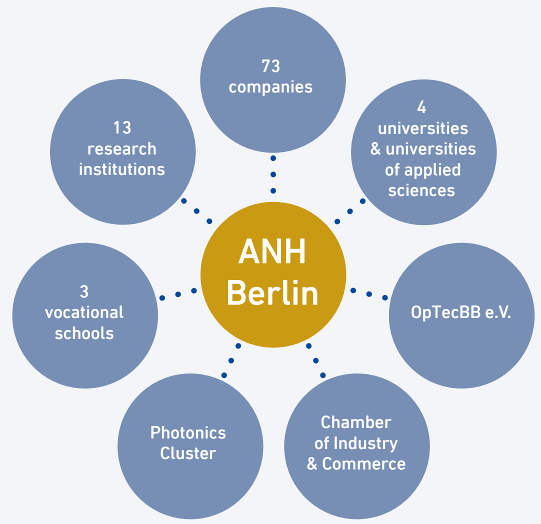
- informiert auf Ausbildungsmessen und bei Karrieretagen in Schulen
- bewirbt offene Ausbildungsplätze auf großen Online-Ausbildungsplattformen
- sichtet Bewerbungen, übernimmt die Vorauswahl und leitet passende Kandidat*innen weiter

Benefiting from the network

Vom Netzwerk profitieren

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 education. Thus, the partners benefit from the extensive know-how and reliable contacts of the network. All services are offerd thanks to support from regional, national and EU funding.

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 von dem umfangreichen Know-how und verlässlichen Kontakten des Netzwerks. Alle Dienstleistungen werden dank der Unterstützung durch regionale, nationale und EU-Fördermittel angeboten.



ANH Berlin informs about future-oriented apprenticeships

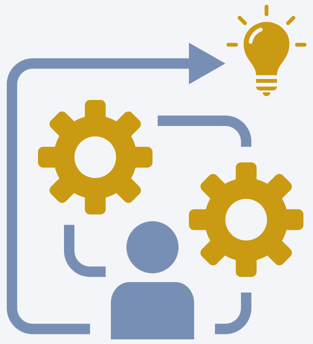
ANH Berlin informiert über zukunftssichere Ausbildungen

- represented at **10** job fairs in 2018

- 2018 auf **10** Karrieremessen vertreten

Creating insights into work environments

Einblicke in Arbeitswelten schaffen



For school students:

- **29** companies and research institutions opened their doors for over **150** students at the Ausbildungs-Allianz-Adlershof in 2018

For parents:

- with the offer "parents on tour" about **20** parents learned more about career opportunities for their children – on site at the FBH

For multipliers:

- **5** workshops for teachers and vocational counselors

Für Schüler*innen:

- **29** Unternehmen und Forschungseinrichtungen öffneten bei der Ausbildungs-Allianz-Adlershof 2018 für über **150** Schüler*innen ihre Türen

Für Eltern:

- mit dem Angebot "Eltern auf Tour" lernten etwa **20** Eltern mehr über Karrierechancen für ihre Kinder – vor Ort am FBH

Für Multiplikatoren:

- **5** Workshops für Lehrkräfte und Berufsberater*innen

Workshops for companies

Workshops für Unternehmen

- **4** workshops held for **39** companies and research institutions

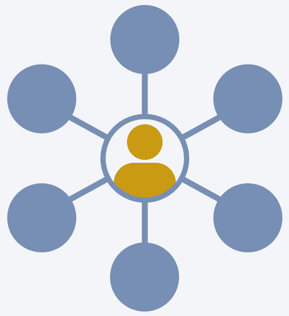
- **4** Workshops für **39** Unternehmen und Forschungs-einrichtungen durchgeführt

Application management for partners of ANH Berlin

Bewerbungsmanagement für Partner von ANH Berlin

- **11** vocational training profiles advertised
- **410** applications checked
- **200** applications forwarded to companies according to specified criteria
- **50%** of the "microtechnology" training class staffed through ANH Berlin

- **11** Ausbildungsberufe beworben
- **410** Bewerbungen geprüft
- **200** Bewerbungen anhand vorgegebener Kriterien an Unternehmen weitergeleitet
- **50%** der Ausbildungsklasse „Mikrotechnologie" über ANH Berlin besetzt



Projects in 2018

Projekte in 2018

- **HAI** high-tech training in Berlin-Brandenburg
- **beMINT.** Hands-on career opportunities
- **PHABLABS 4.0**

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

For further information:

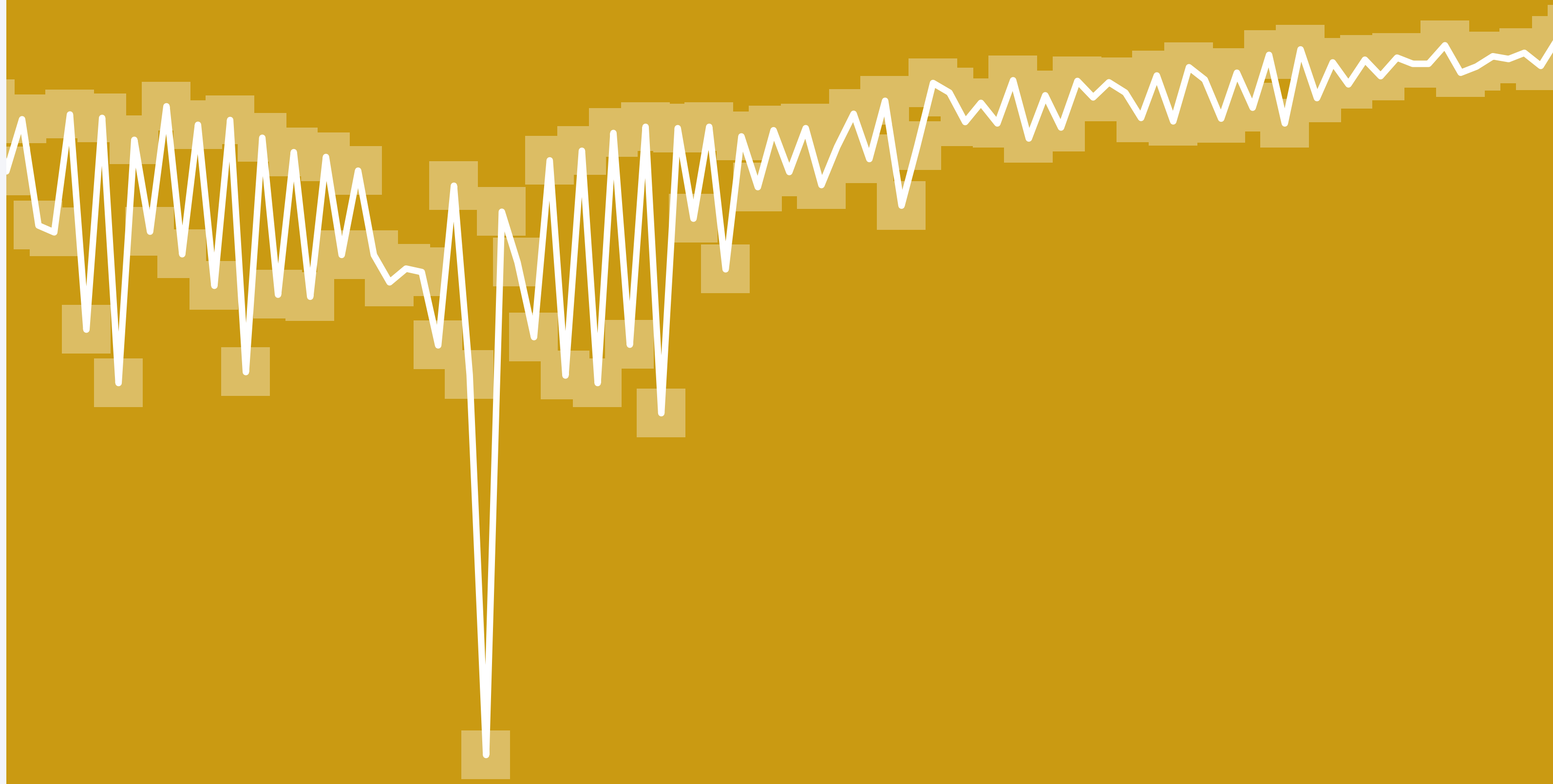
Prototype Engineering Lab

https://www.fbh-berlin.com/prototype-engineering

ANH Berlin

https://www.anh-berlin.de

Highlights
Schlaglichter



Research Fab Microelectronics Germany – one-stop-shop for the complete micro and nanoelectronics value chain

Forschungsfabrik Mikroelektronik Deutschland – Technologie-Know-how aus einer Hand Hochtechnologie – ANH Berlin

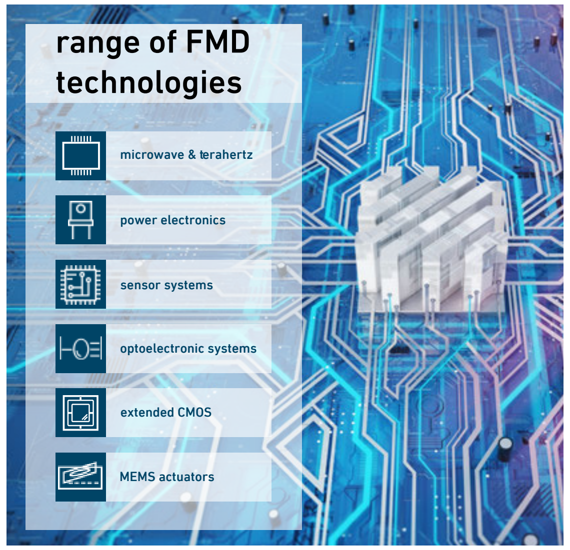
Forschungsfabrik Mikroelektronik Deutschland

Ferdinand-Braun-Institut is one of 13 members of the Research Fab Microelectronics Germany (FMD) – Europe's largest cross-location R&D alliance for microelectronics and nanoelectronics with over 2000 scientists. FMD bundles the know-how and technological infrastructure in this competence area and offers customers comprehensive access to innovations and future technologies as a one-stop shop. Small and medium-sized companies and start-ups in particular are expected to benefit from this collaboration. The aim of FMD is to strengthen the innovative capability of the semiconductor and electronics industry in Germany and Europe in global competition.

The FMD office is the central contact point for potential and existing customers. Thus, cross-institutional application solutions from a single source are also possible. In this way, customers can realize combined and optimized system solutions with FMD and its institutes. For 2018, projects with a volume of more than 41 million euros have been identified based on FMD investments, which signifies a great success in this early phase. Industry already accounted for 30 percent of this project volume.

Das Ferdinand-Braun-Institut ist eines von 13 Mitgliedern der Forschungsfabrik Mikroelektronik Deutschland (FMD) – dem mit über 2000 Wissenschaftlerinnen und Wissenschaftlern größten standortübergreifenden FuE-Zusammenschluss für die Mikro- und Nanoelektronik in Europa. Die FMD bündelt Know-how und technologische Infrastruktur in diesem Kompetenzbereich und bietet Kunden als One-Stop-Shop einen umfassenden Zugang zu Innovationen und Zukunftstechnologien. Davon sollen insbesondere kleine und mittelständische Unternehmen sowie Start-ups profitieren. Ziel ist es, mit der FMD die Innovationsfähigkeit der Halbleiter- und Elektronikindustrie in Deutschland und Europa im globalen Wettbewerb zu stärken.

Die FMD-Geschäftsstelle ist die zentrale Kontaktstelle für potenzielle und bestehende Kunden. Auch institutsübergreifende Anwendungslösungen aus einer Hand sind daher möglich. Kunden können so kombinierte und optimierte Systemlösungen mit der FMD und ihren Instituten realisieren. Für das Jahr 2018 lassen sich Projekte mit einem Volumen von mehr als 41 Millionen Euro auf Basis der FMD-Investitionen identifizieren, was einen großen Erfolg in dieser frühen Phase darstellt. Der Industrieanteil bei diesem Projektvolumen lag bereits bei 30 Prozent.



The Federal Ministry of Education and Research (BMBF) has been funding the establishment of the FMD since April 2017 with a total of 350 million euros. One and a half years after launching the project, numerous new laboratory facilities were put into operation at FMD locations throughout Germany. The FBH is receiving 34 million euros in funding to bring its research infrastructure up to date.

Ferdinand-Braun-Institut at the 1st FMD Innovation Day

The FBH was represented at the symposium of the Innovation Day especially in the session "Environmental Sensors with LiDAR". A corresponding live demonstrator for pulsed laser sources was presented at the accompanying exhibition. Pulse duration and intensity could be flexibly adjusted per tablet and monitored on screen in real time. The system is based on FBH's PLS flex laser sources and delivers pulses in the range of 2 -10 ns. The sources can be equipped with diode lasers of different wavelengths (630 - 1180 nm) and power ranges. Laser diodes, which are wavelength-stabilized at 905 nm, reach output powers of up to 100 W at ambient temperatures of up to 85 °C. This makes them ideally suited for use in LiDAR systems. FBH offers the chips in a complete development environment with driver electronics and control software.

Das Bundesministerium für Bildung und Forschung (BMBF) fördert den Aufbau der FMD seit April 2017 mit insgesamt 350 Millionen Euro. Eineinhalb Jahre nach dem Projektstart wurden zahlreiche neue Laboranlagen an den deutschlandweit verteilten FMD-Standorten in Betrieb genommen. Das FBH wird mit 34 Millionen Euro gefördert und bringt damit seine Forschungsinfrastruktur auf den neuesten Stand.

Das Ferdinand-Braun-Institut beim 1. Innovation Day der FMD

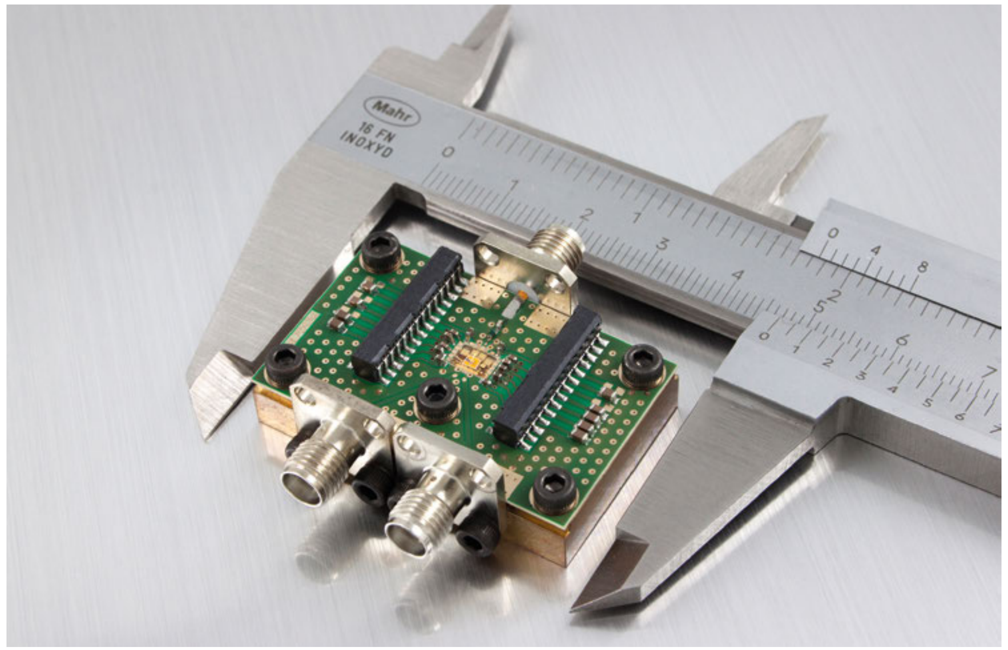
Das FBH war auf dem Symposium des Innovation Day insbesondere in der Session „Umfeldsensorik mit LiDAR" vertreten. Einen entsprechenden Live-Demonstrator für gepulste Laserquellen stellte es auf der begleitenden Ausstellung vor. Hierbei konnten Pulsdauer und -intensität per Tablet flexibel eingestellt und in Echtzeit am Bildschirm verfolgt werden. Das System basiert auf den PLS flex Laserquellen des FBH und liefert Pulse im Bereich von 2 – 10 ns. Die Quellen können mit Diodenlasern verschiedenster Wellenlängen (630 - 1180 nm) und Leistungsbereiche bestückt werden. Laserdioden, die bei 905 nm wellenlängenstabilisiert sind, erreichen Ausgangsleistungen von bis zu 100 W bei Umgebungstemperaturen bis 85 °C. Somit eignen sie sich ideal für den Einsatz in LiDAR-Systemen. Das FBH bietet die Chips in einer kompletten Entwicklungsumgebung mit Treiberelektronik und Steuerungssoftware an.

Pushing the limits – GaN high-efficiency, high-speed switching devices

Die Grenzen erweitern – hocheffizientes Hochgeschwindigkeits-Schalten mit GaN

As a wide-bandgap material, gallium nitride (GaN) stands out against the more conventional semiconductors silicon, gallium arsenide, and indium phosphide due to its high Johnson figure of merit, the product of breakdown field with saturation velocity. This has fueled research and development of GaN devices over the past two decades, with remarkable success. In the past years, GaN has gained a steadily growing market share in power electronics for switching frequencies in the higher MHz range as well as in efficient microwave and mm-wave power amplifiers. The unprecedented high-power high-speed switching capabilities of GaN devices have opened up new opportunities to realize functionalities that have not been feasible with silicon or III-V technologies so far.

Als Material mit großer Bandlücke übertrifft Galliumnitrid (GaN) die konventionelleren Halbleiter Silizium, Galliumarsenid und Indiumphosphid mit seiner hohen "Johnson figure of merit", dem Produkt aus Durchbruchsfeldstärke und Sättigungsgeschwindigkeit. Diese Materialeigenschaft hat die F&E-Aktivitäten bei GaN-Bauelementen seit einiger Zeit auf einen Höchststand gebracht – mit bemerkenswerten Resultaten. GaN hat einen stetig wachsenden Marktanteil in der Leistungselektronik für Schaltfrequenzen im höheren MHz-Bereich sowie bei effizienten Mikrowellen- und Millimeterwellen-Leistungsverstärkern erobert. GaN-Bauelemente können mit gleichzeitig hoher Leistung und Geschwindigkeit schalten und bieten damit einzigartige Eigenschaften. Mit ihnen lassen sich Funktionalitäten realisieren, die bislang weder mit Silizium- noch mit III/V-Technologien möglich waren.



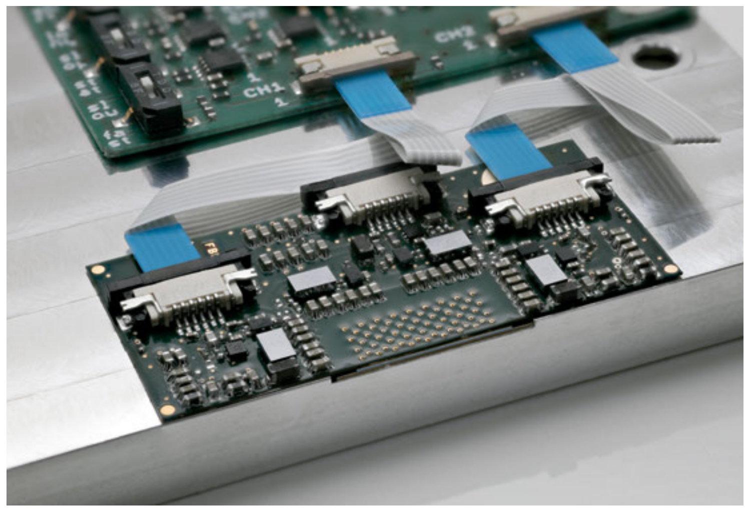
Fully digital GaN-based transmitter module for 5G mobile communication infrastructure.
Voll-digitales GaN-basiertes Sendemodul für die 5G-Mobilfunkinfrastruktur.

Several labs at FBH utilize this potential to push the frequency limits of digital functions on various power levels, thus promoting digitization in the true meaning of the word. The applications targeted range from next-generation wireless communications to LiDAR systems for autonomous driving. FBH activities encompass

- a fully digital transmitter chain for base stations in wireless communications,
- a switched envelope tracking concept, the so-called class-G approach, where the supply voltage of the microwave PA is varied between discrete values to ensure high energy efficiency for the modern wireless communication signals,
- a driver circuit for pulsed laser sources with more than 100 W optical peak power and up to almost 1 kA of peak current, which is to be used in LiDAR systems, for instance,
- high-speed DC-DC converters for ultra-compact solutions in power electronics.

Dieses Potenzial nutzen mehrere Labs am FBH, um die Frequenzgrenzen digitaler Funktionen auf verschiedenen Leistungsstufen zu verschieben – und treiben so die "Digitalisierung" im eigentlichen Sinne des Wortes voran. Das bedeutet, die analoge durch eine digitale Signalverarbeitung zu ersetzen. Die angestrebten Anwendungen reichen von der drahtlosen Kommunikation der nächsten Generation bis hin zu LiDAR-Systemen für das autonome Fahren. Die Aktivitäten des FBH beinhalten

- eine voll-digitale Sendekette für Mobilfunk-Basisstationen,
- ein geschaltetes "Envelope-Tracking"-Konzept (Klasse-G), bei dem die Versorgungsspannung des Mikrowellen-Leistungsverstärkers zwischen diskreten Werten variiert wird – dies sorgt für energieeffizienten Betrieb bei den in der modernen drahtlosen Kommunikation verwendeten Signalen,
- eine Treiberschaltung für gepulste Laserquellen mit mehr als 100 W optischer Spitzenleistung und einem Maximalstrom bis nahezu 1 kA, die beispielsweise in LiDAR-Systemen eingesetzt werden soll,
- Hochgeschwindigkeits-DC-DC-Wandler, mit denen sich ultrakompakte Lösungen in der Leistungselektronik realisieren lassen.



Pulsed laser modules with integrated GaN-based driver offer unprecedented performance in terms of current and pulse width.
Gepulste Lasermodule mit integrierten GaN-basierten Treibern erreichen Spitzenwerte hinsichtlich Strom und Pulsweite.

Exemplary technology transfer and industrial cooperation ensure German technological sovereignty

Beispielhafter Technologietransfer und Industriekooperationen sichern die technologische Souveränität Deutschlands

Fiber-coupled pump laser source for high-energy-class solid-state systems – in cooperation with TRUMPF.
Fasergekoppelte Pumplaserquelle für Hochenergieklasse-Festkörpersysteme – in Kooperation mit TRUMPF.

FBH's close cooperation with industrial partners and research institutions guarantees that its research results are quickly translated into industrial applications – this way, FBH has generated 22 million euros over the last seven years. With its trend-setting university cooperations, FBH also successfully bridges the gap between basic and application-oriented research. The institute is a nucleus that creates industrial value in Berlin and thus contributes significantly to securing German technological sovereignty. FBH has initiated a total of eleven spin-offs – most recently BeamXpert founded in 2018 – and stimulated several high-tech companies to establish production plants or branch offices in Berlin, including TRUMPF Group and JENOPTIK AG. With around 13,400 employees, TRUMPF is one of the world's leading companies for machine tools, lasers and electronics for industrial applications. FBH cooperates closely with the company in the field of high-power diode lasers, e.g., for materials processing. JENOPTIK is a global technology corporate with operations in over 80 countries. The close cooperation with FBH resulted in opening a high-tech production facility for semiconductor lasers in the immediate vicinity of the institute in 2006, which was expanded in 2012. In 2018, JENOPTIK again invested a double-digit million amount in its production facilities in order to shorten delivery times.

Die enge Zusammenarbeit des FBH mit Industriepartnern und Forschungseinrichtungen garantiert die schnelle Umsetzung seiner Forschungsergebnisse in industrielle Anwendungen – 22 Millionen Euro hat das FBH auf diese Weise in den letzten sieben Jahren erwirtschaftet. Mit seinen wegweisenden Hochschul-Kooperationen schlägt das FBH zugleich erfolgreich die Brücke zwischen grundlagen- und anwendungsorientierter Forschung. In Berlin ist das Institut ein Nukleus für die industrielle Wertschöpfung und leistet damit wichtige Beiträge zur Sicherung der technologischen Souveränität Deutschlands. Insgesamt elf Ausgründungen – zuletzt das 2018 gegründete Spin-off BeamXpert – und die Ansiedlung von etlichen Hightech-Unternehmen hat das FBH initiiert, darunter die Berliner Niederlassungen der TRUMPF-Gruppe und der JENOPTIK AG. TRUMPF zählt mit seinen rund 13.400 Mitarbeitern zu den weltweit führenden Unternehmen für Werkzeugmaschinen, Laser sowie Elektronik für industrielle Anwendungen. Das FBH kooperiert eng mit dem Unternehmen im Bereich der Hochleistungs-Diodenlaser, u.a. für die Materialbearbeitung. JENOPTIK ist ein global agierender Technologie-Konzern, der in über 80 Ländern präsent ist. Durch die enge Zusammenarbeit mit dem FBH eröffnete das Unternehmen 2006 in unmittelbarer Nachbarschaft seine Hightech-Produktion für Halbleiterlaser, die 2012 erweitert wurde. JENOPTIK investierte 2018 erneut einen zweistelligen Millionenbetrag in seine Ausstattung, um die Lieferzeiten zu verkürzen.

Record values with high-power diode lasers

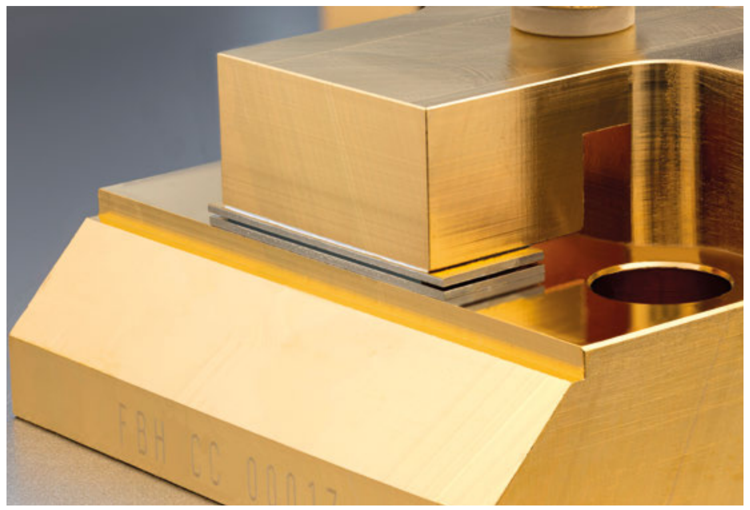
Spitzenwerte mit Hochleistungs-Diodenlasern erzielen

Major laser applications in industry and academia require ever-better diode laser performance. Thus, Ferdinand-Braun-Institut conducts in-depth studies of the device physics to guide developments in epitaxial layer design and device technology. As a result, FBH technology makes novel devices and modules possible and enables new kinds of applications. Inventions are protected by a broad patent portfolio.

The FBH team recently developed the concept of a triple asymmetrical epitaxial layer design, which precisely manipulates the optical field and leads to both higher efficiency and higher output powers. Diode lasers that make use of these sophisticated epitaxial designs have been developed and fabricated at FBH using high-quality low-defect device technology, achieving higher performance in the application. For example, 1-cm laser bars are in wide industrial use, directly and as pump sources. Increased power directly lowers costs in €/W, reduces system size, and can also improve performance (higher brightness pumping). FBH research has enabled a 2- to 4-fold increase in the peak output power of such diode laser bars over the last ten years, in a first step in quasi-continuous-wave (QCW) mode for pumping of pulsed solid-state laser systems. In parallel, efficiency has been increased at 1 kW per bar, from ~ 35% to 65%. Improved layer designs were an important part of these developments. Currently, TRUMPF and the FBH are collaborating closely on such high-power bars, demonstrating kW output in CW mode at the highest reported operating temperature (298 K ≙ 25 °C), and working to continuously increase efficiency and beam quality.

Großlaseranlagen in Industrie und Wissenschaft benötigen immer leistungsfähigere Diodenlaser. Das Ferdinand-Braun-Institut führt daher fundierte physikalische Untersuchungen zum epitaktischen Schichtdesign und zur Bauelementtechnologie durch. Derartig optimierte Diodenlaser sind die Grundlage für neuartige Geräte und Module und erschließen neue Anwendungsgebiete. Die Erfindungen in diesem Bereich sind durch ein breites Patentportfolio geschützt.

Kürzlich hat das FBH-Team ein Konzept für ein dreifach asymmetrisches epitaktisches Schichtdesign entwickelt, mit dem sich das optische Feld präzise manipulieren lässt. Damit können sowohl Wirkungsgrad als auch Ausgangsleistung erhöht werden. Weitere ausgefeilte Epitaxie-Designs wurden entwickelt und mithilfe der leistungsfähigen Bauelemente-Technologie am FBH realisiert. So sind beispielsweise Laserbarren mit 1 cm Streifenbreite in industriellen Anwendungen weit verbreitet – sie werden als Direkt-Diodenlaser oder als Pumpquellen eingesetzt. Eine höhere Leistung führt hier unmittelbar zu niedrigeren Kosten (in Euro pro Watt). Das ermöglicht kompaktere Systeme mit zugleich höherer Leistungsfähigkeit (Pumpen mit höherer Brillanz). Die Forschungsarbeiten des FBH führten zu entsprechenden Verbesserungen. Im ersten Schritt konnte die Spitzenausgangsleistung von Diodenlaserbarren im quasi-kontinuierlichen (QCW) Betrieb zum Pumpen von gepulsten Festkörperlasersystemen in den letzten Jahren um das Zwei- bis Vierfache gesteigert werden. Parallel wurde der Wirkungsgrad bei 1 kW pro Barren von ~ 35% auf 65% erhöht. Dabei spielten verbesserte Schichtstrukturen eine wichtige Rolle. TRUMPF und das FBH kooperieren hierbei eng miteinander, um die Effizienz und Strahlqualität solcher Barren weiter zu steigern. Zuletzt wurden Kilowattleistungen im CW-Modus bei der höchsten berichteten Betriebstemperatur (298 K ≙ 25 °C) demonstriert.



QCW diode laser bar on passive heat sink suitable for the kilowatt power range.
QCW-Diodenlaserbarren für den Kilowatt-Leistungsbereich auf passiver Wärmesenke.

Diode lasers for high-resolution microscopy
Diodenlaser für die hochauflösende Mikroskopie

For applications in medicine and biophotonics, FBH develops short-pulse lasers that emit in the yellow-green spectral range from 532 nm to 590 nm. Lasers with short pulses are required, for example, for imaging methods in biosciences such as FLIM (FLIM = fluorescence lifetime imaging microscopy) and STED microscopy (STED = Stimulated Emission Depletion). Both methods are much more sophisticated than conventional laser scanning microscopy. STED microscopes enable structures smaller than 100 nm to be resolved, and the FLIM method can even be used to observe dynamic processes in living cells.

FBH cooperates with leading manufacturers of high-resolution microscopes. These instruments require light sources that deliver short, intense laser pulses with pulse lengths of around 100 ps and pulse peak powers of several watts. The FBH offers such beam sources with excellent beam quality, long lifetime, high power stability, and high-speed modulation capability.

A number of laser modules have been developed using pulsed near-infrared lasers whose emission is then amplified and frequency doubled. The modules deliver short, yellow-green laser pulses in the range of a few picoseconds with peak pulse powers of up to 2.7 W. Their light can be used either as a free beam or be fiber-coupled for microscopy applications. As a result, prototypes for the next generation of high-resolution optical imaging methods are now available, allowing systems for end users to become significantly smaller.

Für Anwendungen in der Medizin und Biophotonik entwickelt das FBH Kurzpulslaser, die im gelb-grünen Spektralbereich von 532 nm bis 590 nm emittieren. Laser mit kurzen Pulsen werden unter anderem für bildgebende Verfahren in den Biowissenschaften benötigt, etwa für die FLIM-Mikroskopie (FLIM = fluorescence lifetime imaging microscopy/Fluoreszenzlebensdauer) und die STED-Mikroskopie (STED = Stimulated Emission Depletion). Beide Verfahren sind deutlich leistungsfähiger als die herkömmliche Laser-Raster-Mikroskopie. So ermöglichen es STED-Mikroskope, Strukturen kleiner als 100 nm aufzulösen, und mit dem FLIM-Verfahren lassen sich sogar dynamische Prozesse in lebenden Zellen beobachten.

Das FBH kooperiert hierbei mit führenden Herstellern hochauflösender Mikroskope. Diese Geräte benötigen Lichtquellen, die kurze, intensive Laserpulse mit Pulslängen um 100 ps und Pulsspitzenleistungen von mehreren Watt liefern. Solche Strahlquellen bietet das FBH mit hervorragender Strahlqualität, langer Lebensdauer, hoher Leistungsstabilität und Hochgeschwindigkeits-Modulationsfähigkeit.

Unter anderem wurden Lasermodule entwickelt, bei denen ein gepulster Nahinfrarotlaser nachverstärkt und frequenzverdoppelt wurde. Damit liefern die Module kurze, gelbgrüne Laserpulse von wenigen Pikosekunden mit Pulsspitzenleistungen bis 2,7 W. Das Licht der Lasermodule kann entweder als Freistrahl oder fasergekoppelt für den Einsatz in Mikroskopen genutzt werden. Mit dieser Entwicklung stehen Prototypen für die nächste Generation von höchstauflösenden optischen Bildgebungsverfahren bereit, wodurch Geräte für Endanwender deutlich kleiner ausfallen können.

Different pulsed diode laser modules for medical diagnostics and treatment
Verschiedene gepulste Diodenlaser-module für die medizinische Diagnostik und Behandlung.

By precisely adjusting the grating period in the semiconductor laser, any wavelength in the yellow-green spectral range can be addressed. This allows exotic dyes to be excited that could not be used as biomedical markers so far. In the future, new marker substances and analytical methods have the potential to be used for personalized gene therapies to treat cancer. Further information can be found on p. 46.

Durch die präzise Einstellung der Gitterperiode im Halbleiterlaser kann jede beliebige Wellenlänge im gelb-grünen Spektralbereich adressiert werden. Dadurch lassen sich auch exotische Farbstoffe anregen, die bislang keine Verwendung als biomedizinische Marker finden konnten. Neue Markerstoffe und Analyseverfahren könnten zukünftig für personalisierte Gentherapien in der Behandlung von Krebserkrankungen eingesetzt werden. Weitere Informationen dazu gibt es auf S. 46.

Opening up industrial applications for UV light-emitting diodes – internationally visible with ICULTA
Industrielle Anwendungen für UV-Leuchtdioden erschließen – international sichtbar mit der ICULTA

The chair of the program committee Markus Weyers during a discussion of a talk at ICULTA 2018.
Der Vorsitzende des Programmkomitees Markus Weyers während der Diskussion eines Vortrages auf der ICULTA 2018.

Advanced UV for Life addresses UV LED technology along the entire value chain – from the development of novel UV light-emitting diodes (LED) to their specific application. The consortium brings together around 50 partners from research and industry and is coordinated by FBH. Aim is to advance the technical development, the availability, and the use of UV LEDs on a broad scale.

In 2018, the consortium made its progress internationally visible with the first ICULTA conference.

Advanced UV for Life beschäftigt sich mit der UV-LED-Technologie entlang der kompletten Wertschöpfungskette – von der Entwicklung neuartiger UV-Leuchtdioden (LED) bis hin zur konkreten Anwendung. Das Konsortium vereint rund 50 Partner aus Forschung und Industrie und wird vom FBH koordiniert. Ziel ist es, die technische Entwicklung, die Verfügbarkeit und den Einsatz von UV-LEDs in breitem Maße voranzubringen.

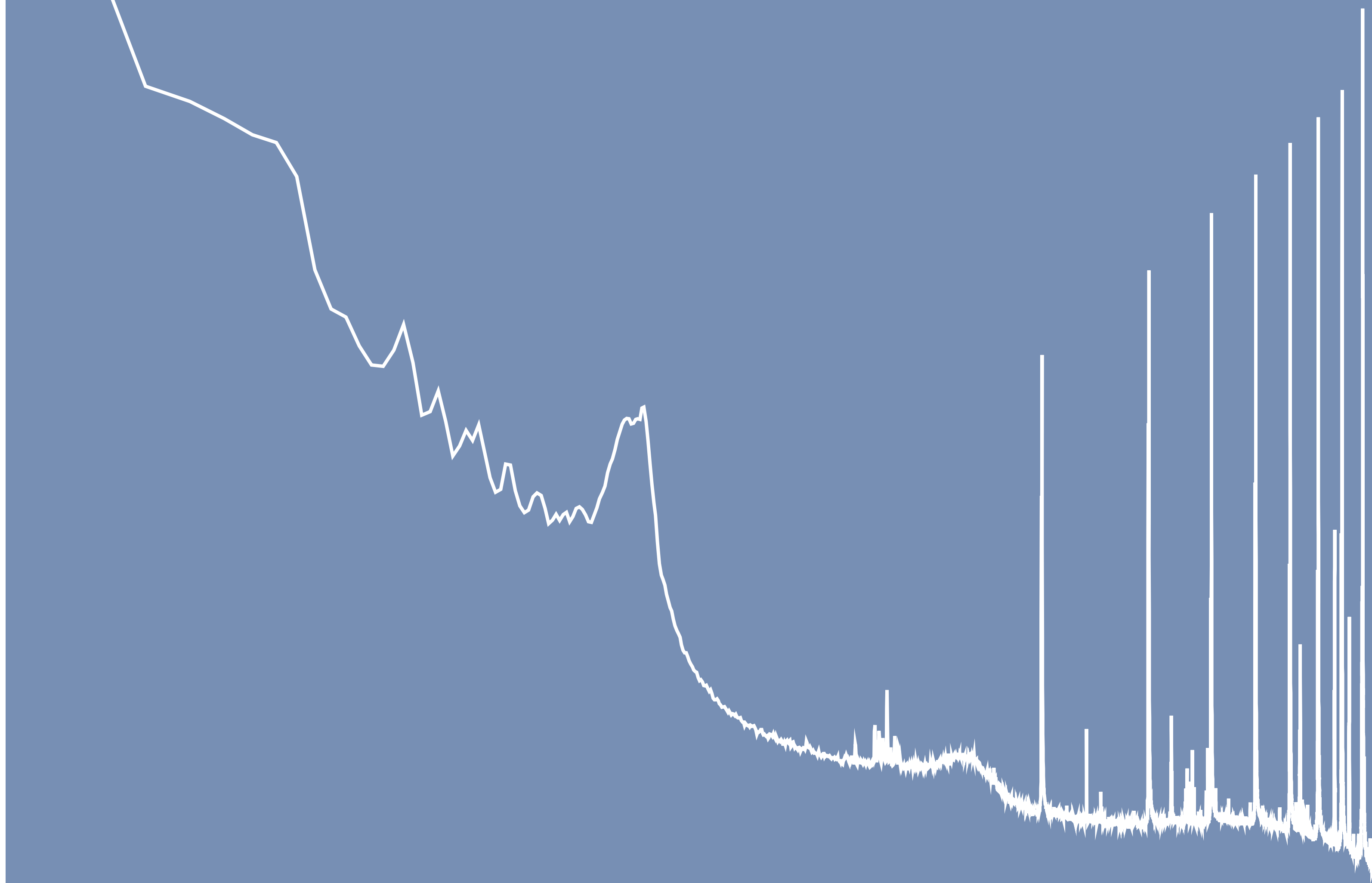
260 participants from 23 countries exchanged information and experiences on manufacturing technologies, current developments, applications and trends for UV LEDs in Berlin. The conference was jointly organized by *Advanced UV for Life* and the *International Ultraviolet Association*. The Ferdinand-Braun-Institut was also closely involved in the conference committee: Prof. Michael Kneissl, head of the Joint Lab GaN Optoelectronics, as co-chair of the conference and Prof. Markus Weyers, head of the Materials Technology Department, as chairman of the program committee. The FBH itself and its spin-off UVphotonics were represented with several (invited) talks and booths at the accompanying exhibition.

The aim of the conference was to bring together developers of UV LEDs and users from different application fields. "As in the *Advanced UV for Life* consortium, we have succeeded in this," confirms Markus Weyers. "We were particularly pleased with the high level of industrial participation, as it shows how attractive UV LEDs have become for industrial applications," says Michael Kneissl, evaluating the proportion of more than 60 percent of participants who came from companies. Thanks to the great international response, a follow-up conference for 2020 is currently being prepared.

Seine Fortschritte machte das Konsortium 2018 mit der erstmalig stattfindenden ICULTA international sichtbar. 260 Teilnehmende aus 23 Ländern tauschten sich in Berlin über Herstellungstechnologien, aktuelle Entwicklungen, Anwendungen und Trends bei UV-LEDs aus. Die Fachkonferenz wurde gemeinsam von *Advanced UV for Life* und der *International Ultraviolet Association* organisiert. Auch in das Konferenz-Komitee war das Ferdinand-Braun-Institut umfassend eingebunden: Prof. Michael Kneissl, Leiter des Joint Lab GaN Optoelectronics, als Ko-Vorsitzender der Konferenz und Prof. Markus Weyers, Leiter des Departments Materialtechnologie, als Vorsitzender des Programm-Komitees. Das FBH selbst und seine Ausgründung UVphotonics waren mit mehreren (eingeladenen) Vorträgen und Ständen auf der begleitenden Ausstellung vertreten.

Die Tagung zielte darauf, Entwickler von UV-LEDs und Anwender aus verschiedenen Applikationsfeldern zusammenzubringen. „Das ist uns, wie schon im Konsortium *Advanced UV for Life*, gut gelungen", bekräftigt Markus Weyers. „Über die hohe Industriebeteiligung haben wir uns besonders gefreut, da sie zeigt, wie attraktiv UV-LEDs inzwischen für industrielle Anwendungen sind", bewertet Michael Kneissl den Anteil von mehr als 60 Prozent der Teilnehmenden, die aus Unternehmen kamen. Dank des großen internationalen Zuspruchs ist eine Nachfolgekonferenz für 2020 derzeit in Vorbereitung.

Photonics
Photonik



Photonik

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.

- ***Lasermetrologie*** – in diesem Bereich werden ultra-schmalbandige Diodenlasermodule entwickelt. Dank der Hochpräzisionsmontage sind sie besonders kompakt und robust und eignen sich daher auch für Weltraumanwendungen. Dieses Know-how bildet die Basis für den neuen Forschungsbereich Integrierte Quantentechnologie, der seit 2019 aufgebaut wird.

- ***GaN-Optoelektronik*** – auf diesem Gebiet entwickelt das FBH Nitrid-Laserdioden und UV-Leuchtdioden, insbesondere für den UVB- und UVC-Spektralbereich. Die LEDs eigenen 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.

Photonics

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.

- ***Laser metrology*** – ultra-narrowband diode laser modules are developed in this field. Due to high-precision mounting they are particularly compact as well as robust and thus perfectly suited for space applications. This know-how forms the basis for the new research area Integrated Quantum Technology, which is being established since 2019.

- ***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.

Red emitting DFB lasers with surface gratings for spectroscopy and medical applications

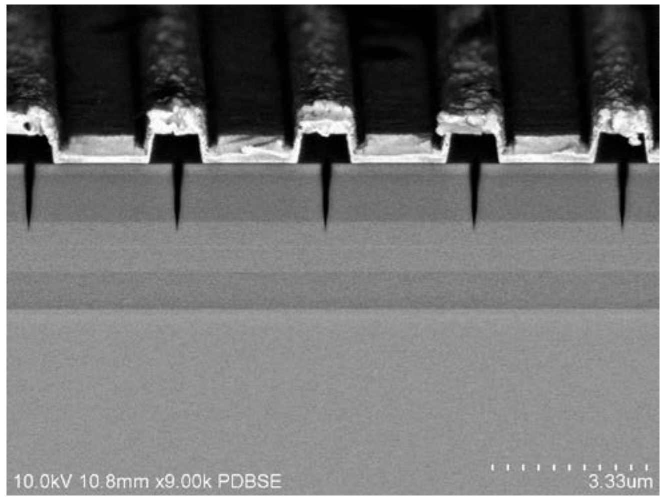


Fig. 1. Scanning electron microscope picture of a Bragg grating with etched and encapsulated grooves

Although the optical spectra of Fabry-Perot diode lasers are already much smaller than those of lamps or light-emitting diodes, they are often still too broad for applications in spectroscopy or medicine. To further shrink the optical spectrum Bragg gratings, i.e. periodic variations of the refractive index along the cavity axis fixing the lasing wavelength, have to be implemented. This can be accomplished either in only a part of the cavity being electrically unbiased (distributed Bragg reflector, DBR laser) or along the whole cavity containing both the laser-active region and the grating (distributed feedback, DFB laser). DBR lasers can be fabricated more easily but they suffer from wavelength jumps and show self-pulsating behavior when current or temperature is varied. On the other hand, DFB lasers exhibit a spectrally and temporally more stable behavior but are more difficult to fabricate, because the gratings are commonly embedded into the epitaxial layer structure employing a two-step epitaxy. This is especially true for lasers containing the semiconductor AlInGaP with emission in the wavelength range between 630 nm and 690 nm.

Therefore, FBH's well proven surface grating technology to fabricate DBR lasers was adapted to DFB lasers. Surface gratings are realized by etching narrow grooves deep into the completed epitaxial layer structure so that no re-growth is necessary. For DBR lasers, typically gratings with Bragg orders in the range between 3 and 10 are used, resulting in grating periods between 0.3 and 1 µm. Utilized in a DFB laser, the small spacing of the etched grooves would hinder the injection of the electrical current into the cavity, containing both the laser-active region and the grating. Therefore, 40th order Bragg gratings with a period of 4 µm were used. The now much larger distance between the grooves can be easily metallized so that a homogeneous current injection can be achieved along the whole cavity.

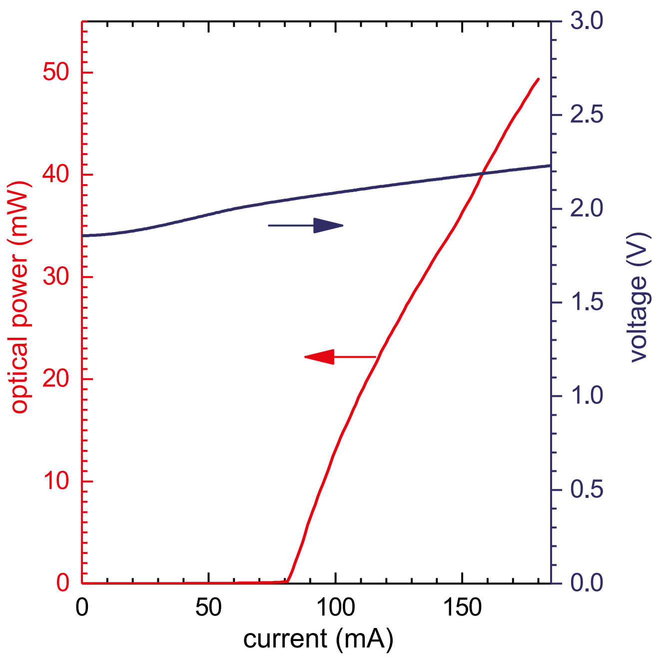


Fig. 2. Continuous-wave output power (left axis) and applied bias (right axis) versus injection current of a 1.5 mm long DFB laser.

To accomplish this, a three layer system consisting of a baked resist, Ti and an electron beam resist is exposed by electron beam lithography and further patterned with an oxygen plasma. The obtained grating is then transferred into the semiconductor layers via reactive ion etching (RIE). The etch depth of the grooves has to be carefully adjusted to achieve an appropriate feedback strength. Furthermore, the grooves must be at least a few tens of nm wide at the bottom to obtain low scattering losses. This is realized by choosing a proper opening of the resist and a tailored etching process to realize V-shaped grooves, see Fig. 1. After etching the ridge waveguides (RWs) for lateral optical confinement, electron beam lithography and similar processing steps as mentioned before were applied to encapsulate the etched grooves by SiN, see Fig. 1. This allows keeping the serial resistance of the device comparable to lasers without gratings.

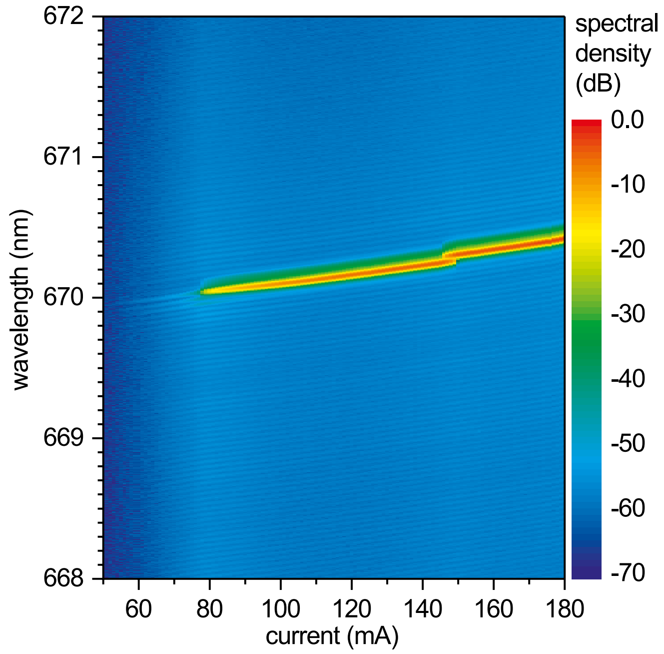


Fig. 3. Color-scale mapping of the optical spectrum.

The fabricated lasers emitting around 670 nm achieved 50 mW output power at an injection current of 180 mA (Fig. 2). A color-scale mapping of the optical spectrum versus injection current indicates single-mode operation over a wide current range with only one mode hop at 150 mA (Fig. 3). The side modes are suppressed by more than 50 dB.

The successful demonstration of 670 nm RW DFB laser operation has proven the effective development of a new technological platform, which can be used to fabricate similar lasers emitting at a multitude of other wavelengths.

Diodenlaser mit schmalem optischem Spektrum, die im roten Wellenlängenbereich zwischen 630 nm und 690 nm emittieren, werden für spektroskopische und medizinische Anwendungen benötigt. Einige Applikationen erfordern zusätzlich einen modensprungfreien und zeitlich stabilen Betrieb in einem variablen Injektionsstrombereich. Diese Anforderungen erschweren oder schließen die Nutzung von DBR-Lasern mit einem Reflexionsgitter aus. Bei DFB-Lasern ist das Gitter über den gesamten Resonator verteilt. Jedoch ist die dafür notwendige Zweischrittepitaxie, um das Bragg-Gitter in die Epitaxiestruktur einzubetten, im AlInGaP-Materialsystem nicht möglich. Daher wurden am FBH erstmalig 1,5 mm lange 670 nm DFB-Laser mit Oberflächengittern 40. Ordnung mit 4 µm Periode hergestellt. Sie erreichen eine Ausgangsleistung von 50 mW bei einer Seitenmodenunterdrückung von 50 dB und eignen sich daher ideal für spektroskopische und medizinische Anwendungen.

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600 W short-pulse laser sources for LiDAR systems

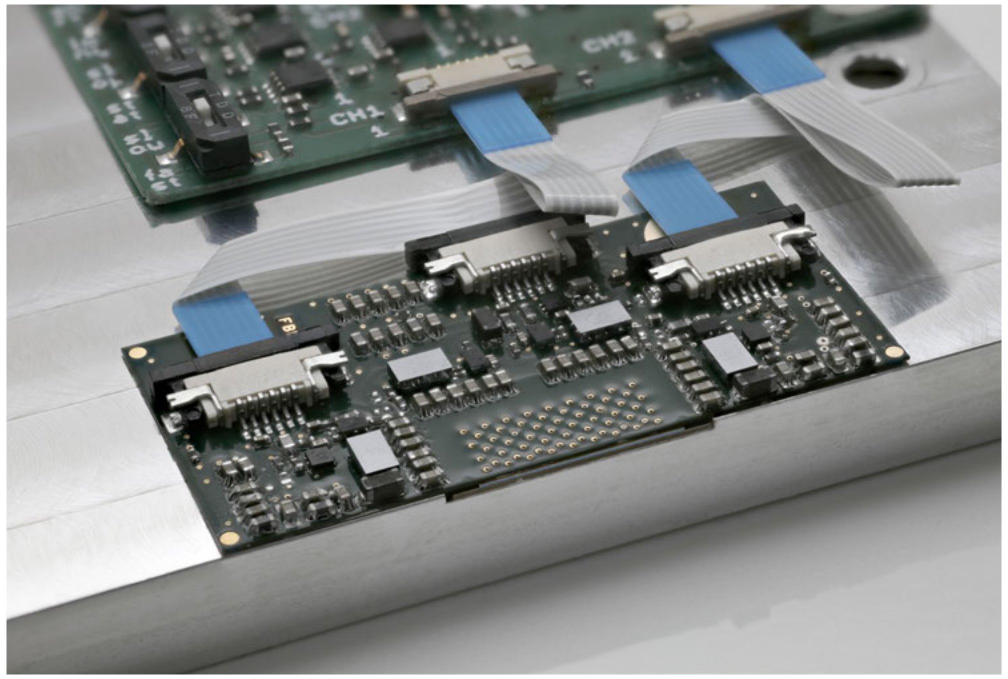

Fig. 1. High-current laser driver with integrated 48-emitter DBR laser bar.

Diode lasers generating short optical pulses with high peak power are key components for compact LiDAR (Light Detection and Ranging) systems. The distances to objects are determined by measuring the time difference between the emission of a laser pulse and its return, after being reflected by an object. To build up a three-dimensional point cloud of object distances, point, line or flash scanning systems can be employed.

For automotive LiDAR systems 100 ps – 10 ns long optical pulses with powers of more than 100 W and a low temperature-related wavelength shift are needed. Shorter pulses offer higher spatial resolution and have advantages concerning eye safety due to lower pulse energy. To be applied under real atmospheric conditions and to avoid absorption by water vapor, the emission wavelength has to be shorter than 920 nm. To fulfill these requirements a wavelength-selective element such as a Bragg grating as part of the laser cavity can be integrated.

For a line scanning LiDAR the FBH developed a distributed Bragg reflector (DBR) broad area laser bar combining 48 single emitters on one chip with a filling factor of ¼. The epitaxial structure is based on the compound semiconductors AlGaAs and InGaAs – the latter in the single quantum well active region. The total length of the cavity, including the 1 mm long DBR section, is 4 mm and the width of the bar is 10 mm. For cost-effective manufacturing the 7th order Bragg grating of the DBR was implemented by dry-etching narrow V-shaped grooves. These were defined by e-beam lithography into the surface of the completed epitaxial layer structure so that no regrowth was necessary. The laser bar was then integrated into a tailored electrically unit, which has been newly developed in-house (Fig. 1). To obtain the desired high power from the bar, a current of 20 A has to be injected in every emitter so that for 48 emitters driven in parallel the driver has to deliver peak currents up to 1000 A. The unique challenges are providing high-speed high-current switching and handling the parasitic inductances arising from the electrical connection of laser and driver board. Due to their advantageous properties, GaN-based transistors are used in the final stages. To obtain the current needed, four driver stages are connected in parallel.

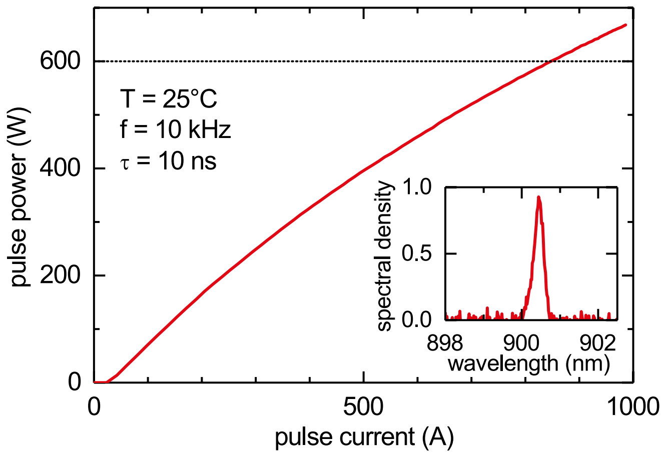

Fig. 2. Optical pulse power from a 48-emitter bar versus driver pulse current for a pulse width of 10 ns. Inset: Optical spectrum at 600 W pulse power.

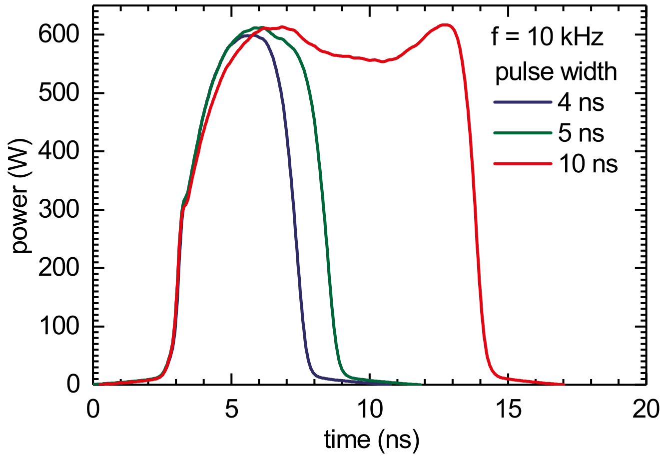

Fig. 3. Power versus time for three pulse widths at 850 A pulse current.

The pulse power in dependence of the pulse current of a 48-emitter bar mounted in the quadrupole driver module is shown in Fig. 2. An optical pulse power of more than 600 W is reached for a pulse width of 10 ns at a repetition frequency of 10 kHz and a temperature of 25 °C. The optical spectrum at 600 W pulse power is shown in the inset. The integrated Bragg grating results in a small optical spectrum with a width of less than 0.6 nm (95 % power content) and a peak spectral density at a wavelength of about 900 nm with a side mode suppression ratio larger than 30 dB. The corresponding optical pulses were measured at three pulse widths (4 ns, 5 ns and 10 ns) at 850 A pulse currents, results are shown in Fig. 4. Stable optical pulses with a nearly rectangular shape are generated. All pulses exhibit a peak power of 600 W independent of their width.

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

Diodenlaser, die kurze optische Pulse mit hohen Spitzenleistungen emittieren, sind Schlüsselkomponenten für LiDAR-Systeme. Dabei wird die Zeit gemessen, die ein Laserpuls von der Emission bis zur Detektion braucht, nachdem er an einem Objekt reflektiert wurde. Aus diesem Wert lässt sich auf die Entfernung zum Objekt schließen. LiDAR-Systeme für den Automobilbereich benötigen Pulse mit Längen zwischen 100 ps und 10 ns, Leistungen von mehr als 100 W und Wellenlängen kleiner 920 nm. Zudem darf sich das optische Spektrum bei Temperaturänderungen nur wenig verschieben. Dies kann durch ein Bragg-Gitter, das in den Resonator integriert wird, erreicht werden. Am FBH wurde ein DBR-Breitstreifen-Laserbarren mit 48 Emittern entwickelt, der als Linienscanner in LiDAR-Systemen eingesetzt werden kann. Passend dazu wurde eine neuartige elektrische Treiberschaltung entwickelt, welche kurze elektrische Pulse mit einer Spitzenstromstärke von 1000 A erzeugt. Damit konnte eine Pulsleistung von 600 W mit einem schmalen optischen Spektrum bei 901 nm erzeugt werden. Die Pulsleistung ist hierbei nahezu unabhängig von der Pulsbreite im Bereich zwischen 4 ns und 10 ns.

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Photonics Photonik

Towards a better theoretical understanding of high-power diode lasers

Tremendous advancements have been achieved in the development of high-power diode lasers during the last two decades. This can be attributed to improved epitaxial structure and cavity designs as well as refined crystal growth, facet passivation, and device cooling technologies. Diode lasers do no longer only serve as optical pumps for solid-state lasers but aim to replace them since they are easy-to-use, compact, efficient and highly reliable. However, diode lasers with a broad emission area to deliver a high optical power suffer from the appearance of multiple peaks in lateral far and near field profiles. These deteriorate the beam quality, in particular at high injection currents. Such effects are caused by simultaneous oscillation of many light modes and by lasing filaments formed by a self-focusing mechanism where the refractive index locally increases in regions of high optical intensity. In order to assess the root causes of these limitations, physics-based modeling and numerical simulation are more important than ever.

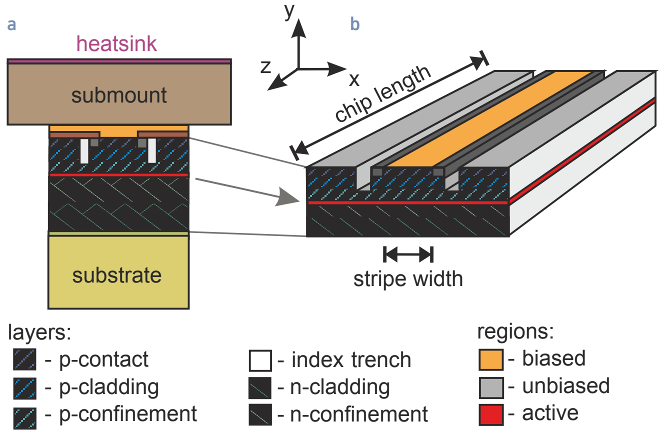

Fig. 1. Schematic cross sectional and three dimensional views of the computational domains for thermal, electronic and optical simulation.

As broad-area lasers exhibit a temporal fluctuating behavior on a sub-ns timescale even for continuous wave (CW) operation, a time-dependent model for the optical field has to be employed. To reduce simulation times, the FBH has developed a tailored tool for numerical simulation of the lateral field dynamics of diode lasers. In cooperation with the Weierstrass Institute for Applied Analysis and Stochastics (WIAS) the physical models were simplified and the computational domains (see Fig. 1) properly adapted.

The heat flow equation that describes the self-heating of the devices is solved in the full transverse (x, y) plane. The drift-diffusion equations describing the transport of the charged carriers to the active region were reduced to equations governing the current flow in the p-doped layers and the carrier diffusion in the active layer along the lateral (y) direction. Finally, the optical field suffices travelling wave equations in the lateral-longitudinal (x, z) plane.

Fig. 2 shows the calculated temperature distribution in the lateral-longitudinal plane within the active region at an output power of 20 W. The temperature has its maximum at the front facet (located at z = 4 mm) in the middle of the contact stripe. The temperate distribution modifies the refractive index in the cavity, which has two consequences as Fig. 3a reveals: First, the lateral variation results in a thermally induced waveguide confining the optical field and thus in an increased beam divergence (far-field blooming), deteriorating the beam quality. Second, the longitudinal variation results in a focusing effect yielding a narrowing of the optical field at the front facet. The corresponding increase of the power density adversely affects the lifetime.

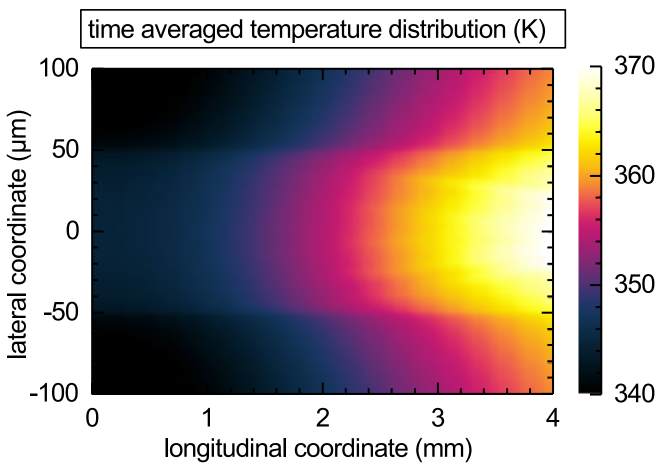

Fig. 2. Calculated intra-cavity temperature distribution.

Whereas the distribution of the optical intensity displayed in Fig 3a is a temporal average over several nanoseconds, the one in Fig. 3b is a snap shot at a certain point of time. It exhibits a complicated spatial pattern, which varies with time (not shown here).

The simulation tool developed will be used in the future to optimize the beam properties of high-power lasers.

This work was supported by the German Federal Ministry of Education and Research contract 13N14005 and 13N14026 as part of the EffiLAS/HotLas and EffiLAS/PLuS projects.

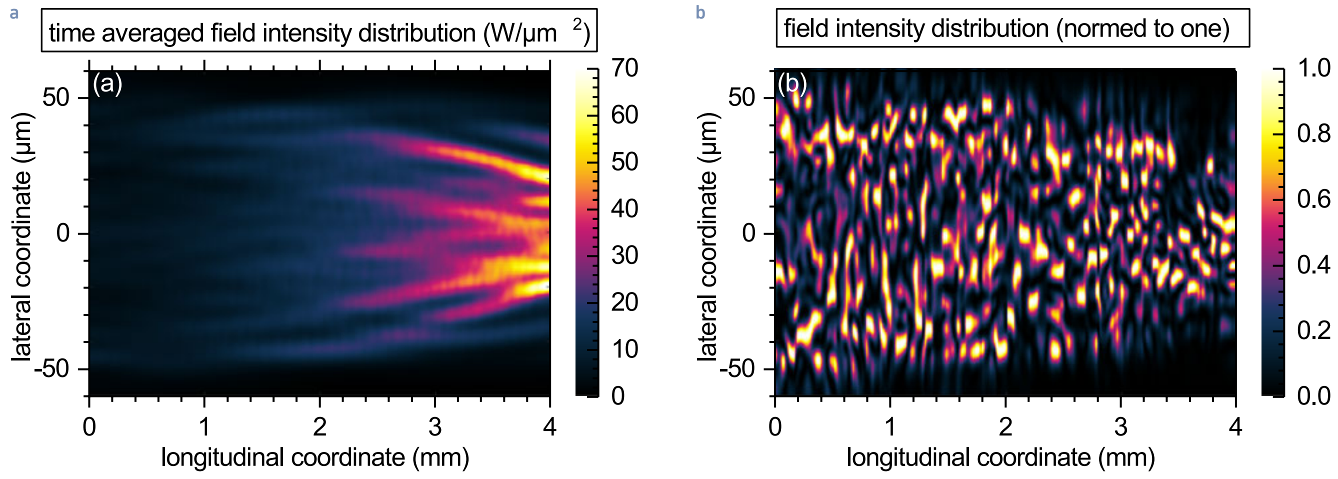

Fig. 3. Optical intra-cavity intensity distributions. (a) time-averaged, (b) snap-shot.

In den letzten Jahren wurden große Fortschritte bei Hochleistungslaserdioden erreicht, jedoch ist deren Strahlqualität immer noch deutlich schlechter als die von Festkörperlasern. Um hier Verbesserungen zu erreichen, müssen numerische Simulationen auf Basis von physikalisch basierten Modellen durchgeführt werden. Dafür muss ein zeitabhängiges, räumlich 3-dimensionales Modell verwendet werden, da die Laser selbst mit einem breiten Emissionsgebiet unter Dauerstrichbetriebsbedingungen ein zeitlich instationäres Verhalten zeigen. Um in überschaubaren Zeiten Rechenergebnisse mit der heutigen Computertechnik zu erhalten, wurden die Modelle für die Selbsterwärmung, den elektrischen Stromfluss und die Ausbreitung der optischen Wellen vereinfacht. Die Rechengebiete wurden geeignet gewählt und schnelle numerische Verfahren entwickelt. Dies erfolgte in enger Zusammenarbeit mit dem Berliner Leibniz-Institut WIAS. Mit dem nun entwickelten Simulationswerkzeug können in Zukunft am FBH die Strahleigenschaften von Laserdioden gezielt optimiert werden.

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A. Zeghuzi; M. Radziunas; H.-J. Wünsche, J.-P. Koester; H. Wenzel, U. Bandelow, A. Knigge, "Traveling Wave Analysis of Non-Thermal Far-Field Blooming in High-Power Broad-Area Lasers", IEEE J. Quant. Electron., vol. 55 (2) (2019).

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Photonics Photonik

Electrical resistance of quantum wells as an efficiency limit in high-power broad area diode lasers

GaAs-based broad area diode lasers are the most efficient high-power light source and are widely used directly and as pumps for solid-state lasers. Continuous improvement is needed in their power and efficiency, driving efforts to better understand their physical limits. For example, devices with the very lowest electrical resistance are needed to maintain high efficiency at high bias. In 2018, FBH scientists reported progress in understanding excess electrical resistance in high-power diode lasers at the IEEE International Semiconductor Laser Conference in Santa Fe, USA. They demonstrated that a significant proportion of the electrical resistance can arise in the (5-7 nm) quantum well, and that the same effect is observed in many different samples [1]. More resistance was shown to arise in the quantum well than in the packaging and cabling used to mount and measure the device. FBH scientists also demonstrated initial success in reducing this excess resistance.

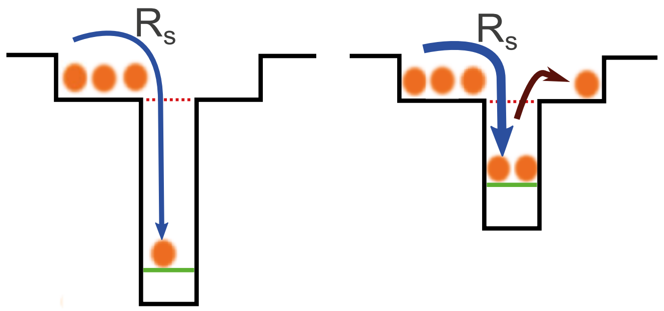

Fig. 1. Schematic of carrier transport in quantum well, left: deep well (high resistance), right: shallow well (low resistance).

A schematic depiction of the conduction band profile around the quantum well is shown in Fig. 1. Here, electrons are driven into a quantum well by an external electric field, where they recombine with holes and generate photons. The well must confine the electrons, so that they efficiently recombine with holes without escaping. The well depth or barrier ΔE must be larger than the thermal energy k_BT to prevent electrons escaping into the waveguide, where they will be lost. In the experimental study, the quantum well was left unchanged, and the bandgap of the $Al_xGa_{1-x}As$ waveguide layers was varied by changing the aluminum concentration x. The wafers were grown with MOVPE (metal-organic vapor phase epitaxy) and processed into single emitters (stripe w = 100 µm, resonator L = 4 mm), then facet coated and packaged. Performance was tested (τ = 1.2 ms, f = 10 Hz) for temperatures T_{HS} =298....208 K, and the series resistance increased as temperature fell, i.e. as $\Delta E/k_BT$ increased, whilst the resistance from all layers outside the quantum well falls – see Fig. 2. The resistance of the quantum well is therefore consistently 5 - 20 mΩ, thus much larger than the ~ 3 – 4 mW package resistance.

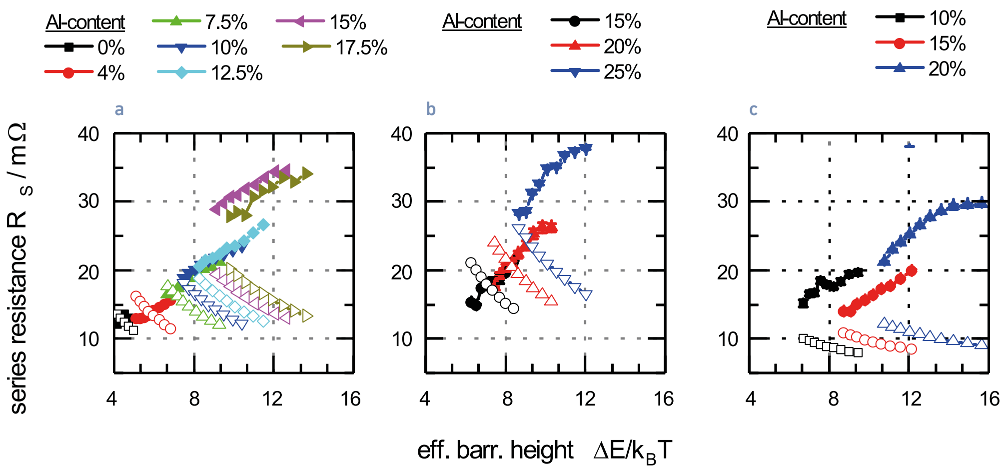

Fig. 2. Measured resistance (closed symbols) and resistance of layers outside the quantum well (open symbols, from bulk mobility) vs. barrier height for vertically symmetrical structures at λ = 970 nm (a) and λ = 890 nm (b), and a highly asymmetrical structure at λ = 970 nm (c).

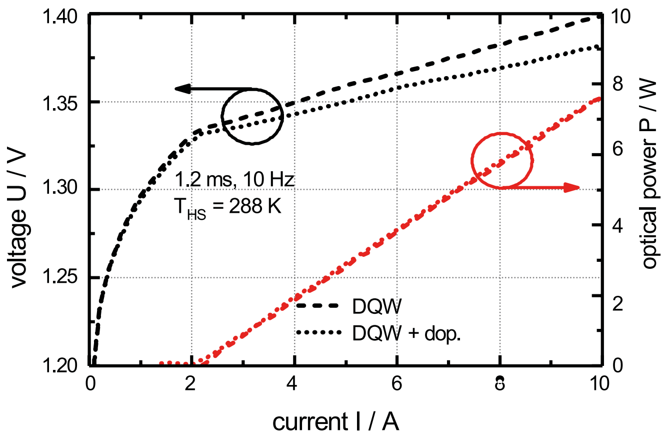

Fig. 3. Measured power and voltage as a function of current for reference devices and those with p-doped active regions.

The increase in R_s at high $\Delta E/k_BT$ is likely due to difficulty in injecting holes into deep wells, owing to their low mobility and high effective mass. Therefore, FBH scientists reduced series resistance by growing the quantum wells with holes included (5×10^{16} cm^{-3} p-type doping), test data is shown in Fig. 3 (single emitters, L = 4 mm, w = 186 µm). When doping was introduced, R_s reduced from 9.1 mΩ to 6.7mΩ (30 % reduction), with no loss in power.

FBH scientists therefore showed that the active region can be a more significant contributor to the electrical resistance in high-power diode lasers than the device packaging, and that it can be improved by design changes. Further efforts are needed to reduce this resistance for increased efficiency.

This work is based on studies supported by the Leibniz Association under contract SAW-2012-FBH-2.

Hochleistungslaserdioden auf GaAs-Substraten sind die effizientesten Lichtquellen der Welt. Sie werden vorwiegend als Pumpquellen für Festkörperlaser genutzt, aber auch direkt eingesetzt. Um die Effizienz und die maximale optische Leistung der Diodenlaser weiter zu erhöhen, haben Wissenschaftler am FBH den elektrischen Widerstand innerhalb der Diode untersucht. Dabei wurde die Materialkomposition um den Quantentrog und somit dessen Tiefe verändert. Es konnte gezeigt werden, dass der elektrische Widerstand mit der Trogtiefe korreliert und dass der Zusatzwiderstand des Trogs wesentlich größer ist als jener der Wärmesenke. Mithilfe einer leichten p-Dotierung in der aktiven Zone konnte der Widerstand dort um etwa 30 % von 9.1 mΩ auf 6.7 mΩ gesenkt werden, ohne die optische Leistung zu reduzieren. Damit wurde erstmals nachgewiesen, dass die extrem dünnen Schichten zur Lichterzeugung einen großen Anteil am Gesamtwiderstand der aufgebauten Laserdioden haben.

Publication

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Advanced beam combination of high-power diode lasers – opening up new applications

The superior and continuously increasing power, efficiency and compactness of diode lasers enable many new laser applications. So far, their use is mainly restricted by the limited output power per laser and the deteriorated beam quality when increasing the maximum power level (e.g., by enlarging laser size or combining several lasers). For this reason, diode lasers are often used as pump source for solid-state lasers, which collect the pump energy to form a beam with high beam quality. This happens at the cost of power, efficiency, compactness and purchase price. Advances in beam combining of high-power diode lasers allow ever brighter applications to be addressed with semiconductor lasers. In 2018, FBH scientists reported significant progress in the development of high-power GaAs-based sources tailored for two key approaches to beam combination, based on control of wavelength (DWDM) or phase (CBC).

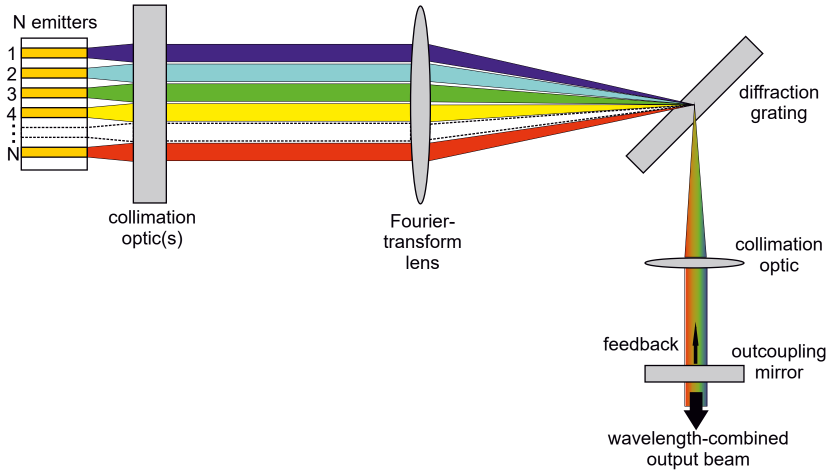

Fig. 1. Dense wavelength division multiplexing (DWDM) using a diffraction grating and external wavelength stabilization.

First, the FBH reported progress in sources for dense wavelength division multiplexing (DWDM), where diode lasers with slightly different wavelengths are superimposed into a single beam using a diffraction grating. A typical DWDM scheme is shown in Fig. 1. Systems using DWDM of broad area lasers (BAL) are already established on the market, but these cannot access applications such as metal cutting due to the limited brightness of the BALs. Single-mode diode lasers deliver their light in a high brightness beam, but have historically been limited in power and efficiency. The FBH reported significant progress in efficiency and power in these bars at 2018's Photonics West conference, in a cooperative project with TRUMPF. The team developed high-performance 1 cm laser bars with 150 - 200 single-mode ridge waveguide lasers that deliver more than 200 W optical power with conversion efficiencies close to 60 % [1, 2]. The bars also showed high polarization and low divergence angles, as needed for DWDM. A multi-channel wavelength locking of a small 5-emitter version of such bars is shown in Fig. 2.

Second, progress was also reported at 2018's Photonic West in the highest brightness of all beam combination methods, coherent beam combining (CBC), sketched in Fig. 3. The research into CBC was performed by FBH scientists in cooperation with the Laboratoire Charles Fabry in Paris. In the approach investigated, emission from a low power, narrow linewidth seed laser is fed into tapered amplifiers customized for CBC, defining an initial phase. The phases of the amplified output beams from the individual amplifiers are then held in a fixed relationship using a feedback loop, and changing the currents in the ridge sections of the amplifiers. Afterwards, the emission from each amplifier is combined into a single beam with fixed phase and narrow spectrum. An optical power of 12.9 W was measured for an elegant architecture using three tapered amplifiers. The quality of the combined beam was shown for the first time to be significantly increased by CBC, resulting in 86 % power content in the central lobe, as shown in Fig. 4, increased from 74 % in previous studies [3]. This offers a path to high power in a high quality beam from a compact, simple direct diode configuration.

Work on efficient sources for DWDM was funded by TRUMPF GmbH, and work on CBC sources is based on studies supported by the European Commission under Grant 314719.

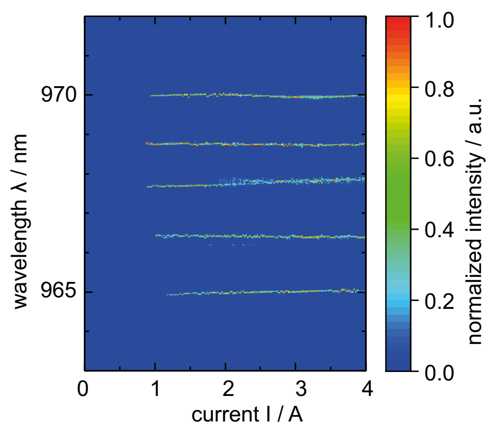

Fig. 2. 5-channel wavelength locked RW laser array. Contour plot of spectra vs. current for a 5-emitter array of laterally single-mode lasers locked at 5 different wavelengths.

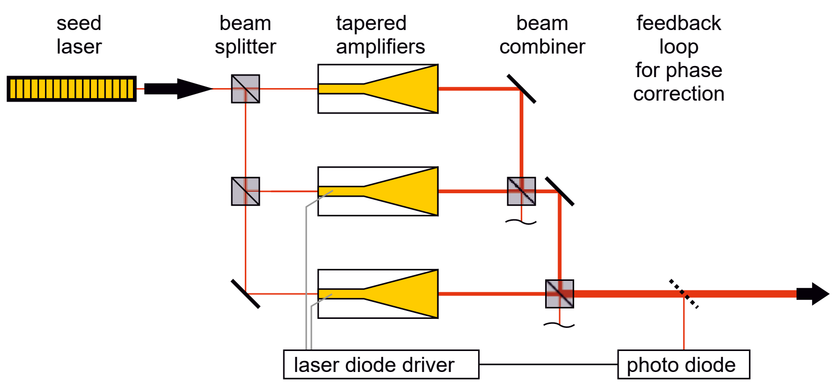

Fig. 3. Coherent beam combining (CBC) with seed laser and three tapered amplifiers.

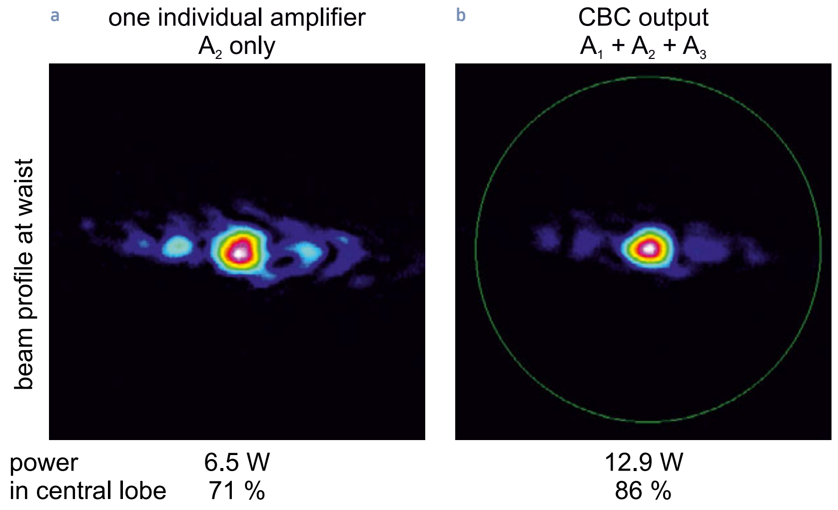

Fig. 4. Beam profiles at waist (a) for one individual amplifier and (b) of the combined beam of three amplifiers.

Diodenlaser werden derzeit meist als Pumpquellen eingesetzt. Verfahren zur Strahlkombination wie ‚Dense Wavelength Division Multiplexing' (DWDM) und ‚Coherent Beam Combining' (CBC), könnten Diodenlasern auch bei der direkten Anwendung zum Marktdurchbruch verhelfen. Das FBH hat hierbei deutliche Fortschritte erzielt. In Kooperation mit der Firma TRUMPF wurden neuartige effiziente DWDM-optimierte Grundmode-Laserbarren entwickelt, die weltweit erstmalig Leistungen bis 200 Watt mit 60 % Effizienz liefern. Bei DWDM wird die Ausgangsleistung mehrerer Diodenlaser mit leicht unterschiedlicher Wellenlänge zu einem brillanten Strahl überlagert. In Kooperation mit dem Laboratoire Charles Fabry wurden zudem neuartige Verstärker mithilfe einer neuen CBC-Konfiguration kombiniert – und so gleichzeitig Leistung und Strahlqualität verbessert. Mittels CBC wird die räumliche Phase von mehreren Halbleiterverstärkern geregelt. Dadurch kann ihre Leistung in einem perfekten, spektral schmalbandigen Strahl zusammengeführt werden.

Publications

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Miniaturized multi watt-level picosecond laser sources in the yellow and yellow-green spectral range for fluorescence spectroscopy

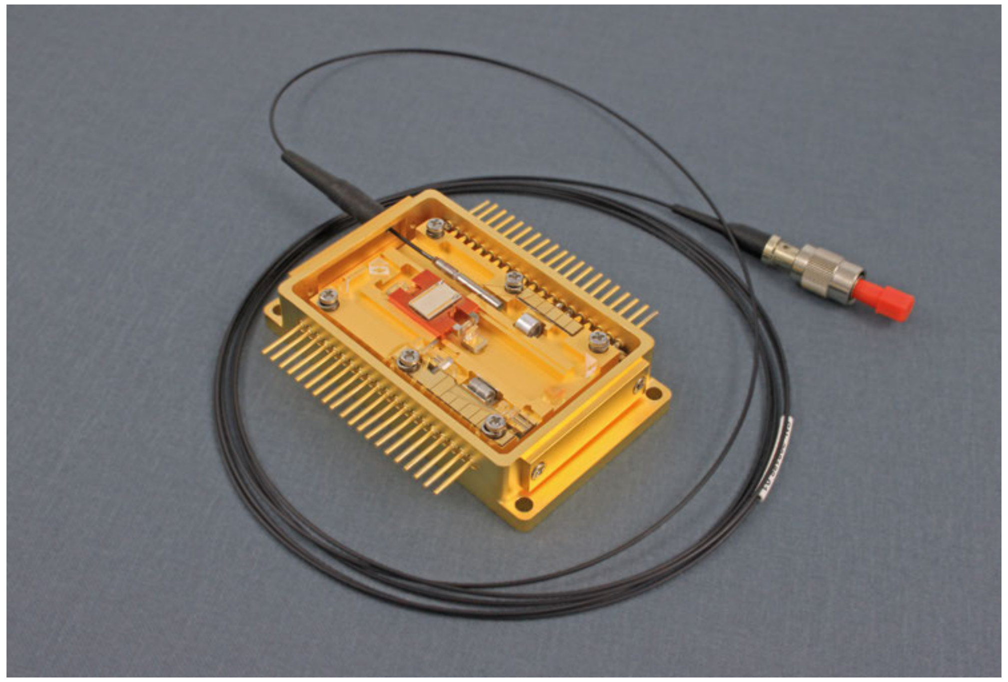

Fig. 1. Diode laser module of the second generation for pulsed operation in the yellow spectral range.

Picosecond (ps) pulsed laser sources emitting in the yellow-green spectral range are demanded for several applications, especially in the field of life sciences. Innovative fluorescence imaging methods like fluorescence lifetime imaging (FLIM) or stimulated emission depletion (STED) microscopy allow for high resolution intra-cellular images, even in situ. Pulsed laser sources with emission wavelengths at 560 nm or 590 nm that allow excitation of fluorescence without labels (e.g., label-free FLIM) are particularly interesting. Optical pulse widths of 100 ps and watt-level peak powers are required, enabling also fast scanning of the sample.

Gain-switched diode lasers are a straight-forward way to generate intense laser pulses with suitable pulse properties, offering a small footprint at the same time. However, direct-emitting diode lasers for life science applications are not yet available in the yellow-green spectrum. Thus, combining diode lasers emitting in the near infrared with single-pass second harmonic generation (SHG) is a promising approach. Over the past years, reliable high-power diode lasers at 1120 nm and 1180 nm have been developed and optimized for micro-integration at the FBH [1]. They were used for efficient SHG, thus halving their wavelengths.

The research during the project Yellow finally resulted in a miniaturized laser module for pulsed operation, which is shown in Fig. 1. The concept is based on a ridge-waveguide (RW) laser with distributed Bragg-reflector, which is operated in gain-switched mode for ps pulses at 1120 nm. A subsequent tapered amplifier in continuous wave operation increases the peak power of the pulses by two orders of magnitude. These laser pulses are finally coupled into a periodically poled lithium niobate crystal with RW structure for efficient SHG. All components are mounted onto a newly developed monolithic inlay for optimal heat dissipation and high mechanical stability.

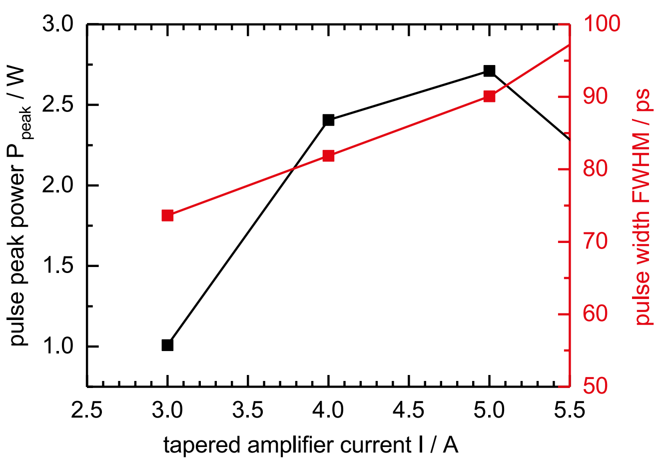

Fig. 2. Dependence of the pulse peak power and pulse width on the current through the tapered amplifier.

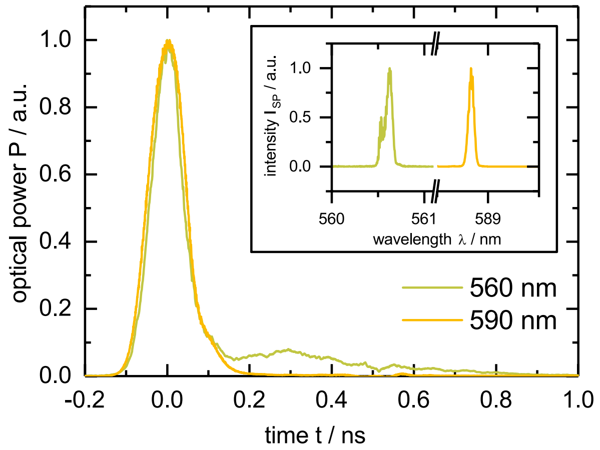

Fig. 3. Temporal pulse shape and emission wavelength of the picosecond pulsed yellow emission of two different setups.

The finally emitted picosecond pulses at 560 nm reach peak powers of more than 2.5 W at pulse widths below 100 ps. The first module generation delivered a peak power of 0.3 W, which has now been increased by almost an order of magnitude in the second generation [2]. In Fig. 2 the dependence of the pulse peak power as well as the pulse width on the tapered amplifier current is given. While the pulse peak power strongly increases with the current, the pulse width is nearly constant. An exemplary temporal pulse shape is presented in Fig. 3 together with the emission wavelength shown in the inset. In addition to the pulse shape and spectrum at 560 nm (yellow-green lines), the pulse characteristics of a second module emitting at 590 nm are given (orange lines). At 590 nm more than 1 W peak pulse power was achieved.

The high peak pulse power of the modules are an increase by at least a factor of 10 compared to existing ps-pulse laser systems at 560 nm, offering the opportunity for fast sample scanning. Furthermore, new wavelengths like 590 nm can be addressed by the modules where currently no laser systems are available. An additional advantage is their small footprint, which allows building compact fluorescence systems.

This research was funded by the German Federal Ministry of Education and Research under grant 03IPT613Y of the project "Yellow".

Kurzpulslaser im gelbgrünen Wellenlängenbereich von 532 nm bis 590 nm werden für verschiedene bildgebende Verfahren in den Biowissenschaften benötigt. Insbesondere für die STED- und FLIM-Mikroskopie sind kurze, intensive Laserpulse in diesem Spektralbereich notwendig, die Pulslängen um 100 ps und Pulsspitzenleistungen von mehreren Watt liefern. Am FBH wurden entsprechende Lasermodule entwickelt, bei denen ein gepulster Nahinfrarotlaser nachverstärkt und frequenzverdoppelt wurde. Damit liefern die Module kurze, gelbgrüne Laserpulse mit Pulsspitzenleistungen bis 2.7 W. Das Licht der Lasermodule kann entweder als Freistrahl oder fasergekoppelt für den Einsatz in Mikroskopen genutzt werden. Mit dieser Entwicklung stehen Prototypen für die nächste Generation von höchstauflösenden optischen Bildgebungsverfahren bereit, wodurch Geräte für Endanwender deutlich kleiner ausfallen können.

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Ideal for spectroscopic applications – compact laser modules with several watt output power based on a miniaturized MOPA system

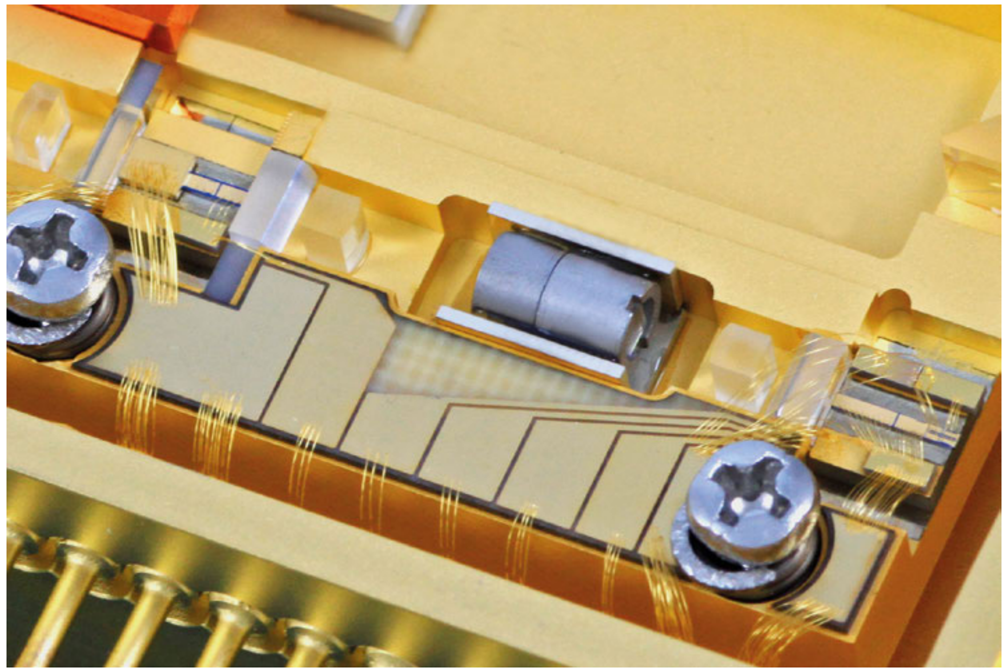

Fig. 1 Master-oscillator power-amplifier for an emission in the near infrared with optical output powers of more than 3 W.

Application fields like spectroscopy, quantum optics and lithography require laser sources emitting in the ultraviolet (UV @ 386 nm to 392 nm) or deep ultraviolet (DUV @ 192 nm to 196 nm) spectral range. Up to now, commercial broadband or pulsed laser systems such as excimer lasers have been employed. Since these laser systems are rather bulky, a reduction in size would allow further integration of functionalities and realizing transportable devices. This would facilitate the transfer of quantum optical technologies into everyday life applications, e.g. enable improved resolution of satellite navigation required for autonomous driving.

Highly brilliant semiconductor laser systems in the near-infrared (NIR) spectral range are suited to be the key enabling technology. They are reliable, small and easy to operate. Since there are no direct emitting laser diodes at DUV wavelengths, single- or double-stage frequency doubling is necessary. The NIR system must therefore emit a spectrally narrow band laser beam with high output power and good beam quality. FBH has now succeeded in developing a diode laser system that precisely meets these specifications.

The miniaturized laser system consists of a master oscillator (MO) and a power amplifier (PA). The MO is a distributed feedback (DFB) ridge waveguide (RW) laser, which emits a single spectral mode with a linewidth of < 3 MHz and a side mode suppression of more than 30 dB. The diffraction-limited laser emission is coupled into the RW section of the PA. Here, the beam is guided to match the tapered section of the PA, thus amplifying its output power up to 3 W. Optical feedback can be minimized by using a micro-optical isolator, which is placed between MO and PA. This way, the hybrid MOPA maintains the excellent spectral and spatial characteristics of the MO. The intensity noise characteristic of the MOPA is comparable to commercially available systems, while the geometric dimensions are drastically reduced.

Finally, a suitable housing had to be developed for the optimized individual components. The FBH chose a 76 x 44 mm² small butterfly package and integrated a finely milled inlay on which all components are mounted. Due to the monolithic design of the inlay, high mechanical stability is achieved. At the same time the custom features enable precise mounting of all active and passive optical elements such as lasers, amplifier, micro lenses, optical isolators, frequency conversion crystals and, if required, a polarization-maintaining optical fiber.

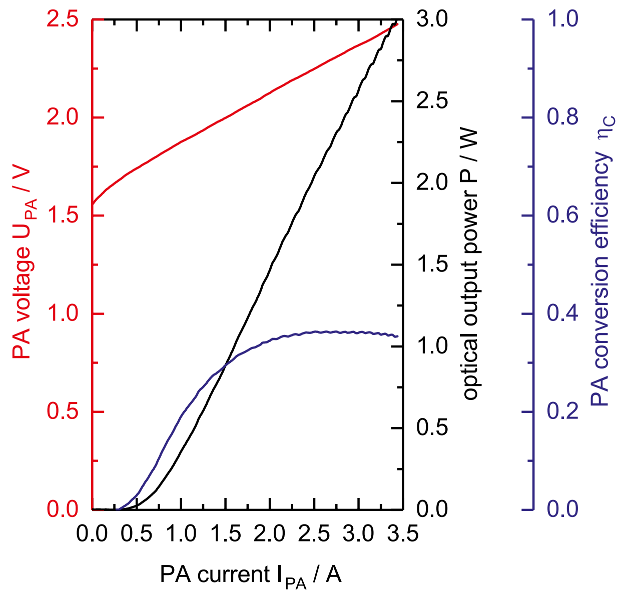

Fig. 2: Optical output power, forward voltage and conversion efficiency as a function of amplifier current. The MO and the PA were stabilized at individual temperatures of T_{MO} = 35 °C, and T_{PA} = 25 °C.

Peltier elements are interposed between the inlay and the package to actively stabilize and control the inlay temperature with an accuracy better than 0.1 K. The package cover can be welded so that a hermetic sealing is possible. An adjustable front panel allows application-specific adaptation, providing either free-space emission or feed-through for a fiber-optic output. Due to its rugged design, compact size and the reduced number of components the laser module is suitable for use in industrial environments. Both the inlay and the butterfly housing are designed to provide many mounting options for different laser sources and assemblies. Therefore, a flexible technology platform for current and future micro-integrated laser sources is now available.

Für Anwendungen in der Spektroskopie, Quantenoptik und Lithografie werden hochkohärente Laser benötigt, die im ultravioletten (UV) Spektralbereich emittieren. Derartige Lichtquellen sind als Diodenlaser bislang nicht oder nur eingeschränkt verfügbar. Daher nutzt das FBH die Frequenzverdopplung von hochkohärenten, nahinfraroten Hochleistungsdiodenlasern im Wellenlängenbereich um 772 nm – 785 nm zur Konversion in den UV-Spektralbereich. Auf diese Weise wurden miniaturisierte Diodenlasermodule hergestellt, die hochkohärente Laserstrahlung mit Linienbreiten unter 3 MHz mit einer optischen Ausgangsleitung von bis zu 3 W emittieren. Als Technologieplattform wurde ein nur 76 x 44 mm² großes Butterfly-Gehäuse mit temperierbarem, gefrästem Inlay entwickelt. Dieses Inlay trägt alle optischen Komponenten und kann je nach Anwendung angepasst werden. Es verleiht dem Modul eine hohe mechanische und thermische Stabilität und dient als flexible Basis für derzeitige und zukünftige miniaturisierte Laserstrahlquellen.

Publication

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Photonics Photonik

Widely tunable master oscillator power amplifier with output powers in the watt range for sensing applications

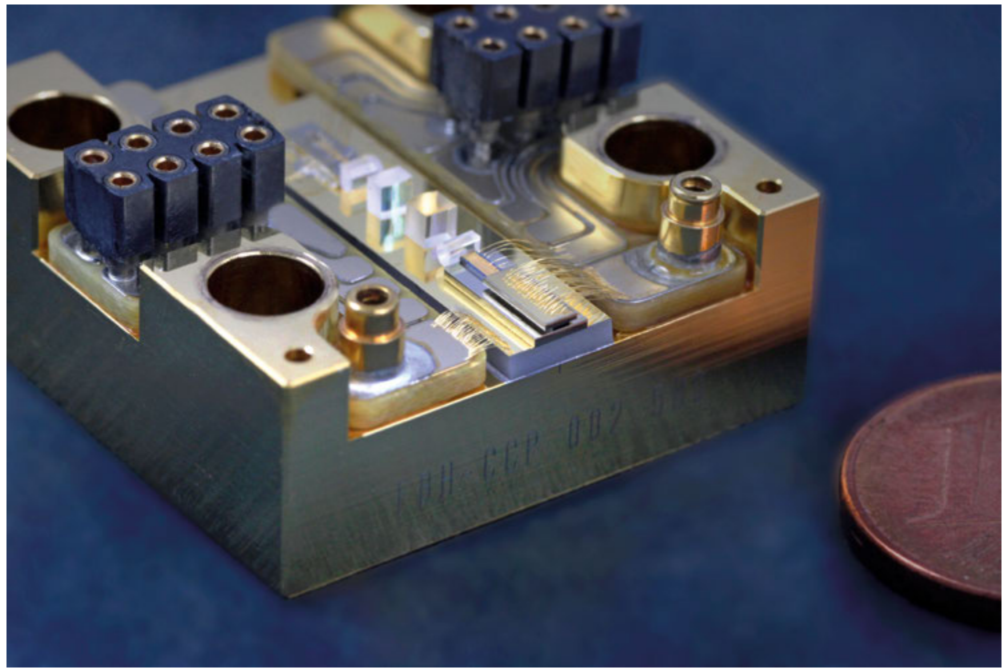

Fig. 1. Photograph of the miniaturized MOPA system.

Tunable diode lasers are key components in absorption spectroscopy, biomedical imaging and in optical telecommunication systems, to mention only a few examples. These laser sources should provide precise control of the emission wavelength, while maintaining a narrow spectral linewidth. Applications such as non-linear frequency conversion additionally require high output power with good beam quality.

Light sources offering these different requirements have recently been developed at FBH. They are based on a hybrid master oscillator power amplifier (MOPA) concept, which utilizes a tunable MO combined with a tapered power amplifier (TPA). While the MO ensures narrow linewidth and spectral tuning, the PA ensures amplification to the watt level from a nearly diffraction limited beam quality. These miniaturized systems are mounted on micro benches, on top of 25 mm × 25 mm laser mounts, see Fig. 1. The emitted light from the MO is collimated and then coupled into the PA using cylindrical micro lenses.

Two concepts of tunable MO lasers have been developed: monolithically combined Y-branch distributed Bragg reflector (DBR) lasers and sampled-grating (SG) tunable lasers, see the insets in Fig. 2 and 3, respectively. In both cases, wavelength tuning is obtained using micro heaters embedded on top of the grating sections. In the first concept, wide wavelength tuning is achieved by combining the tuning of the individual DBR gratings that are spectrally spaced apart, see Fig. 2. The Y-branch based MOPA system provides 9.7 nm of combined wavelength tuning and an output power of 5.5 W from a nearly diffraction limited beam with $M^2 = 2.2$ (measured at $1/e^2$) along the slow axis [1]. Each branch can be tuned by 7.5 nm and by proper distancing of the DBR gratings, a combined tuning of $N \times 7.5$ nm is obtained for N branches. This being said, the total tuning is ultimately set by the available gain width.

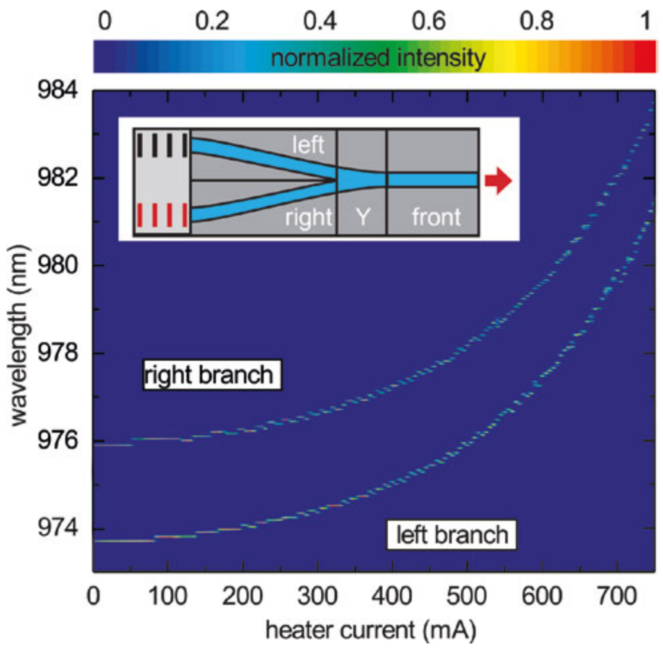

Fig. 2. Emission wavelength of the Y-branch MOPA system as function of the heater current. Inset: Y-branch laser sketch.

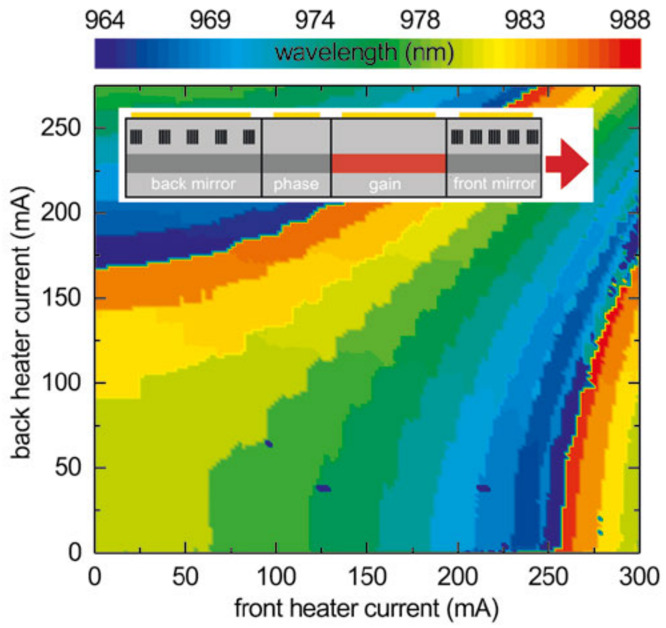

Fig. 3. Emission wavelength of the SG laser as function of the front and back mirror heater currents. Inset: SG laser sketch.

In the second concept, wide wavelength tuning is realized using a SG laser which utilizes the Vernier effect. By operating a single heater, 21.1 nm of discrete wavelength tuning can be achieved with 2.3 nm mode spacing. By operating both heaters embedded on each mirror section, 23.5 nm of quasi-continuous wavelength tuning can be obtained with 115 pm mode spacing [2], see Fig. 3. The SG-based MOPA system amplifies the output power up to 1 W and provides a beam with $M^2 = 1.6$ [3].

Each approach introduces its own advantages and disadvantages. Both light sources emit tunable single-mode emission around 976 nm wavelength with spectral linewidths below 17 pm (spectrometer resolution limit), which is maintained during wavelength tuning. The Y-branch approach has a simple tuning mechanism with mode jumps of the order of 50 pm. Total tuning is limited by the number of branches implemented and the available gain. The SG laser requires a more sophisticated tuning mechanism and manufacturing processes but provides wide tuning, which is ultimately limited by the available gain. In addition, by applying both heaters and the phase section, continuous tuning can be achieved from a SG laser.

Overall, the combination of high power, tunable narrow spectral width, compactness, and stability makes these devices ideal for multiple applications. In particular, non-linear frequency conversion and spectroscopy applications would benefit from these tunable lasers.

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Durchstimmbare Laser werden für die Absorptionsspektroskopie und für die biomedizinische Bildgebung benötigt. Für derartige Anwendungen muss die Emissionswellenlänge kontrollierbar, die Emissionsbreite schmal und die Strahlqualität beugungsbegrenzt sein. Am FBH wurden dazu sehr kompakte Master Oszillator Power Amplifier (MOPA) Systeme mit einer Grundfläche von nur 25 x 25 mm² entwickelt. Für die spektrale Stabilisierung und die Durchstimmbarkeit wurden zwei Varianten als Master Oszillator (MO) neu entwickelt und realisiert: Y-DBR-RW-Laser sowie sogenannte Sample Grating (SG) Laser. Power Amplifier mit einer Trapezstruktur wurden für eine Leistungsverstärkung der Emission eingesetzt. Mit einem zweiarmigen Y-DBR-RW-Laser, über dessen DBR-Sektionen Heizer implementiert sind, konnte ein Durchstimmbereich von 9,7 nm und eine Ausgangsleistung von 5,5 Watt realisiert werden. Im Falle der SG-Laser betrug der Durchstimmbereich 23,5 nm bei einer Leistung von 1 Watt. In beiden Fällen war die Emission nahezu beugungsbegrenzt mit einem M² kleiner 2,2.

Publications

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First iodine-based frequency reference demonstrated in space with an FBH diode laser module

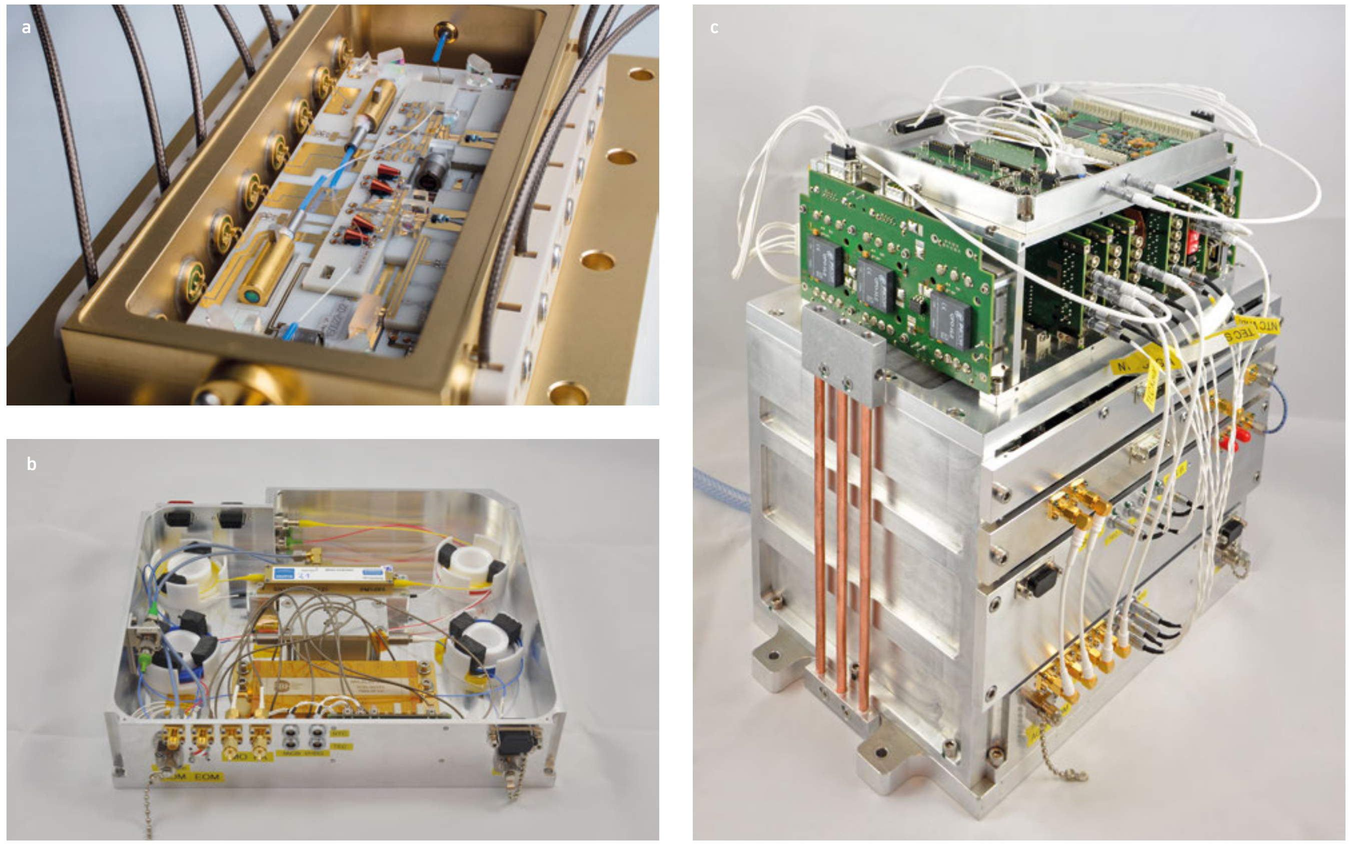

Fig. 1. ECDL-MOPA laser module (a), laser system tray with laser module inside, located in the foreground (b), fully assembled JOKARUS payload with laser system tray at the bottom (c).

In May 2018, the JOKARUS experiment on board the sounding rocket TEXUS54 demonstrated a frequency reference based on molecular iodine for the first time in space. JOKARUS is the German acronym for iodine comb resonator under weightlessness. The successful frequency reference is an important milestone towards laser interferometric distance measurements between satellites as well as for optical clocks in space. The latter technology is a cornerstone of next-generation satellite-based navigation systems like GNSS that provide data for accurate positioning. Frequency references are equally indispensable for fundamental physics investigations such as measuring the gravitational field of the Earth and detecting gravitational waves.

The JOKARUS experiment demonstrated the fully automated frequency stabilization of a frequency-doubled laser emitting at a wavelength of 1064 nm on a molecular transition in iodine. At the heart of the scientific payload, a compact and robust laser system primarily developed by Humboldt-Universität zu Berlin (HUB) and the Ferdinand-Braun-Institut, demonstrated its suitability for space. The laser module designed, built and delivered by FBH is based on a master-oscillator power-amplifier (MOPA) concept: an extended cavity diode laser (ECDL) serves as the MO, whereas a ridge-waveguide semiconductor optical amplifier provides the PA. With an electrical power of about 3.75 W supplied to the module, 550 mW of optical power are provided out of a polarization-maintaining optical fiber at 1064.490 nm with a technical linewidth of 25 kHz (10 μs). The ECDL-MOPA is micro-integrated on an AlN substrate that is itself adhesively bonded into a Kovar housing. A series of coaxial electrical feedthroughs and two fiber-coupled optical ports provide the electrical and optical interface to the ECDL-MOPA. The module's form factor and mass correspond to 12.5 x 7.5 x 2.3 cm^3 and 750 g, respectively. Fig. 1 shows the ECDL-MOPA laser module micro-integrated at FBH (a), the laser system tray with integrated ECDL-MOPA laser module after assembly at HUB (b), and the complete JOKARUS payload (c) assembled at HUB.

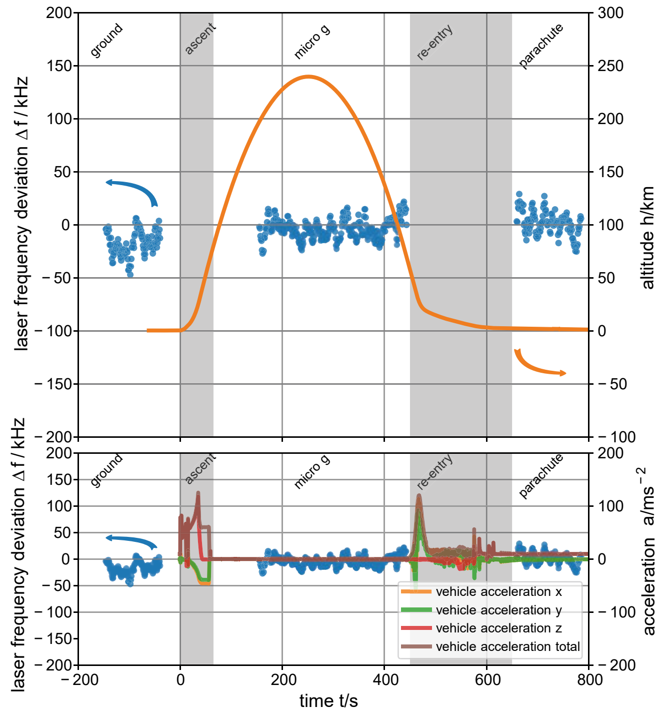

Fig. 2. Laser frequency deviation between iodine reference and frequency comb vs. altitude (top) and acceleration (bottom) of the sounding rocket.

JOKARUS was the first experiment where a fully-packaged micro-integrated ECDL-MOPA laser module from FBH was operated outside the laboratory. Thanks to integrated software and appropriate algorithms, the laser system worked completely autonomously during the flight. For the sake of comparison, a frequency measurement with an optical frequency comb in the separate FOKUS II experiment was carried out during the same space flight. Fig. 2 depicts the altitude data of the sounding rocket versus the beat note of the frequency measurement between the iodine reference and the frequency comb (top), as well as the same beat note versus acceleration data of the sounding rocket. For its maiden flight, the laser module withstood vibration and shock levels up to 21 g, which occur on landing. It was still functioning within specifications during frequency locking tests carried out after recovery of the payload.

Im Mai 2018 wurde im Rahmen des JOKARUS-Projektes auf einer Höhenforschungsrakete erstmals eine optische Frequenzreferenz auf Basis von molekularem Iod erfolgreich demonstriert – ein Meilenstein in Richtung laserinterferometrischer Abstandsmessungen zwischen Satelliten oder für künftige Navigationssatellitensysteme. Das Herzstück der wissenschaftlichen Payload ist ein kompaktes und robustes Lasersystem, das von der Humboldt-Universität zu Berlin und dem Ferdinand-Braun-Institut entwickelt wurde. Damit konnte gezeigt werden, dass sich das System für den Einsatz im Weltraum eignet und auch unter extremen Umgebungsbedingungen reibungslos funktioniert. Als Referenzlaser diente ein mikrointegriertes Lasermodul aus dem FBH. Es besteht aus einem Extended Cavity Diode Laser (ECDL) als Master-Oszillator (MO) mit einer technischen Linienbreite von 25 kHz (1 ms) und einem optischen Halbleiter-Verstärker (PA). Dieser sorgt für eine Ausgangsleistung von 550 mW aus einer polarisationserhaltenden Faser. Der ECDL-MOPA emittiert bei einer Wellenlänge von 1064 nm und wird mittels Frequenzverdopplung auf Iod stabilisiert.

Publications

V. Schkolnik, K. Döringshoff, F.B. Gutsch, M. Oswald, T. Schuldt, C. Braxmaier, M. Lezius, R. Holzwarth, C. Kürbis, A. Bawamia, M. Krutzik, A. Peters, "JOKARUS-Design of a compact optical iodine frequency reference for a sounding rocket mission", Euro. Phys. J. QT 4, 1-10 (2017).

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An ultra-narrow linewidth diode laser for the gravitational wave observatory mission LISA and beyond

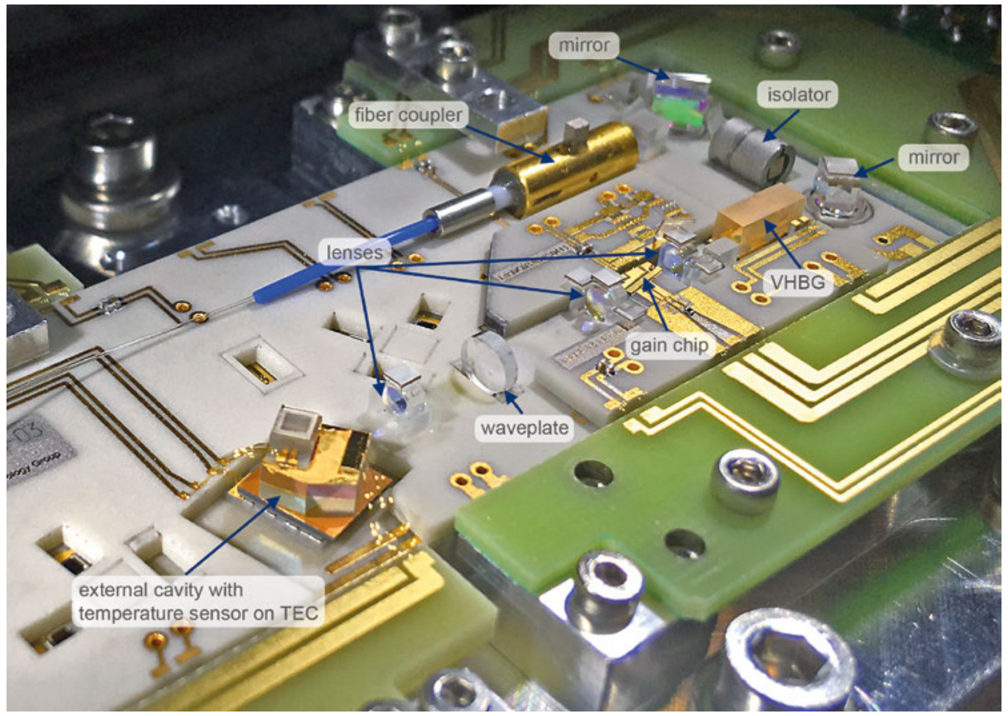

Fig. 1. Micro-integrated narrow linewidth diode laser. The optical components are bonded to an AlN micro-optical bench with a foot print of 80 x 30 mm².

The FBH has developed an ultra-narrow linewidth diode laser which is intended to be deployed in space within the LISA mission. Laser Interferometer Space Antenna (LISA) necessitates lasers with very low phase noise. This requirement is, combined with the fundamental challenges of space deployment, up to now, essentially only met by nonplanar ring oscillator (NPRO) lasers. These light sources are also used for free-space coherent optical satellite communication and are based on optical pumping of solid-state lasers by means of diode lasers. Hence, a diode laser module that directly delivers the required spectral stability would significantly reduce the system complexity for the LISA mission – and also for free-space coherent optical satellite communication applications.

There are a variety of approaches towards narrow linewidth diode lasers. Basically all of them rely on extending the laser resonator beyond the actual laser diode. In extended cavity diode laser (ECDL) geometries, this extended cavity is realized in free space or as a waveguide. To further narrow down the laser linewidth, the length of the extended cavity needs to be increased. This can be achieved effectively by coupling the laser diode to an external cavity. Such an approach has been demonstrated with table-top cavities as well as with micro-resonators. At FBH, an approach towards an ultra-narrow linewidth diode laser module is pursued, which is based on resonant optical feedback from a monolithic cavity. This concept is sketched in Fig. 2.

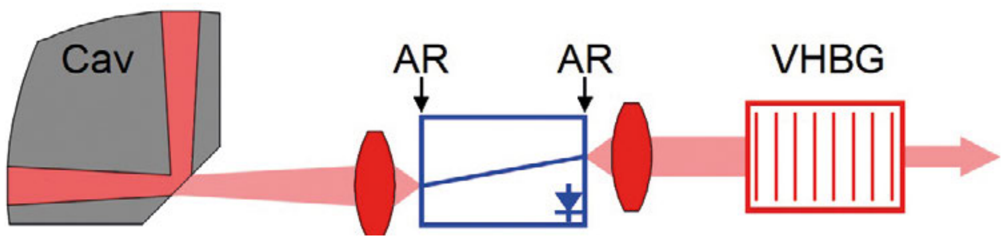

Fig. 2. Diode laser with resonant optical feedback – principle setup consisting of external cavity, AR coated laser diode, VHBG, and lenses.

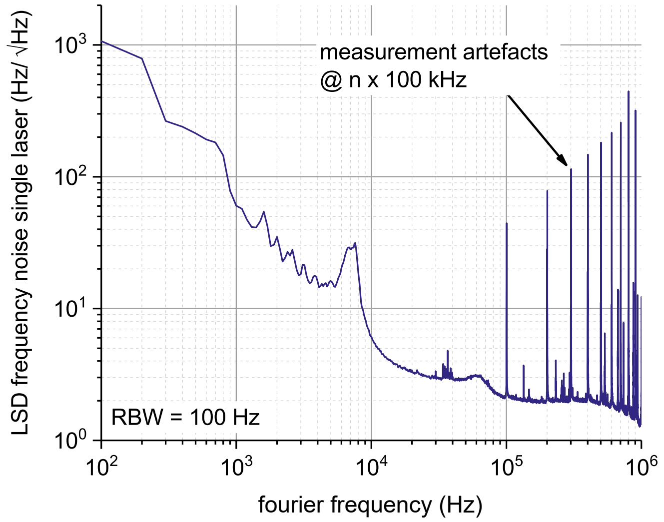

Fig. 3. Linear spectral density (LSD) of the frequency noise of the single laser analyzed with an RBW of 100 Hz.

A first prototype of this laser was realized at 1064 nm, consisting of a diode laser chip, a volume holographic Bragg grating (VHBG), an external cavity, and micro-lenses. The module employs a hybrid micro-integration technology, which allows for a compact and robust setup without any movable parts. The fiber-coupled micro-integrated module is depicted in Fig. 1. All optical components are attached to a structured AlN optical bench with a footprint of 80 x 30 mm², which is surrounded by PCBs serving as electrical interfaces.

Coarse frequency selection is realized with the VHBG via thermal tuning. Coarse frequency tuning is done by means of the external cavity's temperature, which allows for a tuning coefficient of about -8.7 GHz/K. In order to also enable fast frequency tuning and hence high servo bandwidth, electro-optical tuning of the $LiNbO_3$ cavity is employed. This mechanism allows for very fast fine tuning of the frequency with 6.6 MHz/V. To evaluate the laser's frequency stability, a self-delayed-heterodyne measurement was carried out. The resulting frequency noise linear spectral density of the single laser is depicted in Fig. 3. The level of the white frequency noise can be estimated to be $2\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at maximum. This corresponds to a Lorentzian linewidth of less than 13 Hz. Towards lower Fourier frequencies, the frequency noise increases with a slope on the order of $10^5\ \mathrm{Hz}^{1.5}$ / f. The low frequency behavior results in a FWHM linewidth of 34 kHz for a 10 ms measurement time. Hence, the employment of an external cavity with a linewidth in the range of a few tens of MHz enabled to significantly reduce the phase noise compared to monolithic diode lasers or even standard extended cavity diode lasers.

This work was supported by the European Space Agency (ESA) within the activity "Gravitational Wave Observatory Metrology Laser", ESA Contract No. 4000119715/17/NL/BW.

Für die LISA Weltraummission hat das FBH einen ultra-schmalbandigen Diodenlaser entwickelt, der das benötigte geringe Phasenrauschen liefert. Die für dieses Einsatzszenario erforderlichen Werte wurden bisher im Prinzip nur von NPRO-Lasern erreicht – das heißt Festkörperlasern, die von Diodenlasern optisch gepumpt werden. Nun wurde die geforderte Schmalbandigkeit auch mit einem Diodenlaser durch resonante optische Rückkopplung von einem externen Resonator erreicht. Das Konzept wurde mikro-integriert umgesetzt, was einen kompakten und robusten Aufbau ohne bewegliche Teile ermöglicht. Mit diesem Diodenlasermodul wurde ein weißes Frequenzrauschen von weniger als $2\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ erreicht. Dies entspricht einer Lorentz-Linienbreite von weniger als 13 Hz. Das niederfrequente Rauschen ergibt eine FWHM-Linienbreite von 34 kHz (@ 10 ms). Dank eines externen Resonators aus $LiNbO_3$ kann die Emissionsfrequenz des Lasers zudem schnell elektro-optisch durchgestimmt werden, was wiederum hohe Regelbandbreiten erlaubt.

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Photonics Photonik

High-power UVB LEDs with enhanced functionality

High power conversion efficiencies and long-term stability are crucial features of ultraviolet-B (UVB) light emitting diodes (LED) for use in applications such as phototherapy, plant growth lighting, and sensing. The FBH develops new techniques to increase the efficiency of (In)AlGaN-based UVB LEDs (280 nm – 320 nm) and to improve the lifetime and functionality of the devices. This is addressed by working on all aspects of the fabrication chain – from epitaxy through chip processing to packaging.

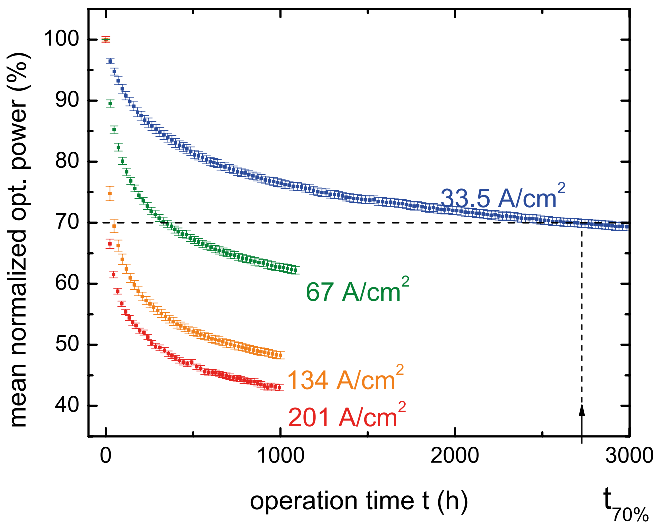

Fig. 1: Optical power vs. time of UVB LEDs run at different current densities. The values are normalized to the initial value. The junction temperature was kept at (90 ± 5) °C.

To improve their lifetime, the degradation behavior of UVB LEDs was investigated under various operating conditions, such as temperature, ambient atmosphere and current density. In addition, the influence of the heterostructure design and growth conditions as well as the device processing and packaging on the lifetime of the LEDs was studied. The current density was determined to be one of the key factors as the lifetime of the devices shows an inversely proportional relationship to the cube of the current density (Fig. 1). In future experiments, the footprint of the LED chip will therefore be increased to reduce the current density. Moreover, material analysis indicates that hydrogen-containing defect complexes in the p-side and active region break due to interaction with hot-carriers. The effect likely results in the formation of acceptor states which act as non-radiative recombination centers and decrease LED efficiency. Hydrogen may arise from the gas environment during epitaxial growth, from the insulation layer used during chip processing or from deoxidizing atmospheres employed for UVB LED chip packaging. To improve the lifetime of the LEDs, methods to reduce the hydrogen in the device will be investigated. Currently, the best UVB LEDs, run at 100 mA, show extrapolated lifetimes of up to 3,000 hours (L70) and 40,000 hours (L50), respectively.

To increase the functionality of UV LEDs, a new silicon SMD package was developed by FBH's Advanced UV for Life consortium partner CiS Forschungsinstitut für Mikrosensorik, see Fig. 2. The cost-efficient package offers a low thermal resistance and can integrate versatile features such as an aluminum reflector for increased light extraction and ESD protection diodes. The packages can be hermetically sealed using quartz lids to protect the LED chip. Furthermore, a Fresnel lens was developed to obtain a more directed emission of the light. An alternative method to protect the LED chip, when hermeticity is not required, is to use a UV-transparent encapsulant. This technique offers the additional advantage of improved light extraction from the LED chip due to the decrease of total reflection inside the chip. Initial tests using encapsulants in the shape of a hemispherical dome on UVB LEDs showed a nearly two-fold increase in the output power up to 65 mW at 350 mA. Investigations on the reliability of the devices are currently in progress.

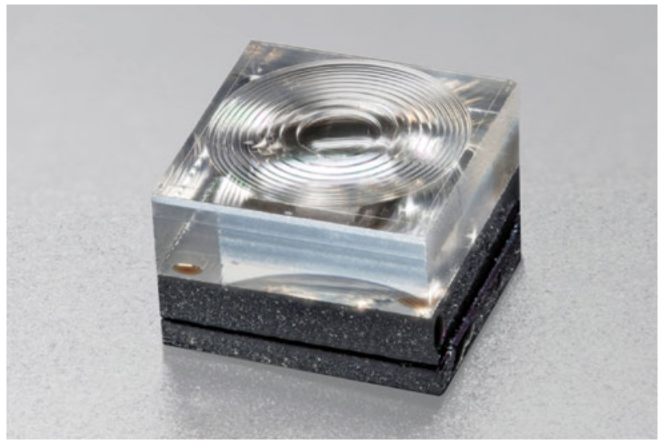

Fig. 2: Silicon SMD cavity package developed by CiS with soldered UVB LED chip, integrated Zener diode and quartz Fresnel lens.

By combining the described methods to increase efficiency and reliability of UVB LEDs, FBH has developed irradiation modules emitting at 310 nm, which are successfully being used for plant growth lighting (Fig. 3).

This work was supported by the German Federal Ministry of Education and Research (BMBF) within the Advanced UV for Life consortium.

Fig. 3: Irradiation module for plant growth investigations consisting of UVB LEDs (310 nm) combined with red (660 nm) and blue (451 nm) LEDs.

Das FBH entwickelt neue Technologien, um die Effizienz, Lebensdauer und Funktionalität von (In)AlGaN-basierten UVB-LEDs zu verbessern. Diese Arbeiten finden entlang der gesamten Herstellungskette statt – von der Epitaxie und Chipherstellung bis hin zur Chipmontage. Studien zum Degradationsverhalten von UV-LEDs mit einer Emissionswellenlänge von 310 nm haben gezeigt, dass insbesondere die Stromdichte und das Vorhandensein von Wasserstoff in der LED-Heterostruktur die Lebensdauer begrenzen. Daher werden künftig die Abmessungen der LED-Chips erhöht und Methoden untersucht, um den Wasserstoff im Bauelement zu reduzieren. Beim Advanced-UV-for-Life-Partner CiS Forschungsinstitut für Mikrosensorik wurde ein neues Siliziumgehäuse entwickelt, das die Funktionalität der UV-LEDs erhöht. Das Gehäuse mit Aluminiumreflektor, integrierter ESD-Schutzdiode und Quartz-Fresnellinse resultiert in einer gerichteteren Lichtemission. Zusätzlich führten erste Tests mit verschiedenen Verkapselungsstoffen zu einer Verdopplung der Ausgangsleistung auf bis zu 65 mW bei 350 mA.

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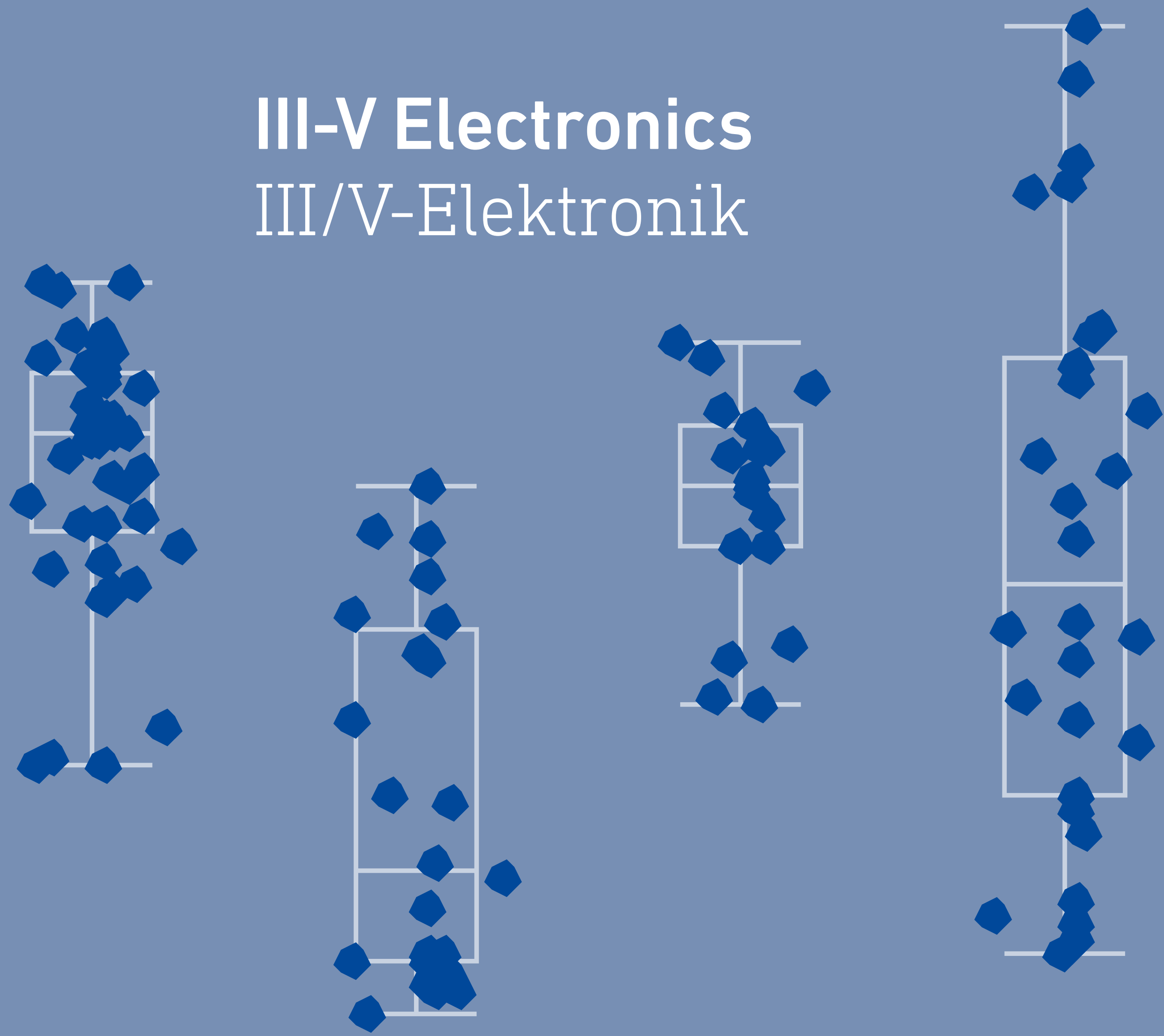
For further information:

https://www.fbh-berlin.com/research/photonics

III-V Electronics
III/V-Elektronik



III/V-Elektronik

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) und zur Erhöhung der Frequenzagilität (BST-Varaktoren).

- ***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 Indium-Phosphid (InP) Heterobipolartransistoren (HBTs) mit Betriebsfrequenzen von derzeit bis zu 530 GHz. 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 Phänomene versprechen eine Einsatzmöglichkeit 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 Ga_2O_3*** – 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.

III-V Electronics

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 amplifier modules based on GaN for the use in base stations for mobile communications*** – the focus is on concepts improving energy efficiency (supply modulation/envelope tracking) and enhancing frequency agility (BST varactors).

- ***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 operating at frequencies up to 530 GHz 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 phenomena promise 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.

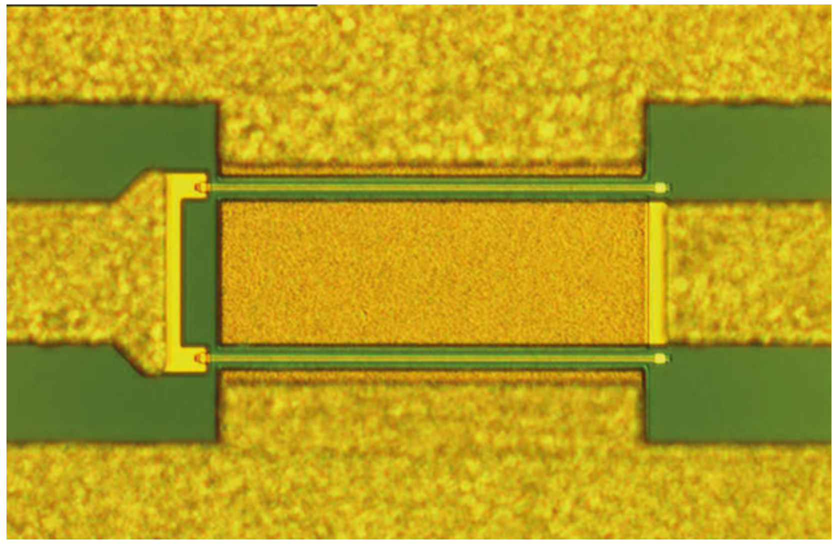
- ***Lateral and vertical GaN-based switching transistors & Schottky diodes for high voltages*** – for high-efficiency power converters with high clock speed, low weight, and volume. They are well-suited for a great variety of applications, e.g., in the field of electro-mobility.

- ***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-bandgap materials such as AlN and Ga_2O_3*** – 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.

Improved modeling of trapping effects in GaN HEMTs – enables reliable and simplified circuit design



250 µm AlGaN/GaN HEMT in a 250 nm GaN-on-SiC process.

GaN high electron mobility transistors (HEMTs) are regarded as one of the most promising RF power transistor technologies thanks to their high-voltage high-speed characteristics. However, GaN HEMTs suffer from trap-related dispersive effects, which hamper achievable output power and linearity. Dispersion and memory effects have a significant impact on microwave circuit behavior. It is therefore required to augment common HEMT models with accurate trap models that can reliably be determined from measurement. An accurate and efficient trap model has been developed within FBH's Joint Lab BTU-CS – FBH Microwave, operated together with Brandenburg University of Technology Cottbus-Senftenberg (BTU-CS).

The well-established Chalmers (Angelov) model was employed as the basis. Fig. 1 shows the equivalent circuit of the trap model which combines two approaches. The first part of the model relies on scaling the trap-sensitive Chalmers model parameters depending on trap states, which yields a convenient parameter extraction. However, it is of little use in predicting the RF output conductance under large-signal condition. Thus, the so called Quéré model was integrated to overcome this drawback. This model determines an effective pseudo gate source voltage related to the trap states according to a fitting parameter k. However, no publication so far exactly addressed how to determine and describe this parameter. In contrast to the Quéré model's complicated bias dependence of the parameter k, the values of k for the combined model tend to be constant. This is owed to the prediction of the behavior of the related traps through the parameter-scaling model and can significantly simplify the model parameter extraction process.

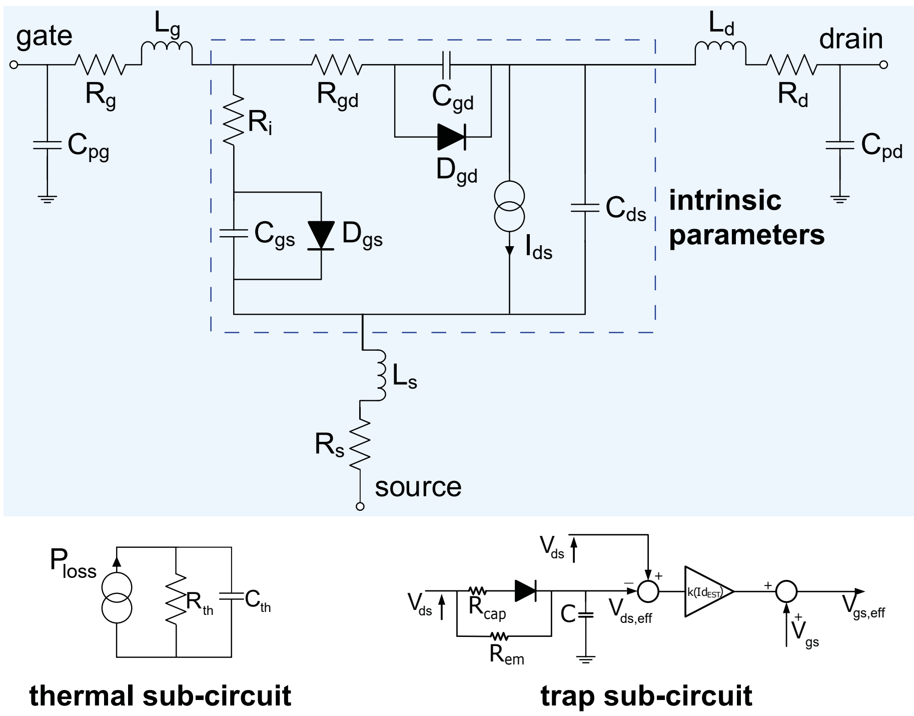


Fig. 1. Large-signal model topology for GaN HEMTs with trapping sub-circuit.

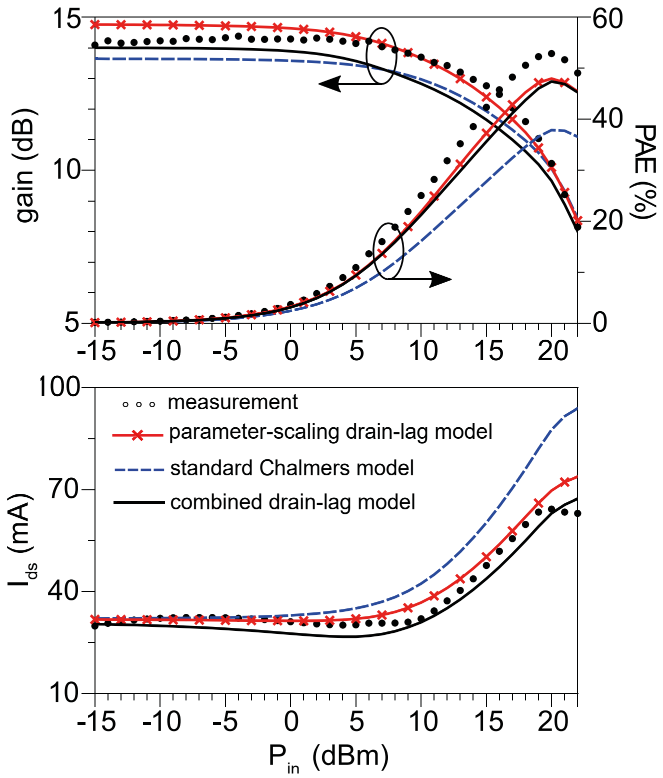


Fig. 2. Measured and simulated Gain, PAE, and mean Ids as a function of input power P_{in} at 8 GHz for V_{ds} = 28 V.

The augmented Chalmers model including the trap model was then implemented in a Verilog-A design kit for the ADS simulator. To verify this large signal model, load pull measurements at 28 V and at 8 GHz were performed. The source and load impedances were chosen as optimum impedances for providing maximum output power.

The impact of trapping effects on the average output drain-source current is particularly obvious, since the trapping effects significantly hamper the achievable output power and degrade the output current. Results are shown in Fig. 2. The traditional Chalmers model does not predict GaN HEMTs very well. The parameters-scaling model significantly improves the prediction accuracy for PAE and mean output current, especially at higher V_{ds} condition, where the impact of trapping effects is more pronounced. Finally, the combined model further increases accuracy in the linear and nonlinear domain.

As a result, an accurate and efficient trap model for GaN HEMTs based on the Chalmers model is available. The improved model combines two trap descriptions, not only benefiting from the advantages of both models but also overcoming their drawbacks. Since only four constant model parameters have to be extracted, the modeling procedure for trapping effects is greatly simplified. It therefore enables swift and reliable circuit design in the FBH GaN-HEMT process.

GaN-HEMTs zählen dank ihrer hohen Durchbruchspannungen und Driftsättigungsgeschwindigkeit zu den vielversprechendsten Technologien für HF-Leistungstransistoren. Allerdings sind sie anfällig für Trapping-Effekte, die sowohl Ausgangsleistung wie auch Linearität verschlechtern. Daher müssen diese Effekte für ein gutes nichtlineares Großsignalmodell bei GaN-HEMTs genau und umfassend modelliert werden. Das Joint Lab BTU-CS – FBH Microwave hat ein entsprechendes Trap-Modell entwickelt, das auf dem Chalmers Modell beruht, einem gängigen Großsignalmodell für Transistoren, das in kommerzieller Entwurfssoftware weit verbreitet ist. Das neu entwickelte Trap-Modell kombiniert zwei Ansätze, die zu hochgenauen Simulationen führen, bei denen die Parameter zugleich einfacher bestimmt werden können. Anhand von Großsignalmessungen wurde die Gültigkeit dieses Modells nachgewiesen. Das FBH nutzt den verbesserten Modellierungsansatz, um seine Schaltungen in GaN-HEMT-Technologie zuverlässig und präzise zu entwerfen.

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III-V Electronics III/V-Elektronik

Improving efficiency for wideband operation for future wireless communications and space

Mobile communication has evolved into world-wide mobile networks with an ever increasing demand for higher data rates. Since the number of users in urban areas rise, cells will become smaller to make efficient use of limited spectrum, and more base stations will be deployed. To achieve a higher bandwidth, carrier aggregation is required, signals will become more complex and will exhibit higher peak-to-average power ratios (PAPR). At the same time, full coverage in rural areas remains an issue.

Therefore, present high-power 4G systems will be enhanced with new features and the future 5G telecom standard will include vastly different base station technologies at different frequencies and output powers. A key aspect for this scenario is energy awareness: Information and communication technology (ICT) consumes about 5 % of the worldwide electrical power, with an annual growth rate of about 10 % for communication networks. Hence, the consumed energy per transmitted bit has to be minimized, which motivates improved designs of mobile devices and ICT infrastructure. The main power consumer in the mobile network infrastructure is the RF power amplifier (PA) which is responsible for more than half of the power consumption of a base station. This is true for the established systems but is expected to worsen for future systems as the operational frequency, the instantaneous bandwidth, and the PAPR of the signal increases. Considering the fact that the number of units is also expected to rise, the overall dissipated power from base station PAs will increase drastically.

FBH developments play an important role in achieving very efficient flexible solutions meeting the requirements of future 5G systems in the mm-wave range. Two main tracks are followed: first, improving back-off efficiency by dynamically modulating the supply voltage of a linear amplifier according to the instantaneous power of the signal and second, the fully digital transmitter. Both approaches rely on very efficient GaN switching stages, whose design and fabrication have become an FBH specialty. State-of-the-art results have been shown both in high-power discrete level supply modulated (class-G) systems and in fully digital transmitter topologies, reaching back-off efficiencies superior to established solutions.

MMIC with integrated class-G switching stage for discrete level supply modulation for 5G and space applications

The PA efficiency is drastically reduced for high PAPR signals due to the low back-off efficiency of linear PAs. Therefore, the back-off efficiency has to be improved. A promising method to enhance efficiency is class-G or discrete level supply modulation, with FBH being in the frontline with state-of-the-art performance for its hybrid solutions in the 2 – 3 GHz range. The supply voltage is dynamically adjusted in discrete steps according to the instantaneous power of the signal. A schematic of a two level system is shown in Fig. 1. At low power levels, the PA is supplied by the low voltage (V_{LOW}) over the diode (D_0). With increasing signal power, however, the transistor (T_1) is switched, the diode blocks and the high voltage (V_{HIGH}) supplies the PA. Apart from the external isolated gate driver, this is a very simple topology to be easily implemented as a MMIC with expected switching frequencies in the GHz range. A single-stage amplifier for operation in the 19 – 26 GHz range, targeting space applications and 5G, is shown in Fig. 2. It has a built-in switching stage to allow very fast class-G switching between two supply voltages in the 8 – 28 V range. It was implemented in the 150 nm gate width technology at FBH. At 20 GHz it has approximately 7 dB linear gain. Large-signal characterization indicates a peak output power density of more than 2 W/mm gate width and a peak drain efficiency above 40 %. Quasi static measurements show a possible maximum efficiency improvement of 28 %-points at 26.6 dBm output power when the supply voltage is reduced from 28 V to 8 V. Post processing using a 10.6 dB PAPR signal for 1 W peak output power exhibits a possible drain efficiency improvement for the PA alone of 10 %-points (from 5% to 15%). This result was achieved with a 2-stage class-G modulator operating at 8 V and 20 V based on an ideal switch.

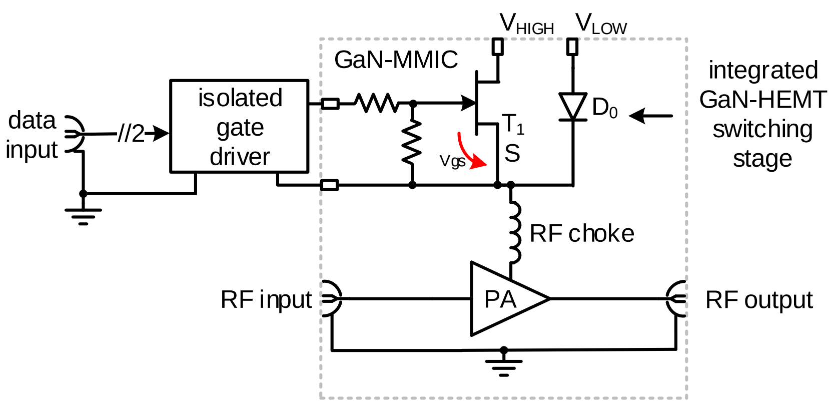

Fig. 1. Schematic of a class-G system with a two-level supply modulator [1].

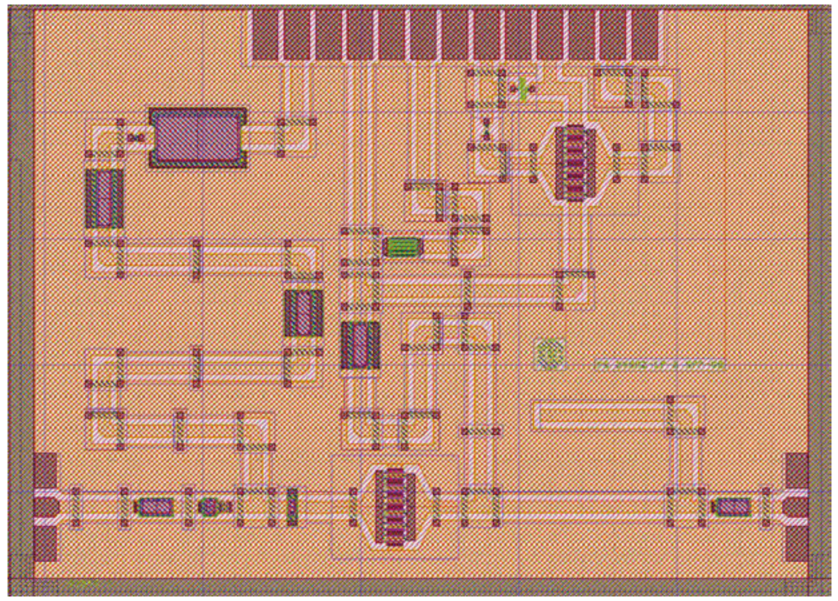

Fig. 2. MMIC class-G amplifier with voltage switch. Designed for operation in the 20 - 26 GHz range. Based on 12 x 50 µm transistors [1].

This MMIC will be the core building block for first investigations using class-G modulation for very wide-band applications like 5G-MIMO systems. Verifying already performed theoretical investigations of supply modulated MIMO systems [2] will soon be possible at FBH thanks to a new multichannel MIMO measurement system, which is scheduled to be in operation by the end of 2019. Funding for this equipment was provided by the German Federal Ministry of Education and Research within Research Fab Microelectronics Germany (FMD).

Etwa 5 % des weltweiten Energieverbrauchs entfallen auf den Einsatz von Informations- und Kommunikationstechnologien – mit einer jährlichen Steigerung von 10 %. Die geplanten 5G-Systeme nutzen höhere Frequenzen und ermöglichen dadurch eine größere Signalbandbreite. Das FBH arbeitet an zwei Lösungen, um deren Energieeffizienz zu verbessern: Versorgungsspannungsmodulation für Linearverstärker und vollkommen digitale Sendeempfänger. Diese wurden bereits für niedrige Frequenzen erfolgreich realisiert und werden nun als integrierte monolithische Mikrowellenschaltkreise (MMIC) für höhere Frequenzen umgesetzt. Ein Beispiel ist ein Leistungsverstärker für Raumfahrtanwendungen und 5G im Frequenzbereich 20 - 27 GHz mit einem integrierten Klasse-G-Modulator. Damit wird die Betriebsspannung für den Leistungsverstärker in diskreten Spannungsstufen der momentanen Signalleistung angepasst. Dieser MMIC ermöglicht weitere Untersuchungen, um neue hocheffiziente 5G-Systeme und die dafür erforderliche Steuerung der Richtwirkung von Mehrantennensystemen zu entwickeln.

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III-V Electronics III/V-Elektronik

Versatility, bandwidth and efficiency – a novel digital power amplifier MMIC

The rapid success of digital logic over the past few decades revealed the impressive versatility of digital circuits. Not only logic operations but also switch mode power supplies benefit from the targeted exploration of discrete states. GaN HEMT transistors enable the use of digital techniques for RF power amplification by combining very high switching speed with high-power handling capability. Since several years, FBH is pursuing the digital power amplifier (PA) approach for mobile base stations. In 2018, a novel robust, compact and as efficient as flexible chip with reduced complexity has been realized (see Fig. 1) using the in-house 0.25 µm GaN-HEMT process. To prove the versatility of the digital concept, the device was used to build three different modules, each targeted to enhance efficiency in 5G mobile communications: a complete digital transmitter chain, a discrete supply modulator and a continuous supply modulator (DC/DC converter).

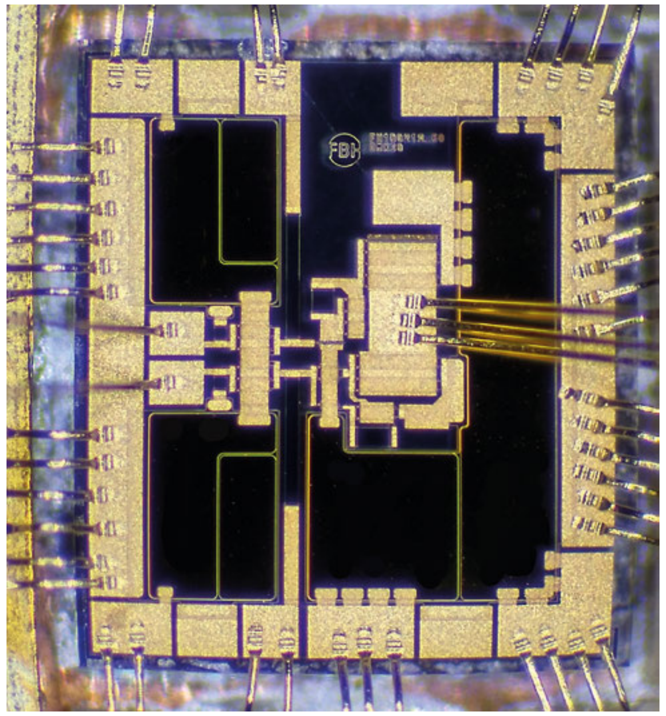

Fig. 1. Fabricated novel digital power amplifier MMIC; size: 1.8 x 1.8 mm².

Digital transmitter chain

The architecture of today's mobile base stations is almost completely digitized except for the RF power amplifier part. A complete digital solution is therefore highly desirable in order to improve efficiency and compactness and thus save cost. The digital transmitter fully replaces the analog Tx chain from the upconverter to the output filter. In addition to the novel PA MMIC, the realized digital Tx chain (Fig. 2) includes a digital modulator, a simple lumped-element output bandpass filter and a T/R switch to separate between transmit and receive path. For a typical communication signal with 5 MHz bandwidth, the digital transmitter chain provides highest efficiency (47 %) and linearity (> 52 dB ACLR), which is competitive with comparable analog solutions. Also, no bulky high-Q filter technologies are necessary, which makes this digital solution even smarter. The realized digital transmitter chain with its compact size is predestined for any (massive) MIMO application, utilizing beam forming techniques to multiple receivers where it can be mounted right on the back of each antenna element.

Supply modulators

Since the digital PA approach is inherently broadband it is also interesting for other efficiency and bandwidth enhancement techniques like supply modulation. Here, the supply voltage of a highly efficient analog PA is modulated according to the envelope of the modulated input signal. This helps significantly reducing losses, which boosts efficiency.

When configured as a DC/DC converter for continuous supply modulation, a modulation bandwidth of 300 MHz was demonstrated. This is the highest value a switch-mode supply modulator reached so far. When configured as a discrete supply modulator, which switches between discrete voltage levels, excellent rise and fall times in the 100 ps range are achieved. This leads to clock rates easily reaching 3 GHz and beyond, enabling extreme IQ modulation bandwidths up to 6 GHz.

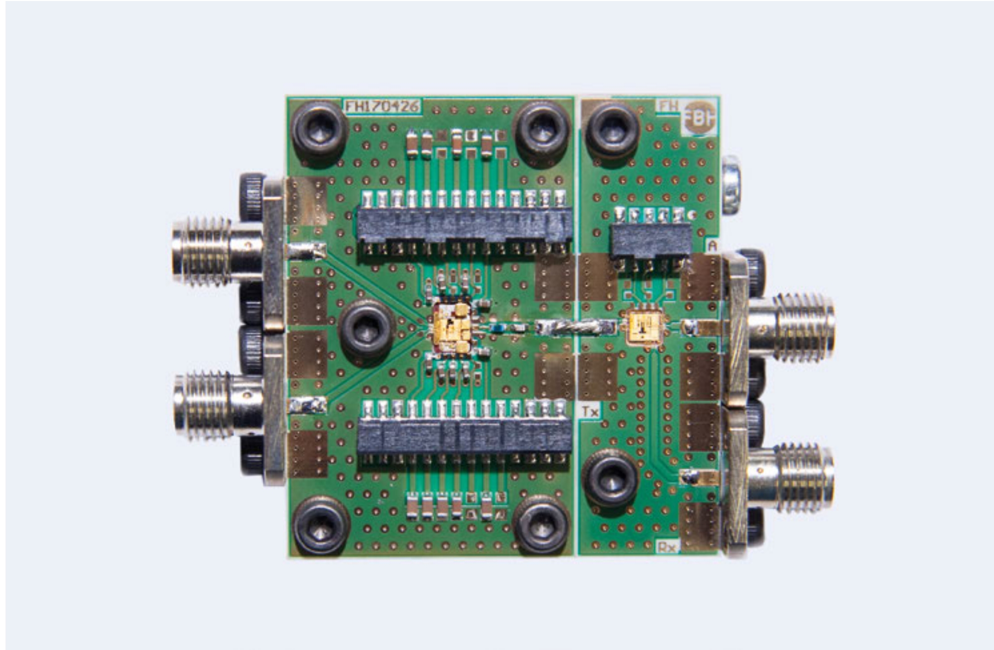

Fig. 2. Digital transmitter module including digital power amplifier chip, output bandpass filter and transmit/receive switch.

These results prove the suitability for the use in future efficient RF power amplifier solutions in 5G communication systems and beyond.

The work was supported by the German Research Association (DFG) under ref. "WE 6288/1-1".

Digitale Leistungsverstärker sind die ideale Lösung, wenn es darum geht, die mobile Infrastruktur zu digitalisieren. Einen dafür geeigneten effizienten Verstärker-Chip hat das FBH auf seinem 0,25 µm GaN-HEMT Prozess realisiert. Mit dem neuartigen, kompakten Chip wurden drei Module aufgebaut, die verschiedene Konzepte verfolgen, um die Energieeffizienz der mobilen Infrastruktur zu steigern: Ein digitaler Transmitter liefert höchste Linearität und Effizienz für breitbandige Signale und eignet sich damit besonders für Mehrantennensysteme, bei denen der kompakte Tx auf der Rückseite der Antenne montiert wird. Mit dem Chip wurden zudem zwei Supply-Modulatoren für Envelope-Tracking-Systeme realisiert. Sie verstärken sehr effizient Signale mit extremen Modulationsbandbreiten. Die realisierten Module belegen, dass sich das digitale Verstärkerkonzept flexibel anpassen lässt und sich somit ausgezeichnet für die Infrastruktur von 5G eignet, der Mobilfunkgeneration der Zukunft.

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Millimeter and terahertz components for communications and imaging

The continuously and rapidly growing internet traffic calls for ever higher bandwidth. Hence, wireless networks are driven to drastically increased operation frequencies, eventually to the terahertz (THz) range [1]. Also, radar and imaging at THz frequencies offers a complementary approach to non-destructive x-ray imaging of dielectric materials such as plastic, ceramic and composite materials. Currently, emerging THz applications in the range from 100 GHz to 1000 GHz lack cost-effective integrated electronic solutions with sufficient output power and bandwidth. These requirements, however, are a prerequisite for applications beyond niche markets that can only be fulfilled by advanced semiconductor process technology.

The FBH has developed an InP MMIC transferred substrate process in recent years, as InP-based semiconductor devices offer the highest cut-off frequencies and largest breakdown voltages. This process exhibits reduced parasitic capacitances compared to standard triple mesa processes and thus better scaling capabilities towards THz frequencies. Heterointegrated with SiGe BiCMOS, bandwidth and power generation capability of InP DHBT technology is combined with the feasibility of complex circuits on a single chip, therefore avoiding coupling losses and reducing packaging costs.

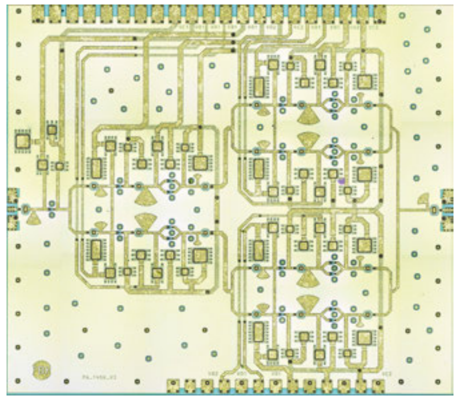

Fig. 1. Increasingly complex – 140 GHz high-power amplifier consisting of 19 DHBT transistors, 39 NiCr resistors, and 72 capacitors.

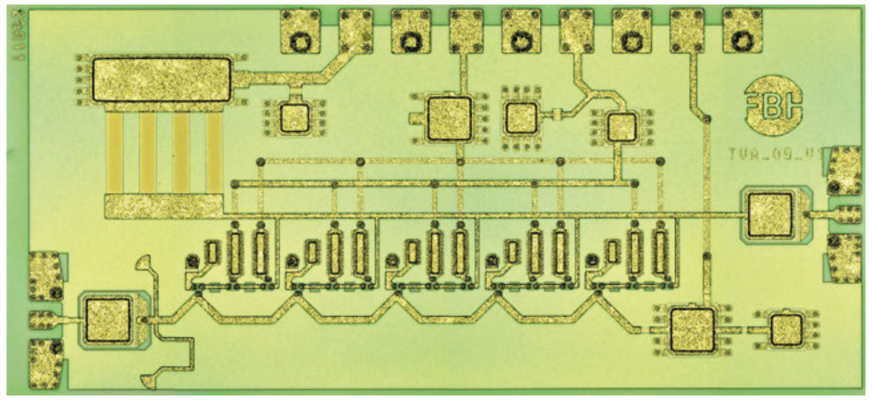

Fig. 2. Extremly broadband circuits – highly linear travelling wave amplifier with 11 dB gain and a 3 dB bandwidth derived from 175 GHz.

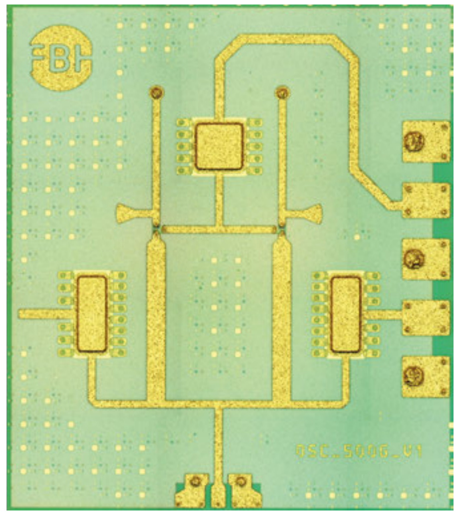

Fig. 3. Circuits at highest frequencies – push-push oscillator operating at 480 GHz with -11 dBm output power.

Increased circuit complexity and process stability plus simplified packaging

With 20 lithographic layers, the InP process is the most complex process at FBH that has been stabilized over the last years. In 2018, more complex circuits became feasible, such as the 140 GHz high-power amplifier shown in Fig. 1, consisting of 19 DHBT transistors, 39 NiCr resistors, and 72 capacitors. A circuit yield of 88 % was verified for a mixer with 6 DHBTs and 18 capacitors on-wafer prior to packaging.

To simplify packaging, grounded through silicon vias (TSV) have been introduced as standard module into the process [4], suppressing the propagation of substrate modes at THz frequencies. The silicon host substrate with TSVs needs to be thinned only to a final thickness of 125 µm. This avoids aggressively thinning fragile III-V wafers to 50 µm or less and thus greatly simplifies backend processing and package assembly.

InP MMICs for THz communications and imaging

A highly linear travelling wave amplifier consisting of 15 HBTs, 24 capacitors and 8 NiCr resistors (Fig. 2) was realized, exhibiting 11 dB gain with 3 dB bandwidth at 175 GHz [6,13]. Moreover, a power amplifier at 140 GHz with 13 dBm output power was demonstrated.

Recent improvements in its InP HBT technology enabled FBH to realize push-push oscillators operating at 480 GHz with -11 dBm output power and a DC-RF conversion of 0.6 % (Fig. 3). These oscillators can be applied in source arrays used in THz imaging applications, for example in conjunction with the THz plasmonic camera realized in FBH's 250 nm GaN process.

This work was supported in part by the Leibniz Association within the Leibniz Competition project THz InP HBT and by the German BMBF within the "Research Fab Microelectronics" framework under ref. 16FMD02. Further support was provided by the German National Aeronautics and Space Research Centre under project MIMIRAWE and by the European Commission under the Horizon 2020 project Ultrawave.

Entwicklungen im Terahertz-Bereich eröffnen neue Anwendungen in der Breitbandkommunikation und der durchleuchtenden Bildgebung. Derzeit fehlen jedoch integrierte elektronische Lösungen, die kosteneffizient sind und die erforderlichen Ausgangsleistungen und Bandbreiten liefern. Da Bauteile auf InP-Basis höchste Grenzfrequenzen mit größten Durchbruchspannungen aufweisen, hat das FBH in den vergangenen Jahren entsprechende InP-MMICs entwickelt. Diese Schaltungen basieren auf dem hauseigenen Substrattransferprozess und bieten eine exzellente Skalierbarkeit bis hin zu höchsten Frequenzen. 2018 wurde eine Vielzahl von InP-Schaltkreisen entwickelt, die immer komplexer werden, wie etwa ein 140 GHz-Leistungsverstärker, der aus 19 DHBT-Transistoren, 39 NiCr-Widerständen und 72 Kondensatoren besteht. Des Weiteren wurde ein hochlinearer Wanderwellenverstärker mit 11 dB Gewinn und einer 3 dB Bandbreite bei 175 GHz bzw. einem 480 GHz-Oszillator mit -11 dBm Ausgangsleistung entwickelt.

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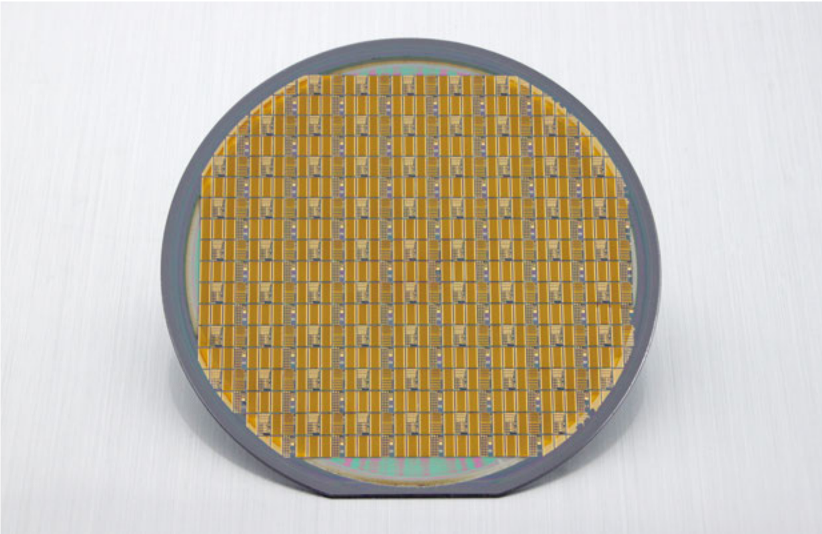
III-V Electronics III/V-Elektronik

Low-dispersion power transistors based on aluminum nitride buffer structures – targeting efficient power amplification and high-voltage switching



4" wafer with AlGaN/GaN transistors for power electronic applications.

Lateral gallium nitride (GaN)-based transistors (HEMTs) have recently demonstrated superior performance in efficient RF power amplification in the GHz regime and as high-speed switch in small and light-weighted power converters up to 600 V. For both fields of application, advantage is taken from the GaN material high breakdown strength and from the well-confined high electron density and mobility in the transistor channel at the AlGaN/GaN hetero contact. While GaN transistors for RF and for power-electronic applications are already commercially available, FBH now targets new aluminum nitride (AlN) based devices that promise to surmount performance limitations of the current GaN transistor technology.

One challenge of the currently used GaN transistor design is the GaN buffer beneath the transistor channel. GaN compensation doping with iron (Fe) or carbon (C) is needed to keep the channel electrons well confined inside the GaN channel at high drain voltages and to suppress off-state leakage currents. The dopant-related trap states are, however, the root cause for dispersion effects, frequently seen in GaN transistors. They are interpreted as current collapse for RF applications and increased dynamic on-state resistance for power-switching applications.

Using the ultra-wide band gap material AlN instead of GaN as buffer material would allow for excellent transistor channel confinement without requiring compensation doping. Dispersion effects thus should reduce. The high material breakdown strength and heat conductivity are additional benefits of AlN.

FBH now confirmed the principal benefits of AlN buffer layers and demonstrated AlGaN/GaN HEMTs with higher breakdown strength and with less dispersion as compared to AlGaN/GaN HEMTs with conventional GaN buffer. When pulsing (0.2 µs) into the on-state IV curve from off-state drain bias points (30 V and 50 V), the saturation current reduces (current collapse) and also the slope in the linear regime drops (dynamic on-state resistance increase) with increasing drain bias, see Fig. 1. Both dispersion signatures are considerably reduced for the new AlN-buffer device (Fig. 1, right) as compared to a conventional GaN-buffer device (Fig. 1, left). The decreased dispersion for the AlN-buffer devices is also statistically fortified, since their current collapse parameter D, giving the relative reduction of the saturation current, is less than that for 156 transistors from 6 recent process runs using the conventional GaN:Fe buffer, see Fig. 2.

Further, the new AlN-buffer devices combine a high breakdown voltage scaling of 140 V/µm gate-drain separation with low increase in dynamic on-state resistance of only 18 %, when pulsing for 0.2 µs from 65 V off-state drain bias into device on-state, see Fig. 3. In comparison, GaN-buffer devices grown on SiC substrates show significantly reduced breakdown strengths and GaN-on-Si devices have significantly more dispersion.

Financial support by the German BMBF within the 'Research Fab Microelectronics (FMD)' framework under ref. 16FMD02 and of the Leibniz Association within its 'Leibniz Competition' program in the frame of the funding scheme 'Leibniz Competition' is gratefully acknowledged.

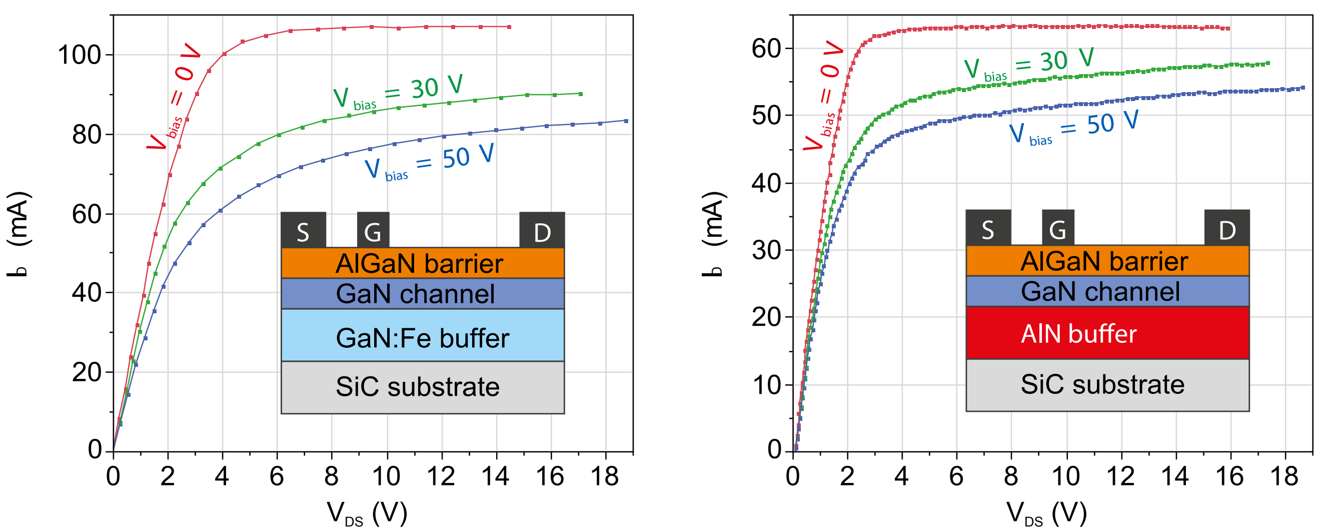


Fig. 1. Pulsed (0.2 µs) on-state IV curves with 0 V (red), 30 V (green) and 50 V (blue) off-state drain bias for a GaN transistor with conventional GaN:Fe buffer (left) and one with the new AlN buffer (right).

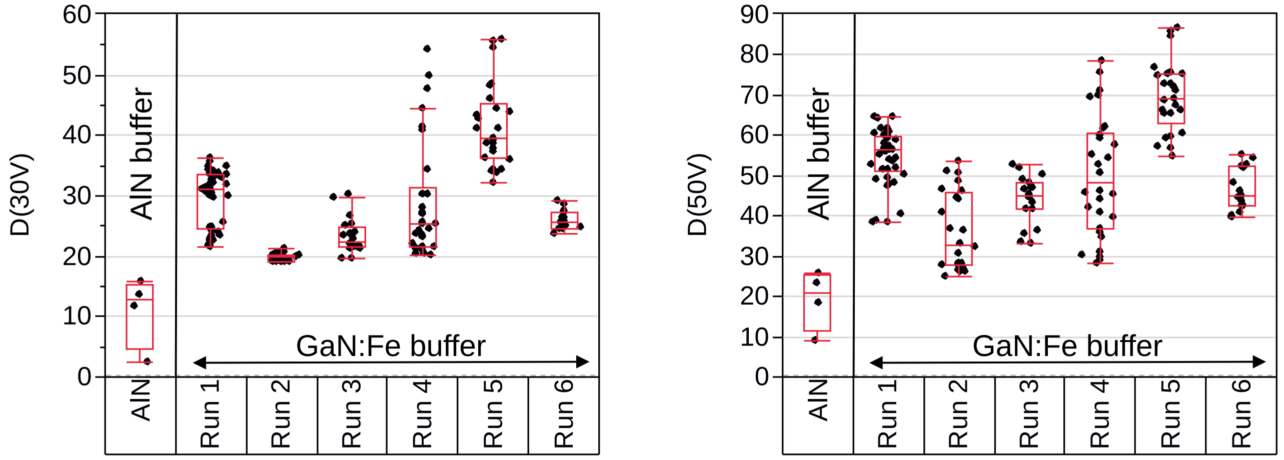


Fig. 2. Percentage of saturation current reduction, D, at V_{DS} = 10 V (see Fig. 1) for 50 V off-state drain bias. The new AlN buffer transistors are compared to transistors with GaN:Fe buffer from 6 recent process runs.

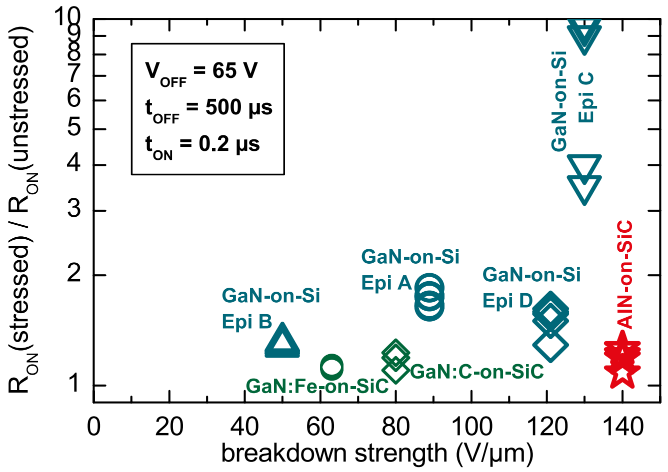


Fig. 3. Dynamic on-state resistance increase versus breakdown voltage scaling for different GaN transistors using either compensation-doped GaN buffer structures (green, cyan) or an AlN-buffer (red).

Das FBH hat die Zusammensetzung der Pufferstruktur bei lateralen AlGaN/GaN-Transistoren so angepasst, dass sich mit ihnen die HF-Leistung effizienter verstärken und die Schaltgeschwindigkeiten in Leistungskonvertern erhöhen lassen. Üblicherweise wird der Puffer mit Eisen oder Kohlenstoff dotiert, damit er eine ausreichend hohe rückseitige Barriere zum Transistorkanal bildet. Auf diese Weise werden unerwünschte Leckströme bei hohen Sperrspannungen unterdrückt. Allerdings erzeugen die Dotanden lokalisierte Ladungsträger im GaN-Puffer, die bei den Transistoren zu unerwünschten Dispersionseffekten führen. Wird Aluminiumnitrid (AlN) als Puffermaterial genutzt, entsteht auch ohne Kompensationsdotierung eine sehr hohe rückseitige Barriere. So lassen sich Dispersionseffekte wie der Sättigungsstromeinbruch oder die Erhöhung des dynamischen Einschaltwiderstands beim Einschalten des Transistors aus dem Sperrzustand heraus reduzieren. Zusätzlich führt die hohe rückseitige AlN-Barriere zu einer besonders hohen Durchbruchspannungsskalierung von 140 V pro µm Gate-Drain-Abstand.

Publication

F. Brunner, O. Hilt, A. Reis, J. Würfl, M. Weyers, "MOVPE Growth of AlN/GaN/AlN HFET Structures on 4H-SiC", Compound Semiconductor Week (CSW 2018), Cambridge/Boston, USA, pp. 177-178 (2018).

III-V Electronics III/V-Elektronik

Large-scale vertical trench GaN MISFETs for power switching electronics

Emerging GaN-based vertical trench MISFETs outperform Si devices. They may even compete with SiC devices due to their combination of larger breakdown fields and high bulk mobility. However, design and manufacturing of such devices require the development of many building blocks. These include a thick epitaxial drift region with low background impurities, a well-defined highly doped blocking layer with sharp transition interfaces, and a robust gate insulator with stable threshold voltage and high breakdown strength under positive bias for normally-OFF power switching operation.

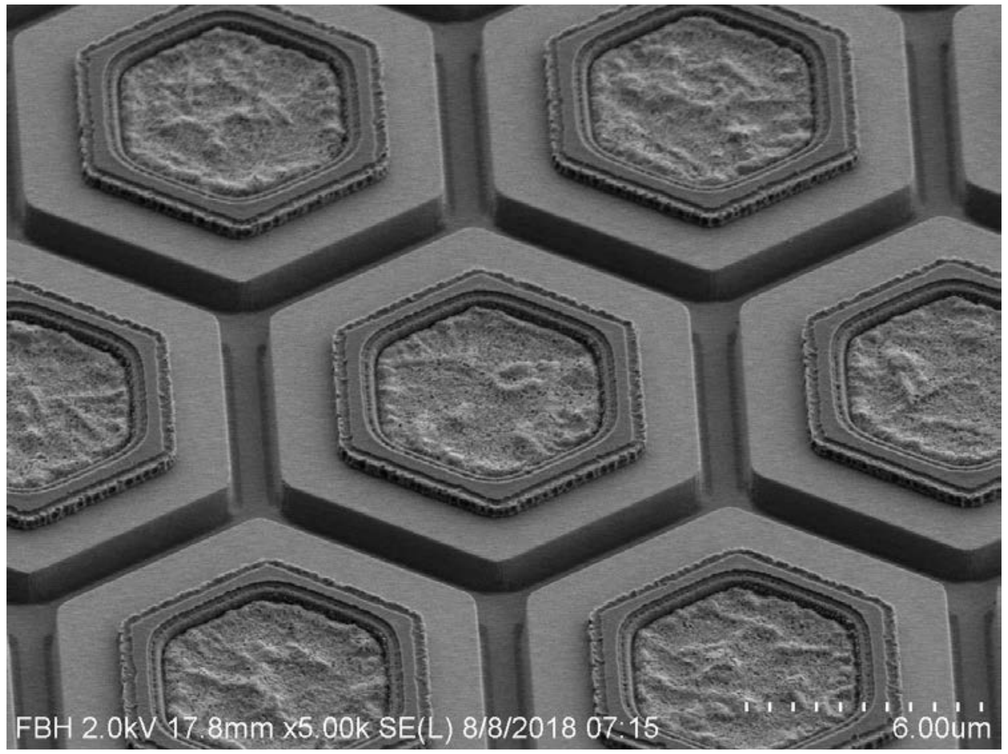


Fig. 1. SEM micrograph from the inline processing of a hexagonal trench transistor design with gate periphery density of approx. 550 mm/mm² and unit cell pitch of 3.25 µm.

FBH has also devoted considerable attention to the gate oxide technology combined with trench etching and surface/interface treatment procedures. The Atomic Layer Deposition (ALD) method was used for Al_2O_3 gate insulator layers. Challenges occurring with these layers are related to the accumulation of undesired interface oxides and charges. These in turn result in threshold voltage instability, limited ON-state channel inversion, reduced OFF-state blocking capability and low oxide breaking strength. Trench etching and oxide deposition process was optimized in terms of surface low damage wet etch, high temperature in situ Ammonia plasma pretreatment combined with deposition methods (i.e. thermal ALD and plasma enhanced ALD), the deposition process parameters, and the reduction of the interface oxide and oxide-semiconductor interface charges. These process optimizations lead to enhanced device electrical properties such as reduced forward bias hysteresis and robustness, and low gate leakage current.

Besides gate oxide optimization, reducing the area specific ON-state resistance is crucial to finally demonstrate competitive devices with current levels around 50 A. Since high quality flat 50 mm GaN substrates became recently available for the first time, a high-resolution lithographic process using an industrial stepper is now possible. FBH's i-line stepper lithography is capable of high resolution better than 0.5 µm and accurate overlay capability better than 0.2 µm, which translates into a compact scaled down cell pitch design of 3.25 µm. In other words, a trench transistor with approx. 300 mm/mm² (gate periphery per mm² semiconductor area, i.e. mm/mm²) finger design or approx. 550 mm/mm² using a hexagonal design approach may be realized.

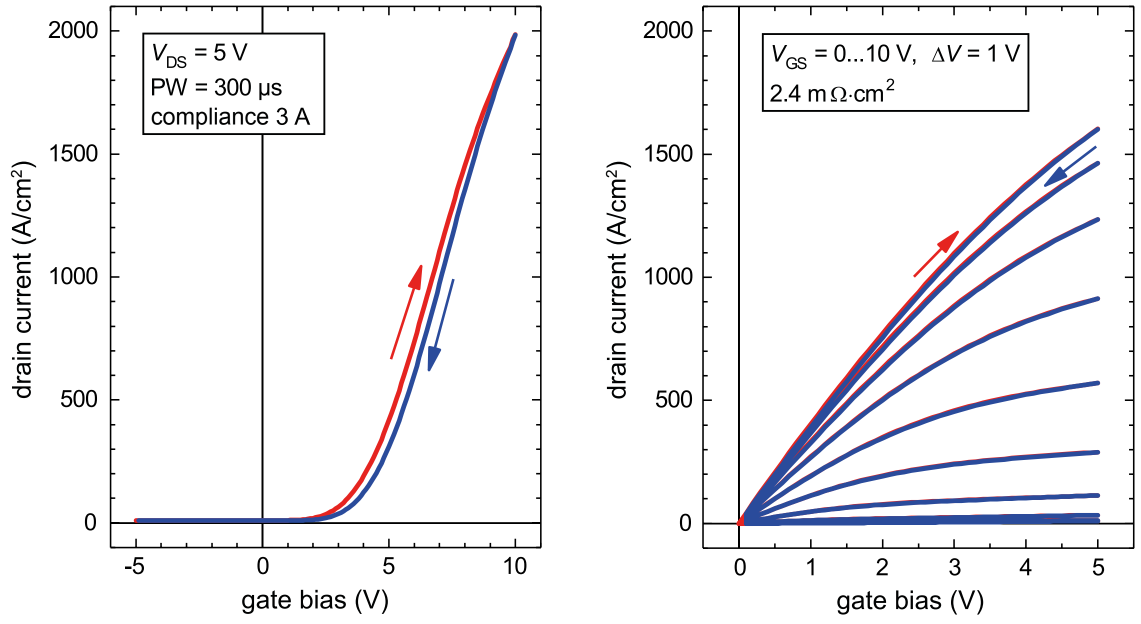


Fig. 2. Vertical multi-finger GaN trench MISFET transfer and output characteristics, device scaling of 100 mA/mm².

Fig. 1 shows a SEM micrograph from of a hexagonal trench transistor design with a gate periphery density of approx. 550 mm/mm² and a unit cell pitch of 3.25 µm. Fig. 2 depicts the electrical characteristics of a large periphery approx.100 mm/mm² multi-finger vertical GaN transistor. Here, FBH demonstrated vertical trench GaN transistors manufactured on highly conductive ammonothermal GaN substrates with improved gate insulator deposition technology. The integrated devices demonstrate a low hysteresis ON-state conduction current up to 2000 A/cm² with a resistance of 2.4 mΩ/cm² and a forward bias gate leakage current lower than 10^{-4} A/cm².

This work was supported by the European Fund for Regional Development (ERDF).

Das FBH fertigt GaN-basierte vertikale Trench-MISFET, die dank ihrer großen Durchbruchfeldstärken und hohen Bulkmobilität mit SiC-basierten Transistoren konkurrieren. Erst seit kurzem sind hochwertige 50 mm GaN-Substrate verfügbar, auf denen mit einem hochauflösenden lithografischen Prozess derartige Transistoren mit Fingerdesign oder mit einem hexagonalen Designansatz hergestellt werden können. Für die Herstellung des Al_2O_3-Gate-Isolators wird die Atomlagenabscheidung verwendet. Das FBH hat sich intensiv mit der Gate-Oxid-Technologie in Kombination mit Trenchätzen und mit Verfahren zur Oberflächenbehandlung beschäftigt. Dadurch konnten die hierbei entstehenden Herausforderungen, wie etwa die instabile Schwellenspannung und die eingeschränkte Kanalinversion im Einschaltzustand (ON-State), gelöst werden. Durch diese Prozessoptimierungen wurden auf ammonothermen GaN-Substraten wettbewerbsfähige Transistoren mit Strom im Einschaltzustand von bis zu 2000 A/cm² demonstriert. Sie zeigen einen Gate-Leckstrom in Vorwärtsspannung von weniger als 10^{-4} A/cm².

Publications

[1] E. Bahat-Treidel, O. Hilt, J. Stöver, V. Hoffmann, F. Brunner, K. Ickert, S. Hochheim, F. Naumann, H. Gargouri, B. Martinez, M. Weyers, J. Würfl, "GaN-Based Vertical n-Channel MISFETs on Free Standing Ammonothermal GaN Substrates", phys. stat. sol. (a), vol. 215, no. 8, pp. 1700422 (2018).

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For further information:

https://www.fbh-berlin.com/research/iii-v-electronics

III-V Technology
III/V-Technologie

III/V-Technologie

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 und III/V-Elektronik:

- ***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 sowohl für die Bauelemententwicklung am FBH als auch für externe Kunden. Darüber hinaus werden SAM-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 AlN und Ga_2O_3. 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 Halbeiterstrukturen. 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, Epitaxiestrukturen liefern oder Gerätedemonstratoren entwickeln und fertigen.

III-V Technology

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 und III-V electronics 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 for device development at FBH as well as for external customers. Also, SAM 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 and Ga_2O_3. 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, deliver epitaxial wafers or develop and build demonstrator systems.

Investigations on aluminum nitride for high-power ultraviolet light emitting diodes

Light emitting diodes (LEDs) with emission wavelengths in the ultraviolet (UV) spectral range between 200 nm and 320 nm enable a wide field of applications. These include medical diagnostics, phototherapy, gas sensing, UV curing, and water disinfection. The semiconductor devices are based on thin crystalline layers of aluminum gallium nitride (AlGaN) grown on sapphire crystals. To achieve highly efficient light generation in the active region embedded between n-AlGaN and p-AlGaN (Fig. 1a) the initial AlN layer on sapphire has to be as defect-free as possible. Therefore, the FBH works on optimizing the growth of AlN starting layers on sapphire.

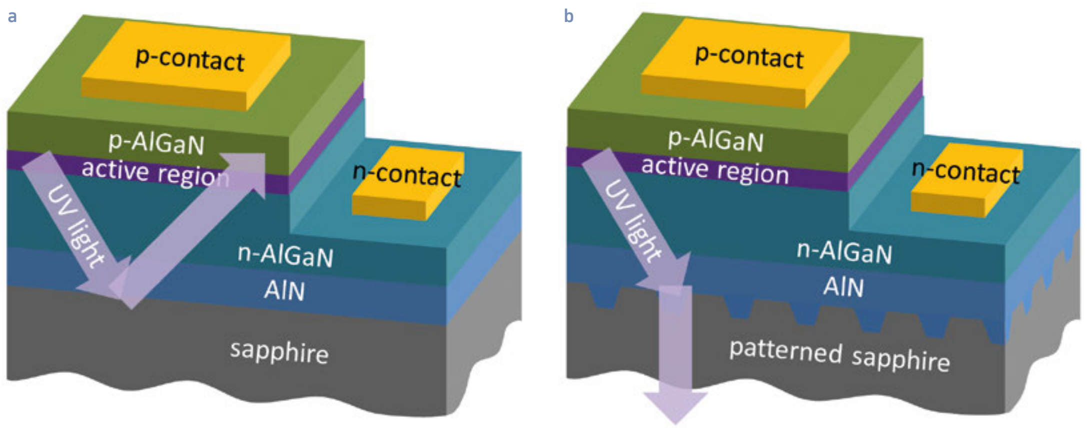

Fig. 1. Schematic of UV light emitting diode with planar AlN-sapphire interface (a) and with patterned interface for improved light extraction (b).

AlN crystal defects can partially be removed by applying a high temperature of about 1700 °C for several hours. This technique helps to decrease the defect density in AlN by one order of magnitude and has been developed into a stable process for sample sizes of up to 2 inch in diameter. Using such an annealed starting layer allows a lower defect density in the active region of the LED and therefore more efficient light generation. However, high annealing temperatures can disturb the AlN surface by conversation of AlN and sapphire into aluminum oxynitride (AlON) over a large area (Fig. 2). This AlON formation can be suppressed by increasing the AlN layer thickness from 350 nm to 450 nm and by avoiding annealing temperatures above 1700 °C. LEDs emitting at 265 nm were successfully realized on high temperature annealed AlN within FBH's Joint Lab GaN Optoelectronics operated together with TU Berlin. These devices show 25 times higher light output power compared to those with non-annealed AlN starting layer.

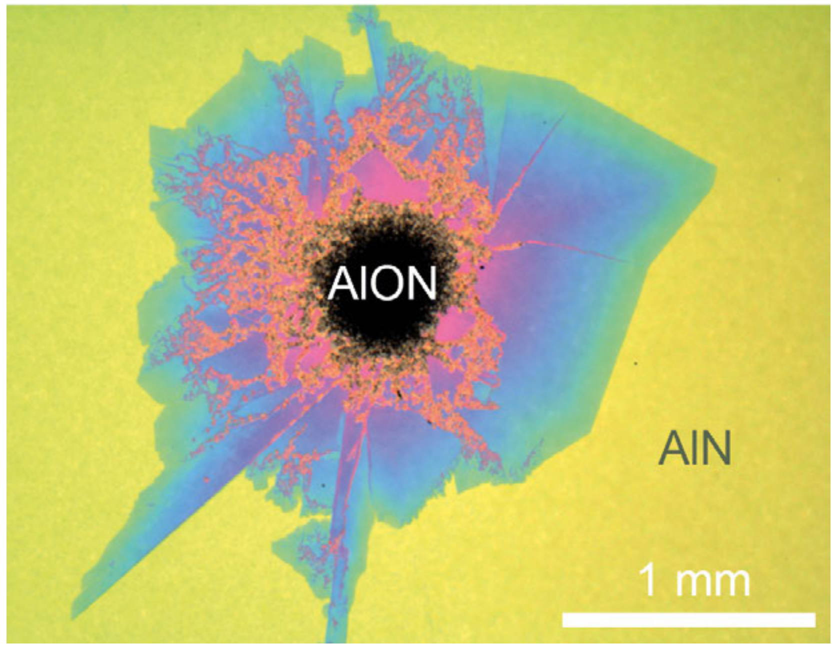

Fig. 2. Light microscopy image of an AlN surface disturbed by aluminum oxynitride (AlON) formation.

Unfortunately, the light extraction, which usually occurs through the sapphire crystal, suffers from total reflection at the planar AlN-sapphire interface (Fig. 1a). Improved light extract can be reached by applying a patterned AlN-sapphire interface (Fig. 1b). Accordingly, the growth on patterned sapphire surfaces (PSS) with holes (Fig. 3a) and cones (Fig. 3b) was investigated. Growing AlN on PSS and achieving an atomically smooth AlN surface for further AlGaN growth is a challenging task as unwanted misaligned crystal growth can occur (Fig. 3c). This is prevented by protecting the sub-micron sized PSS structures against decomposition by an initial AlN layer deposited at a low temperature before heating to 1300 °C. Also unwanted surface steps higher than 20 nm can form when the surface closes. Smooth surfaces are obtained using PSS with only small miscut and adapted growth conditions in the coalescence phase (Fig. 3d). LEDs emitting at 265 nm showed a 4 times higher emission power when fabricated on atomically smooth AlN-PSS compared to AlN-PSS substrates with several nanometer high surface steps.

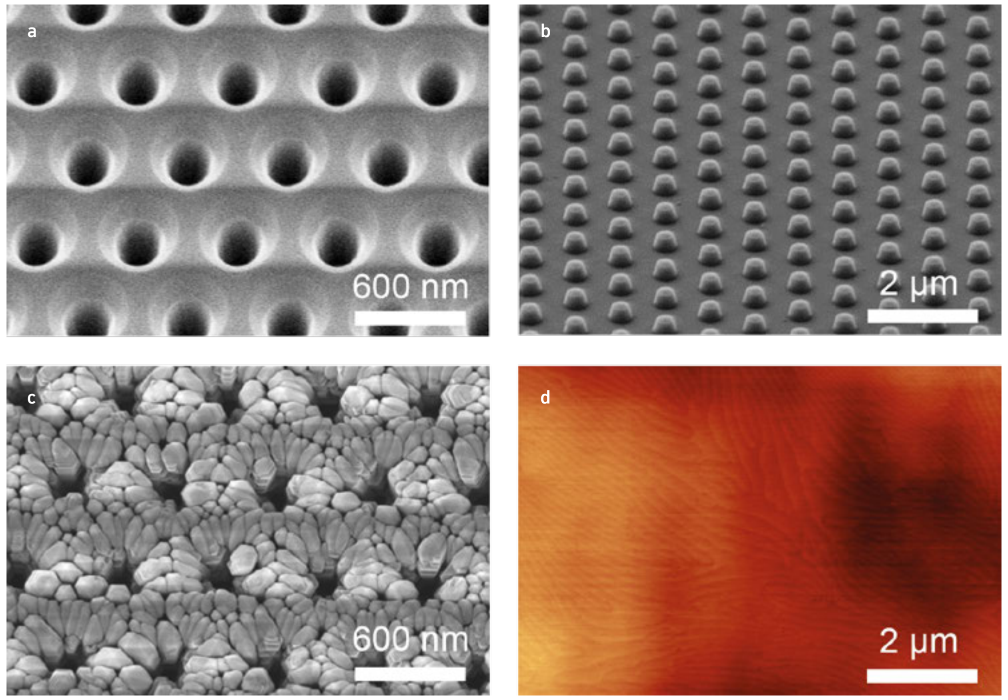

Fig. 3. Patterned sapphire substrates (PSS) with holes (a) and truncated cones (b). Misaligned AlN crystallites on PSS with holes (c). Smooth AlN surface with atomic steps grown on PSS with cones (d).

Another challenge is to avoid layer cracking during overgrowth of PSS with hole pattern (Fig. 3a), since AlN is incorporating tensile strain when grown on the continuous uppermost surface of the substrate. High temperature annealing of a 300 nm thick uncracked starting layer on such a PSS was found to solve the problem by decreasing the AlN in-plane lattice constant and hence enabling further AlN growth without incorporation of tensile strain.

These studies pave the way for combining low defect density with high light extraction efficiency. This work has been funded by the German Federal Ministry of Education and Research within the Zwanzig20 consortium Advanced UV for life (project UV Power).

Leuchtdioden (LEDs) mit Emissionswellenlängen im ultravioletten (UV)-Spektralbereich zwischen 200 nm und 320 nm eignen sich für vielfältige Anwendungen. Um ihre Effizienz und Ausgangsleistung zu erhöhen, optimiert das FBH deren Halbleiterschichten. UV-LEDs basieren auf dünnen kristallinen Schichten, die auf Saphirkristallen aufgewachsen sind. Für effiziente LEDs muss die Anwachsschicht aus Aluminiumnitrid (AlN) auf Saphir möglichst defektarm sein. Die Dichte von Kristallfehlern im AlN lässt sich durch Ausheizen bei etwa 1700 °C um eine Größenordnung reduzieren. Auf entsprechend behandeltem AlN wurden LEDs, die bei 265 nm emittieren, erfolgreich im Joint Lab GaN Optoelectronics von FBH und TU Berlin realisiert. Diese Bauelemente zeigen eine 25-fach höhere Lichtausgangsleistung im Vergleich zu LEDs mit nicht ausgeheizter AlN-Startschicht. Auch strukturierte Saphiroberflächen wurden mit atomar glatten AlN-Schichten überwachsen. Dies verbessert zukünftig die Lichtauskopplung aus den LEDs.

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S. Hagedorn, S. Walde, A. Mogilatenko, M. Weyers, L. Cancellara, M. Albrecht, D. Jaeger, "Stabilization of sputtered AlN/sapphire templates during high temperature annealing", J. Crystal Growth 512, 142 (2019).

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Lateral current confinement and non-absorbing mirrors in broad-area lasers via 2-step epitaxy – targeting lower cost per photon

12x4" MOVPE reactor for GaAs-based layer structures.

GaAs-based high-power diode lasers are important near-infrared light sources for a great variety of applications. Broad area lasers (BALs) emitting in the 9xx nm range, for example, are highly requested for optical pumping of fiber and solid-state industrial lasers. For such high-performance applications, high energy conversion efficiency, high beam quality, maximum operation power and high reliability are targets in order to decrease the cost per usable photon.

Introducing buried carrier confinement structures in BALs can increase the energy conversion efficiency by reducing the carrier losses due to lateral carrier spread. This process step also improves the beam quality by eliminating carrier accumulation at the edges of the active region (which is again related to the lateral current spread). The introduction of non-absorbing mirrors (NAMs) can increase the power threshold for catastrophic optical mirror damage (COMD), allowing for higher maximum operation power and improved reliability. To realize these features, two alternative technological approaches are currently pursued at FBH, both based on 2-step epitaxial growth.

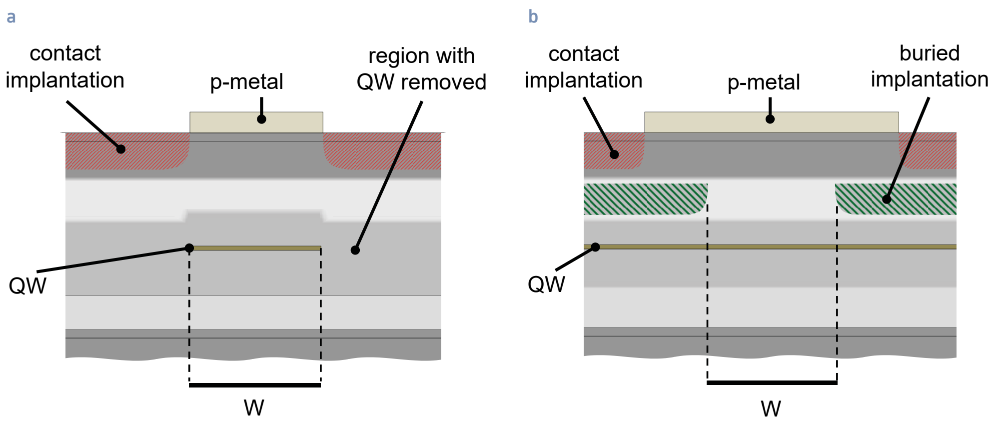

Fig. 1. Cross section schematic of a buried mesa laser (a) and a lateral buried implantation laser (b).

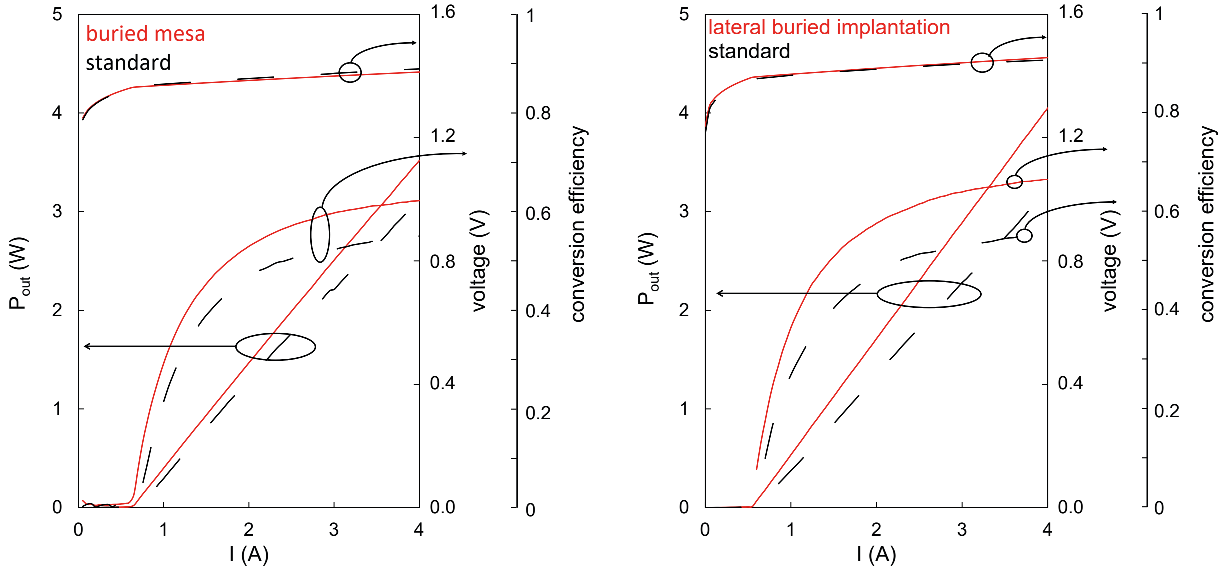

Fig. 2. PVI curves of a buried mesa laser (a) and a lateral buried implantation laser (b) both compared to a standard laser fabricated with the same vertical structure (dashed lines).

The buried mesa approach starts with the growth of the vertical structure up to the active region. After the growth, chemical etch is used to remove the active region - and thus absorption as well as gain - from the sides and from the facets of the laser stripe. The vertical structure is then completed in a second growth step, starting on a patterned, non-planar surface. As a result, challenges like local composition modulation in ternary layers arise.

The second approach confines the current by implanting ions (Si or O) at the sides and at the facets of the laser stripe impeding current flow. Depending on the targeted position of this current aperture, the first growth step ends in the upper p-type waveguide. In this case, the second regrowth step starts on a planar surface.

Both approaches for current confinement result in reduced threshold current and higher slope efficiency compared to reference standard devices. Together with improved beam quality this yields a gain in overall efficiency. For the buried mesa approach, also a higher COD threshold has been confirmed when the active region is removed at the facets.

For the buried implantation approach, an improvement of the beam quality is obtained thanks to a more top-hat shape of the near-field lateral profile and a reduced far-field width. This promises more efficient coupling to optical fibers and enhanced systems efficiency, for example in diode laser systems for materials processing.

Part of this research has been executed within the HoTLas project funded by the German Federal Ministry of Education and Research.

Für industrielle Laseranwendungen wie Schweißen oder Schneiden sollen die Kosten pro nutzbarem Photon stetig sinken. Das FBH arbeitet daher an Breitstreifenlaserdioden mit verbesserter Effizienz, Strahlqualität und Ausgangsleistung bei zugleich langer Lebensdauer. Durch Konzentration der Ladungsträger auf die laseraktive Fläche lassen sich die Verluste in den Randbereichen reduzieren – und dies erhöht die Effizienz. Dazu kann beispielsweise die lichtemittierende aktive Zone außerhalb der laseraktiven Fläche entfernt werden. In einem zweiten Epitaxieschritt wird der p-seitige Wellenleiter überwachsen. Dabei startet das Wachstum für eine solche vergrabene Mesa jedoch auf einer strukturierten Oberfläche, was z.B. zu lokal unterschiedlicher Materialzusammensetzung führen kann. Ionenimplantation oberhalb der aktiven Zone etwa mit Silizium ist ein anderer Weg, bei dem der zweite Epitaxieschritt auf einer glatten Oberfläche beginnt. Beide Ansätze führen zu Laserdioden mit reduzierter Schwellenstromdichte und höherer Steigungseffizienz sowie verbesserter Strahlqualität verglichen mit konventionellen Lasern, die in einem Epitaxieschritt hergestellt werden.

Publications

D. Martin, P. Della Casa, T. Adam, C. Goerke, A. Thies, K. Häusler, O. Brox, H. Wenzel, P. Crump, M. Weyers, A. Knigge, "Current Spreading Suppression by O- and Si-Implantation in high Power Broad Area Diode Lasers", Proc. SPIE 10900, Photonics West, USA, 109000M (2019).

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Integrated optical micro-resonators and waveguides for quantum spectroscopy

To a great extent, modern communication technology is based on optical transmission of information by photons in glass fibers. This transmission channel, however, is prone to eavesdropping and manipulation, thus requiring encryption to allow a minimum of safety and privacy. Using single photons, at least to exchange an encryption key, would open up an inherently secure communication path, as eavesdropping attacks would be immediately detected. The FBH is working on this highly topical research field by fabricating optical micro-resonators and waveguides within the three-year EU research project "Error-Proof Bell-State Analyzer (ErBeStA)". This challenging project tackles the realization of an analyzer for Bell states. The concept of Bell states originates from quantum information technology and describes states of quantum entangled particle pairs. Entangled quantum objects are connected to each other without any direct physical interaction. Exploiting these states is expected to lead to a plethora of new technologies in computing, sensing, simulation and communication. An error-free analyzer for Bell states is a key component for optical quantum computers and quantum communication; and its realization would be a milestone for all information technologies including high-precision time measurement, tap-proof communication, and quantum cloud computing.

The consortium of seven European research institutes aims to achieve this progress by combining new developments in the fields of quantum optics and nanophotonics. The strong nonlinearities of Rydberg atoms and single quantum emitters such as nano diamonds coupled to optical micro-resonators will be combined with microscopic optical waveguide devices. By precisely controlling the propagation of light on the scale of the wavelength of light, these devices will enable the technological breakthrough.

FBH contributes its expertise in the field of process technology. Optical micro-resonators and waveguides are manufactured in the institute's cleanroom environment using semiconductor technology including modern lithography and etching processes. Structures as small as 400 nm are produced using stepper lithography. For even smaller dimensions electron beam lithography is available, allowing structure dimensions down to 50 nm. The structures generated in a photoresist are then transferred to the optical material using adapted plasma etching processes.

To minimize optical losses the use of low-damping silicon oxide with extremely low fluorescence is being investigated as optical material. It is particularly challenging to separate the tiny waveguide structures from the wafer so that the guided light is not attenuated by the wafer and, at the same time, to obtain a sufficiently tight connection between the optical components and the wafer. The component should be mechanically stable enough that it can be used not only in laboratory set-ups, but also in commercial assemblies.

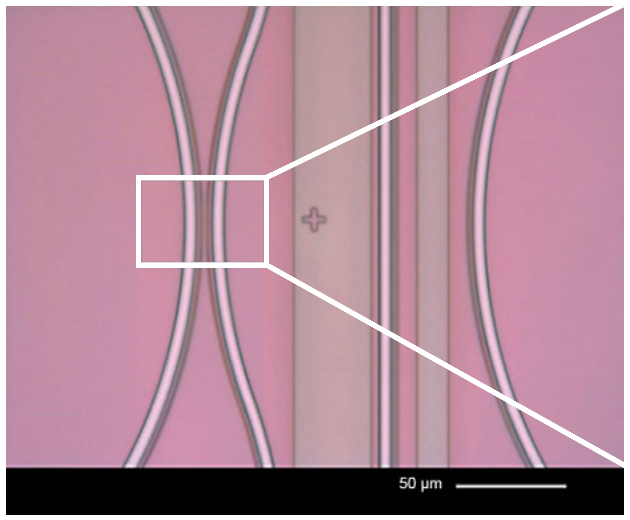


Fig. 1. a) Optical micrograph of a top-down view of the designed resonator – waveguide system in the coupling region.

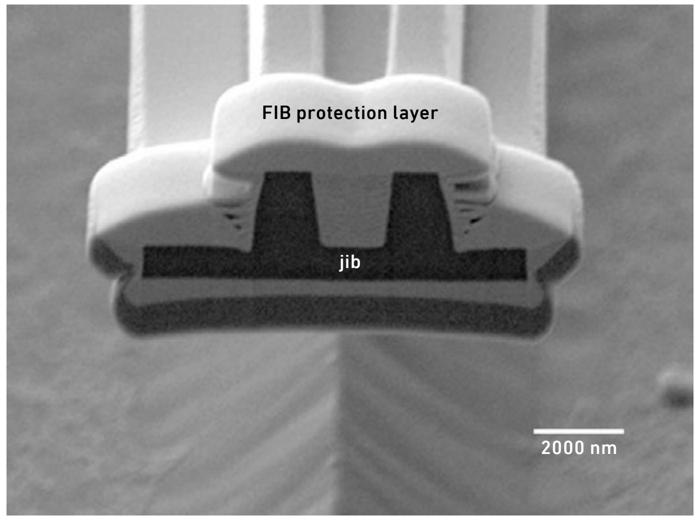


Fig. 1. b) SEM picture of a focused ion beam cut of the coupling section of waveguide and ring resonator.

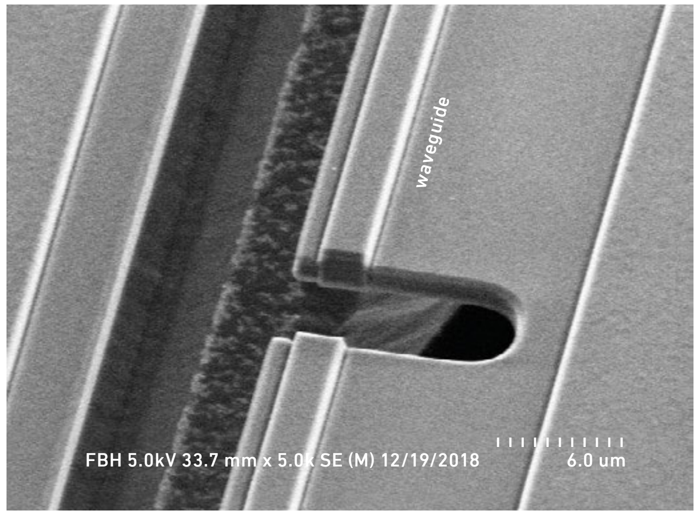


Fig. 2. Intermittent wave guide section to allow for interaction between Rydberg atoms and light.

FBH has developed a technology that allows manufacturing such components from thermally grown silicon oxides on silicon in a 4-step production process. Fig. 1 shows a scanning electron microscope (SEM) image of a cross section of the coupling region of a ring resonator to a waveguide realized in oxide. Fig. 2 shows an SEM image of an intermittent waveguide that allows interaction between Ryberg atoms and guided light.

The first components were sent to our partners for optical characterization. Based on their input, design and fabrication processes will be optimized to tailor the properties to the desired needs.

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

Das FBH ist Partner in einem Verbund von sieben europäischen Forschungseinrichtungen in Dänemark, Großbritannien, Österreich und Deutschland, die es sich zum Ziel gesetzt haben, in einem im dreijährigen EU geförderten Forschungsprojekt einen Analysator für Bell-Zustände zu realisieren. Ein fehlerfrei arbeitender Analysator für Bell-Zustände ist eine Schlüsselkomponente für optische Quantencomputer und die Quantenkommunikation über weite Entfernungen, z.B. über Glasfaserkabel. Seine Verwirklichung wäre ein Meilenstein für alle Informationstechnologien.

Das FBH bringt seine Kompetenz auf dem Gebiet der Prozesstechnologie in diese hochaktuelle Forschungsthematik ein. Optische Mikroresonatoren und Wellenleiter werden im Reinraum mit modernen Verfahren der Lithografie und Ätzprozessen hergestellt. Um optische Verluste gering zu halten, wird der Einsatz von wenig dämpfenden Siliziumoxiden untersucht. Die am FBH entwickelten Bauteile werden dann in enger Zusammenarbeit mit den Projektpartnern ausgiebig optisch charakterisiert und weiterentwickelt.

Publications

[1] C. Pyrlik, J. Schlegel, F. Böhm, A. Thies, O. Krüger, O. Benson, A. Wicht, G. Tränkle, "Integrated Thermal silica micro-resonator wave guide system with ultralow Fluorescence", IEEE Photonics Technol. Lett., vol. 31, no. 6, pp. 479-482 (2019).

[2] F. Böhm, N. Nikolay, C. Pyrlik, J. Schlegel, A. Thies, A. Wicht , G. Tränkle, O. Benson, "On chip integration of single solid state quantum emitters with a SiO_2 photonic platform", New J. Phys., vol. 21, no. 4, pp. 045007 (2019).

III-V Technology III/V-Technologie

SiC-based UV detector arrays for miniaturized spectrometers

A growing number of most diverse applications demands for detectors to monitor and control UV radiation. Applications include food, air and drinking water disinfection and purification, UV curing as well as chemical and biological analysis of the impact of the sun's erythema-active radiation. FBH has been delivering single p-n-junction photodiode chips (Fig. 1) for the Berlin-based company sglux GmbH for many years. Recently, FBH and sglux combined their expertise to develop a miniaturized spectrometer and camera module for the UV spectral range, taking advantage of the benefits of silicon carbide (SiC) photodetectors. In this context, FBH extends its device processing capabilities in the area of UV detector chips towards SiC-based photodiode arrays.

Commercial spectrometers and cameras for the UV range use silicon detector chips. The intrinsic absorption of visible and infrared light in silicon-based sensors, however, causes noise that limits the detectability of low UV intensities in bright ambient light. The wide-bandgap semiconductor SiC perfectly matches the requirements for efficient detection of radiation in the UV spectral range, e.g., between 200 nm and 380 nm. SiC photodetectors are long-term stable even under intense UV irradiation, enable room-temperature operation and provide intrinsic visible blindness, i.e., detecting low UV radiation even in highly intense visible or infrared ambient light.

Fig. 1. Packaged UV photodiode. The edge length of the square chip is 1 mm.

The FBH developed and produced monolithic detector lines consisting of 512 separate, side-by-side packed SiC p-n junction photodiodes (Fig. 2). Device design and chip size had to take the specific requirements of chip packaging and assembly into account. The fabrication relied on modern semiconductor micro-structuring techniques such as dry- and wet-chemical processing as well as deposition of metals and dielectrics. I-line stepper lithography provided the basis to efficiently pattern the 3-inch wafers with high precision, good yield, and excellent reproducibility. The active area of the p-n junction diodes was defined by mesa etching using an inductively coupled plasma. Patterned Al-Ti and Ni-Cr metal alloys form the p-type and n-type contacts, respectively. On the front of the diodes a metallic fan-out connects the pixel's p-type ohmic contacts to the 70 x 70 μm^2 metal pads for wire bonding. The metallization of the chip's backside acts as a plane electrical contact that is attached to the package next to the read-out integrated circuit. The project partner sglux took care of prototyping, i.e., package assembly and integration with read-out electronics and control software. The detector arrays showed excellent reproducibility of the response signal under UV illumination and did not add any noise to the system's response in the dark. Preliminary results demonstrated a pixel-to-pixel homogeneity of the photo response of about ±5%.

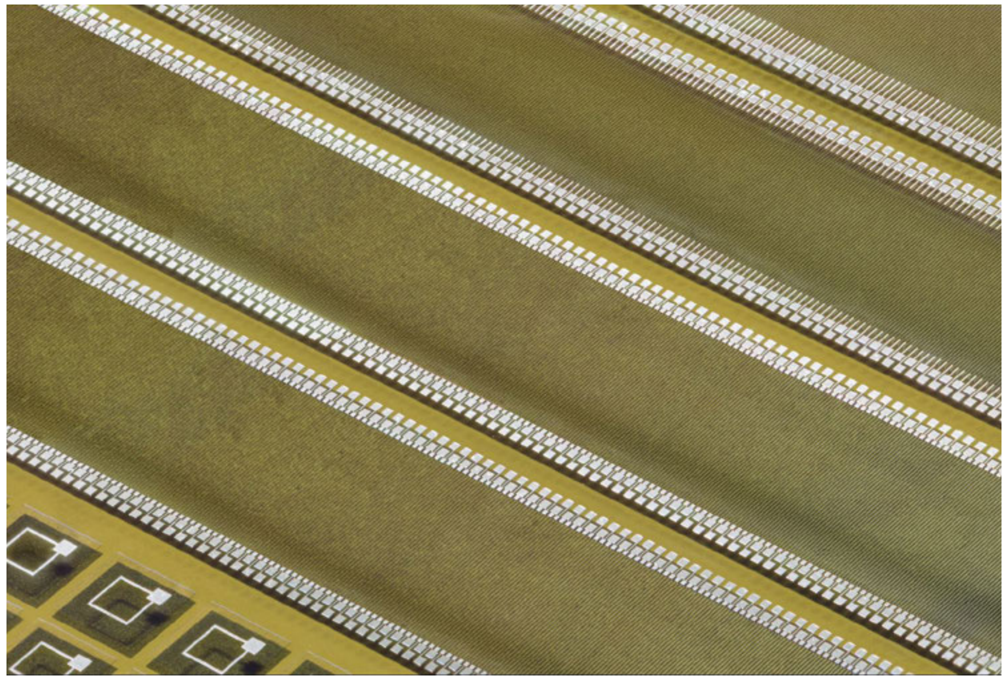


Fig. 2. Section of 512 pixel arrays on a 3-inch wafer. In the lower left corner single detector devices (squares with 1 mm side length) are shown for reference.

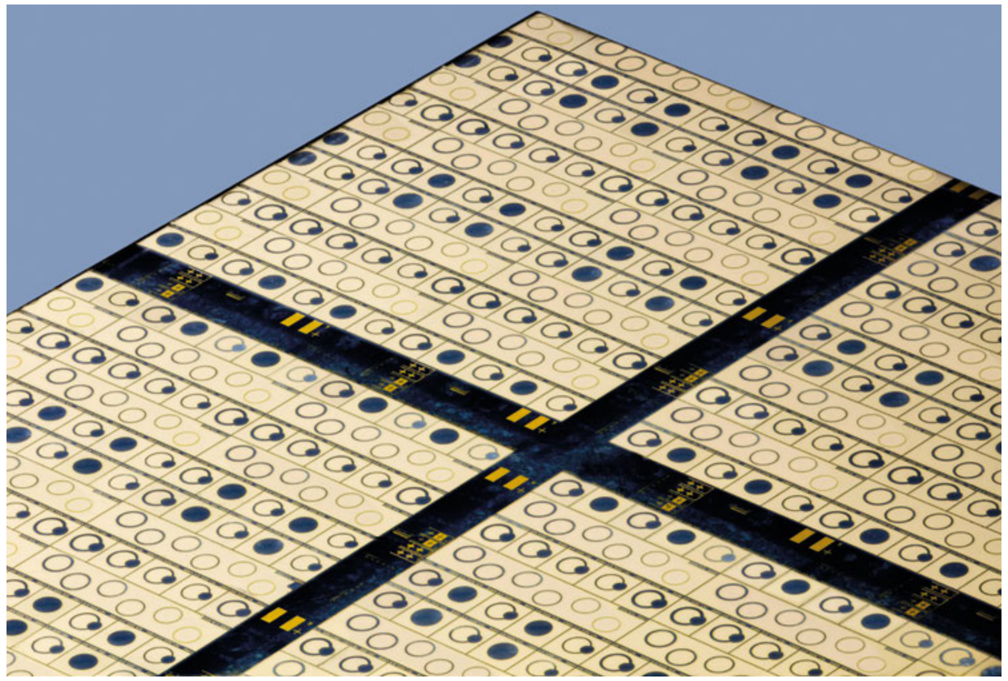
From the fabrication point of view, there is potential for further development in the future. The current chip size of the 512 pixel detector of 13 x 2 mm^2 could be shrunk by reducing the size of the bond pads. Also, the number of pixels on a single chip could be increased by enlarging the chips and upscaling the process to 4-inch wafers.

The work was funded by the BMBF under contract 03ZZ0119B in the framework of the 'Zwanzig20 - Advanced UV for Life' initiative.

Das FBH produziert seit vielen Jahren SiC-Fotodiodenchips für die Berliner Firma sglux GmbH und hat kürzlich seine Fertigungskompetenzen auf Detektorarrays ausgeweitet. Die Partner haben nun ihre Kompetenzen bei der Chipproduktion und der Systemintegration von UV-Messtechnik in einem BMBF-Projekt gebündelt, um ein miniaturisiertes Spektrometer und Kameramodul für den UV-Bereich zwischen 200 nm und 380 nm zu entwickeln. Dazu wurden am FBH monolithische Detektorzeilen, die aus 512 Fotodioden bestehen, entworfen und mittels moderner Fertigungsverfahren der Halbleitertechnologie hergestellt. Die derzeit 13 x 2 mm^2 großen Chips wurden von sglux montiert, mit Ausleseelektronik integriert und erfolgreich getestet. Fertigungstechnologisch lassen sich die Chipgröße und die Pixelzahl des Arrays an spezielle Forderungen zukünftiger Anwendungen anpassen.

III-V Technology III/V-Technologie

Nitrogen ion implantation for effective inter-device isolation of β-Ga_2O_3 power transistors



Circular transistor and test structures on (100) β-Ga_2O_3 wafer.

The ultra-wide bandgap semiconductor Ga_2O_3 has received great attention in recent years due to its potential to outperform conventionally used materials for future power electronic applications. The estimated dielectric strength of 8 MV/cm in combination with the expected Baliga's figure of merit are promising indicators, paving the way to realize power devices with even higher breakdown voltages and efficiencies than their SiC and GaN counterparts. Up to now, several studies have demonstrated the successful realization of Schottky barrier diodes and field-effect transistors based on Ga_2O_3 – with promising results for the development of high-efficiency power converters. In order to electrically isolate devices on wafer, dry etching of mesa structures into the Ga_2O_3 is commonly carried out. However, isolation by ion implantation is an attractive alternative, as shown in several reports on GaN-based devices. This method allows to maintain wafer surface planarity and thus significantly improves the yield in fine-pitch lithography.

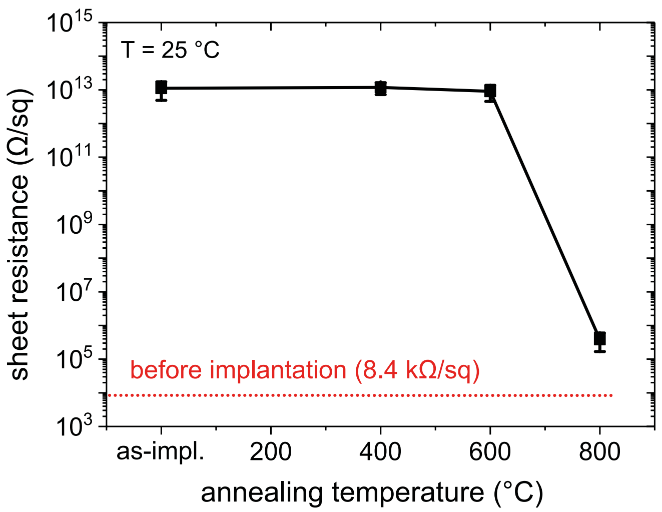


Fig. 1. Sheet resistance of nitrogen implanted Ga_2O_3 measured at T=25 °C as a function of annealing temperature.

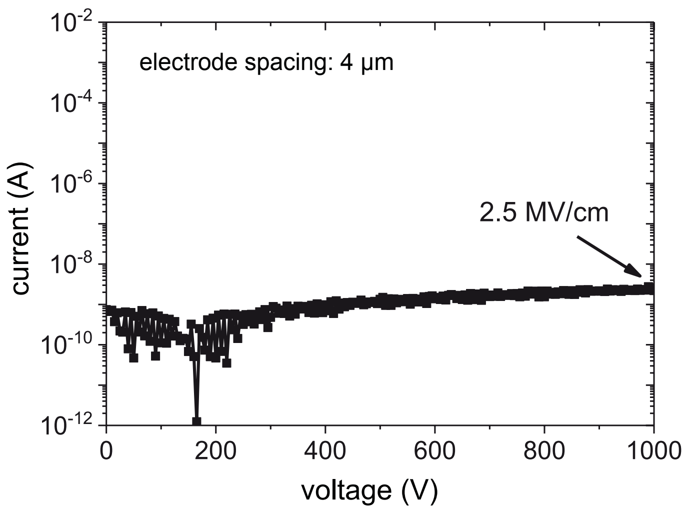


Fig. 2. Leakage current measurements of a TLM structure with an electrode spacing of 4 µm illustrating the excellent blocking properties of nitrogen implanted Ga_2O_3.

Following this approach, FBH has developed a reliable process for selective area isolation of Ga_2O_3 using multiple energy N^+ ion implantation. This causes mid-gap damage-related trap levels in the semiconducting material and enhances the sheet resistance by several orders of magnitude. The experiments on N^+ implantation were carried out on 220 nm thick n-doped Ga_2O_3 layers that were homoepitaxially grown on semi-insulating β-Ga_2O_3 (100) substrates by metalorganic vapor phase epitaxy. To extract the sheet resistances, circular transmission line method (TLM) structures were fabricated by standard lift-off lithography processes using Ti/Au for the ohmic contacts. In order to achieve a uniform distribution of vacancies within the epitaxial Ga_2O_3 layer, the samples were subjected to a multiple energy N^+ ion implantation process with implantation energies of 30 keV, 160 keV and 360 keV and doses of 8×10^{12} cm^{-2}, 2.3×10^{13} cm^{-2} and 3×10^{13} cm^{-2}, respectively. After implantation, some of the as-implanted samples were subjected to rapid thermal annealing at 400, 600 and 800 °C for 60 seconds to investigate the thermal stability of this process.

The sheet resistance extracted from TLM characterization as a function of different annealing temperatures obtained from N^+ implanted β-Ga_2O_3 are shown in Fig. 1. At room-temperature, the sheet resistance of the as-implanted samples was around 1×10^{13} Ω/sq. This is more than nine orders of magnitude higher than the sheet resistance of the non-implanted samples. The sheet resistance remains constant up to annealing temperatures of 600 °C and drops down to 4×10^5 Ω/sq at 800 °C, which is only one order of magnitude higher than the initial value of 8.4 kΩ/sq before implantation. The electrical stability of the isolation was further tested by applying high voltages to the TLM structures. Fig. 2 emphasizes that reliable blocking of voltages of 1000 V at an electrode spacing of 4 µm can be achieved, which equals an electrical field of 2.5 MV/cm.

All these results demonstrate that N^+ ion implantation opens an effective and reliable way to achieve planar inter-device isolation in Ga_2O_3. The outcome of this work is an important step towards a more robust fabrication method of electronic devices based on Ga_2O_3 for high-efficiency power electronics of the next generation.

Funding is provided by the German Federal Ministry of Education and Research under contract no. 03VP03711.

Der Halbleiter Galliumoxid besitzt eine ultra-große elektronische Bandlücke und eignet sich damit ideal für Anwendungen in der Leistungselektronik. Um hocheffiziente Leistungstransistoren mit diesem Material zu entwickeln, muss die elektrische Isolation zwischen Bauelementgruppen auf dem Wafer ausgezeichnet und zuverlässig sein. Am FBH wurde ein entsprechendes Verfahren entwickelt, das durch gezielte Implantation von Stickstoff-Ionen den Schichtwiderstand lokal signifikant erhöht. Auf diese Weise lassen sich einzelne Bauteile elektrisch voneinander isolieren. Im Gegensatz zur üblicherweise verwendeten Mesa-Strukturierung bleibt bei dieser Implantation die Substratoberfläche planar und dies erhöht die Ausbeute der Bauelemente maßgeblich. Nach der Stickstoffimplantation steigt der Schichtwiderstand um neun Größenordnungen an und bleibt bei Temperaturen von bis zu etwa 600 °C stabil. Die implantierten Schichten halten zudem elektrischen Feldstärken von mindestens 2,5 MV/cm zuverlässig stand. Sie erfüllen somit die Voraussetzungen, um damit Leistungstransistoren der nächsten Generation herzustellen.

Publications

K. Tetzner, A. Thies, E. Bahat Treidel, F. Brunner, G. Wagner, J. Würfl, "Selective area isolation of β-Ga_2O_3 using multiple energy nitrogen ion implantation", Appl. Phys. Lett., vol. 113, no. 17, pp. 172104 (2018).

K. Tetzner, E. Bahat-Treidel, A. Thies, G. Wagner, J. Würfl, "Ion Implantation for adjusting electrical conductivity of β-Ga_2O_3 by Nitrogen and Germanium Incorporation", Proc. of the 42nd Workshop on Compound Semiconductor Devices and Integrated Circuits held in Europe (WOCSDICE), Romania (2018).

Flip-chip bonding of UV LEDs – electroplated micro stud bumps approach outperforms soldering with gold-tin

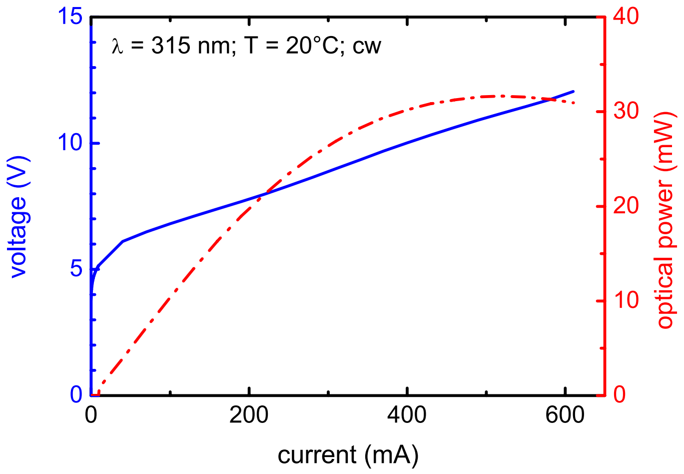


Fig. 1. PUI curve of a UV LED bonded with micro Au-stud.

LEDs emitting in the UVB and UVC spectral range are attractive for various applications such as water, air and surface disinfection, medical diagnostics, curing of materials and plant growth lighting. Usually, the LED structures are epitaxially grown on UV transparent but insulating sapphire substrates. Both chip contacts – cathode and anode – are on one chip side, and complex chip structures like finger shape or other segmentation designs are used to handle the heat spreading within the chip. Compared to LEDs in the visible spectral range, the conversion efficiency of less than 10 % for these UV LEDs is still quite low. To improve UV LED performance, flip-chip bonding on structured submounts or packages ensuring efficient heat extraction is a must (Fig. 1).

The FBH has compared a new bonding approach with FBH's standard bonding technology utilizing gold-tin (AuSn) or tin-silver-copper solder (SAC). However, all defects of the isolation layer between the solder-wetted anode pad on top of the cathode layer are potential sources to short the device. Since the solder spreads during melting, the risk of short-circuit faults between anode and cathode forces to separate the contact pads a few hundred micrometers from each other. This, in turn, lowers the effective area for heat dissipation.

These drawbacks can be overcome by AuAu thermocompression bonding with electroplated micro Au-studs, which can be easily formed by means of lithography using a 12 µm thick negative photo resist in a wafer level process. Moreover, the studs can be designed much smaller than Au bumps formed by Au wires for bonding. Based on 3D thermal simulations, the FBH developed Au-studs with a diameter and height of 15 µm and 8 µm, respectively, forming hexagonal contact arrays within a 30 µm pitch (Fig. 2). For these parameters, the loss of effective area due to the stud matrix and the better thermal conductivity of Au compared to the solder is almost balanced. By varying compression pressure, bonding time and temperature, an area of stable and reliable thermocompression bonding was determined. Subsequently, the UV LEDs were assembled and compared to those using solder bonding.

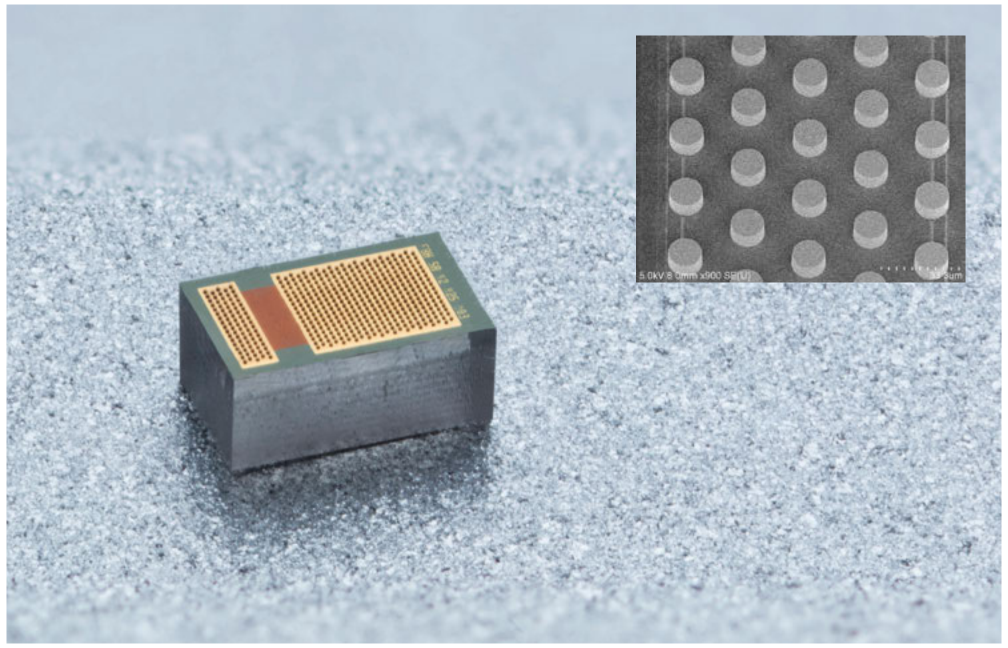


Fig. 2. Complete UV LED with micro Au-studs, enlarged section with Au-studs (inset).

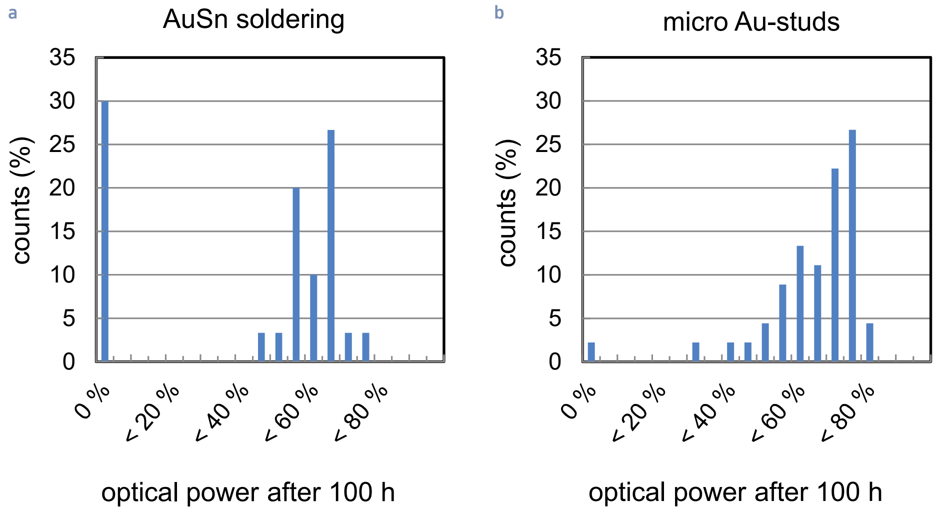


Fig. 3. Optical power of UV LEDs after 100 h aging, comparing devices using AuSn solder (a) and micro Au-studs (b), respectively.

Both UV LEDs obtain comparable optical output powers due to the same cooling level of the chips. After 100 h aging, however, the advantages of the new approach become evident and can be seen in Fig. 3. Although only a small difference in decrease of the optical power of the UV LEDs mounted by micro stud bumps and soldered with AuSn is observed, much less devices suffer catastrophic failure. A reason for this might be the lower area coverage of the studs compared to the solder fully covering the pad area. This way, probably not all defects in the isolation layer cause a catastrophic failure, and the mechanical stress for the devices might be lower when using thermocompression bonding.

Chips with an optimized design for micro stud bonding without the large gap between anode and cathode due to solder spreading are expected to bring even better results. The FBH is working on further improvements to show the full potential of the new electro-plated stud bump approach for UV LED mounting.

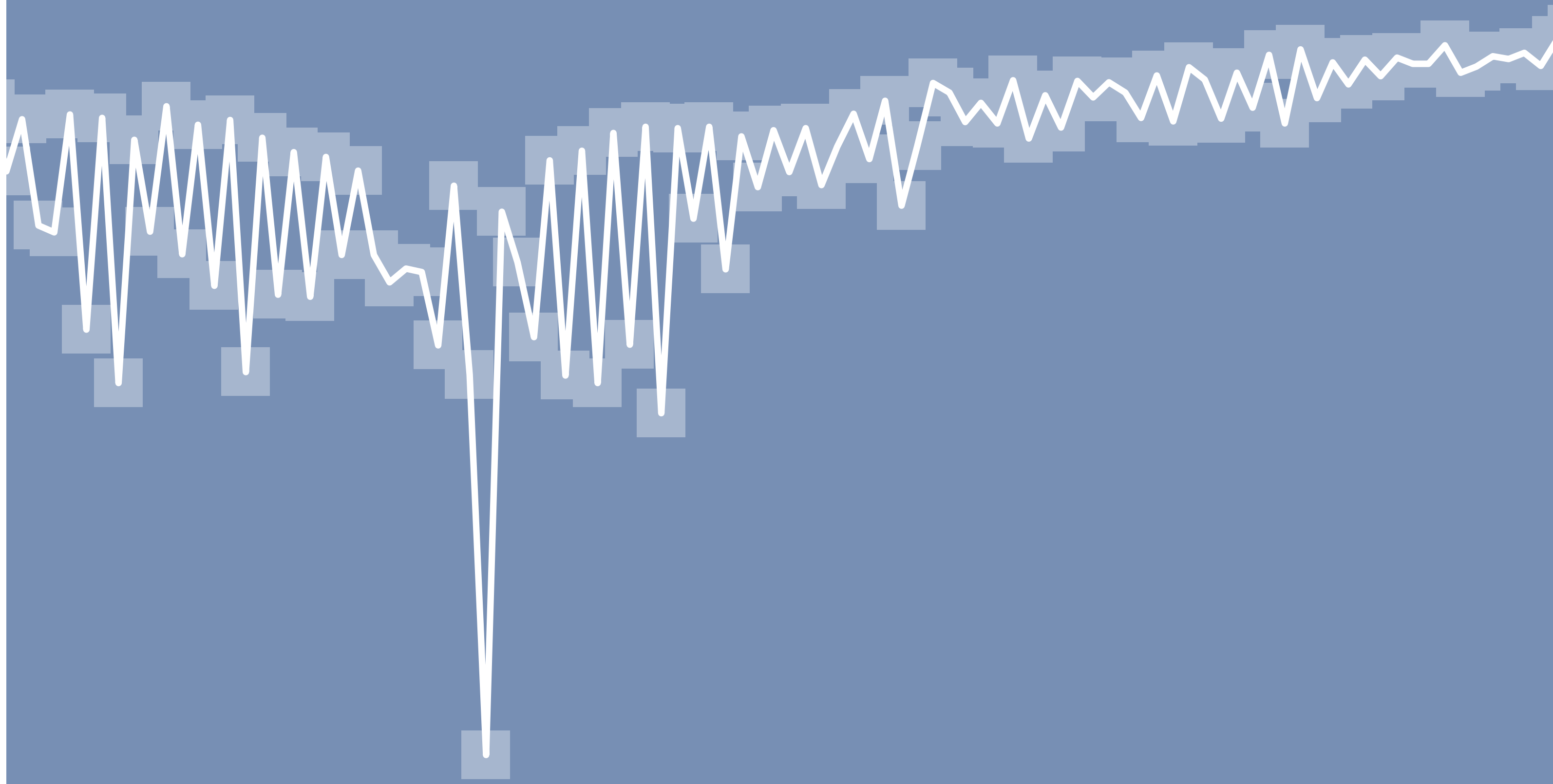
LEDs im UVB- und UVC-Spektralbereich eigenen sich für Anwendungen wie Desinfektion, medizinische Diagnostik oder Pflanzenbeleuchtung. Aufbau und Entwärmung der Chips spielen eine zentrale Rolle, wenn es darum geht, den Wirkungsgrad der UV-LEDs von aktuell < 10 % zu erhöhen – und sind somit von essentieller Bedeutung für den Anwendungserfolg. Das FBH hat dazu einen neuen Aufbau mit galvanischen Mikrobumps untersucht, der bei der Kontaktierung mittels Thermokompression vergleichbare thermische Widerstände wie bei der klassischen Lötung erreicht. Die hexagonalen Bump-Felder bieten jedoch Vorteile im Design und senken die Ausfallrate. Chips mit für die Lötung entworfener Geometrie zeigten beim Aufbau mit Mikrobumps nach 100 h Alterung einen mit der Lötung vergleichbaren optischen Leistungsverlust, jedoch war ihre Ausfallrate geringer. Weitere Verbesserungen sind zu erwarten, wenn die Vorteile der Thermokompression mittels galvanischen Mikrobumps im Chipdesign gegenüber der Lötverbindung konsequent genutzt werden.

III-V Technology III/V-Technologie

For further information:

https://www.fbh-berlin.com/research/iii-v-technology

Annex
Anhang



Facts & Figures
Zahlen & Fakten

Founded 1992
Gegründet 1992

	2017	2018
Staff / **Team**	290	305
Scientists / Wissenschaftlerinnen & Wissenschaftler	101	111
PhD candidates / Promovierende	41	41
Student assistants & bachelor/master students / Studentische Hilfskräfte & Bachelor-/Masterstudierende	29	24
Trainees / Auszubildende	12	13
Projects / **Laufende Projekte**	221	233
Publications (peer reviewed) / **Publikationen (referiert)**	111	106
Patents / **Patente**	274	283
Talks (invited) / **Vorträge (eingeladene)**	124 (30)	152 (15)
Budget (in million Euros) / **Umsatz (Mio. Euro)**		
Basic funding: State of Berlin and Federal Government / Grundfinanzierung durch das Land Berlin und den Bund	14.5	14.9
Public project funding / Öffentliche Drittmittel	15.6	19.2
Industrial contracts / Industrielle Auftragsforschung	2.9	3.8

2017
2018

Personnel & Awards
Personalia & Auszeichnungen

Markus Krutzik awarded by Capital magazine
The business magazine Capital has selected Markus Krutzik as a talent in the category "Society and Science" for his "Young Elite – Top 40 under 40". The scientist conducts research at Humboldt-Universität zu Berlin and has also been working at the Ferdinand-Braun-Institut since 2017.

Innovation award goes to Til Bartel
Til Bartel works at the FBH on digital control of process and value chains within the Research Fab Microelectronics Germany. He won the Innovation Award Berlin Brandenburg 2018 with his startup SiQAl for a process that allows almost waste-free production of aluminum oxide and silicon.

Rudolf Jaeckel Prize 2018 awarded to Prof. Günther Tränkle
Günther Tränkle was honored with the Rudolf Jaeckel Prize for his achievements in the field of III-V semiconductor technology. The prize was assigned for his life's work and presented during the annual conference of the German Vacuum Society in Kaiserslautern.

Young Researcher's Paper Award for FBH publication
Nobel Laureate Hiroshi Amano presented the "Young Researcher's Paper Award" to Johannes Glaab at the 6th international "Conference on Light Emitting Devices and Their Industrial Applications" in Yokohama, Japan. He was honored for the paper "Degradation of electro-optical parameters and electromigration of hydrogen in (In)AlGaN-based UVB LEDs" (J. Glaab, J. Ruschel, T. Kolbe, A. Knauer, J. Rass, N. Lobo Ploch, M. Weyers, M. Kneissl, S. Einfeldt).

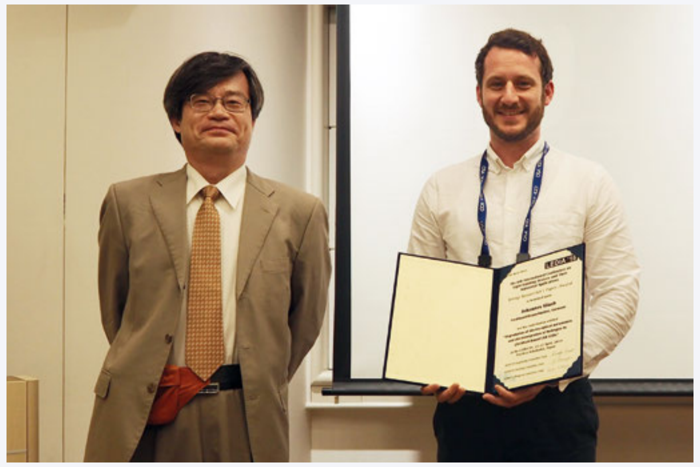
Markus Krutzik vom Magazin Capital ausgezeichnet
Das Wirtschaftsmagazin Capital hat Markus Krutzik als Talent in der Kategorie „Gesellschaft und Wissenschaft" für seine „Junge Elite – Top 40 unter 40" ausgewählt. Der Wissenschaftler forscht an der Humboldt-Universität zu Berlin und ist seit 2017 auch am Ferdinand-Braun-Institut tätig.

Innovationspreis geht an Til Bartel
Til Bartel arbeitet am FBH an der digitalen Steuerung von Prozess- und Wertschöpfungsketten im Rahmen der Forschungsfabrik Mikroelektronik Deutschland. Mit seinem Startup SiQAl gewann er den Innovationspreis Berlin Brandenburg 2018 für ein Verfahren, mit dem Aluminiumoxid und Silizium nahezu abfallfrei produziert werden können.

Rudolf-Jaeckel-Preis 2018 an Prof. Günther Tränkle verliehen
Günther Tränkle wurde mit dem Rudolf-Jaeckel-Preis für seine Leistungen auf dem Gebiet der III/V-Halbleitertechnologie ausgezeichnet. Der Preis wurde für sein Lebenswerk vergeben und im Rahmen der Jahrestagung der Deutschen Vakuumgesellschaft in Kaiserslautern überreicht.

Young Researcher's Paper Award für FBH-Publikation
Physik-Nobelpreisträger Hiroshi Amano überreichte die Urkunde an Johannes Glaab anlässlich der 6. LEDIA-Konferenz (Conference on Light Emitting Devices and Their Industrial Applications) in Yokohama, Japan. Ausgezeichnet wurde er für die Publikation „Degradation of electro-optical parameters and electromigration of hydrogen in (In)AlGaN-based UVB LEDs" (J. Glaab, J. Ruschel, T. Kolbe, A. Knauer, J. Rass, N. Lobo Ploch, M. Weyers, M. Kneissl, S. Einfeldt).

Markus Krutzik



Hiroshi Amano, Johannes Glaab

Oral Presentation Award
The joint presentation of U. Arz, S. Zinal, T. Probst, G. Hechtfischer, F.-J. Schmückle and W. Heinrich entitled "Establishing Traceability for On-Wafer S-Parameter Measurements of Membrane Technology Devices up to 110 GHz" was awarded the Oral Presentation Award at the ARFTG conference. Authors are from Physikalisch Technische Bundesanstalt, Rohde & Schwarz and FBH.

FBH again received TOTAL E-QUALITY award
In October 2018, the Ferdinand-Braun-Institut has again been awarded the TOTAL E-QUALITY award for its commitment to equal opportunities and successful implementation of related measures. FBH received this award for the first time in 2009.

Oral Presentation Award
Der gemeinsame Vortrag von U. Arz, S. Zinal, T. Probst, G. Hechtfischer, F.-J. Schmückle und W. Heinrich mit dem Titel „Establishing Traceability for On-Wafer S-Parameter Measurements of Membrane Technology Devices up to 110 GHz" wurde auf der ARFTG-Konferenz mit dem Oral Presentation Award ausgezeichnet. Die Autoren kommen von der Physikalisch Technischen Bundesanstalt, Rohde & Schwarz und FBH.

TOTAL E-QUALITY Prädikat erneut verliehen
Im Oktober 2018 wurde dem FBH erneut das TOTAL E-QUALITY Prädikat für sein Engagement für Chancengleichheit und die gezielten Maßnahmen zur erfolgreichen Umsetzung verliehen. Erstmalig erhielt das FBH diese Auszeichnung 2009.

Events
Veranstaltungen

for experts

Once again, FBH presented its research results at the key industry and science meetings and was represented with contributions at around 15 international conferences and workshops in 2018.

In 2019, the FBH exhibited for the second time at **Photonics West**, the world's largest photonics trade fair in San Francisco, USA – this year together with its spin-off UVphotonics. As in previous years, the institute was also prominently represented at the associated conferences with numerous scientific contributions.

Together with its spin-off UVphotonics, FBH presented current UV LED developments at the **ICULTA 2018** – International Conference on UV LED Technologies & Applications. The conference took place in Berlin for the first time and was organized by *Advanced UV for Life* – the office of the consortium is located at the FBH – together with the international organization IUVA. Due to the great response, the second conference scheduled for 2020 is currently in preparation. For more information see p. 31.

FBH presented its developments in III-V electronics at **SEMICON Europa** 2018 at the booth of the Research Fab Microelectronics Germany. As a highlight, the institute introduced a compact atmospheric plasma source and activated surfaces on site with its flexible handheld system. The procedure is necessary in order to prepare materials like plastics for subsequent coating, painting or gluing.

für das Fachpublikum

Erneut hat das FBH seine Forschungsergebnisse auf den zentralen Branchentreffs vorgestellt und war 2018 insgesamt auf rund 15 internationalen Fachkonferenzen und Workshops mit eigenen Beiträgen vertreten. Hier eine Auswahl:

2019 stellte das FBH zum zweiten Mal auf der **Photonics West**, der weltweit größten Photonik-Messe in San Francisco, USA, aus – in diesem Jahr gemeinsam mit der Ausgründung UVphotonics. Auch auf den angeschlossenen Konferenzen war das Institut – wie bereits in den Jahren zuvor – mit zahlreichen wissenschaftlichen Beiträgen prominent vertreten.

Gemeinsam mit seinem Spin-off UVphotonics stellte das FBH auf der **ICULTA 2018** – International Conference on UV LED Technologies & Applications aktuelle UV-LED-Entwicklungen vor. Die Konferenz fand erstmalig in Berlin statt und wurde von *Advanced UV for Life* – die Geschäftsstelle des Konsortiums sitzt am FBH – gemeinsam mit der internationalen Organisation IUVA organisiert. Aufgrund des großen Zuspruchs ist die zweite Konferenz für 2020 aktuell in Vorbereitung. Weitere Informationen gibt es auf S. 31.

Am Messestand der Forschungsfabrik Mikroelektronik Deutschland auf der **SEMICON Europa** 2018 präsentierte das FBH seine Entwicklungen aus der III/V-Elektronik. Als Highlight stellte das Institut eine kompakte atmosphärische Plasmaquelle vor und aktivierte mit dem flexiblen und handlichen System vor Ort Oberflächen. Dieser Arbeitsschritt ist notwendig, um Materialien wie Kunststoffe später beschichten, lackieren oder verkleben zu können.

At the **European Microwave Week 2018** in Madrid, FBH made its topics known with 10 presentations. The talk "Highly compact GaN-based all-digital transmitter chain including SPDT switch for massive MIMO" by Florian Hühn made it on the short list for the Microwave Prize (= Best Paper). To a similar extent, FBH was represented at the **International Microwave Symposium** 2018 in Philadelphia.

for the interested public

FBH opened its laboratories again to a broad audience in 2018. More than 700 people visited the FBH for the **Science Night** 2018. The program range included laboratory and cleanroom tours as well as hands-on experiments.

To make it easier for school students to choose a career, FBH 2018 and 2019 took part in the **Education Alliance Adlershof** and **Girls' Day**, among other events. The institute provided information on professions related to microtechnology, research and development. Further information can be found on p. 17.

for ourselves – FBH also successful in sports

In 2018 and 2019, colleagues were again active in sports. The FBH team won the Adlershof Company Relay in the men's category. And as in the previous year, the FBH team was the fastest running group from the Forschungsverbund Berlin at the Berlin Company Run in 2019. Christoph Stölmacker, Nicolas Hübener and Veit Hoffmann even finished 9[th] in the overall ranking

Auf der **European Microwave Week 2018** in Madrid machte das FBH seine Themen mit 10 Vorträgen sichtbar. Der Vortrag „Highly compact GaN-based all-digital transmitter chain including SPDT switch for massive MIMO" von Florian Hühn schaffte es in die Short List für den Microwave Prize (= Best Paper). In ähnlichem Umfang war das FBH auch auf dem **International Microwave Symposium** 2018 in Philadelphia vertreten.

für die interessierte Öffentlichkeit

Auch 2018 öffnete das FBH seine Labore wieder für ein breites Publikum. Zur **Langen Nacht der Wissenschaften** 2018 besuchten mehr als 700 Interessierte das FBH. Das Programm reichte von Labor- und Reinraumführungen bis hin zu Mitmachexperimenten.

Um Schülerinnen und Schüler die Berufswahl zu erleichtern, beteiligte sich das FBH 2018 und 2019 unter anderem an der **Ausbildungs-Allianz-Adlershof** und am **Girls' Day**. Das Institut informierte zu Berufen rund um Mikrotechnologie, Forschung und Entwicklung. Weitere Informationen dazu gibt es auf S. 17.

für uns selbst – FBH auch sportlich erfolgreich

Auch 2018 und 2019 waren Kolleginnen und Kollegen wieder sportlich aktiv. So gewann das FBH-Team die Adlershofer Firmenstaffel bei den Männern. Und wie bereits im Vorjahr war das FBH-Team 2019 beim Berliner Firmenlauf die schnellste Laufgruppe aus dem Forschungsverbund Berlin. Christoph Stölmacker, Nicolas Hübener und Veit Hoffmann erliefen sich in der Gesamtwertung sogar den 9. Platz.

FBH team at Berlin Company Relay 2019: M. Mohammadi, C. Stölmacker, K. Czajkowski, N. Hübener, V. Hoffmann, H. Christopher (from left).

Structure of the institute
Institutsstruktur

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.

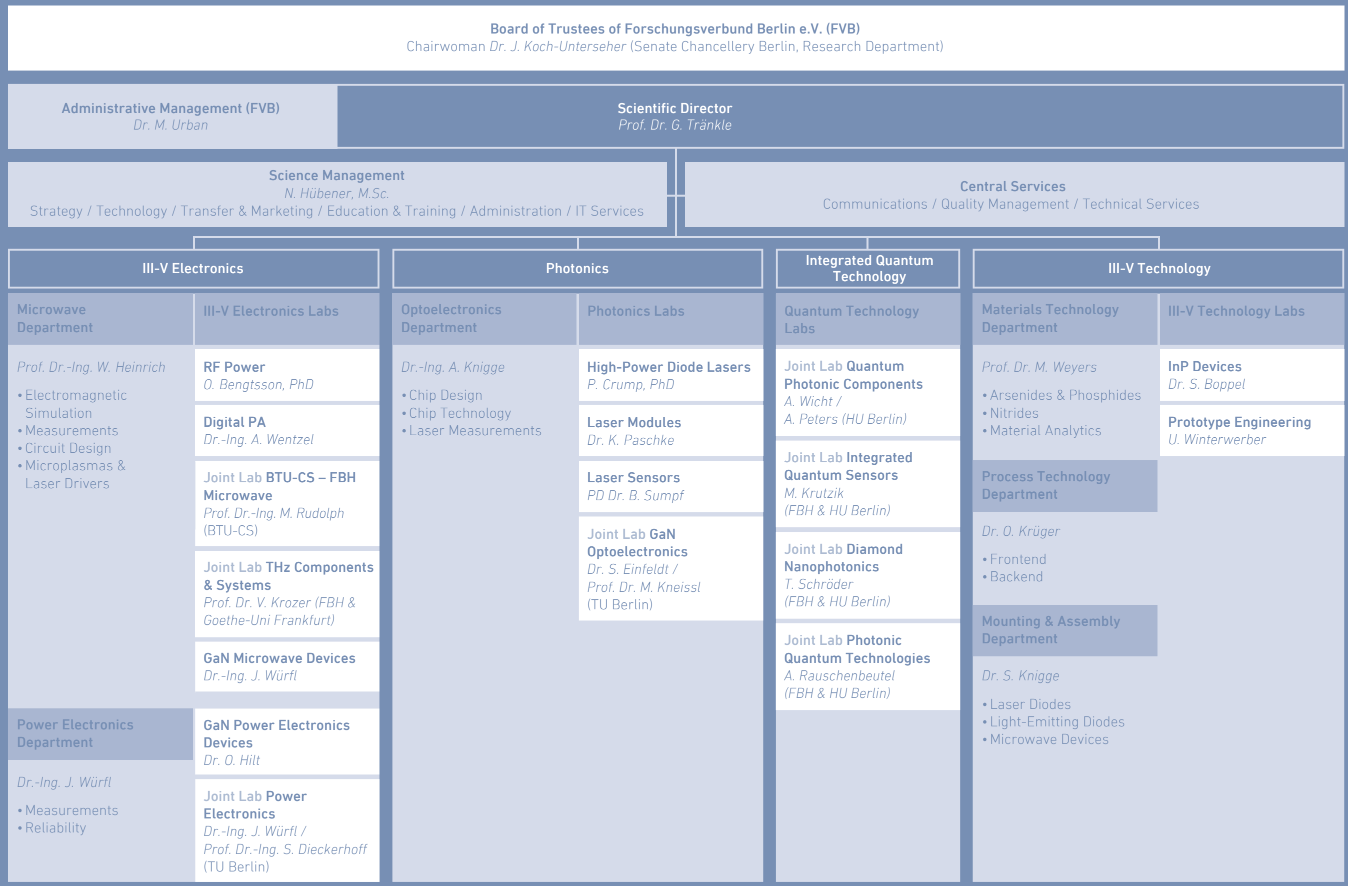
With its Science Management the institute provides an interface between science, industry and education/training. The department coordinates various networking projects in the high-tech field and is also responsible for administration and IT services. An efficient, process-oriented quality management system and the communications 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.

* in development since 2019 / seit 2019 im Aufbau

Organizational chart
Organigramm



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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 95 independent research institutions. The corresponding institutes employ around 20,000 people and manage a total budget of approximately 1.9 billion euros.

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 95 selbständige Forschungseinrichtungen. Die zugehörigen Institute beschäftigen knapp 20.000 Personen und haben einen Gesamtetat von mehr als 1,9 Milliarden Euro.

www.fv-berlin.de
www.leibniz-gemeinschaft.de

How to get in touch
Wie Sie uns erreichen

Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik im Forschungsverbund Berlin e.V. Gustav-Kirchhoff-Str. 4 12489 Berlin, Germany	Phone +49.30.6392-2600 Fax +49.30.6392-2602 Email fbh@fbh-berlin.de Web www.fbh-berlin.de
Director Direktor	Prof. Dr. rer. nat. Günther Tränkle Phone +49.30.6392-2601 guenther.traenkle@fbh-berlin.de
Assistant to the Director Referentin der Institutsleitung	Doreen Friedrich, M.Sc., Dipl.-Ing. (FH) Phone +49.30.6392-3391 doreen.friedrich@fbh-berlin.de
Science Management Wissenschaftsmanagement	Nicolas Hübener, M.Sc., Dipl. Kfm. (FH) Phone +49.30.6392-3396 nicolas.huebener@fbh-berlin.de
Communications Kommunikation	Petra Immerz, M.A. Phone +49.30.6392-2626 petra.immerz@fbh-berlin.de

Central Contact for Research Areas
Fachliche Ansprechpartner für die Forschungsbereiche

Photonics Photonik	Prof. Dr. rer. nat. Günther Tränkle Phone +49.30. 6392-2601 guenther.traenkle@fbh-berlin.de
III-V Electronics III/V-Elektronik	Deputy Director Stellvertretender Direktor Prof. Dr.-Ing. Wolfgang Heinrich Phone +49.30.6392-2620 wolfgang.heinrich@fbh-berlin.de
III-V Technology III/V-Technologie	Prof. Dr. rer. nat. Markus Weyers Phone +49.30.6392-2670 markus.weyers@fbh-berlin.de
Integrated Quantum Technology Integrierte Quantentechnologie	Dr. rer. nat. Andreas Wicht Phone +49.30.6392-3958 andreas.wicht@fbh-berlin.de

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Ferdinand-Braun-Institut
Leibniz-Institut für Höchstfrequenztechnik
Gustav-Kirchhoff-Str. 4
12489 Berlin, Germany
Phone +49.30.6392-2600
Fax +49.30.6392-2602
Email fbh@fbh-berlin.de
Web www.fbh-berlin.de

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Ferdinand-Braun-Institut
Leibniz-Institut für Höchstfrequenztechnik
Gustav-Kirchhoff-Str. 4
12489 Berlin

www.fbh-berlin.de