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LEIBNIZ INSTITUTE *of* PHOTONIC TECHNOLOGY // Annual Report 2015

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LEIBNIZ INSTITUTE *of* PHOTONIC TECHNOLOGY
ipht jena

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Dear Reader,

» Light is the fundamental basis of all life. It is of significant cultural relevance and the subject of many research areas. To highlight its importance, 2015 was declared the International Year of Light by UNESCO. The opening ceremony in particular, which was held at the Jena Sparkasse Arena in January, and the Physics Highlights in September of last year delighted thousands of visitors. As the Leibniz Institute of Photonic Technology, we used these events and others as an opportunity to present our research activities to the general public under the motto “Photonics for Life.”

The development of photonic solutions for applications in the life sciences requires fundamental and broad technological competencies. In this context, IPHT can draw on its long-standing expertise in the areas of micro and nano technologies, fiber technologies and system technology. The current annual report focuses on the area of fiber technologies. We would like to present you with an overview of our research work so far and current topics from this area. In addition, we will introduce selected application possibilities in detail.

As usual, our scientists report on current research results in the form of technical contributions. You will find these contributions on our website and in the IPHT app. For the first time, this app will not only be available for iPads but for Android tablets as well.

Without the continued support by the Free State of Thuringia, the Federal Government and the European Union, the successes presented here would not have been possible. For this, we would like to extend our heartfelt gratitude. Furthermore, a “thank you” goes out to all our partners with whom we have worked well together on a basis of trust during research projects, alliances, networks, and within the Leibniz Association. Particular acknowledgement is owed to the scientific council, the advisory board, and the general assembly at IPHT for their long-standing and goal-oriented cooperation. In addition, we would like to thank the entire staff of the institute for their great commitment during the past months and years. We look forward to future successful cooperation.

Prof. Dr. Jürgen Popp
Scientific Director

Frank Sondermann
Administrative Director

Prof. Dr. Jürgen Popp //
Scientific Director

Frank Sondermann //
Administrative Director

Cover: Preform of a hollow core fiber with a microscope image of a fiber cross section drawn out of this preform

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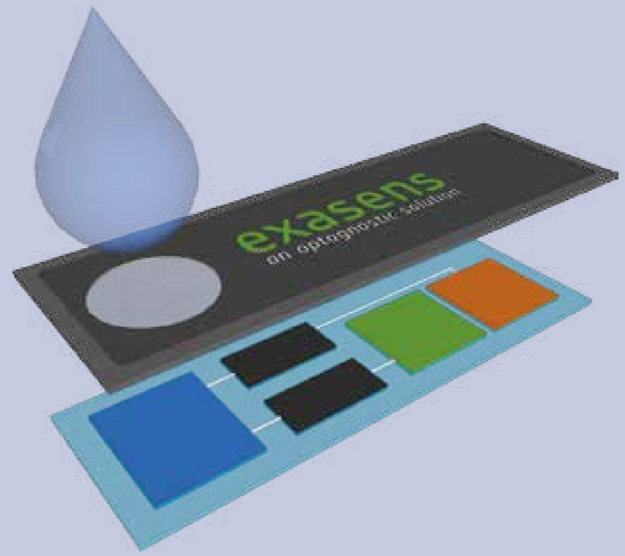

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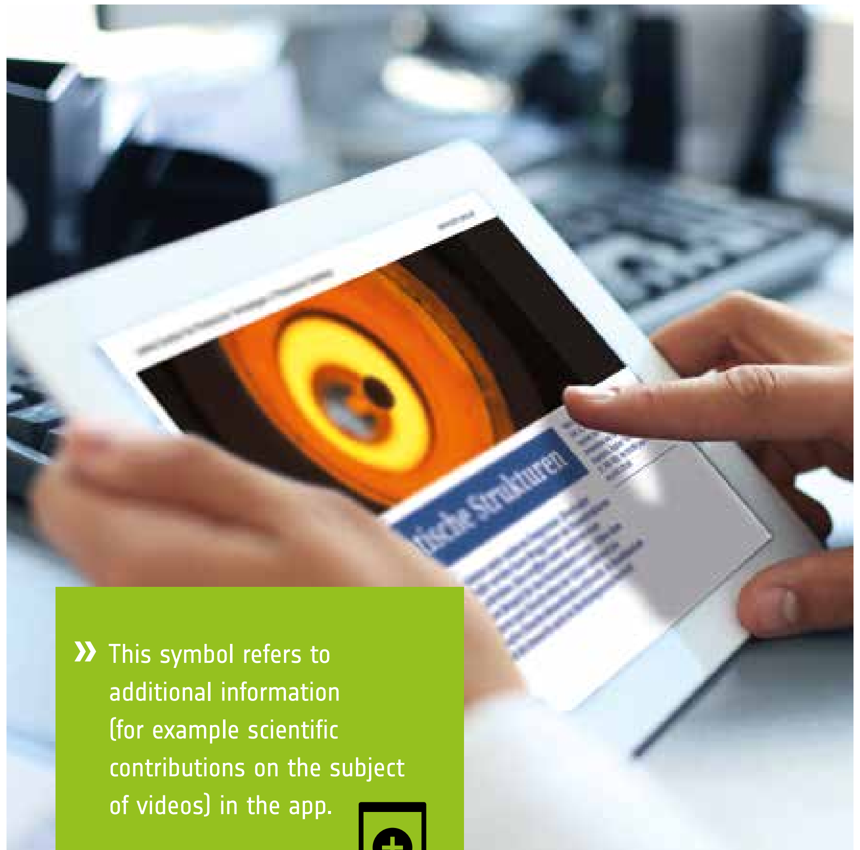
In addition to fundamental technological research in the fields of biophotonics, fiber optics, and photonic detection, the importance of system technology at IPHT continues to increase. Consequently, a workgroup focusing on system integration was established at IPHT.

» *Spot our Annual Report as App!*



» This symbol refers to additional information (for example scientific contributions on the subject of videos) in the app.

The IPHT app for tablets is available at the App Store and at Google play. In addition to the content of the printed version the user friendly app contains current scientific contributions from the research ares Biophotonics, Fiber Optics and Photonic Detection. The textual content is made up by multimedia features and a detailed appendix including the entire publication list of the IPHT. Moreover the integrated news feed informs about the latest reports and press releases.

2015 Annual Review

In addition to the events held as part of the International Year of Light, IPHT drew attention to itself with various other events. A brief selection in review …

» The first event of 2015 was “LIGHT Phenomena,” moderated by WDR’s Ralph Caspers (A Science Wonder!) as part of the International Year of Light. Approximately 2,700 visitors came to the sold-out Jena Sparkasse Arena for the show. This knowledge show was organized by IPHT in cooperation with the Fraunhofer Institute for Applied Optics and Fine Mechanics and the city-owned and operated company JenaKultur supported by JenaWirtschaft. Another public magnet as part of this theme year was the “Highlights of Physics” held in September. During this event, which lasted several days, more than 50,000 guests visited Jena. In addition to IPHT, renowned research institutes and companies from all across Germany presented their work on the subjects of optics and photonics. The German Physical Society and the Friedrich Schiller University of Jena hosted this event organized by Prof. Dr. Gerhard Paulus.

» Numerous prizes, with which scientists at IPHT were awarded this past year, are proof of the excellent research work performed at the institute. Yet another group at IPHT was awarded with the renowned Thuringian Research Award. Prof. Dr. Hartmut Bartelt, head of the fiber optics department and professor in the physical astronomy department of the Friedrich Schiller University of Jena, and his team received the prize in the category of “transfer.” Together with their partners from FBGS Technologies GmbH, they researched a method of producing fiber sensors for the efficient and costs-effective measurement of temperature, pressure, and strain. This award was presented by Wolfgang Tiefensee, Thuringia’s Minister of Economic Affairs, Science, and Digital Society.

» IPHT is gaining importance as an attractive research institute for international visiting scientists. Last year, Dr. Michael Vetter and Dr. Stephen Warren-Smith both performed research at IPHT for which they were granted one of the coveted Marie Skłodowska Curie stipends. Part of this European Commission funding program is the support of informational exchange between young research scientists and experienced researchers, as well as the career development of research scientists. During his stay at the institute, Michael Vetter researched a new method of producing crystalline silicon thin-film solar cells made of glass. Stephen Warren-Smith from the Centre for Nanoscale BioPhotonics (CNBP) in Adelaide, Australia, is working on the further development of miniaturized sensors on fiber optics for biomedical applications.

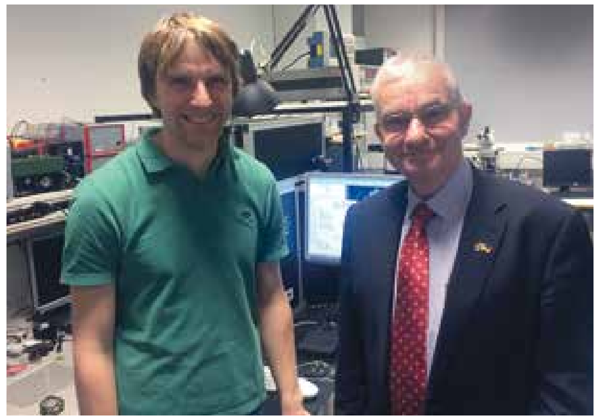
» Structural approaches to improving the translation of technological solutions into marketable products and options for optimizing collaboration in research and medicine are of particular strategic interest to IPHT. More than 60 participants from medicine, science, and industry discussed this issue during the “Optical Diagnostics Workshop” held at the Center for Applied Research in July. IPHT organized this event together with the Leibniz Research Alliance Medical Technology and the Jena Research Campus InfectoGnostics.

» Social responsibility towards employees and optimization of family-friendly work conditions are central issues at the institute. With admission into the Jena Family Alliance in November of last year, IPHT hopes to gain valuable insight into optimizing and expanding its existing measures. IPHT will primarily be involved in the workgroup “Balancing Work and Family Life.”.

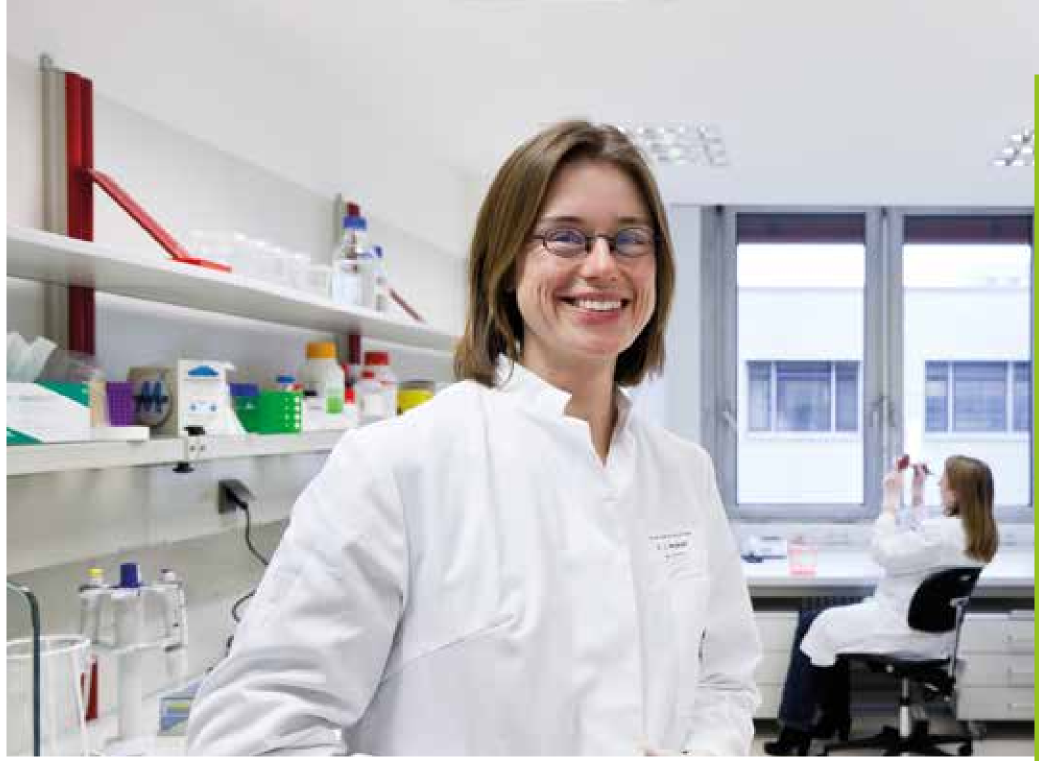
Information on the organizational structure and current figures can be found on pages 36-42

+ Appendix including the list of publications

Sensational dance performance by the international group of artists “Feeding the Fish” during the opening event for the International Year of Light in Jena.



Dr. Dave Lowe (right), coordinator at the New Zealand Ministry of Economy visits the laboratory of Tobias Meyer at the IPHT.



Dr. Ute Neugebauer: Honored as the best young research scientist with the Science Award Life Sciences and Physics 2015 on the Jena Beutenberg Campus.

Presentation of the Thuringian Research Award by Wolfgang Tiefensee (left), the Thuringian Minister of Economic Affairs, Science, and Digital Society, to Prof. Dr. Harmut Bartelt and his team.

» Distinguished Employees

Last year, many of the outstanding achievements of IPHT’s scientists were presented with national and international awards – including several poster prizes for doctoral students. A selection:

Hartmut Bartelt, Christoph Chojetzki, Jens Kupis, Eric Lindner, Manfred Rothhardt, and Sonja Unger // Thuringian Research Award in the category Transfer

Thomas Bocklitz // Bruce R. Kowalski Award in Chemometrics Administered by the Society for Applied Spectroscopy (SciX Conference 2015)

Volker Deckert // Fellow of the Royal Society of Chemistry (RSC)

Yan Di // Raman Young Investigator Award (8th International Conference on Advanced Vibrational Spectroscopy (ICAVS), Vienna)

Izabella Hidi // Entrepreneurship Challenge Winner (Biophotonics 2015, SPIE)

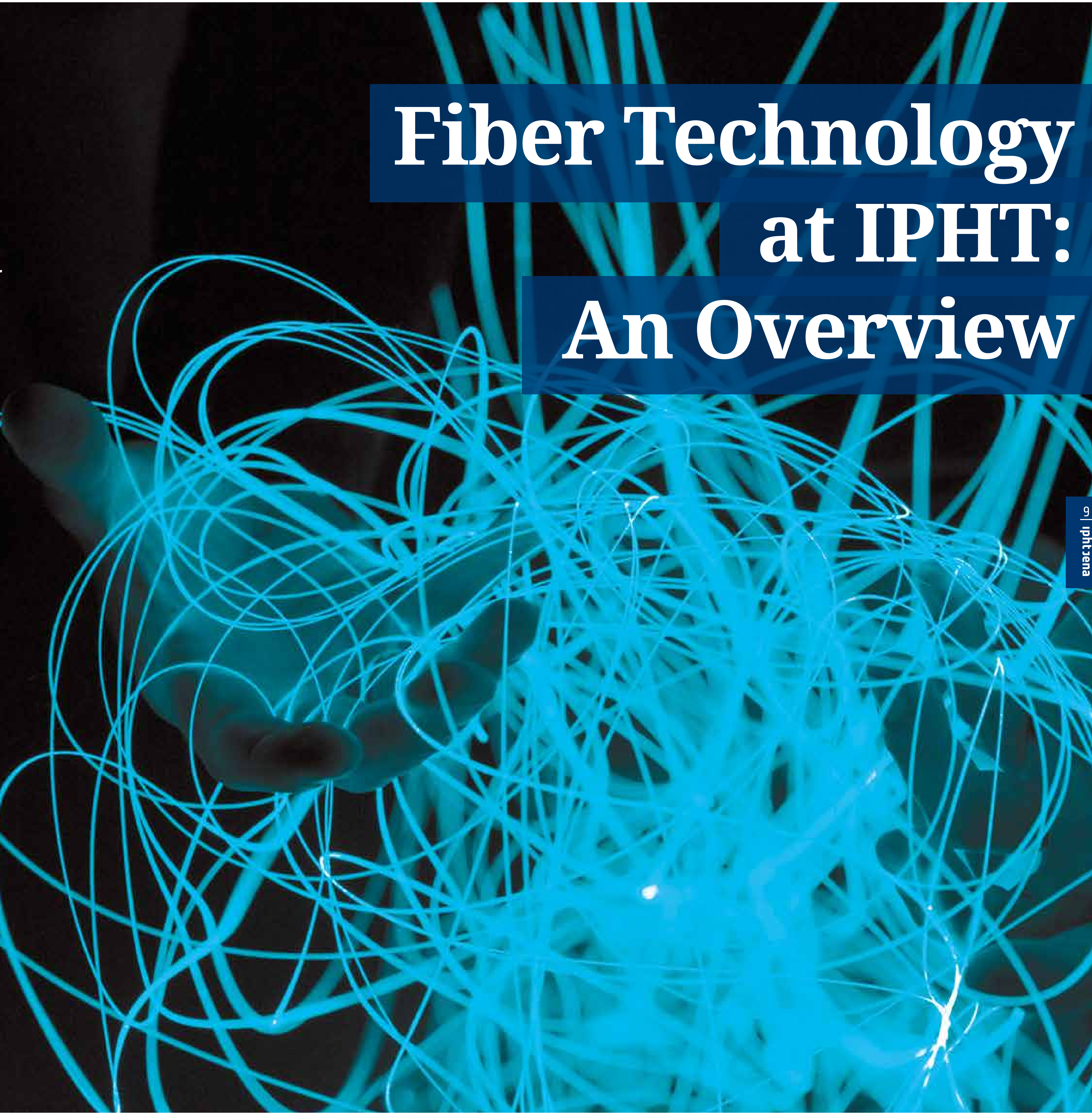
Hans-Georg Meyer, Thomas Schönau, and Ronny Stolz // iENA gold medal 2015 (67th international expert trade show for “Ideas-Inventions-Novelties” iENA 2015, Nuremberg)

Ute Neugebauer // Science Award Life Sciences and Physics 2015 (Beutenberg Campus Jena)

Jürgen Popp // Pittsburgh Spectroscopy Award of the Spectroscopy Society of Pittsburgh (SSP), (PITTCON 2016)

Fiber Technology at IPHT: An Overview

Light is the central focus of research at the Leibniz Institute of Photonic Technology. Fiber optics has been the research focus at the institute for more than 30 years. With an outstanding technological basis and the distinct expertise of its employees, IPHT now features a state-of-the-art, closed technology chain. Research and development comprises fiber design, preform production, fiber drawing, material and fiber characterization, as well as the development of fiber-based optical components. This diversity makes IPHT a globally much-sought-after partner in industry and science in the field of fiber optic technology. »



» Preform Technologies at IPHT

Since the late 1970s, the predecessor of IPHT has performed research on the production of optical fibers based on synthetic quartz glass. The goal was to develop low-loss optical fibers for optical communication which, back then, was still in its infancy.

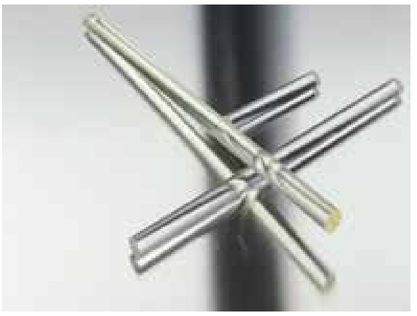
MCVD process

For the production of fiber preforms, from which fibers are later drawn, the modified chemical vapor deposition (MCVD) process was introduced at the institute. In close collaboration with Jenaer Glaswerk Schott & Gen., the MCVD process was brought onto the market. After the successful transfer of telecommunications fibers from basic research to application, IPHT concentrated at the beginning of the 1990s on the research and development of optical fibers for specialty applications such as fiber lasers and fiber-based sensors for measuring, for example, pressure or temperature. Application fields include medical technology, environmental monitoring, and the automotive industry.

The rapidly increasing demands of the industry for higher power levels in fiber lasers represent a major challenge in the design of thicker fiber cores. Although the MCVD process is still the standard technology at IPHT for the production of preforms, it has technological limits with regard to the production of a corresponding core material. Starting in 2006, the patented REPUSIL process (reactive powder sintering of fused silica) for the preparation of the material was researched and developed at IPHT in close cooperation with industrial partners.

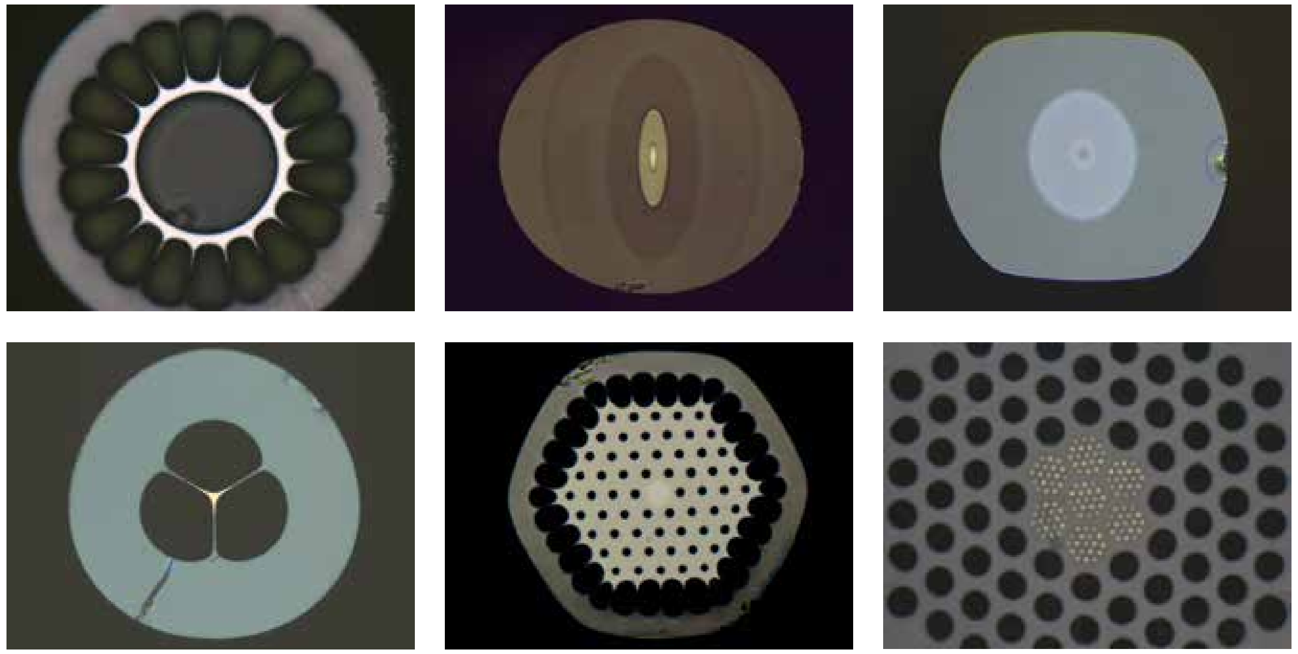
The crucible melting process, which was established at IPHT in 2007, is another complementary method of production of preforms for optical specialty glasses. With the crucible melt, large volumes of glass are produced with different dopants. The glass can be used in compact form or drawn into fibers.

Crucible melting process

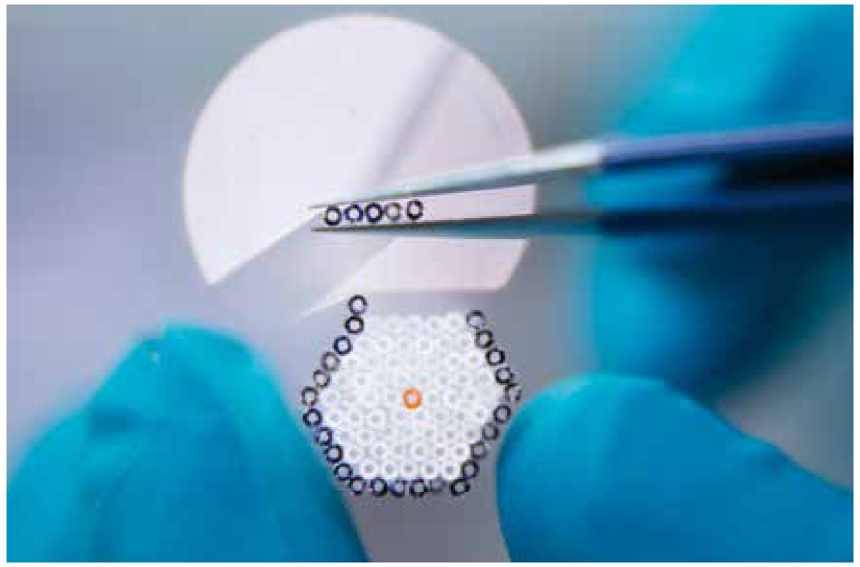


Rare-earth-doped bulk silica glass, which was made by the REPUSIL process

» In 2012, scientists at IPHT were awarded the Thuringian Research Award in the field of applied research for the research and development of the REPUSIL process.



Microscope images of cross-sections of special optical fibers produced at IPHT.



Silica glass capillaries bundle as basis for highly complex fiber structures

» Highly Complex Fiber Structures for Diverse Applications

Based on broad expertise in the drawing of fibers and technological equipment, highly complex fiber structures are implemented at IPHT.

"The inner structure of a fiber plays a major role in its functional characteristics." // Prof. Dr. Hartmut Bartelt, Head of Department Fiber Optics at IPHT

By modifying these structures in a targeted manner, one can create light in the fiber more efficiently, transmit at higher optical power, and implement more sensitive spectral fiber sensors for the detection of gases and liquids. The structure in the preform is created manually by arranging glass rods and glass capillaries. When drawing the preform, drawing temperature and speed, as well as the pressure in the capillaries, must be adjusted and controlled precisely to transfer the microstructure into the fiber. Years of experience and the expertise of the fiber technologists at IPHT enable the development and production of different microstructures for various applications.

» Fiber Drawing Tower

Since 1982, the drawing of simple preforms has been performed at IPHT in a self-developed, five-meter-high fiber drawing tower. To meet the requirements of the production and drawing of more complex fiber structures, another drawing tower (about 14 meters high) has been operated at the institute since 2009. The tower was built with the financial support of the European Union, the Free State of Thuringia and the Federal Ministry of Education and Research.

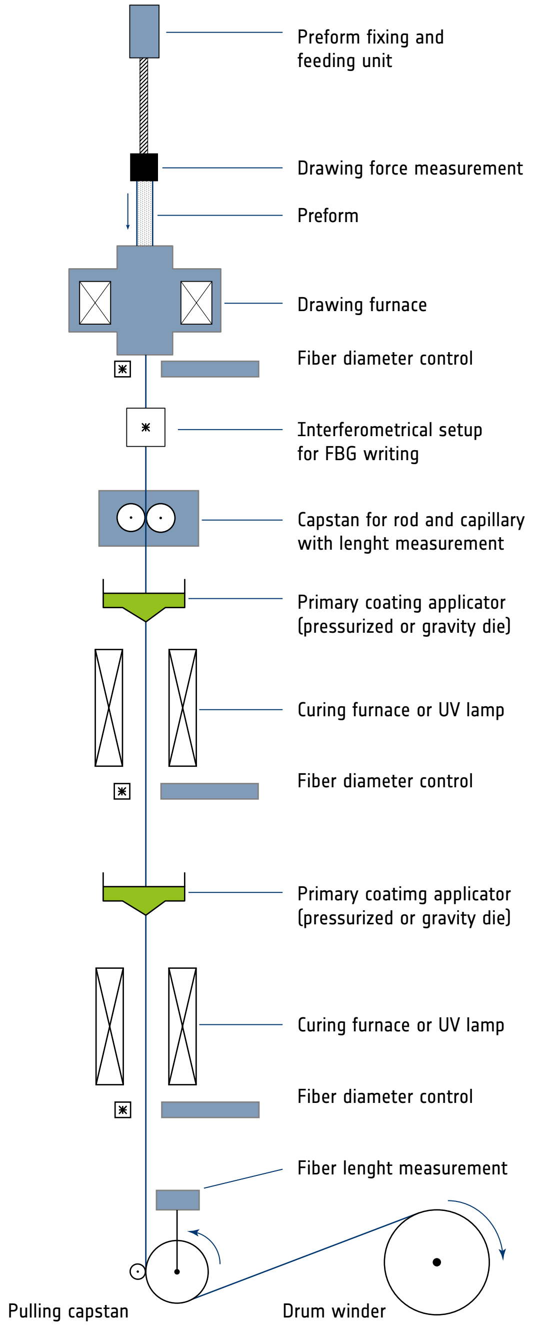
"Our drawing tower is much more than just a production facility. It is one of the most modern drawing tower in research throughout Europe." // Dr. Jens Kobelke, fiber technologist at IPHT

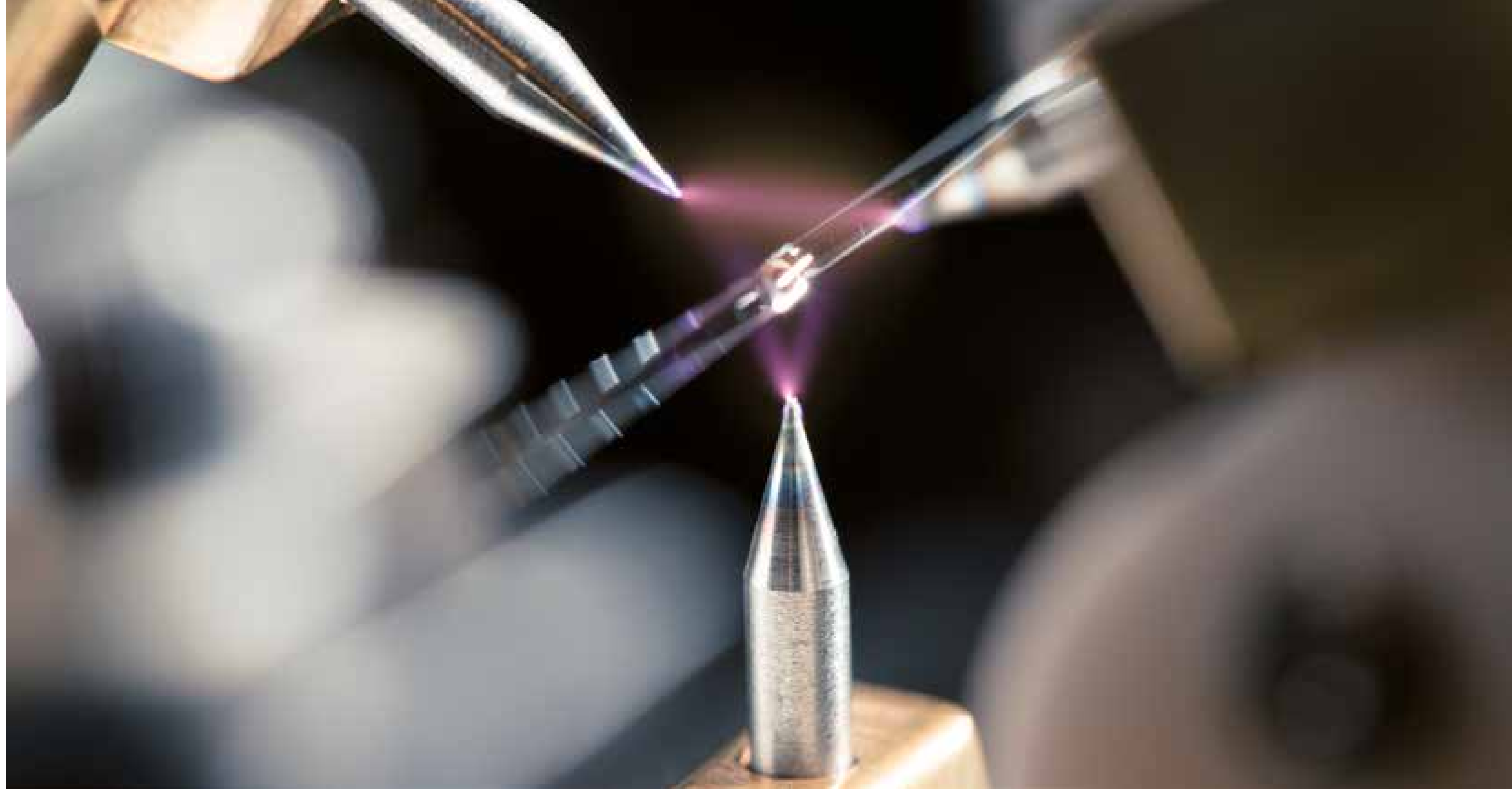
Thanks to ultra-modern equipment, almost all drawing parameters such as the drawing speed, the drawing temperature, or the curing conditions of the polymer coating of the fiber can be changed within wide ranges.

A world-leading method for inscribing structures into the fiber core with laser pulses during the fiber drawing process was developed at IPHT. Fiber Bragg gratings (FBGs) cause a wavelength specific reflection of the light.

» The FBG inscription method developed at IPHT was spun off into the company FBGS Technologies GmbH. For the transfer of science into application, Prof. Dr. Hartmut Bartelt and his team were awarded the 2015 Thuringian research award. The variety of applications for fiber Bragg gratings and the variety of materials used in modern optical fibers require a continuous development of the methods for inscribing fiber Bragg gratings.

View into the fiber draw tower





Splicing of fibers

» Process and Material Characterization

Various characterization methods accompany all steps of glass and fiber production at IPHT. This allows the research of the relationships and dependencies between the glass composition and the subsequent optical properties of a fiber. One focus is on the study of light induced optical losses, for example photodarkening in laser fibers. This self-damaging process systematically reduces the efficiency of a fiber laser. Examinations help to draw conclusions about the dependence of photodarkening on the glass material composition. The findings from process and material characterization flow directly into the optimization of the manufacturing processes for preforms and fibers.

» Photodarkening

This self-damaging in the application process systematically reduces the efficiency of a fiber laser. Optimization of the glass material composition will improve the stability of future fiber lasers.

» Integration Technologies

Many fiber optical applications such as fiber lasers require a post-processing of the optical fiber for which techniques such as tapering or splicing are available at IPHT. Using these methods, different light sources are able to be coupled into a single fiber core. It is also possible to melt the fiber ends of the same type of fiber (or even different types) into innovative fiber components. Such processed fibers form the basis for the development of novel laser concepts at IPHT.

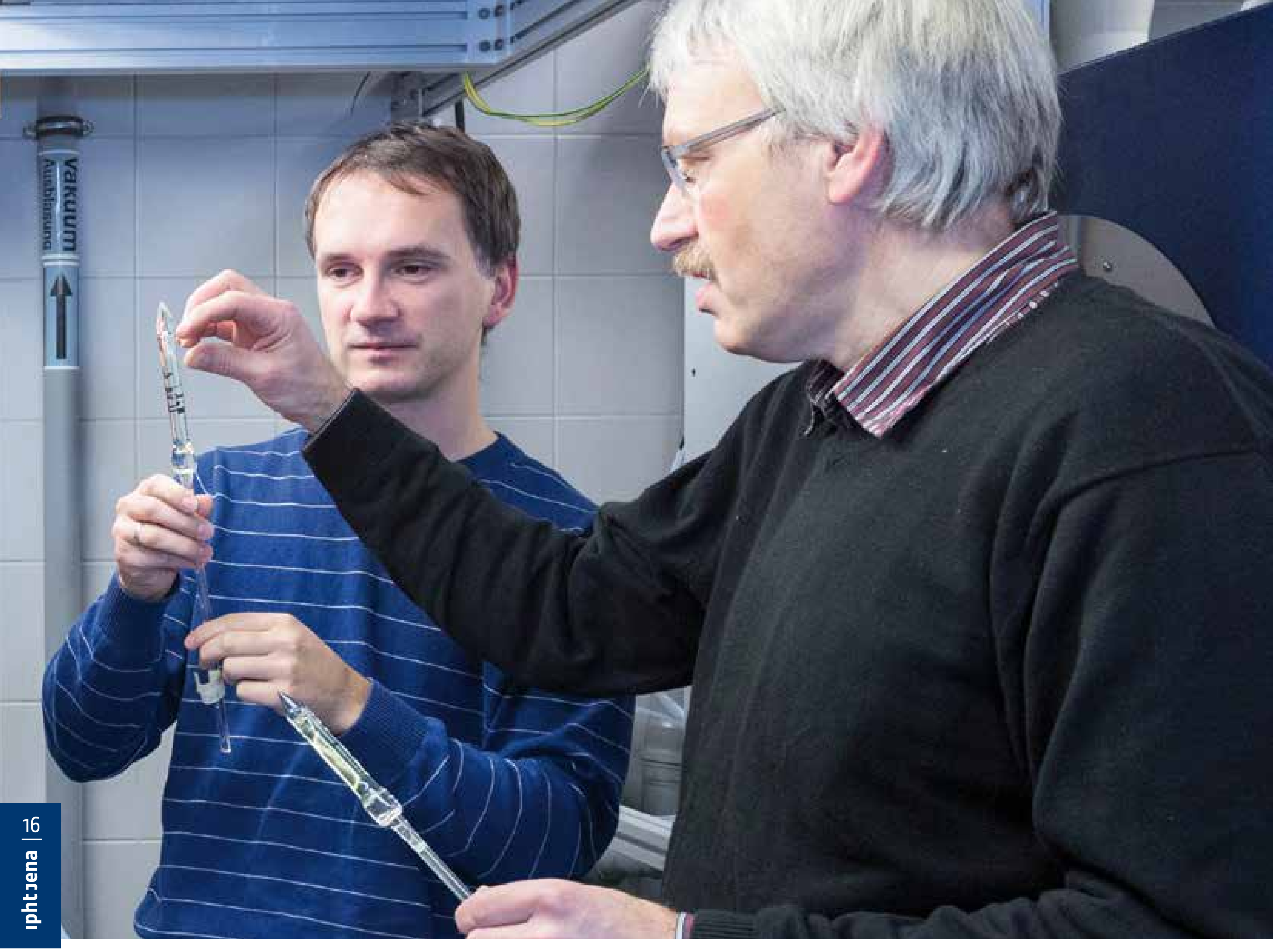
- ***Film IPHT Fiber Drawing Tower***
- ***Scientific Contribution "Diffusion and Sintering Effects in Compact Micro-structured Fibers"***
- ***Scientific Contribution "Incoherent Combination of Fiber Lasers in a 7x1 Fiber Coupler with Average Powers > 5kW and High Brightness"***

» Enabling Technology

Fiber optics is a fundamental technology at IPHT. The close cooperation and permanent exchange between fiber experts forms the basis for this. "Based on excellent basic and applied research in fiber optics innovative fibers or fiber concepts can be realized. These finds application in various fields like health, safety, environmental and energy, according IPHT's guiding principle 'From Ideas to Instruments,'" said Professor Dr. Jürgen Popp, scientific director of IPHT.

Specialty Fibers for High-power Lasers

Optical fibers are used in a variety of ways for the transmission of light. Today, fibers are used in communications technology, measurement technology, or for illumination purposes. Modern specialty fibers offer the ability to produce light inside the fiber as well. One such light source with a particularly high beam quality is the fiber laser. Fiber lasers are used, for example, in the automotive industry to cut or drill metal sheets that are several millimeters thick and to permanently join materials that cannot be welded together by conventional means. In cooperation with the company Heraeus Quarzglas, IPHT has developed an alternative method of production of base materials for optical fibers. In this way, the output power extracted from a single fiber was able to be increased up to five kilowatts. »



Scientists at IPHT looking at preforms made out of the REPUSIL process.

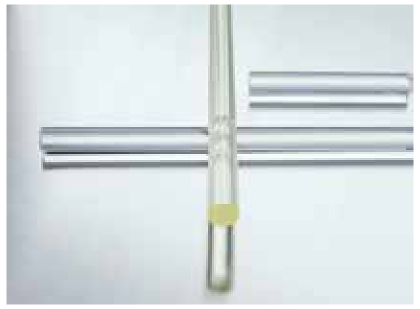
» *Fibers for high laser power*

The central element of a fiber laser is a specialty optical fiber. The core of such a fiber contains rare-earth ions and serves as a gain medium. Due to the long length of the fiber, pump light guided through the fiber creates a very high gain. The ever-increasing output power of fiber lasers in the range of several kilowatts – which is demanded by the industry – cannot be implemented with classic fibers that have a diameter of 125 µm because the energy produced per unit of area and time (power density) destroys the glass material.

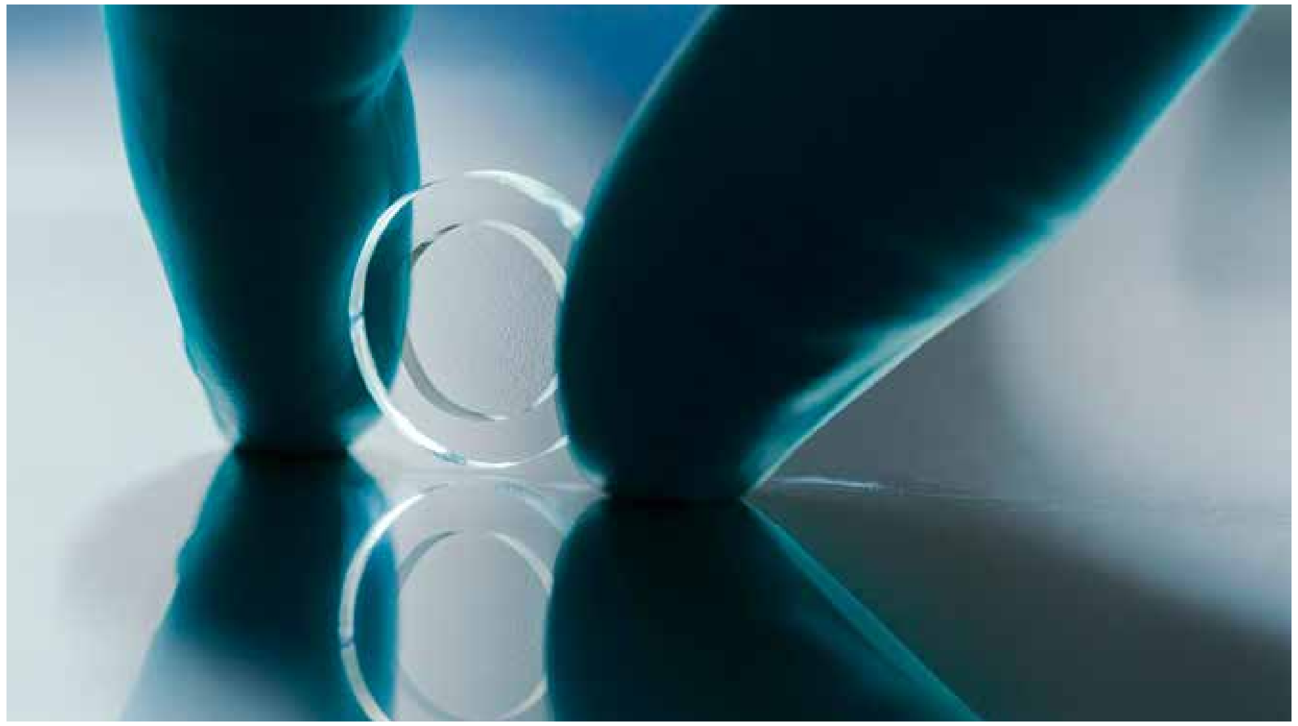
Conventionally, this problem is solved by coupling several individual fibers. One alternative is thicker fibers. The production of correspondingly thicker fiber cores that possess very homogeneous material properties is particularly challenging here. Together with partners from Heraeus Quarzglas, scientists at IPHT jointly developed a novel process for the production of this core material in homogeneous blocks.

Fiber preform production is carried out in several process steps. Bulk, rare earth-doped fused silica, which is manufactured via the reactive powder sintering (REPUSIL) process, forms

Pulver is the basis for the bulk silica glass



Rare-earth-doped bulk silica glass



Exceptionally large core rod dimensions can be implemented by the REPUSIL process.

the basis of these fiber preforms. The REPUSIL process is advantageous over conventional methods of fiber laser glass production because it allows the implementation of extraordinarily large core rod dimensions that, in turn, allow novel fiber designs with very large core volumes.

> ***"REPUSIL is globally unique. It has already noticeably expanded the range of fibers that can be produced at IPHT. Simultaneously, there is still a lot of potential with respect to doping, homogenization, and structuring which will be fully exploited in other research projects."***
> ***// Dr. Kay Schuster, fiber expert at IPHT***

The optical fiber preform produced via the REPUSIL process can either be drawn directly into a massive fiber or further processed into a microstructured fiber.

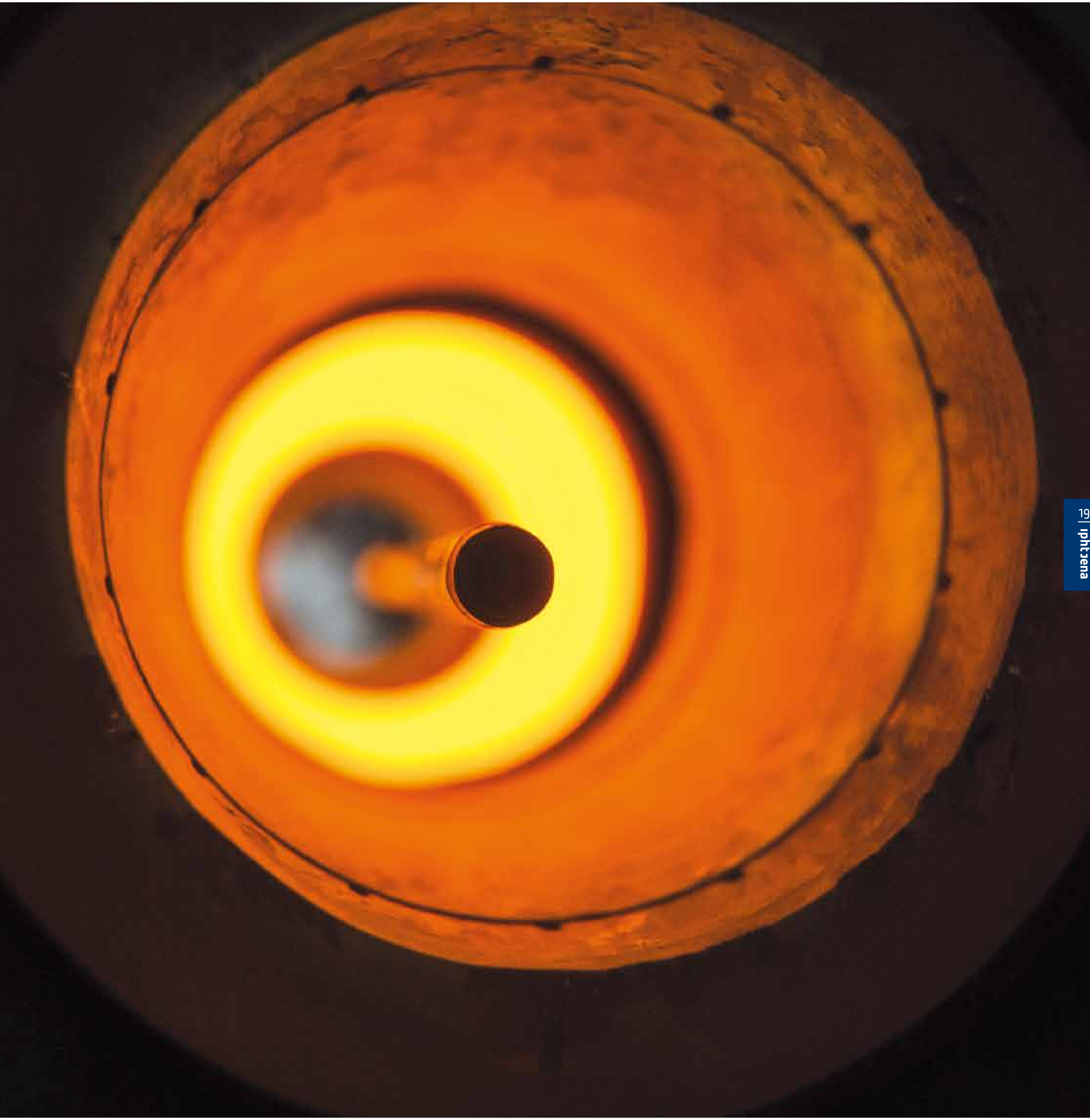
This new method perfectly complements the processes for the production of optical fiber preforms already established at IPHT.

For nearly 10 years, IPHT is working to a steadily increasing extent on the research of REPUSIL technology. In 2015, seven projects (funded both publicly and by the industry) involved, among others, the establishment of new dopings in order to significantly expand the application range of REPUSIL glasses. Such material developments are connected with extensive research into the advancement and optimization of the technological processes. Existing project/funding commitments for the coming years confirm the strong interest by industry, academia, and public sponsors in the REPUSIL process itself, as well as in the excellent optical glasses produced using this technology.

+ ***Scientific contribution "Fluorine Doping via the REPUSIL Process for Adjustment of the Optical Properties of Fused Silica Materials"***

» The REPUSIL process was developed as part of several collaborative projects funded by the Federal Ministry of Education and Research (BMBF). Using the REPUSIL material, our project partner Heraeus Quarzglas manufactures laser fibers which have been used for several years now by Laserline in multi-kilowatt beam converters. In 2015, output levels in excess of five kilowatts of laser power were able to be generated.

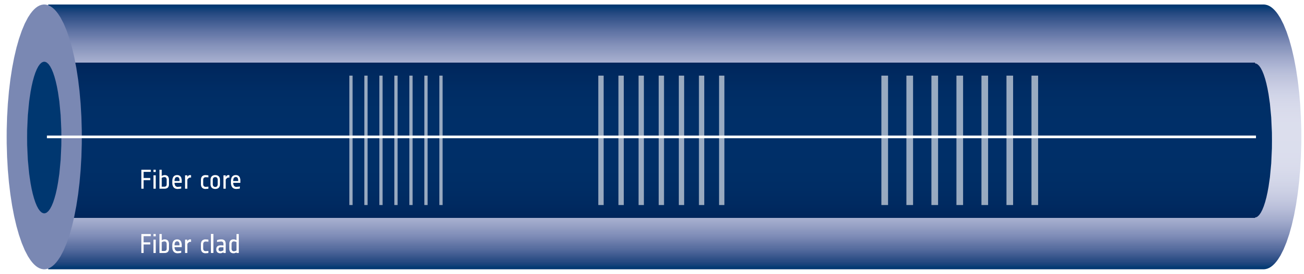
Fiber Optical Structures



Fiber-based sensors can be utilized to measure temperature, pressure, or strain, etc. For this purpose, fiber Bragg gratings as nanostructures are directly inscribed into the fiber core. This opens up new application possibilities, such as tunable lasers. In addition to the method developed at IPHT for inscribing gratings during fiber drawing, alternative inscription methods are being explored. The combination with new materials enables for example high-temperature sensors. »

» Fibers for Fiber Lasers

The basis for the inscription of fiber Bragg gratings (FBG) is a photosensitive optical fiber (i. e., a fiber which can be processed using UV light). To inscribe the grating into the fiber, the polymeric protective layer around the fiber is usually removed. The grating structure is inscribed with a laser and the fiber subsequently recoated – a costly and interference-prone method. Utilizing a process developed at IPHT, fiber Bragg gratings are able to be inscribed during the manufacture of the optical fiber and prior to applying the protective layer in the fiber drawing tower.

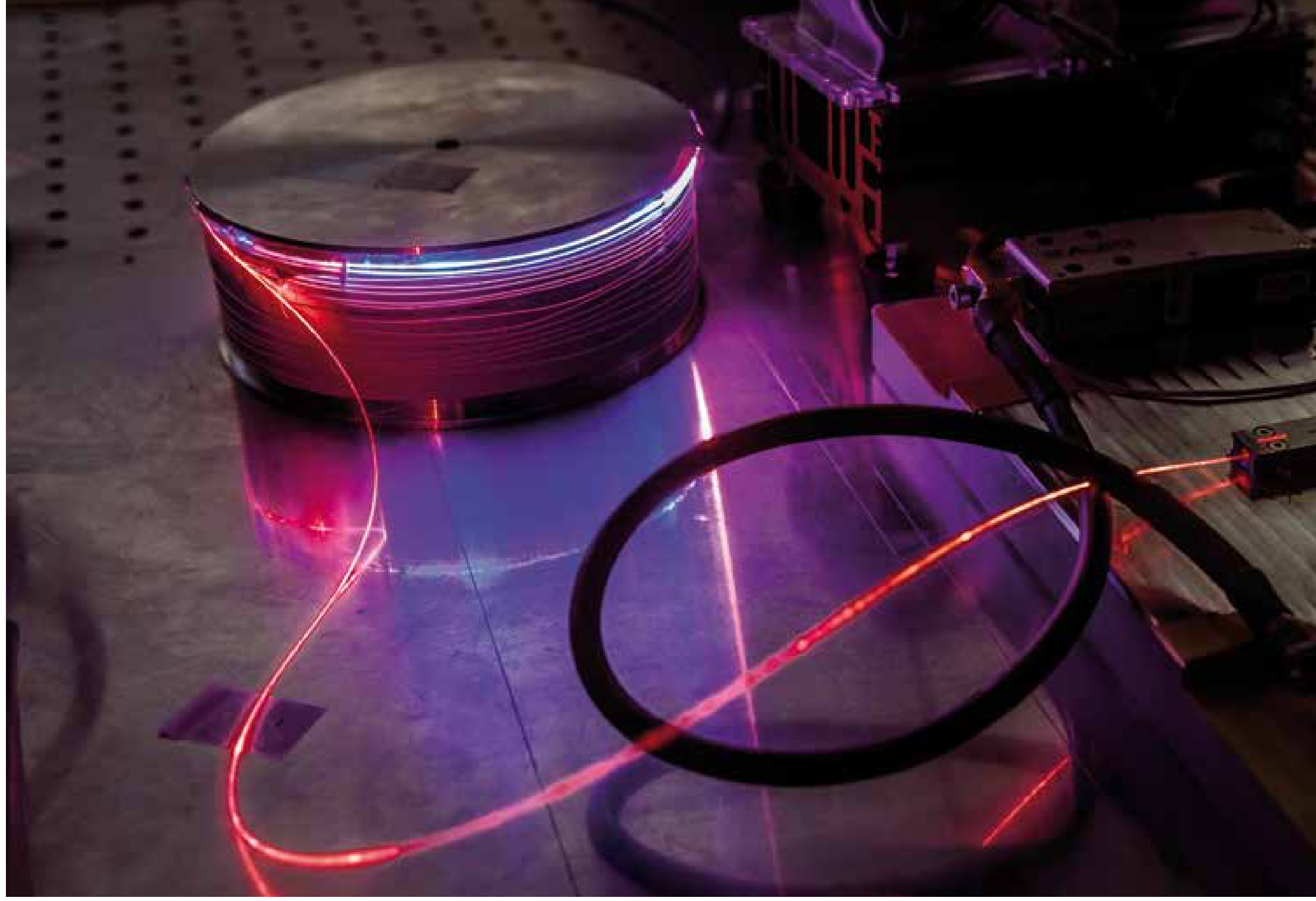


Fiber with Fiber Bragg Grating Array

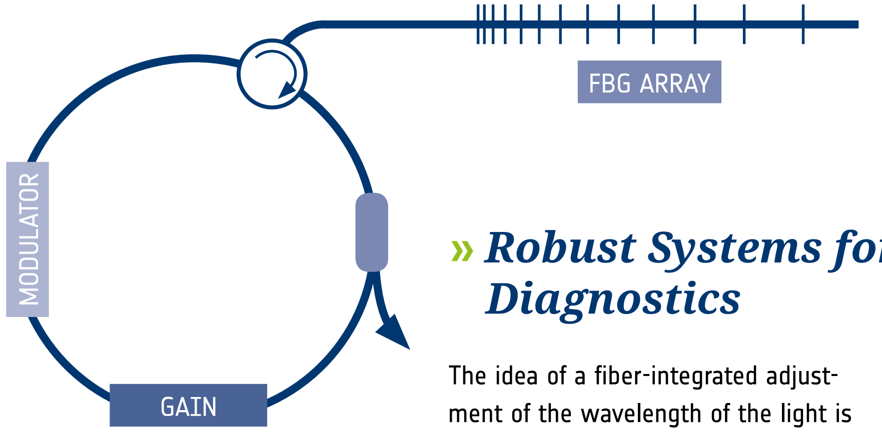
Due to the rapid and cost-effective inscription of fiber Bragg gratings during fiber production, fibers are able to be produced that feature a very high number of gratings and positions of the individual reflection wavelengths. These wavelengths can be largely determined in a flexible manner. Scientists at IPHT have used this for a new functional concept of spectrally tunable fiber lasers. This makes it possible to adjust the active wavelength of the fiber laser very quickly and flexibly. It is of particular interest for spectroscopic applications or material processing with laser pulses.

This concept is based on a special laser design, also known as a ring resonator. The basis of this fiber laser is a special actively doped fiber. For excitation of the laser process, light is coupled into the laser fiber and a fluorescence radiation generated in the fiber core. In conventional laser resonators, additional metallic or dielectric mirrors at the fiber ends reflect this radiation, which is amplified during repeated passes through the laser fiber. "In our approach, we use an FBG array manufactured at the fiber drawing tower as a reflector which can be thought of as a combination of many spectrally different mirrors," said Tobias Tieß, a scientist at IPHT. This fiber part is connected to the actual laser fiber (in which the light is generated and amplified) to create a ring-shaped resonator.
If light hits an individual grating, a specific wavelength is reflected back into the active fiber according to the grating structure. Laser pulses are controlled in their repetition rate and thus in their circulation time in the resonator via a modulator integrated in the setup. Depending on the round-trip time, a specific grating mirror of the FBG array is thereby addressed. "This enables us to amplify a specific wavelength in the laser cavity," said Tieß. In addition, the light pulses in the nanosecond range are able to be shaped electrically via the modulator. "This is particularly important for the desired power of the laser," said the IPHT scientist. The shorter the light pulse, the higher the light intensity.

» Fiber Bragg gratings (FBGs) are structures that are a few millimeters long and inscribed into the core of a fiber. They exhibit a periodic change in the refractive index along the fiber. Depending on the grating structure, multispectral (e.g., white) light passing through the fiber is reflected according to the wavelength and can be measured by sensors. Based on the analysis of reflection wavelengths, conclusions are able to be drawn about, for example, temperature, pressure, or strain.



Ring resonator



» Robust Systems for Medical Diagnostics

The idea of a fiber-integrated adjustment of the wavelength of the light is not new. So far, however, only single chirped gratings have been used that exhibit a continuously changing grating period and are subject to great technological challenges in the production and restrictions of the optical functionality for large bandwidths. Thus, the wavelength range of light can only be varied to a limited extent.

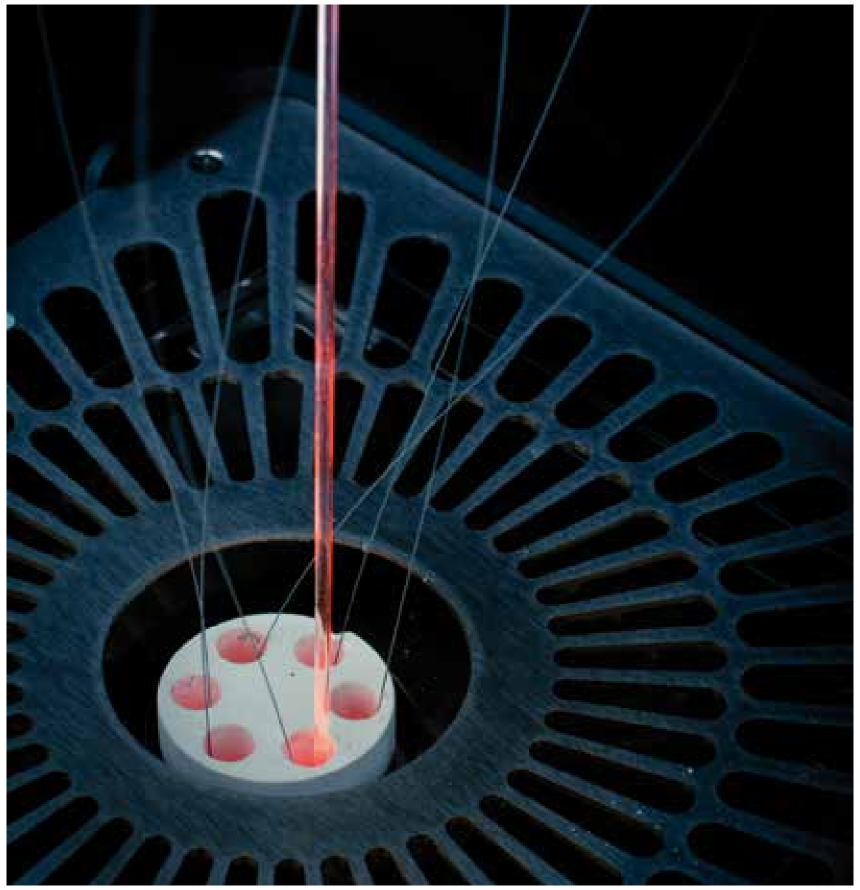
"The tunable fiber laser is a good example of the successful combination of results from our basic research in the field of fiber optics and photonic detection and its application in the life sciences." // Professor Jürgen Popp, scientific director of IPHT

The advantage of IPHT's design lies in the option of adjusting the spectral bandwidth across a wide spectral range in a targeted manner and in the high robustness of the system with a high stability and excellent beam quality. With tailored spectral tuning ranges, scientists at IPHT are able to spectroscopically examine single molecules more easily and quickly. This is the basis for improved medical diagnosis.

» Fiber Sensor for Extreme Conditions

Fibers with inscribed fiber Bragg gratings can be utilized not only for controlling light intensity and pulse duration but also as fiber optic sensors for measuring temperature, pressure, or strain. They are used primarily when high precision or electromagnetic compatibility of the sensor is required. When measuring temperatures, however, classic commercially-available gratings are only suitable for temperatures up to several hundred degrees Celsius. At higher temperatures, both the fibers and the inscribed structures become soft, and the FBGs disappear. The application of fiber Bragg gratings in high-temperature areas, such as the monitoring of coal power plants or the optimization of gas turbines, presents new challenges.

Compared to conventional optical fibers based on quartz glass, sapphire fibers possess much better high-temperature properties. They only melt at 2050 °C. Unlike conventional fibers, sapphire fibers are not photosensitive to UV exposure and must be manufactured in a complex process. Due to this special manufacturing process, they are usually not longer than two meters. Due to the lack of photosensitivity, fiber Bragg gratings are not inscribed into the sapphire fiber at the drawing tower with a single laser pulse but by longer exposure with a femtosecond laser.



Fiber sensors during high-temperature testing

» Fiber Grids in Sapphire Fibers

Compared to the laser at the drawing tower, the inscription of the grating is made possible by significantly shorter laser pulses and thus stronger light intensity.

Since sapphire fibers do not possess a core (as conventional fibers do) and thus guide the light in the entire fiber, they are susceptible to external influences such as dust or touch. Therefore, a capillary made of corundum offers protection during measurements. Manfred Rothhardt and his team were able to perform repeated measurements up to 1500 °C and measure the temperature with an accuracy of 1 Kelvin. Conventional measurements at high temperatures occur with thermo-elements or pyrometers that function as a kind of thermal camera. These measurements, however, often exhibit temperature deviations of quite possibly more than 10 Kelvin.

***"We are the only research group in the world that has been able to demonstrate and publish* the temperature stability of gratings in sapphire fibers up to 1,900 °C."** // Manfred Rothhardt, IPHT scientist*

* Habisreuther, T., Elsmann, T., Pan, Z., Graf, A., Willsch, R., & Schmidt, M. (2015). Sapphire fiber Bragg gratings for high temperature and dynamic temperature diagnostics. Applied Thermal Engineering, 91, 860–865. doi:10.1016/j.applthermaleng.2015.08.096

Interferometer inscribing fiber Bragg gratings into the fiber core

» Aluminosilicate Fibers

To enable fiber Bragg gratings that are stable at high temperatures in fibers that are less susceptible to interference and possess a much larger length, a novel type of fiber was researched at IPHT. The basis of this fiber is a sapphire rod as a core material which is placed in a quartz glass cladding tube.

***"Manufacturing aluminosilicate glass fibers is very difficult since we work with temperatures above 2,000 °C during the drawing process."** // Dr. Jens Kobelke, fiber technologist at IPHT*

When drawing this preform into a fiber at extremely high temperatures, both materials diffuse into each other and react with each other. This results in a fiber core made of aluminosilicate glass with an aluminum oxide content of about 50 %. The gratings inscribed into this fiber are stable up to 900 °C and can be used in fibers of several dozens of meters in length. In addition, this fiber has a core which is protected by a stable quartz glass cladding. In contrast to unstructured sapphire fibers, this fiber offers significantly improved handling and lower susceptibility to fiber contamination.

Due to low cladding glass viscosity, the high temperatures require relatively quick drawing at very low fiber tension. This complicates the fiber drawing process with respect to stable fiber diameter control. However, due to the experience and expertise in the manufacture of various specialty fibers, a solution has been found.

- *+ Scientific Contribution "Fiber Bragg Gratings in Fibers with an Aluminosilicate Core that Are Stable at High Temperatures"*
- *+ Scientific Contribution "Wavelength-tunable Fiber Laser with Record Bandwidth based on Fiber Bragg Grating Arrays"*
- *+ Video of the ring resonator*

Fibers with very small Structures – Hollow-core Fibers for the Analysis of Gases and Liquids

As part of an industrial research group funded by the federal state of Thuringia and the European Social Fund, scientists at IPHT developed novel hollow-core fibers for the Raman spectroscopic analysis of contaminated water. With these fibers, small sample volumes can be identified and quantified in a fast and reliable way on site. The fibers are also suitable for the analysis of other liquids and gases. »

» *Sensor fibers with a hollow core*

Access to clean water is a human right. Nevertheless, water pollution continues to increase. According to estimates by the United Nations, up to 5 million people a year die globally from diseases associated with dirty water. In this context, rapid and inexpensive methods of water analysis are urgently needed.

"To date we have been filling contaminated water in cuvettes and detecting contaminants by way of Raman spectroscopy. The aim of the industrial research group was to optimize this method by means of hollow-core fibers," says Dr. Torsten Frosch, project leader within the industrial research group. Compared to conventional measurements in a cuvette, the interaction between light and the substance to be analyzed can be utilized across a much larger interaction length and, simultaneously, at a very small sample volume with such a sensing fiber. Thus, even the smallest traces of contaminants are detectable.

One very special microstructured optical fiber is the hollow-core fiber. Its core can be filled with liquids or gases for spectroscopic purposes. Hollow-core fibers not only feature an extraordinary inner design, but the way they guide light is also unusual for optical fibers. Even though the analyte, with which the central hollow core is filled, exhibits a lower refractive index than the surrounding cladding structure, light guidance in hollow-core fibers is possible according to the principle of anti-resonance. If dimensioned properly, the core of such a fiber guides the light in exactly the wavelength ranges in which spectroscopy is to be performed.

The strands between the cavities should be extremely thin and precise in order to guide as much light in broad spectral ranges at as little loss as possible in the hollow core of the sensor fiber. Such extreme demands require sound planning, high-precision preform preparation, and expertise in the drawing of fibers. This year, the fiber technologists at IPHT were successful in manufacturing a novel hollow-core fiber possessing a core of 20 microns in diameter. The core-limiting quartz strands of this fiber are extremely thin at a size of only 400 nanometers.

> ***"We needed a fiber that can work with wavelengths in the UV range, i.e. with very short wavelengths. The shorter the wavelength, the stronger the Raman signal. This provides us with the basis for a highly sensitive Raman spectroscopic analysis."** // Dr. Torsten Frosch*

» *Filigree structures*

Very thin-walled fused silica capillaries are needed as base components for the preparation of such a hollow-core fiber. These are drawn at IPHT, manually bundled into a hollow-core arrangement, and subsequently placed in a very thin-walled glass tube that surrounds the future complex hollow-structure section of the fiber, thereby protecting and stabilizing it. In a first temperature step, this loose capillary stack is consolidated and simultaneously elongated. Depending on the process conditions, the glass capillaries connect selectively or completely with each other and with the surrounding cladding tube. This offers a variety of possibilities to affect the structure of the final hollow-core fiber. Further structural adjustments are possible during the subsequent drawing of the resulting preform into a fiber. If the capillary ends of the preform are closed, for example, the internal pressure inside the capillaries resulting from the drawing of the fiber affects the filigree structure in the fiber. An open capillary stack, by contrast, makes it possible to design the internal structure of the hollow-core fiber by selectively applying positive or negative pressure.

Within the industry research group, the fiber experts at IPHT had the chance to intensively deal with all stages of the process for the production of hollow-core fibers and their very delicate structures. They were able to significantly expand their expertise in this regard.

> ***IPHT is one of only two institutes in Germany that possess expertise to produce hollow-core fibers with filigree structures."** // Dr. Jörg Bierlich, fiber technologist at IPHT*

Because of the thin-walled strand structures, this novel hollow-core fiber exhibits relatively low optical losses. "This is due to the double anti-resonance," says Professor Markus Schmidt of IPHT. "That is, the very thin strands around the core and the air holes result in improved reflection behavior, which causes a particularly large amount of light to be retained in the core area," says Schmidt.

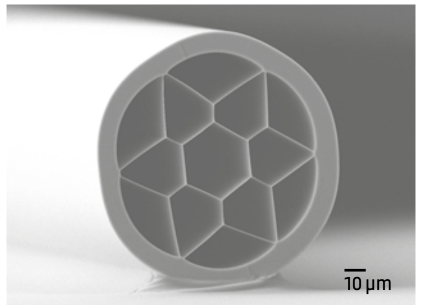
Such hollow-core fibers are of particular interest for environmental sensors based on sensitive Raman and absorption spectroscopy. Because of the significantly improved detection sensitivity and mobile usability, further areas of application, such as medical technology, are conceivable in addition to their use in environmental analysis. "Currently we are working intensively with local industrial and scientific partners to bring these novel hollow-core fiber sensors into applications," said Dr. Frosch.

+ ***Scientific Contribution***
"Single-mode guidance in large-hollow-core fibers"

» Microstructured fibers

In addition to conventional optical fibers in which both the core and the cladding are made entirely of glass, there is a wide variety of innovative optical fibers available nowadays. So-called microstructured fibers, for example, usually possess a solid glass core while the cladding contains tiny holes/capillaries. The optical properties of these fibers depend on the diameter of the core, as well as the diameter, number, and spacing of the cladding holes. Depending on the structure, the properties of such a fiber can be tailored for various applications.

Preform for a microstructered fiber



Microscope image of a hollow core fiber

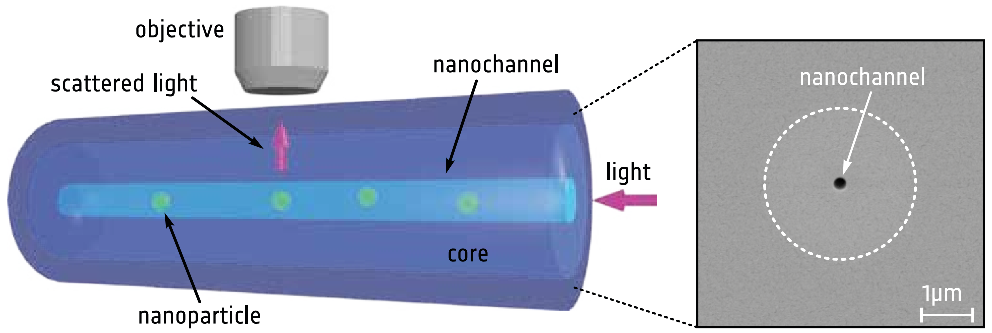
The preform structure is created manually by arranging glass rods and glass capillaries.

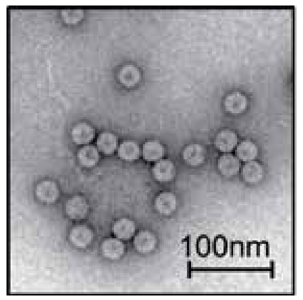
Marker-free Detection of Viruses using Fibers

In light of the increase in viral diseases, a fast and unambiguous detection of viruses is becoming increasingly important. Virological diagnostics provides a number of possibilities, but the viruses need to be fixated and stained. At IPHT, a fiber was developed which allows the label-free determination of the size and movement of freely diffusing viruses with dimensions smaller than 20 nanometers. »

» Viruses are very small: Their diameter is between 20 and 200 nanometers. Thus, viruses are much smaller than a human hair, which is 100,000 to 200,000 nanometers thick. Because of their size, objects of less than 100 nanometers often elude conventional characterization methods. Therefore, viruses that are present in high quantity are usually made visible by an electron microscope after fixation and staining with a fluorescent dye or binding of fluorescently labeled antibodies. However, marking a virus with a dye changes its properties.

"Part of our work concentrates on the implementation of nano and microstructured elements in fibers for the biophotonics research focus. Therefore, we have pondered how we can utilize this expertise to employ fibers in the long-term measurement of freely diffusing, marker-free viruses," said Professor Dr. Markus Schmidt, head of the fiber sensor research group. Together with colleagues from the University of Leiden (Netherlands) and his team, he designed a novel type of fiber. A nanohole with a diameter of 200 nanometers in the core extends along the entire fiber. Test viruses floating in water are introduced to this hole and light is coupled into the fiber core. The refractive index of the water is always smaller than that of the quartz glass core surrounding it. However, the basis for guiding light in an optical fiber is a refractive index that is decreasing from core to cladding.





CCMV-Test viroses

"Our partner Heraeus Quarzglas developed a custom fiber for us by increasing the refractive index of the quartz glass around the nanohole in a targeted manner with the help of dopants in order to generate a core region. As a result, the coupled light in the fiber core does not break out at the interface to the undoped quartz glass cladding but remains trapped in the fiber." says Schmidt.

If the light coupled into the capillary hits a virus, a portion of the light is deflected from its direction of propagation (i. e., scattered). Based on this light scattering and using a microscope, the size of the virus can be determined. In addition, the movement of a virus can be observed and recorded over a period of up to 10 seconds.

The first measurements of the test viruses were carried out at the University of Harvard, USA, and the University of Leiden, Netherlands.

The fiber developed can be integrated into standard microscopes, thereby extending their detection range to other nanoparticles. Applications range from medical diagnostics to drinking water analysis.

+ ***Scientific Contribution "Single virus detection inside nanobore optical fiber using elastic light scattering"***
+ ***Link technical article, ACS Nano Journal***

Knowledge of Nine Leibniz Institutes United on a Single Chip

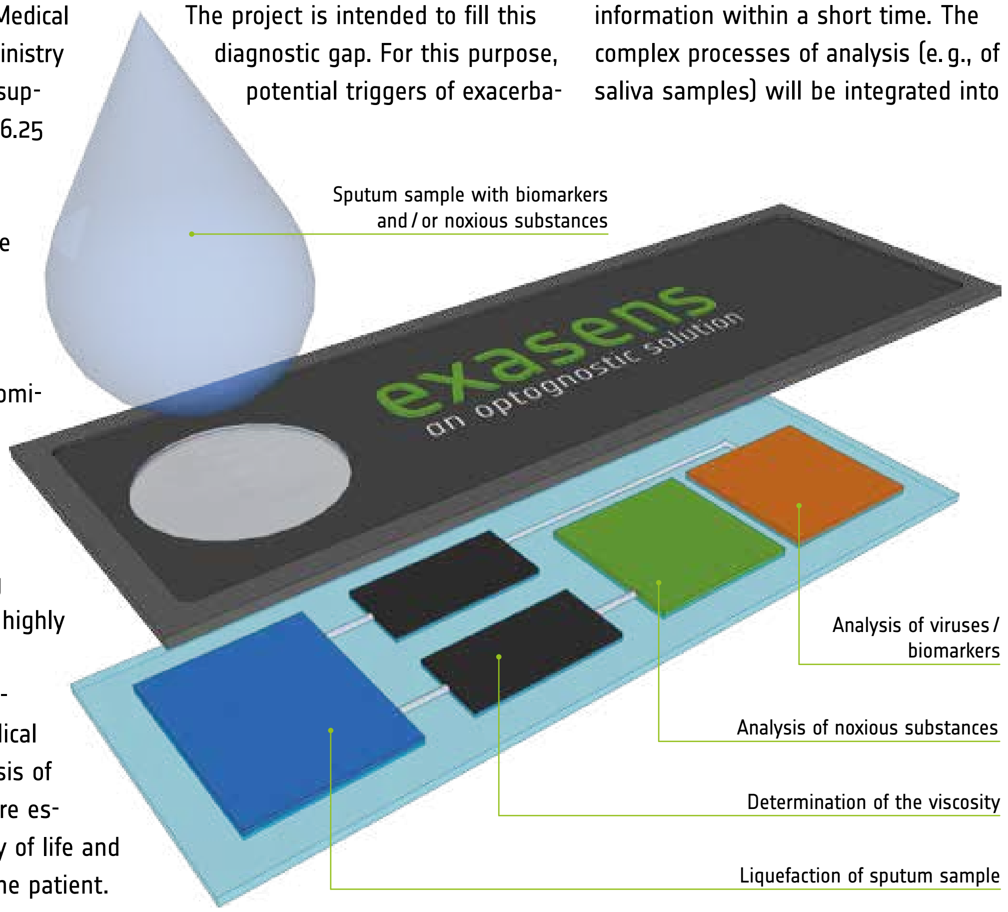
Sensor platform for predicting paroxysmal exacerbations of chronic inflammatory airway diseases.

» Over the next three years, scientists from different disciplines from nine Leibniz institutes will research a system for predicting and diagnosing the chronic inflammatory airway diseases asthma and chronic obstructive pulmonary disease (COPD) in the Exasens joint research project. Exasens is the first project started as part of the Leibniz Research Alliance "Medical Technology". The Federal Ministry of Education and Research supports the project with EUR 6.25 million.

More than 10 percent of the German population suffers from chronic inflammatory airway diseases, making them important both economically and in terms of health policy. Acute, paroxysmal exacerbations of these diseases which can lead to life-threatening complications are clinically highly relevant and of particular relevance to patients. Accurate monitoring of the medical condition and early diagnosis of impending exacerbations are essential for improved quality of life and the optimal treatment of the patient.

Conventional methods are based on pulmonary function tests and the subjective assessment by an experienced doctor. The results obtained in this way are not specific enough to diagnose the cause of the exacerbation, make predictions, and take early individual treatment measures.

The project is intended to fill this diagnostic gap. For this purpose, potential triggers of exacerbations, such as bacteria, viruses, fungal spores, or dust, are initially characterized by optoelectronic and photonic methods and specific indicators defined which allow a reliable prediction. At the same time, a modular cartridge is developed in which all the necessary steps for the preparation and analysis of patient samples will be performed. To do so, researchers will focus on lab-on-a-chip technologies. By combining several dime-sized chips of different functionality, a measurement platform is created that will provide the user with disease-specific information within a short time. The complex processes of analysis (e.g., of saliva samples) will be integrated into an intuitive device that can be applied at the doctor's office or at home. Physicians can thus detect a worsening in the progression of the disease at an early stage and initiate cause-specific and individual therapeutic measures.



Modular cartridge for the preparation and analysis of patient samples

Due to its compact design and easy handling, this technology is also suitable for telemedicine applications. Affected patients are able to independently and reliably monitor disease progression and submit the test results online to the primary care physician or a clinic. The number of unnecessary outpatient treatments or even emergency medical responses and the resulting costs to the healthcare system will be able to be drastically reduced.

> ***„Targeted cross-disciplinary collaboration within the Leibniz Research Alliance puts us in a position to handle a topic along the entire innovation chain from fundamental research to the marketing of solutions and methods through industrial partners."** // Dr. Karina Weber, Jena Biochip Initiative*

In addition, the close cooperation of the Leibniz institutes with clinics and institutions of biological and medical research enables validation of the technologies researched. The future involvement of companies will lead to a rapid transfer of the sensor platforms into everyday applications.

Paul Klemm and Linda Lattermann from the Jena Biochip Initiative work together on the characterization of bacteria to be able to derive indicators for the prediction of exacerbations.

» EXASENS

POC sensor platform for chronic inflammatory airway diseases

Project volume: 6.25 Mio. €

Project duration: December 1, 2015 to November 30, 2018

Funded by: Federal Ministry of Education and Research

Partner:

- Leibniz Institute of Photonic Technology (IPHT), Jena
- Research Center Borstel - Leibniz Center for Medicine and Biosciences (FZB), Borstel
- Leibniz-Institut für Höchstfrequenztechnik (FBH), Berlin
- Leibniz Institute of Polymer Research Dresden (IPF), Dresden
- Leibniz Institute for Interactive Materials (DWI), Aachen
- Leibniz Institute for Natural Product Research and Infection Biology - Hans Knöll Institute (HKI), Jena
- Innovations for High Performance Microelectronics (IHP), Frankfurt / Oder
- Leibniz-Institut für Analytische Wissenschaften (ISAS), Dortmund
- Halle Institute for Economic Research (IWH), Halle

System Integration – From Ideas to Instruments

In addition to fundamental technological research in the fields of biophotonics, fiber optics, and photonic detection, the importance of system technology at IPHT continues to increase. Consequently, a workgroup focusing on system integration was established at IPHT. »

» With its establishment of a workgroup on system integration, IPHT aims to transfer the technological solutions gained from research to compact systems more intensively. The aim is to research and develop these systems to an extent to which they can be transferred to applications even better than before. Fields of application are, inter alia, Life sciences, food safety and medicine. By developing this expertise, IPHT puts its motto "From Ideas to Instruments" strongly into practice.

One example of successful integration of technologies into a compact system is PAUL – a photonic analytics universal laboratory. PAUL combines a powerful spectrophotometer with advanced microfluidic technology. Thanks to a replaceable cartridge, it is adaptable to various tasks. PAUL will find applications in microanalytics and the life sciences. In addition to the technical equipment and a miniaturized footprint, both user friendliness and design played a role in the development of PAUL.

Scientists of the sensor systems workgroup, headed by Dr. Rainer Riesenberg, also developed a compact system for medical applications. The blood cell counter is based on lensless in-line holographic imaging and was implemented during the European joint project "Hemospec". With this device, doctors are able to detect changes in blood cells online.

The researchers succeeded in optimizing the required components and technologies and harmonizing them so that they fit in the housing of an external hard drive. A commercial laser diode (as is typical for laser pointers) is built into the fluidic chip-based holographic microscope. Thanks to this compact and inexpensive illumination unit, first-time videos of the blood cell flow in a fluidic channel were able to be shown.

PAUL, a compact universal laboratory for analytics, combines a powerful photospectrometer with state-of-the-art microfluidic technology.

Due to the high phase sensitivity that is typical for holography, the system is able to not only image well-visible red blood cells but also map and classify white blood cells (leukocytes) without staining. These findings help in diagnosis and personalized treatment decisions. Other application possibilities of the blood cell counter include on-site analysis, the direct monitoring of patients, and future telemedicine.

Medicars is another system that is being developed further at IPHT for use in clinics. The compact CARS microscope for medical diagnosis produces high-resolution multimodal images of tissue samples without prior staining. Diseased tissue can be localized precisely and selectively removed. In recent years, scientists have been working on the miniaturization of what was once a complex lab setup to make it portable. Present work focuses on the automation of the process and the optimization of the software-aided image evaluation. Further down the road, Medicars will be applied in preclinical studies and also allow in vivo diagnostics.

Based on the expertise gained in the past in the field of system technology, both practicality and the technical readiness level (TRL) of additional procedures will be improved in the future and said procedures converted into compact systems or components. Thus, the new system integration workgroup provides a valuable contribution to the transfer of research results into industry and application.

Medicars – a compact CARS microscope for the medical diagnosis of tissue.

The blood cell counter is based on lensless microscopy. A laser diode serves as the light source.

Wissenschaftliche Beiträge in der App

» *Biophotonik*

In the biophotonics research focus, IPHT implements innovative photonic methods and tools – based on applied fundamental research – in molecular spectroscopy and hyperspectral imaging as well as in fiber, chip, and nanoparticle based analytics. The application fields range from fundamental research in the life sciences to food and environmental safety to clinical diagnostics. **In the app, you will find the following contributions on this research topic:**

» **Raman-based Imaging for the Detection and Contact-free Study of Intracellular Bacteria**
Große // Dellith // Bauer // Popp // Neugebauer

» **Raman FLIM Fiber Sensor for the In-Vivo Screening of Tissue**
Dochow // Popp // Ma // Latka // Bocklitz // Hartl // Bec // Fatakdawala

» **Localization of Intracellular Mycobacteria using Raman Microscopy**
Silge // Bocklitz // Rösch // Popp

» **Detection of Relevant Food Dyes using Surface-enhanced Raman Spectroscopy (SERS)**
Jahn // Peksa // Patze // Bocklitz // Weber // Cialla-May // Popp

» **LOC-SERS as bioanalytical tool for drug monitoring in human urine**
Hidi // Jahn // Henkel // Weber // Cialla-May // Popp

» **Bottom-up prepared plasmonic nanostructures for label-free SERS DNA detection**
Yüksel // Schwenkbier // Ziegler // S. Pollok // Görke // Hübner // K. Pollok // Langenhorst // Weber // Cialla-May // Popp

» **Leakage correction method for gas monitoring within environmental chambers experiments**
Jochum // Popp // Frosch

» **Magnetic Apatite for Structural Insights on Plasma Membrane**
Stanca // Müller // Fritzsche // Dellith // Nietzsche // Stöckel // Biskup // Deckert // Krafft // Popp

» **Chemo-Spectroscopic Sensor for Carboxyl Terminus Overexpressed in Carcinoma Cell Membrane**
Stanca // Matthäus // Neugebauer // Nietzsche // Fritzsche // Dellith // Heintzmann // Weber // Deckert // Krafft // Popp

» **Defined Synthesis of Plasmonic Nanoparticles Using Microfluidics**
Thiele // Csáki

» **Advances in matrix supported fabrication of plasmonically-active particles**
Müller // Schmidl // Zopf // Hübner // Stranik // Fritzsche

» **Colloids designed as sensors with applications in nanomedicine**
Stanca // Fritzsche // Dellith // Undisz // Deckert // Fröhlich // Krafft // Popp

» **DNA Origami as a Self-organizing Molecular Technique for the Implementation of Innovative Photonic Materials**
Kopielski // Csáki // Fritzsche

» **Lab-on-a-chip System Development for Everyday Laboratory Use**
Kielpinski // Henkel

» **Surface Characterization of Amyloid Fibrils**
Deckert-Gaudig // Deckert

» **Micro Ensemble Spectroscopy**
Deckert // Singh

» **Blind Reconstruction of Structured Illumination Microscopy (SIM) data**
Jost // Tolstik // Feldmann // Wicker // Sentenac // Heintzmann

» *Fiber Optics*

In the fiber optics research focus, IPHT performs fundamental research on the propagation properties and efficient and flexible control of fiber-guided light; it also researches fiber modules and systems for a wide range of applications. **In the app, you will find the following contributions on this research topic:**

» **The influence of the fiber drawing process on intrinsic stress and birefringence of PM fibers**
Leich // Just // Spittel // Bierlich // Grimm // Jäger // Bartelt

» **Single-mode guidance in large-hollow-core fibers**
Hartung // Kobelke // Schwuchow // Bierlich // Popp // Schmidt // Frosch

» **Fluorine Doping via the REPUSIL Process for Adjustment of the Optical Properties of Fused Silica Materials**
Schuster // Grimm // Kalide // Dellith // Leich // Schwuchow

» **Diffusion and Sintering Effects in Compact Microstructured Fibers**
Kobelke // Bierlich // Wondraczek // Matthes // Schuster

» **The origin of waveguide dispersion of surface plasmons on metallic wires**
Spittel // Bartelt // Schmidt

» **Fiber Bragg Gratings in Fibers with an Aluminosilicate Core that Are Stable at High Temperatures**
Elsmann // Yazd // Lorenz // Habisreuther // Dellith // Schwuchow // Bierlich // Schuster // Rothhardt // Kido // Bartelt

» **Wavelength-tunable Fiber Laser with Record Bandwidth based on Fiber Bragg Grating Arrays**
Tieß // Rotthardt // Bartelt // Jäger

» **Incoherent Combination of Fiber Lasers in a 7x1 Fiber Coupler with Average Powers > 5 kW and High Brightness**
Jäger // Eschrich // Kobelke // Unger // Bartelt

» **Employing the Plasmonic Properties of Thin Niobium Films for Sensors**
Wieduwilt // Schmidt

» **Single virus detection inside nanobore optical fiber using elastic light scattering**
Schmidt // Faez // Lahini // Weidlich // Garmann // Wondraczek // Zeisberger // Orrit // Manoharan

» **Multiscale Fiber Spectroscopy**
Kröckel // Schmidt

» *Photonic Detection*

The photonic detection research focus deals with the research and implementation of systems for the highly sensitive temporally, spatially, and spectrally resolved detection of light. **In the app, you will find the following contributions on this research topic:**

» **A Planar Thin-Film Peltier Cooler for the Thermal Management of a Dew-Point Sensor System**
Ihring // Kessler // Kunze // Billat

» **Improving the sensitivity of optically pumped magnetometers by hyperfine repumping**
Schultze // Scholtes // IJsselsteijn // Meyer

» **Trend to Nano-SQUIDs – A Tool for the Investigation of Small Spin Systems**
Schmelz // Stolz // Zakosarenko // Schönau // Anders // Linzen // Meyer

» **Single and Two-photon Lasing by a Superconducting Qubit**
Il'ichev // Neilinger // Rehak // Grajcar // Oelsner // Hübner

» **IPHT Sensors on the Comet Churyumov-Gerasimenko**
Kessler // Knollenberg

» **Highly-Sensitive Absolute Measurement of the Earth's Magnetic Field as the Technological Key to Efficient Exploration of Earth's Treasures**
Schönau // Zakosarenko // Schmelz // Stolz // Anders // Linzen // M. Meyer // H.-G. Meyer

» **Passive Video Camera for the 350 GHz Band with Application in the Screening of People**
Heinz // May // Born // Zieger // Anders // Meyer

» **Metamaterials for Ultrasensitive Surface-enhanced Molecular Spectroscopy**
Hübner // Mayerhöfer // Knipper // Cialla-May // Weber

» **Monitoring Long-lived ^{3}MLCT States in Fe(II)-Terpyridine Complexes**
Wächtler // Kübel // Dietzek

» **Deep-Level Transient Spectroscopy Studies on Silicon Nanowires**
Sivakov // Venturi // Castaldini // Schleusener // Cavallini

» **Light-induced Catalysis Spectroscopically Illuminated**
Wächtler // Dietzek

» **Laser Spectroscopic Characterization of the Ignition of Fuel Droplets and SiO2 Layer Deposition**
Burkert // Paa // Müller // Wagne

IPHT at a Glance – Key Figures of 2015

1327,5 T Euro
EU-third party funding, thereof ERA-Net/ERA-NetPlus, JPI et al 510,7 T Euro

3.398,0 T Euro
Industry projects

4.205,0 T Euro
National projects, thereof DFG 808,5 T Euro

10.700,4 T Euro
Institutional funding

45,5 % = Project funding

19,6 Mio Euro
Total budget

12 Projects funded by the EU
4 of them coordinated by IPHT

62 Media Reports
Print, TV, Online and Radio

64 Invited Talks
2 of them Keynotes

Participation in
143 Conferences

212
Peer-reviewed publications

313 Female and male employees

16
Doctorades
7
of them woman

14
Patent applications
6
Patent grants

1
Habilitation

52
Academic teaching employees

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Prof. Dr. Jürgen Popp	Prof. Dr. Hartmut Bartelt	Prof. Dr. Markus Schmidt
Quantum Detection	***Nanoscopy***	***Research Group Magnetometry***
Prof. Dr. Hans-Georg Meyer	Prof. Dr. Volker Deckert	Dr. Ronny Stolz
Nanobiophotonics	***Functional Interfaces***	***Junior Group Clinical Spectroscopic Diagnostics***
PD Dr. Wolfgang Fritzsche	Prof. Dr. Benjamin Dietzek	Dr. Ute Neugebauer
Microscopy		
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4H Jena Engineering GmbH, represented by	Michael Boer
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Frank Sondermann	Leibniz Institute of Photonic Technology e.V., Jena
Prof. Dr. Herbert Stafast	Jena

Budget of the Institute 2015

	in T Euro
Institutional Funding (Free State of Thuringia)	10.700,4
Project Funding	8.930,5
	19.630,9
Institutional Funding: Use	
Staff	6.804,3
Materials	3.311,4
Investments	584,7
	10.700,4
Categorization of Project Funding	
Federal Ministries	2.954,5
(Thereof for EU measures such as ERA-Net / ERA-NetPlus, JPI et al 510,7 T Euro and for projects for the Leibniz Research Alliance Medical Technology 74,3 T Euro)	
DFG	808,5
(In addition, IPHT scientists spent DFG Funds of 152,1 T Euro at the University of Jena)	
Free State of Thuringia	751,4
(Thereof for Restructuring within the Framework of EFRE: 366,4 T Euro)	
EU	816,8
Contracts of Public Institutions	170,4
Other Fundings	201,3
Subcontracts	174,6
R&D Contracts	3053,0
	8.930,5

Staff of the Institute 2015

	Full-time Equivalents				People
	Institutional Funding	*Third Party Funding*	*Professors*	*Total*	
Scientists	28,47	49,52	4,5	82,49	89
Visiting Scientists**	-	-	-	-	18
External Finance Scientists*	-	-	-	-	11
External Finance Employers*	-	-	-	-	1
External Finance Doctoral Candidates*	-	-	-	-	46
Doctoral Candidates	5,5	20,82	-	26,32	44
Technical Staff	34,98	35,82	-	70,8	76
Administration	12,83	2,31	-	15,14	16
Scientific Coordination	2	1,5	-	3,5	4
Public Relations	2,5	2,25	-	4,75	5
Management	1	-	0,5	1,5	2
Trainees	1	-	-	1	1
Total Staff	**88,28**	**112,22**	**5*****	**205,5**	**313**

* Employees who are not payed through the payroll of IPHT, but have their main focus on IPHT.

** Visiting scientists who worked more than a month on IPHT in 2015. No use of the key date regulation 31.12.2015.

*** Plus 2x0,5 full-time fquivalents financed by the Friedrich Schiller University Jena.

Imprint

Publisher:
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www.genausonuranders.de

Photographes:
Sven Döring _Agentur Focus // Hamburg; shutterstock; Heraeus Quarzglas _Hanau; IPHT Jena

Printing:
Grafisches Centrum Cuno GmbH und Co KG, Calbe (Saale)

www.leibniz-ipht.de

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