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visit

[Laser, Quantum Technology & Active Sensor Systems]

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Dear friends of Fraunhofer IOSB,

quantum technology is often seen as a difficult, not intuitively understandable scientific subject – even for scientists. Nevertheless, it will more than before influence and shape our living in the 21st century. Over decades quantum computers were predicted and their possible game-changing capabilities were advertised – now first systems are a reality. The laser, a quantum technology first experimentally realized by Maiman in 1960, extends its applications to more and more wavelengths with increasing power levels and thus enables many new fields of application and new capabilities. Profiting from these evolutions, new active optro-nic sensor systems emerge that combine lasers, optics, opto-electronic sensors and image exploitation and pave the way for new methods to make objects better visible and measu-rable to humans and machines.

In this visIT issue we want to shed some light onto the topics of lasers, photonic quantum technology and related active optronic sensor systems by giving you an insight into the con-tributions of Fraunhofer IOSB to these future key technologies in civil and defense applica-tions. The focus of this visIT hereby lies mainly on the near-to-mid infrared spectral range.

We start our overview with quantum ghost imaging, a technology creating images from entangled photons that actually never have seen the object. As the object is illuminated by single photons, it is predicted that such imaging can be realized without any possibility of being detected. Yet more classical, we then discuss latest results on 3D gated viewing, which uses direct laser illumination, and current work on an active compressive sensing camera. As last example for optronic systems, we show that they can be used to speed up maintenance and safety tasks in wind parks using laser Doppler vibrometry on rotor blades of wind turbines.

All these applications rely on specific laser sources. Thus, laser source research is a prerequi-site for future novel applications. Especially in the defense sector – but more and more also for civilian applications – access to critical components of laser and optronic systems and a technological sovereignty therein is of utmost importance. Therefore, Fraunhofer IOSB is performing research on critical components, focusing on crystals for lasers and non-linear converters and fiber components for high-power fiber lasers in the short- and mid-wave infrared spectral range in order to cover the critical parts of the whole value chain of IR solid-state and fiber laser sources. Based on the extended capabilities offered through such components, novel laser sources become possible. We finally give an insight into our high-power solid-state and fiber laser sources research and development in the short-wave and mid-wave infrared spectral range.

We wish you an enjoyable and informative reading of this issue.

Fraunhofer IOSB, October 2022

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Editorial



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QUANTUM GHOST IMAGING FOR REMOTE SENSING

Military reconnaissance under adverse conditions demands imaging methods capable of returning high-resolution images through scattering and turbulent media. Active imaging is the method of choice for critical applications where high precision and reliability is required. Complete control over the illuminating light source enables the extraction of a high level of information about the characteristics of distant targets, especially detailed range information with 3D resolution. In addition to that, active imaging systems can exclude noise and look through fog, smoke and fire with time gating techniques. By taking advantage of fundamental properties of single photons, quantum light sources can surpass traditional sources for these systems in many aspects and promise to revolutionize active imaging in the future.

Fraunhofer IOSB is already living this future by building technology demonstrators for the novel concept of quantum imaging for remote sensing (Fig. 1). Work on quantum imaging at the institute was initiated by

the Fraunhofer Lighthouse project QUILT («Quantum Methods for Advanced Imaging Solutions») in late 2017.

Quantum ghost imaging (QGI) uses the information of entangled photon pairs to obtain images of remote targets by secure coincidence measurements that are virtually noise-free [1].

The specialty of QGI is that it takes advantage of two spectral ranges to surpass classical imaging system in terms of quality:

- Illumination photons reside in the IR spectral range with ideal atmospheric transmission properties, low scattering cross-section and superior eye-safety.
- The entangled partner photons reside in the VIS spectral range with high detection efficiency through mature silicon technology and obtain spatial information even though never having interacted with the remote target.

This is possible by coincidence detection of entangled photons whose energies and momenta are linked by conservation laws.



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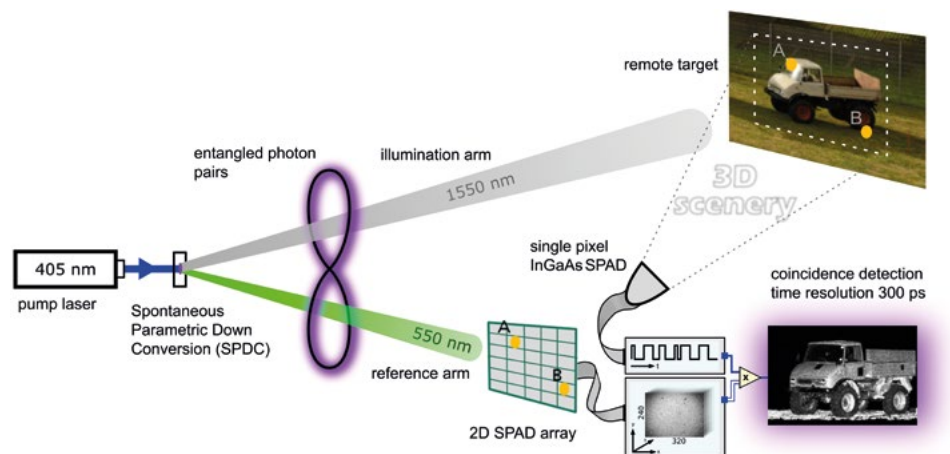


Figure 1: Setup for Quantum ghost imaging for remote sensing

Entangled photon pairs are created through spontaneous parametric down-conversion (SPDC) of photons from a pump laser within a nonlinear crystal that is customized to support the efficient generation of broadband entangled photon pairs in user-defined spectral ranges. Fraunhofer IOSB has a custom-designed quantum light source for the emission of entangled photon pairs with 1550 nm and 550 nm (Fig. 2). The SPDC source further emits photons randomly in space and time and is thereby inherently hardened against accidental detection by an external observer and hostile jamming attacks [2]. Only the observer is able to separate the returning quantum signal from ambient noise since only they have access to additional exclusive information from entangled partner photons for filtering.

The advantages of QGI are well established scientifically since its discovery in 1995 by Pittman et al. [3]. Fraunhofer IOSB developed the first asynchronous version of that setup to enable 3D imaging of remote targets without any moving parts [4]. This was only possible following recent advances in single-photon detection technology with state-of-the-art detectors provided by

Fraunhofer IMS. A novel image reconstruction scheme had to be developed and was recently filed as a patent [5].

To date, the system still has a low TRL and serves as a technology demonstrator, but the improved detector technology currently already available will significantly increase the system's performance, and further improvements are already on the horizon. New technological challenges will have to be solved, like transferring and real-time processing of large amounts of data and miniaturization of the system. Each technological upgrade will increase the performance and broaden the field of possible applications over the coming years.

Initial application target areas are applications with disruptive quantum benefits of QGI over traditional systems, such as non-detectable active imaging and range-finding systems. Later, QGI will compete with established traditional systems that have to minimize illumination intensity, whether for reasons of phototoxicity, safety for the eyes, or energy consumption.



Figure 2: Quantum Light source (center) and compact single-photon detector (left)

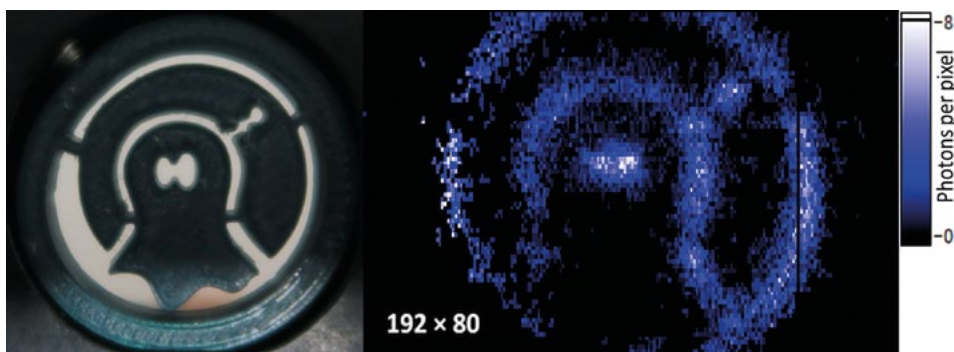


Fig. 3: Quantum Ghost Imaging of an object with only one photon per pixel on average

- [1] D. Walter, C. Pitsch, G. Paunescu, P. Lutzmann, »Quantum ghost imaging for remote sensing,« Proc. SPIE 11134, Quantum Communications and Quantum Imaging XVII (2019); doi: 10.1117/12.2529268
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- [5] D. Walter, C. Pitsch, »System und Verfahren zur Bildrekonstruktion unter Verwendung eines optischen Aufbaus zur aktiven Beleuchtung mit einzelnen Photonen«, Deutsche Patentanmeldung 102020203150.9 (2020).

3D GATED VIEWING: REAL-TIME RESOLUTION AT LONG RANGE

INTRODUCTION

A gated viewing system is an active imaging sensor that uses a pulsed laser to illuminate an observed scene. The laser pulse is very short, typically in the nanosecond range. A gated viewing camera captures the backscattered and reflected laser light. The camera and the laser are synchronized with each other. After a defined delay time relative to the pulse emission, the camera starts the integration time that is typically some hundreds of nanoseconds. Therefore, the detector elements capture only laser photons with a fitting round trip time. As a result, range gated images are generated showing only a certain distance range, the so-called »gate«. The foreground and background are suppressed.

For reasons of laser safety and atmospheric transmission, the wavelength of the illumination laser is approximately $1.5 \mu\text{m}$ in the (invisible) short wave infrared (SWIR, $1\text{-}3 \mu\text{m}$). Concerning safety for the eyes, this allows much higher pulse energies and therefore ranges of the system in comparison to visible or near-infrared (NIR, $0.78\text{-}1 \mu\text{m}$) wavelengths, for example. Of course, the gated viewing camera has to be sensitive

for the used laser wavelength. Depending on systems parameters like pulse energy, detector gain, and optics values, the range of a gated viewing system can reach several tens of kilometers.

Gating out obscuring foregrounds and interfering backgrounds significantly enhances the contrast in gated viewing images compared to non-gated imagery. Situations with low light or poor visibility due to fog, smoke or even fire are eligible application scenarios for gated viewing systems covering the areas of defense and security.

At IOSB, innovative active (and also passive) sensor technologies and concepts such as gated viewing are studied, evaluated, and further developed to add value to the application.

3D GATED VIEWING

Active sensors providing three-dimensional (3D) scene information offer great potential for the support of operational forces in the mission-planning phase, for example. 3D data yields a much more detailed situation awareness and helps to classify and identify targets.

For a gated viewing system, a simple way



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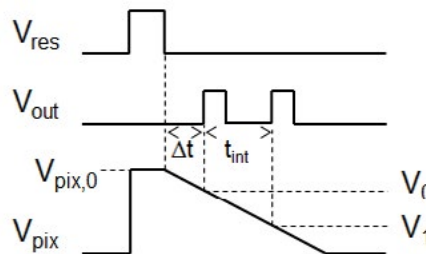


Figure 1: Schematic timing diagram for the principle of correlated double sampling: After the reset trigger (V_{res}), the pixel capacitors are charged to a defined reference voltage ($V_{\text{pix},0}$). The incident photon flux discharges the capacitors. After the times Δt and t_{int} , the residual voltages V_0 and V_1 are read out defining the reset and signal level.

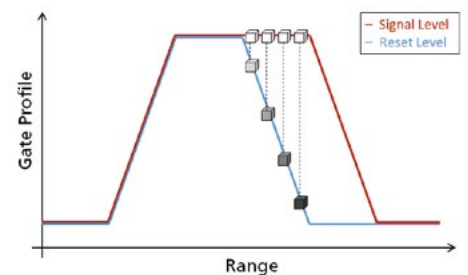


Figure 2: Gate profiles of the reset (blue) and signal level (red) with range-dependent image intensities indicated by the differently shaded cubes.

GENERATION OF 3D DATA WITH HIGH

to generate 3D information is to move the gate through the scenery by increasing the camera delay time from frame to frame. The resulting tomographic sequence can then be used for 3D reconstruction. The drawback of this approach is the long measurement duration and the required time for data post-processing. In the following, a more sophisticated method with real-time capability for the generation of 3D data with a gated viewing system is presented.

The sensitivity within the gate as a function of the distance to the gated viewing system, i.e. the gate profile, has a trapezoidal shape in a first approximation. That is because the gate profile is mathematically the convolution of the laser pulse function and the detector gain function. Therefore, the gate function consists of a rising and a falling slope with a plateau in between.

By correlated double sampling (CDS) whose principle is explained in Figure 1, two gated-viewing images with gate profiles of different lengths are simultaneously generated from one single laser pulse.

In Figure 2, generic gate profiles for the reset and signal level are depicted. Further, four cubes with different degrees of brightness are shown as overlays onto each gate profile where the plateau of the signal level overlaps with the falling slope of the reset level.



Figure 3: Example of a pair of gated viewing images for the reset (left) and signal level (right).

The brightness of each cube corresponds to the image intensity of an object, which would be located at the respective distance. Figure 3 shows the reset and signal level gated viewing images of an example scenario with four persons. Here, the difference in the gate lengths can be clearly seen.

By comparing the pixel gray values in the falling slope of the reset level image with the pixel gray values in the plateau of the signal level image, relative 3D data within this range can be calculated. Finally, with the knowledge of the gate parameters, absolute 3D data as shown in Figure 4 is obtained.

CONCLUSION

The presented technique of CDS-based generation of 3D data works in real-time because the two gated viewing images are simultaneously captured from one single laser pulse. Therefore, in contrast to a system with a scanning concept, this approach is extremely suited for dynamic scenarios with moving objects. The range accuracy can be estimated to be in the centimeters range. Depending on the system design, ranges up to several kilometers are possible.



Figure 4: Color-coded range image (red-blue = 83-86 m) reconstructed from the two shown gated viewing images. The four persons can be clearly distinguished in terms of their distance.

-
- [1] B. Göhler, P. Lutzmann: »Review on short-wavelength infrared laser gated-viewing at Fraunhofer IOSB«, Opt. Eng. 56(3), 031203 (2016)
 - [2] B. Göhler, P. Lutzmann: »Super-resolution depth information from a short-wave infrared laser gated-viewing system by using correlated double sampling«, Proc. SPIE Vol. 10434, 104340M (2017)
 - [3] B. Göhler, P. Lutzmann: »Extending the 3D range of a short-wave infrared laser gated-viewing system capable of correlated double sampling«, Proc. SPIE Vol. 10796, 107960D (2018)
 - [4.] B. Göhler, P. Lutzmann: »Range-intensity profile of a SWIR laser gated-viewing system for varying temporal response of in-pixel amplification«, Proc. SPIE Vol. 11160, 1116003 (2019)

Topic

ACTIVE COMPRESSIVE SENSING CAMERA

Compressive sensing (CS) is an imaging method that makes it possible to replace expensive matrix detectors with small and cheap detectors with one or a few detector elements. It acquires multiple low-resolution measurements, each obtained after image coding by a defined pattern (a »mask«), and processes them to recover a high-resolution image. The term »compressive« applies because the high-resolution image can be reconstructed from a total number of measurements significantly smaller than the number of whole-image pixels.

The CS method may be implemented not only in passive imaging systems but also in active imaging systems using laser illumination. Active CS may be realized in two different experimental configurations, with the spatial light modulation on the sensor side (Fig. 1 top) or on the illumination side (Fig. 1 bottom). The sensor-side approach is similar to passive CS: while the target area is illuminated by a laser, the reflected light is modulated by the spatial light modulator (SLM) and subsequently recorded by the

bucket detector. The illumination-side approach is specific to active CS: the laser light is modulated by the SLM and the detector records the light reflected by the scene. Active CS with pulse laser illumination has an important feature: the time synchronization of the laser pulse to the detector acquisition time can additionally provide depth information. In this way, both intensity and depth maps are recovered and a 3D image of the scene is reconstructed. With time synchronization (time gating methods), it is also possible to look through fog, smoke and fire.

A CS system in the sensor-side approach, developed in IOSB, is shown in Figure 2. The illuminated scene is imaged onto a digital mirror device (DMD) that modulates the light with a binary coding pattern. A DMD is commonly used as a light modulator in the visible and infrared spectral ranges. The device contains single mirror elements that can be individually controlled. Besides the light modulated by the applied patterns, the DMD device simultaneously generates



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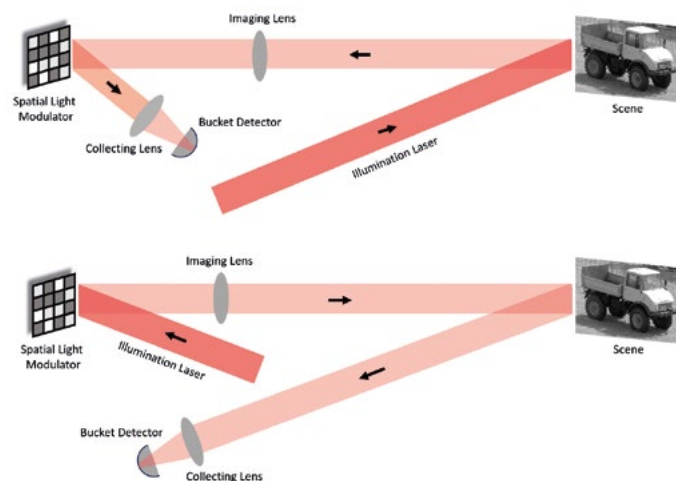


Figure 1. Active CS approaches: sensor-side (top) and illumination-side light modulation (bottom).

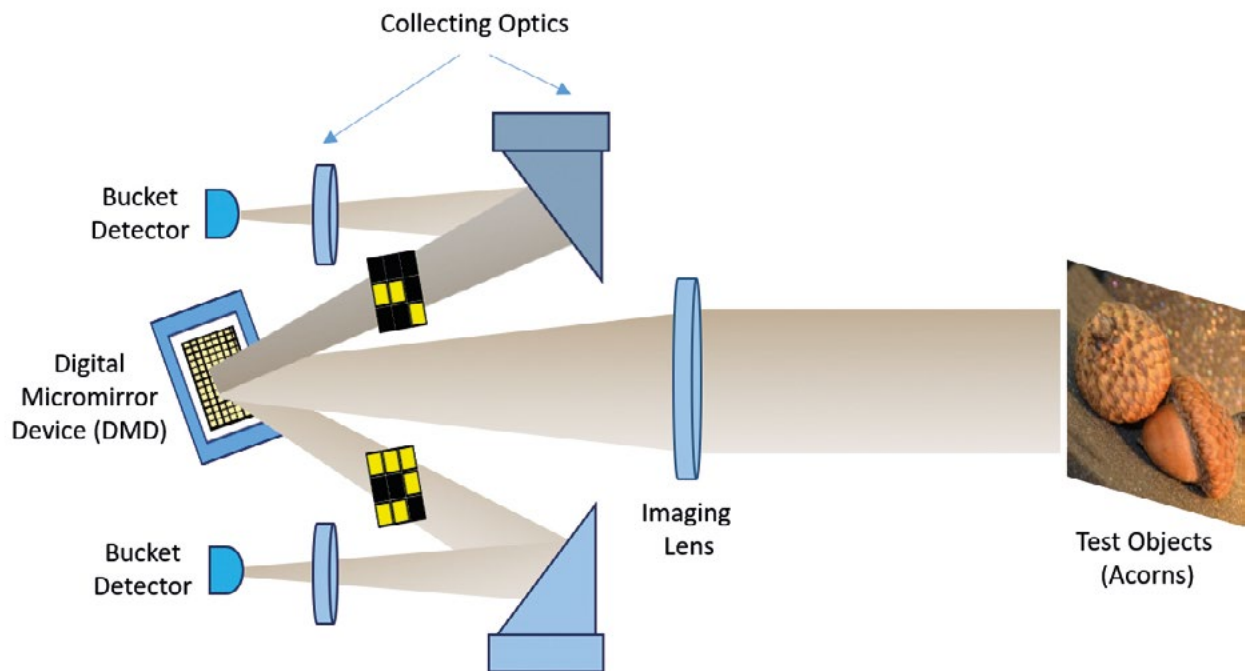


Figure 2. Experimental setup used for active CS in sensor-side approach.

a beam modulated by the complementary patterns. Each reflection is collected and recorded by a single element (bucket) detector. The test objects (acorns) are illuminated by a pulsed fiber laser at a center wavelength of $1.55\ \mu\text{m}$. The trigger output signal of the DMD controls the laser emission and synchronizes the data acquisition with the laser pulse.

Typically, the image is reconstructed using the signal from one detector only. Either the signal modulated by the applied patterns, or the signal modulated by the complementary patterns may be used for the image reconstruction. The simultaneous recording of both signals has important benefits. The quality of the reconstructed image is improved if the difference between them is used for the reconstruction. The variations of the ambient light and the illumination light intensity may be corrected using the signals. Simultaneous image acquisition in two different spectral ranges is possible if suitable detectors and filters are inserted.

There are different possibilities to define the modulation patterns. Figure 3 shows an example of image reconstructions using binary patterns based on Hadamard matrices at different levels of compression.

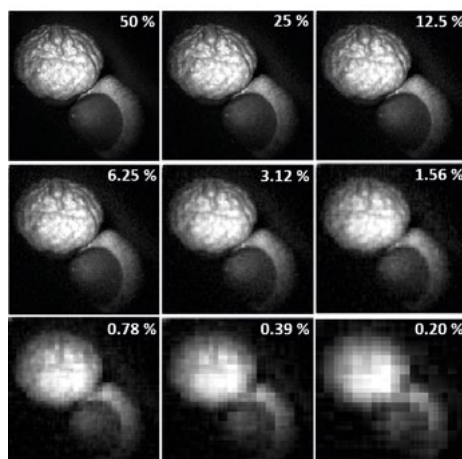


Figure 3. Image reconstruction with different levels of compression M/N [%] using the sensor-side CS approach. $N = 256 \times 256$ is the number of pixels in the reconstructed image and $M < N$ is the number of patterns used for the reconstruction. The target is illuminated by laser pulses at $1.55\ \mu\text{m}$.

CS imaging has the potential to be implemented in active imaging systems and to reduce their complexity and cost. The method can be adapted for very low light levels using single-photon detectors. Furthermore, the distance for active systems is most likely enhanced and atmospheric perturbations might have a smaller effect in some situations. This is of particular interest in defense applications [1].

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Figure 1: Head of the laser Doppler vibrometry system mounted on a pan-tilt unit together with short wave infrared cameras of the tracking system.

LASER DOPPLER VIBROMETRY

In everyday life, noises or vibrations tell us a lot about the functional state of devices such as cars, PC fans or dishwashers. Therefore, condition monitoring systems use vibration sensors to monitor the function of machines and large installations such as wind turbine generators (WTGs). Vibration sensors also provide valuable information for their development and optimization. However, practical and financial constraints limit where and how many sensors can be installed.

Laser Doppler vibrometry (LDV) is an established measurement technique that allows object-independent measurement of vibrations. It uses the Doppler effect, the change in frequency of a wave (like sound or light) when the source and receiver move against each other. It is a familiar phenomenon, e.g. in the case of the change in pitch of a passing car. Vibrations of object surfaces correspond to an up and down movement with velocities up to approximately ± 1 mm/s. When laser light is reflected back from a

vibrating surface, it undergoes a changing frequency shift (e.g. ± 1.3 kHz). The vibration thus modulates the light frequency, just as radio waves from FM stations are modulated with the sound, and the music. A laser Doppler vibrometer measures this frequency shift by comparing the emitted laser light with the received laser light and can thus interpret the frequency modulation as object vibration.

DISTANT VIBRATION MEASUREMENT ON ROTOR BLADES

Fraunhofer IOSB is developing an LDV system that differs from current commercial systems in three aspects:

1. The laser used operates in the short-wave infrared range, at a wavelength of $1.5 \mu\text{m}$. Thus, even higher output powers are still safe for the eyes and allow longer measurement distances of several hundred meters.
2. The vibrometer is mounted on a pan-tilt unit and combined with an image pro-

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ROTOR BLADES OF WIND TURBINES

cessing and tracking system. This allows the laser to follow moving objects and, in particular, enables measurement on the rotating rotor blades of wind turbines during operation.

3. The signal acquisition and processing of the vibrometer determines and compensates for the additional Doppler shift that occurs due to the object's own motion. It exceeds the frequency shift of the vibrations to be measured mostly by several orders of magnitude (powers of ten) and is therefore called »macro Doppler shift«. When viewed from an oblique angle to the rotor plane, the rotor blades move with respect to the measuring device at a speed of up to several times 10 m/s. This relative movement causes a continuously

sine-like varying Doppler shift between e.g. -20 MHz and +20 MHz. The evaluation of the actual vibration signal is thus similarly complex as listening to a radio station whose transmission frequency constantly wanders back and forth over the complete frequency band.

APPLICATION

Measurements on rotor blades in operation have already been successfully demonstrated under field conditions. It enables a variety of potential future applications, which are being explored together with the project partner, Nawrocki Alpin:

- Highly spatially resolved vibration data for validation of simulation models
- Structural and aerodynamic optimization of rotor blades

- Evaluation of the structural condition of a WTG – lifetime extension or repowering?
- Detection of new hidden damage through periodic measurements
- Localization and analysis of altered vibration behavior
- Identification and quantification of sound emission during operation.

Since access to offshore wind turbines for maintenance work is associated with considerable effort, distant measurement methods are of even greater interest here than for onshore turbines. With the development of a sufficiently precise stabilized platform to compensate for ship or wave motion, the tracking and vibrometry system could be used in this environment in the future.

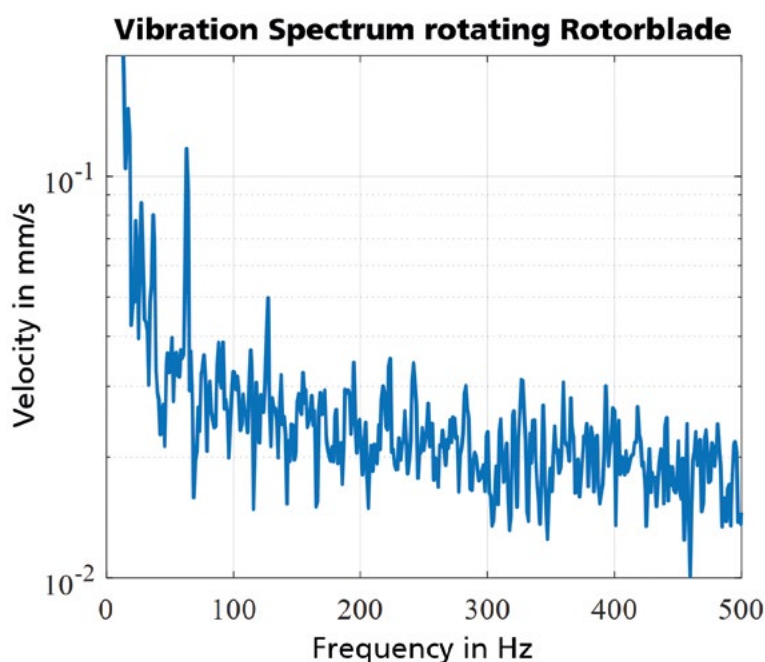


Figure 2: Example of a vibration spectrum of a rotating rotor blade acquired by the laser Doppler vibrometry system.

The project is supported by the Federal Ministry for Economic Affairs and Energy based on a decision by the German Bundestag, reference number 0325287A.

Supported by:



Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

Weitere Informationen über das Projekt finden Sie hier: <https://www.iosb.fraunhofer.de/en/projects-and-products/distant-vibration-measurement-wind-turbines.html>

Topic



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NON-LINEAR AND LASER CRYSTALS: GROWTH AND PROCESSING FOR EFFICIENT COHERENT SOURCES

BACKGROUND

Fraunhofer IOSB is performing research and development of novel coherent sources that are often intended to exceed current limits in terms of power and energy. The requirements on the optical components, especially on the grown crystals used for the generation and conversion of laser radiation, are in consequence high and the crystals available on the market often do not meet these challenging requirements. In addition, certain crystals used in military laser sources are subject to export restrictions on the international market. Availability of suitable materials is therefore severely limited and not guaranteed. In order to achieve technological sovereignty in this field, new and improved materials are being investigated at Fraunhofer IOSB as a basis for further research and development of laser and non-linear sources.

NON-LINEAR OPTICAL MATERIAL

With the materials currently available, high-power laser radiation cannot be generated efficiently by a laser crystal in the mid- and long-wave infrared range. To circumvent this issue, non-linear optical materials (NLO) are used for down-conversion. This allows for the radiation to be adjusted to the desired wavelength. Only certain NLO crystals, which must be transparent and phase-matchable in the corresponding wavelength range, can be used for this purpose. The best results are currently achieved with crystals from the chalcopyrite class (figure 1).

At Fraunhofer IOSB, synthesis, growth and research on new and improved NLO materials are being driven forward owing to a new laboratory infrastructure. Crystals are grown in special furnaces and investigated by X-ray diffraction. Improved growing

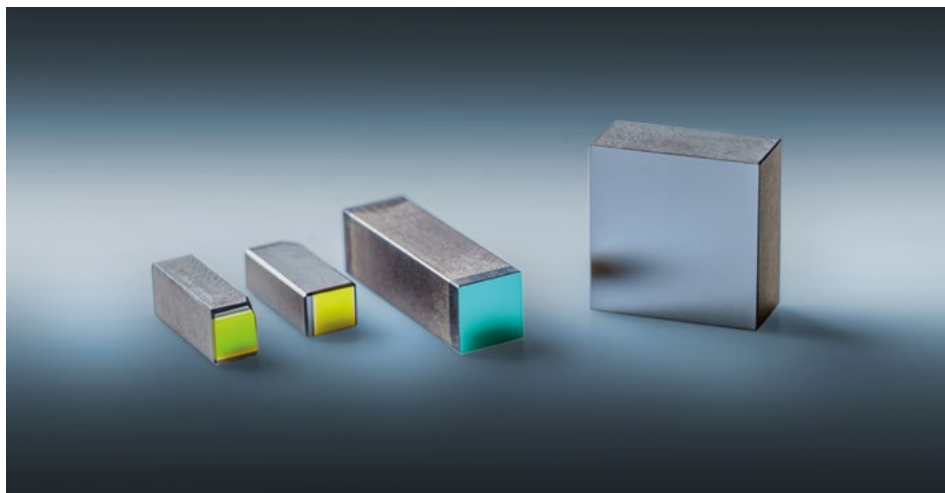


Figure 1: Example of chalcopyrite crystals used for MWIR conversion.



Figure 2: As-grown crystal boules, drilled boule after extraction and extracted laser rods.

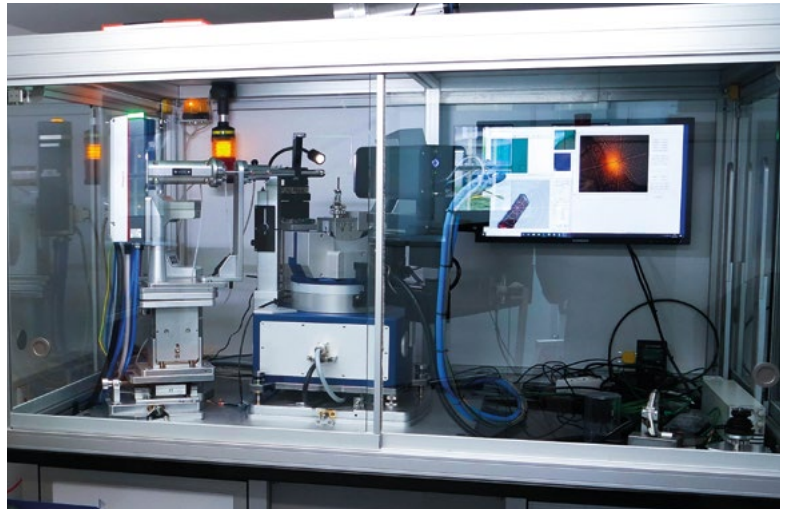


Figure 3: X-Ray diffractometer for qualitative measurements

conditions are being studied to reach and ensure the highest quality of the crystals. The optical components are cut out from the as-grown crystal boules and polished using dedicated processes to improve the optical damage threshold.

NOVEL LASER CRYSTALS

For the generation of laser radiation, crystals from the class of the garnets are currently investigated in particular (figure 2). These laser crystals are rare earth-doped oxide crystals. The performance of laser sources is limited by the physical properties of laser crystals among other limiting factors. At high power, the laser crystal heats up, and temperature differences within the crystal result in undesirable effects like thermal lensing, depolarization and aberrations that negatively affect the beam quality

and severely reduce the efficiency of the laser sources.

At Fraunhofer IOSB we are investigating special laser crystals in a modern laboratory environment. To reduce the thermal lensing effect, laser crystals with special dopants and geometries are being studied in specially designed laser sources. In this context, we are investigating the promising approach of developing laser crystals with gradually graded doping levels.

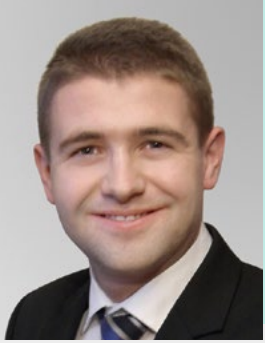
RESEARCH SERVICES FOR CUSTOMERS

A lot of scientific knowledge and expertise from the field of crystal growth will also be made available to Fraunhofer IOSB customers and partners as part of joint research projects in the future. This includes the research and development of new NLO and

laser crystals as well as the exploration of improved processing methods for crystal growth. The equipment at Fraunhofer IOSB comprises also specific measurement technologies enabling comprehensive analysis of crystals (figure 3). X-ray and spectroscopic investigation, interferometry, and the analysis of the laser-induced damage threshold of optical components (at $2\ \mu\text{m}$ and at $3\text{--}5\ \mu\text{m}$) are also available for joint research projects.

Topic

HIGH-POWER SOLID-STATE LASER INFRARED SPECTRAL RANGE



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Since Theodore Maiman realized the first ruby laser by in 1961, laser technology has been an amazing development that nowadays affects almost all aspects of our lives. Today, a large variety of specific laser sources enable very different technological applications. Fraunhofer IOSB focuses in research and development of high-power solid-state lasers based on crystals doped with rare-earth ions (Er^{3+} , Tm^{3+} , Ho^{3+}) and nonlinear sources. While these systems can be used as direct emitters in the short-wave infrared (SWIR), they also have attracted very much attention as ideal pump sources for efficient conversion processes to the mid- to long-wave infrared (MWIR/LWIR) wavelength range, based on the outstanding properties of nonlinear optical materials like ZGP (ZnGeP_2), CSP (CdSiP_2) or orientation-patterned gallium arsenide (OP-GaAs). Such light sources can be used in various technological applications such as molecular spectroscopy, free-space optical communication, LIDAR, remote sensing, and optronic countermeasures against heat-seeking missiles, to name but a few. Industrial and medical applications include the precision welding of plastic, which makes use of the absorption of laser radiation

by molecular absorption lines of functional chemical groups [1], as well as dentistry and surgery, where lasers serve as optical scalpels and for the efficient hemostasis in soft tissue [2].

COMPACT AND POWERFUL

Fraunhofer IOSB is aiming at the continuous improvement of high-power solid-state lasers as well as upscaling the laser output power and pulse energy. Therefore we study the underlying physics and develop stable, robust and compact laser designs. One example is shown in Figures 1 and 2: pump light from a thulium-doped fiber laser is efficiently absorbed in a Ho^{3+} :YAG crystal, while the resonator geometry is optimized for a chosen operation point. To prevent degradation of beam quality at high power or energy, thermal effects must be taken into account, such as the thermal lens that forms in Ho^{3+} :YAG.

The compact laser source is completed by a Q-switch for pulsed operation. In a realization optimized for high-pulse energies, it was possible to demonstrate pulse energies of up to 16 mJ at a high pulse repetition rate of 700 Hz corresponding to an

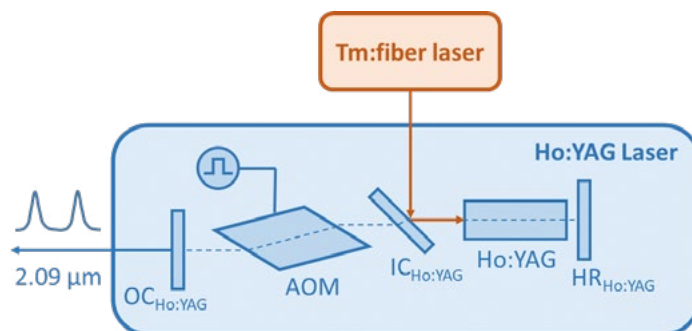


Figure 1: Schematic architecture of a compact pulsed Ho^{3+} :YAG laser.
(OC: Output Coupler, AOM: Acousto-Optic Modulator, HR: High Reflective, IC: Input Coupler)

SOURCES IN THE SHORT-WAVE AND MID-WAVE

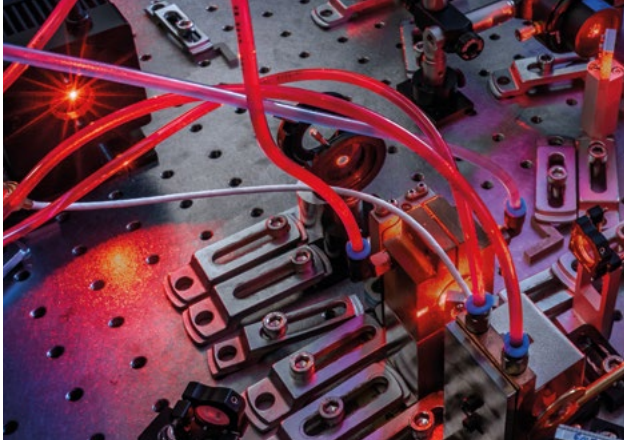


Figure 2: part of the pulsed Ho³⁺:YAG laser setup.

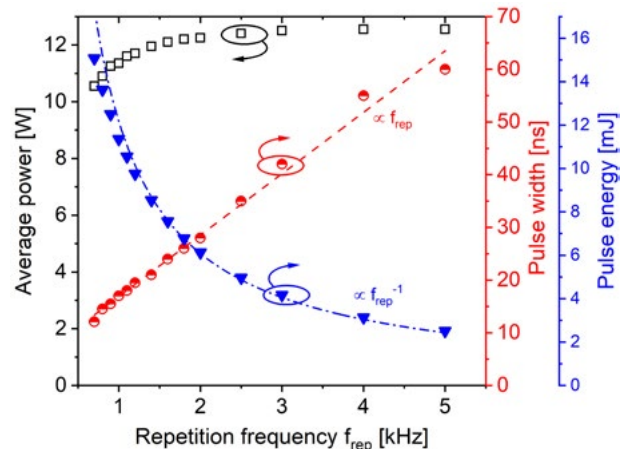


Figure 3: Dependence of pulse energy, pulse duration, and average output power on the pulse repetition rate. [3]

average output power exceeding 10 W (see figure 3) and a pulse power of up to 1.2 MW, while preserving a very good beam quality [3]. Until recently, pulse energies of this order could only be realized at lower repetition rates or were restricted to more complex laser architectures including amplifier stages.

EXPERTISE TO BENEFIT OUR CUSTOMERS

To qualify laser radiation, the research group uses the newest and outstanding measuring equipment, such as infrared cameras, wave-front sensors and optical spectrum analyzers covering the relevant spectral range from SWIR to LWIR.

In accordance with the Fraunhofer model, the technological skills and competences resulting from fundamental research activities flow into the realization of demanding customer projects. The expertise we gained enables us to work on challenging R&D projects aiming at novel solid-state lasers for selected applications in the 1.5–2.1 μm and 3–12 μm spectral range.

A test rig is available at Fraunhofer IOSB for qualifying the laser-induced damage threshold (LIDT) of SWIR laser components and optics. The developed laser technology enables the characterization of the LIDT up to high intensity and fluence values, directly at the wavelength of interest. Due to the lack of suitable laser sources, manufacturers of SWIR laser optics currently often carry out tests at other wavelengths and then, on this basis, only can estimate the damage threshold in the SWIR range. To do so, they have to make assumptions which often represent an unacceptable uncertainty [4], rendering research and optimization of optical damage thresholds difficult. In contrast, our new capabilities both support the development of optics at IOSB and will also be available for our partners and customers as part of joint research projects, aiming at the improvement of production processes and in particular the refinement of optical components.

Similarly, customer- and partner-specific solutions can be realized in joint research projects, in particular in the fields of LIDAR,

optical parametric oscillators (OPO) in the MWIR and LWIR spectral ranges as well as laser sources for tissue ablation in medicine. In order to meet the specific requirements, the laser parameters such as wavelength, pulse duration, and repetition rate can be tuned across a wide range.

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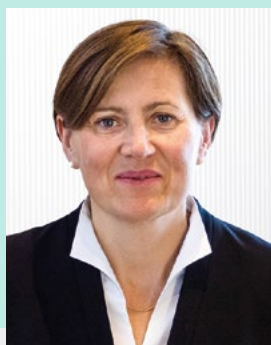
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HIGH-POWER SWIR FIBER LASERS IN CONTINUOUS AND PULSED OPERATION MODES

MOTIVATION

Fiber lasers are coherent light sources exhibiting relatively low cost (free of alignment and maintenance), sturdy realization (resistant to shocks and vibrations), high efficiency, and a compact footprint.

Thanks to all these technological strengths, fiber lasers are currently used in a wide spectrum of industrial applications, ranging from material processing to medical applications and defense. Lasers emitting at wavelengths above 1.4 μm are particularly interesting: these radiations are advantageous as they are safer for the eye than those from 1 μm lasers, allowing for several orders of magnitude in power increase, and the presence of atmospheric transmission windows around 1.5 μm and 2.1 μm supports free-space long-range propagation. Important applications, therefore, include LIDAR (laser imaging, detection, and ranging), free-space telecommunication, countermeasures, or HEL (high-energy laser applications). As an

illustration, LIDARs are used for molecular remote sensing in the atmosphere. The wavelengths of 1572 nm and 2051 nm are well known for carbon dioxide monitoring. Lasers operating at wavelengths above 2 μm allow for efficient processing of transparent plastic material such as marking, welding, or cutting. Non-linear interactions in crystals and fibers are driving processes for generating new wavelengths in supercontinuum sources or optical parametric oscillators (OPO). These light sources rely on power-scaled pulsed 2 μm pump laser sources to generate mid- to long-infrared wavelengths extending up to 12 μm .

The development of high-power fiber laser technology, especially around the wavelength of 2 μm and above, is still young and thus much effort is put into research and development to access new wavelength bands, reach higher output power/energy, or realize more efficient architectures.

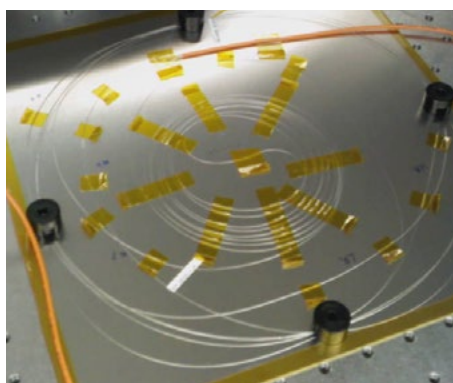


Figure 1: All-fiber pump laser for highly integrated SWIR fiber amplifiers

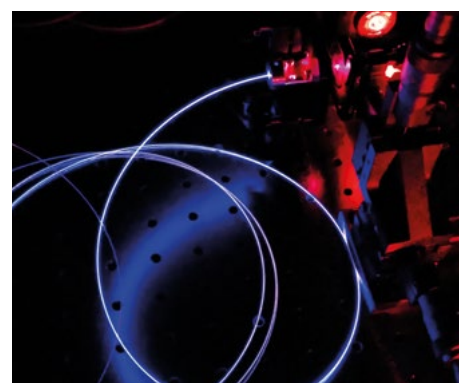


Figure 2: Setup test of a Tm^{3+} fiber laser

COMPETENCES

IOSB provides cutting-edge knowledge to address research and development needs in high-power fiber lasers in the SWIR (short-wave infrared) and MWIR (mid-wave infrared) spectral range. Among those are capabilities to take a laser from concept, to an experimental level and up to a demonstrator packaged ready to emit. Research and development focuses on high-power fiber lasers emitting in the 1.5 μm and 1.9-2.1 μm ranges and beyond, with an emphasis on defense applications.

As often several ways exist to achieve certain output parameters by using different fiber components, pumping schemes, rare earth-doped fibers, and operating regimes, IOSB uses several in-house developed simulation tools to investigate and optimize laser designs prior to realization.

We also design our own optimized fiber components like fiber endcaps, fiber cladding-mode strippers, signal pump combiners, etc., that allow for integrating specific functions or increased damage thresholds for power-scaled lasers. The creation of our new state-of-the-art research facility for development and manufacturing of specialty fibers and their corresponding preforms at our new Oberkochen site, will enable the access to novel fibers for lasers with unique properties well suited for specific applications in the SWIR and MWIR spectral range.

Furthermore, using the latest developed high-power/energy fiber lasers, we perform laser damage testing on fibers and optical (fiber) components in the context of our own laser research. In common research projects, these capabilities are also made available to our partners and clients in research and development of optical components and coatings.



Figure 3: View into a new high-power fiber laser lab

RECENT ACHIEVEMENTS

Lately, we have developed a pulsed 2 μm fiber laser source with single-frequency ultra-narrow linewidth operating with nano-second pulses [1] (figure 1). The structure relies on a master oscillator power amplifier (MOPA) with an adjustable output pulse shape, flexible repetition rates and peak powers in excess of 10 kW. Another fiber laser architecture that we are investigating is based on Q-switching [2] (figure 2). Compared to a MOPA, this topology is more compact. However, the pulse shape and duration is less flexible and determined by the dynamics of the laser, close to a Gaussian pulse shape. We have successfully demonstrated significant pulse energy scaling using both configurations for pumping an OPO to generate wavelengths in the 3-5 μm range. Other applications for these lasers include LIDAR or supercontinuum generation.

With continuous wave fiber lasers, we have achieved record values in power scaling at long wavelengths in silica fibers [3]. The laser configuration was based on an active

fiber surrounded by some free-space optical components. Up to 145 W (resp. 262 W) of output power were extracted at 2.2 μm (resp. 2.1 μm). In addition, we have investigated power scaling of an all-fiber configuration based only on a seed laser and one amplifier. Using this simple MOPA structure, we demonstrated 937 W of output power [4]. The emission properties of this laser are well suited for applications such as material/metal processing and HEL applications. Figure 3 shows typical pumping equipment for kW-class 2 μm fiber lasers.

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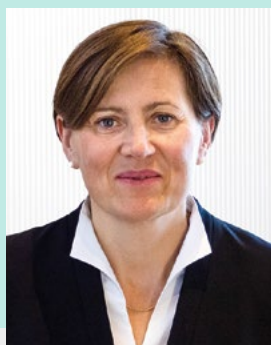
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ACTIVE FIBERS AND FIBER COMPONENTS FOR HIGH-POWER FIBER LASERS IN THE SHORT- AND MID-WAVE INFRARED SPECTRAL RANGE

BACKGROUND

Monolithic fiber lasers are purely fiber-based lasers where fiber components take over the tasks of free-space optics. The monolithic integration of fiber lasers results in a compact design with high resistance against external influences such as high temperature stress, mechanical shocks or dust contamination. Whether in the formation of a laser resonator, insertion or extraction of signal and pump radiation, matching of propagation modes in dissimilar fibers, by removing free-space optics, fiber components are the basis for high-power fiber lasers.

ACTIVE FIBER AND FIBER COMPONENTS

To cover the whole value chain in fiber lasers, Fraunhofer IOSB is currently establishing a state-of-the-art research facility for development and manufacturing of specialty fibers and their corresponding preforms in Oberkochen (figure 1). This includes

the manufacturing of polarization-maintaining, photonic crystal and active fibers with rare-earth dopants such as erbium, thulium and holmium.

In-house manufacturing capabilities for tailored fiber components enable the realization of novel fiber lasers with unique properties that are perfectly suited for specific applications in the SWIR spectral range.

The fabrication and exploitation of fiber components stands out as key technology for the development of high-power fiber lasers. Despite their importance, there is no guarantee of tailored fiber components for the short-wave and mid-wave infrared (SWIR and MWIR) spectral range being available on the market. Therefore, Fraunhofer IOSB is performing research and development of new tailored fiber components as a basis for further research into high-power fiber lasers.

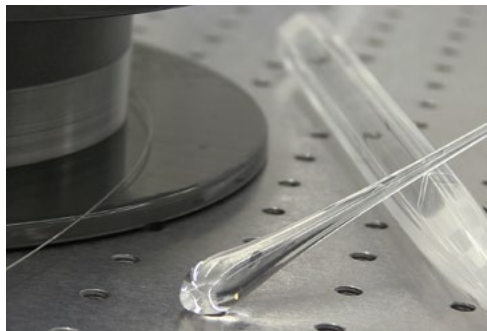


Figure 1: Preform, fiber drop and fiber rolled on a spool

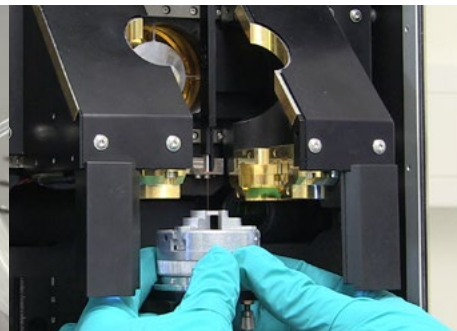


Figure 2: Realization of fiber components

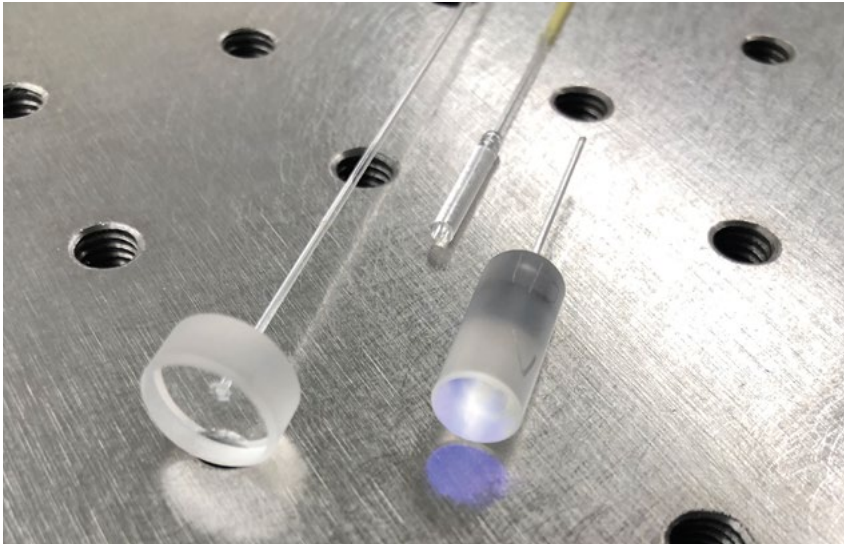


Figure 3: Fiber end caps spliced onto fibers

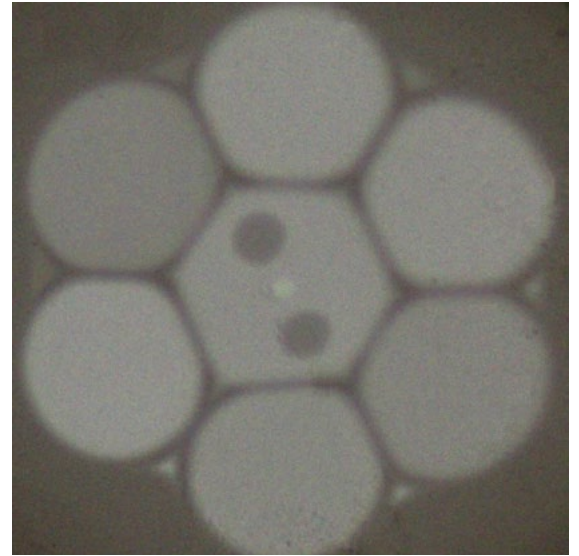


Figure 4: Cross-sectional view of an end face pump combiner with polarization-maintaining central signal fiber.

EXAMPLE OF TAILORED FIBER END CAPS AND PUMP COMBINERS FOR HIGH-POWER FIBER LASERS

In the development of high-power fiber lasers, the increased thermal and optical stress on fiber end faces poses a particular challenge. The high power densities at optical interfaces between air and glass lead to thermal damage or laser-induced ablation of fiber end faces. Splicing fiber end caps to fibers can provide a solution to this issue.

Fiber end caps are substrates often made from fused silica with an aperture of several millimeters. The base surface on the output side has an anti-reflective coating to prevent back reflection of the emerging laser beam. Splicing a fiber end cap to the fiber increases the beam size of the laser beam diverging inside the glass substrate (Figure 2). This reduces the power density of the laser beam below the damage threshold of the air-glass interface while keeping the laser output power constant. Therefore, fiber end caps enable the realization of high-power fiber lasers in the multi-kilowatt

range. Figure 3 shows fiber end caps which have already been spliced onto fibers. The aperture and length of a fiber end cap depend on the laser output power and the optical characteristics of the output fiber.

Power scaling in fiber lasers requires an efficient concept for incoupling the pump radiation. Using free-space optics, highly complex optical systems would be required due to the etendue of the pump sources. The required complexity of such optics ultimately technologically limits the coupled pump radiation and, thus, the laser output power. Pump combiners reduce the complexity of coupling optics to a minimum so that a maximum laser output power can be achieved.

Pump combiners bundle pump radiation from several multimode fibers into one active fiber. This allows the pump sources to be spatially separated from each other, resulting in better heat dissipation, which in turn leads to an increase in durability of the entire laser system. Furthermore, by eliminating coupling optics through

fiber-integrated pump combiners, the launched pump power can be maximized depending solely on the availability of the fiber-coupled pump sources and their brightness.

There are two common designs for pump combiners: side and end face pump combiners. One of the research topics at Fraunhofer IOSB is the fabrication of end face pump combiners, where several pump fibers and a signal fiber are fused. Figure 4 shows a cross-sectional view of an end face pump combiner. The signal fiber is in the center and is enclosed by the six pump fibers.

Future work at Fraunhofer IOSB aims to further develop and optimize new processes that fully control the fabrication of fibers and fiber components. In common research projects, IOSB capabilities are also made available to our partners and clients to investigate and enhance fiber components capabilities.

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