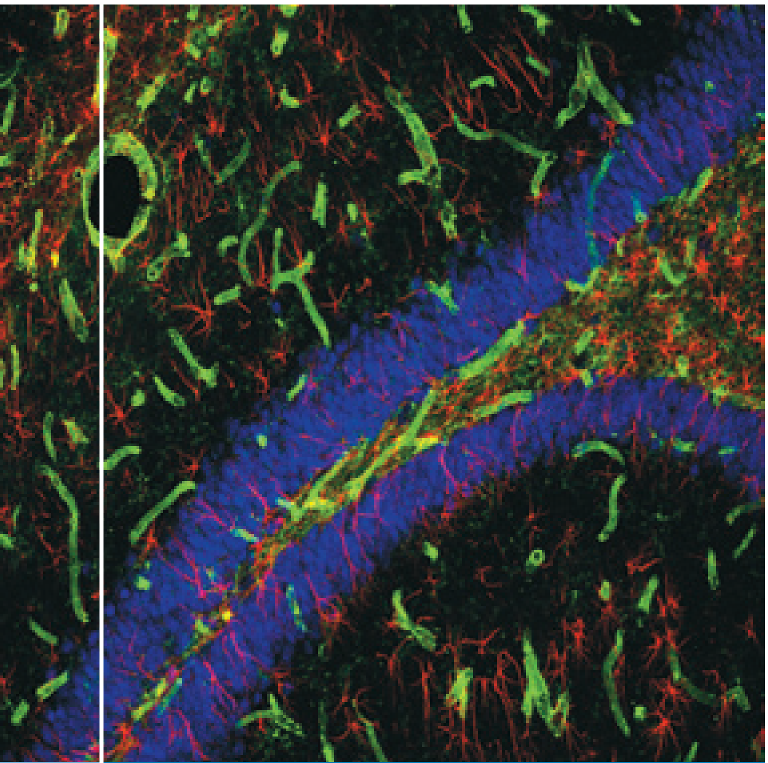
White light lasers and their applications



The generation of white laser light has been a very hot topic of research within the last five years. The term "white laser light" implies a continuous spectrum, including all wavelengths from blue to red and all the way into the infrared spectral range. An incandescent light bulb will also generate such a broad white light spectrum, however, its fundamental properties are completely different. Excellent focusing properties, high spectral density, and a small divergence of the white laser light are some of the unique advantages. Additionally, spectral, temporal, and spatial coherence are especially beneficial properties of the white laser light. Coherence means that two different parts of the laser light have a certain fixed phase relationship with respect to each other.

1. Basics

Generating such white laser light requires very high optical power densities (Gigawatts/cm^2), as the physical mechanism is based on highly nonlinear optical processes. This means that the effects depend on the square, the third, or even higher powers of the electric field of the light. In order to achieve such high power densities, pulsed ultrashort laser sources are being focused into small areas, preferentially into glass fibers with a core diameter of only a few µm. Typically so-called photonic crystal fibers and tapered glass fibers are being used. Pulsed lasers can achieve extreme peak powers of several kilowatts per pulse. As pump sources, typically femtosecond lasers are utilized, however, picosecond and nanosecond pump sources have also been demonstrated to be useful for white light continuum generation.

The major physical processes involved in converting the spectrally narrow pump light into the broad spectrum include self-phase modulation due to Kerr-nonlinearities, soliton formation due to the interplay between anomalous dispersion and self-phase modulation, soliton break-up due to higher order dispersion, and Raman shifting of the solitons, leading to nonsolitonic radiation in the short wavelength regime.

SUMMARY

White light lasers are a new class of lasers, emitting not just a single color, but rather covering a wide range of the wavelength spectrum. White light lasers, covering the whole visible range from blue, green, yellow, red, into the infrared, have been developed. Until recently, such lasers were not available, and only ultrashort laser pulse technology paved the way towards their realization. However, commercial applications were scarce due to their high prize tag. Over the last couple of years, diode pumped ultrashort solid state laser technology together with tapered glass fibers allowed the fabrication of compact, cost-effective white light lasers. We are going to describe the key developments of this field and present a number of applications.

The glass fibers possess a certain dispersion characteristics, i.e., light of different colors travels at different speed inside the fiber. Additionally, the fiber core diameter should be quite small in order to concentrate the light in a small area to increase the power density.

The fiber core diameter also influences the dispersion properties of the fiber, hence, optimizing the white light generation requires a specific fiber design, taking parameters such as group velocity dispersion and power density into account.

In order to achieve a small and rather flat anomalous group velocity dispersion characteristics, the right choice of refractive indices for the different glasses of fiber core and cladding and the optimum dimensions have to be calculated for a given pump wavelength, pump pulse duration, and pump power.

Tapered fibers are manufactured from standard fibers, which are pulled over a gas flame into several centimeter long strands. The diameter of the tapered fiber shrinks from 125 µm to only about 2 µm, and lengths of more than 20 centimeter are attainable. 2 µm is only one fifth of the diameter of a spider web, and only one fifteenth of the diameter of a blonde human hair!

Such a tapered fiber consists after flame-drawing of two untapered parts which resemble a standard single mode fiber, two taper transition regions where the light is being confined, and the waist region where the highly nonlinear processes take place. Its intrinsic advantage over photonic crystal fibers is the convenient, stable, and easy input and output coupling. This is an important prerequisite for possible applications of such fibers.

Astonishingly, tapered fibers are quite robust when encapsulated in an appropriate holder, and even dropping them onto the floor does not necessarily destroy them. This is due to the fact that the weight of the extremely thin waist is much smaller than a hair or a spider yarn – therefore its own inertia cannot destroy it.

Pumping the fiber with pico- or nanosecond pulses requires interaction lengths between the light and the fiber waist of several centimeters – therefore longer tapered fiber waists are required in order to generate white laser light in combination with such cheap, simple, and robust laser systems.

2. Applications: general

Possible applications for white light lasers include optical coherence tomography, frequency metrology, spectroscopy, and linear / nonlinear microscopy. Usually, ultrashort laser pulses are generated by a titanium-sapphire laser, which is pumped by a frequency-doubled diode-pumped solid state laser, using $Nd{:}YVO_4$ as laser crystal. This laser light is coupled into the tapered fiber, and the resulting white light can have output powers up to 400 mW at a repetition rate of 80 MHz. The spectrum stretches from 400 to 1400 nm. Such a white light system, however, has a price tag of more than 100.000 EUR. This number limits the possible applications.

New and modern solid state laser sources with ultrashort pulse durations have become available over the last few years. Combining these sources with tapered fibers results in novel compact and relatively inexpensive white light lasers. An example for such a combination consists of a diode-pumped Yb:glass femtosecond oscillator in combination with a tapered fiber. Size and price of this system are drastically reduced due to the convenient absorption properties of the Yb crystal (at 980 nm, where cheap and high-brightness laser diodes from telecom applications are available) and the SESAM-modelocking technology, which was recently awarded the Leibinger-prize.

The laser emits 200 fs pulses at 20 MHz repetition rate and at a wavelength of 1040 nm. Its output power can reach 1 Watt. The resulting white light continuum has an average power of about 200 mW and stretches from 500 nm to beyond 1700 nm.

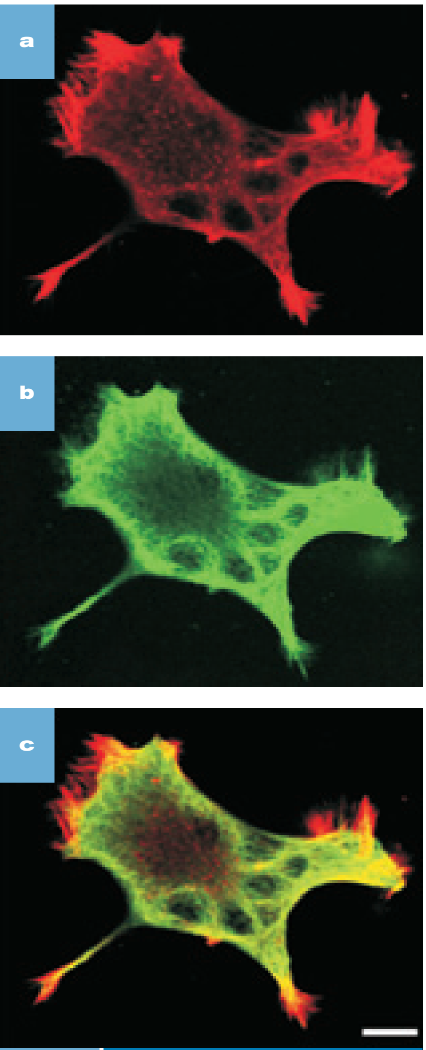
A different pump technology utilizes a passively modelocked $Nd{:}YVO_4$ oscillator, which is diode-pumped at 808 nm. This system, emitting at 1064 nm, offers repetition rates up to 120 MHz and pulse durations of about 8 ps. An amplified version at 80 MHz reaches even average power levels of 30 W. Successful white light generation using three similar tapered fibers that were spliced together resulted in 5.6 W of white light, with a spectrum from 460 nm to 1600 nm. These kinds of power levels enable the user of this white light system for 3-dimensional measurements of objects of several decimeters diameter.

3. Application: Nonlinear microscopy

Possible applications usually require a continuous spectrum with a high spectral power density. One example of such an application is microscopy. Different regions of biological cells are being stained with a variety of fluorescent dyes, allowing the observer to distinguish between the alternating functional units. Each of such dyes absorbs light of a different spectral region and emits a new color. In order to excite the dyes, a finite number of continuous lasers is usually used. Typically three to four lasers are integrated in a fluorescence microscope. This means that, in principle, up to four different species within biological tissue can be distinguished by the different fluorescent colors.

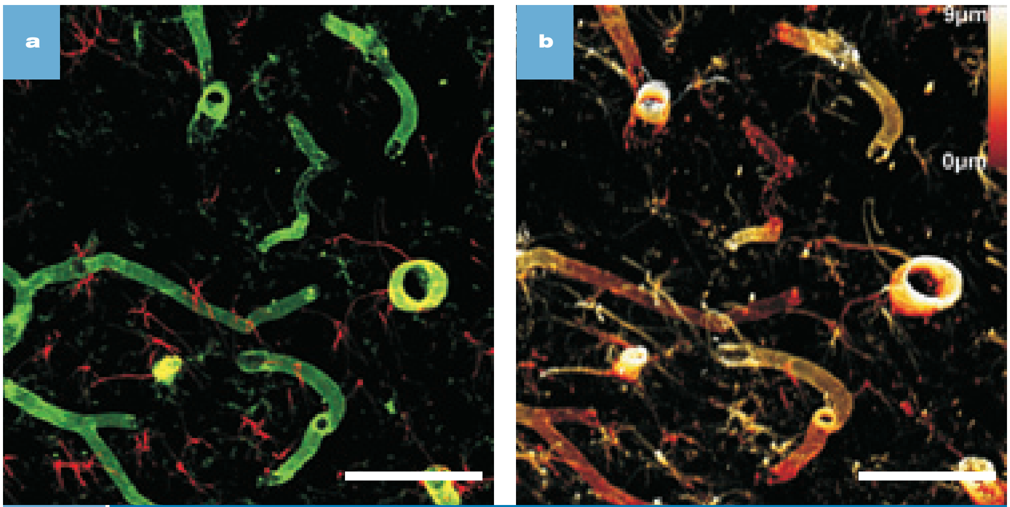
Using a white light laser, basically hundreds of different colors are possible. Recently, quantum dots have become available for dye-staining of biological samples, and in combination with the white light laser, distinguishing between a large number of different species comes into reach.

As an example, we conducted an experiment together with Prof. Käs, Timo Betz, and Daniel Koch at the University of Leipzig, using neuroblastoma cells. **(01)** demonstrates a multi-color fluorescence confocal microscopy image of these cells, differentiating between the actine cytoskeleton, using the dye TRITC-phalloidine **(01 a)**, and the microtubuli cytoskeleton, stained with the dye Alexa-488 **(01 b)**. **(01 c)** demonstrates nicely how the overlay of the two previous image with different colors gives a 3D impression of the cell.



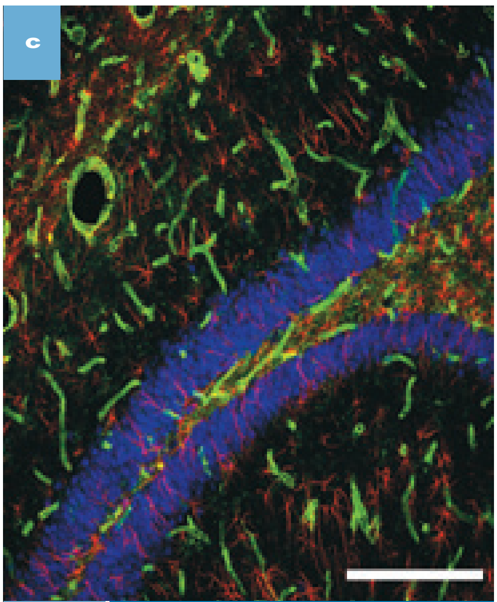
01

__(01 a)__ shows the actine cytoskeleton of a neuroblastoma cell which was stained with TRITC-phalloidine dye. __(01 b)__ shows the microtubuli cytoskeleton, which was stained using Alexa-488 dye. __(01 c)__ is the overlay of __(01 a)__ and __(01 b)__. The white laser light was generated in a tapered fiber with 2.1 µm diameter, using 650 mW of titanium-sapphire laser light at 803 nm and 76 MHz repetition rate. The generated white light had an output power of 280 mW, which was coupled into a commercial Leica CLSM microscope – instead of the standard cw lasers. The scale bar corresponds to 10 µm.



02

3D image of astrocytes of a rat brain, stained with Cy3 (depicted in red) and blood vessels of the brain (depicted in green), stained with Cy2. The scale bar corrsepsonds to 50 µm. The color coding in __(02b)__ contains the information about the third dimension of the tissue structure.



02

Same as __(02a)__ and __(02b)__, but using a third dye (Cy6) to stain the neuronal cell bodies. The scale bar is 100 µm.

The output spectrum of the tapered fiber was optimized in a way to generate most spectral intensity in the blue and green wavelength region, where the two dyes absorb most light. Using filters (for example a combination of acousto-optical beam splitters), the optimum excitation and detection wavelengths could be selected.

(02) demonstrates the use of this method to look into the functional structure of a rat brain. Astrocytes and blood vessels can nicely be distinguished **(02a)**, and with the aid of the confocal microscope, even height information can be retrieved **(02b)**. The dyes for staining in this case were Cy3 for the astrocytes and Cy2 for the blood vessels.

When extending the staining to even three dyes (including Cy6 for the neuronal cell bodies, depicted in blue), the images become even more impressive **(02c)**.

A different way for obtaining height information and slicing the sample optically is multi-photon microscopy. The biological sample absorbs two pump photons only within the laser focus volume, which is about 1 μm^3 in size, and emits at a longer wavelength. The advantage of the white light laser source is besides its large spectral tunability also the short pulse duration and the high spectral power of the laser pulses. Therefore, multiphoton microscopy is possible, even for different pump laser wavelengths.

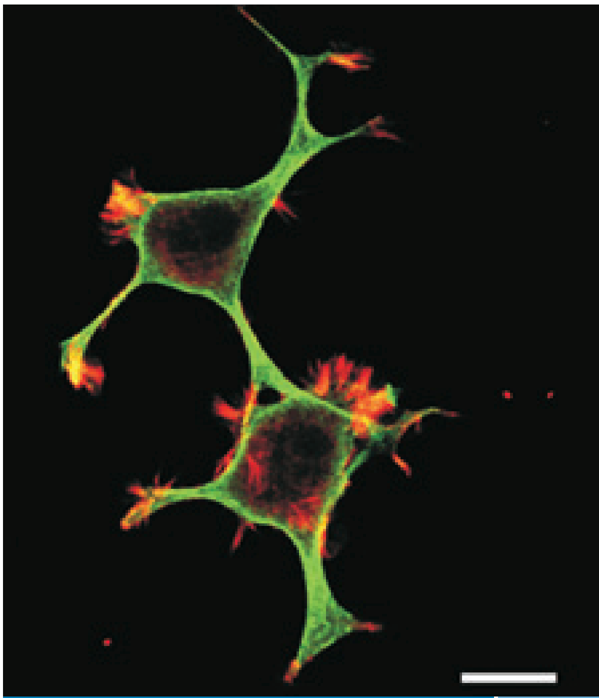
We have demonstrated this simultaneous possibility for the first time, as can be seen in **(03)**. The neuroblastoma cells are being exposed to the spectral region from 700–1300 nm of the ultrashort white light.

4. Application: Laser microdissectioning

The short laser pulses of the white light are also useful for laser dissectioning of cells. The company PALM Microlaser Technologies AG produces systems for microdissection and micromanipulation in cells. They can cut out for example cell nuclei and manipulate them out of the cell framework. The applied method is called LMPC (laser microdissection and pressure catapulting). Conventionally, they focus a nanosecond nitrogen laser onto the cell and cut right through it, for example in order to separate a cell from adjacent tissue. Subsequently, the laser beam is defocused and the water below the cell is instantaneously vaporized. This catapults the individual cell from the microscope slide to a nutrient medium above. Together with PALM we were able to demonstrate the usefulness of the blue part of the white light laser spectrum for cutting of subcellular structures. Cutting widths of around 1.5 µm were obtained **(04)**. The perfect TEM_{00} beam profile of our white light laser allows diffraction-limited laser spots with very small diameters.

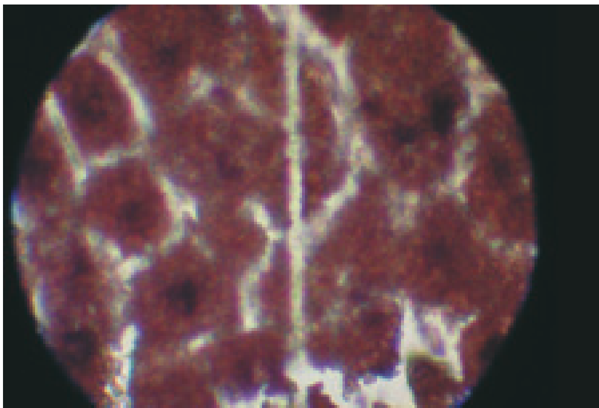
5. Application: Surface metrology

Not only precise cutting, but also micrometer precision in surface measurements was demonstrated using the white light laser source. In collaboration with Precitec Optronik GmbH, noncontact measurements of different samples (ranging from metallic parts, sheet metal, glass, to rubber and teflon) were performed. The technology uses a lens with a strong chromatic aberration **(05)** which gives a series of different longitudinal foci for different colors. The reflection of the laser light is sent back through the lens and imaged onto a pinhole. Only the wavelength that has its focus exactly at the sample surface can pass this pinhole. The reflected light analyzed in a spectrometer, relating different wavelengths to varying sample heights. **(06)** demonstrates the height dependence of the reflected wavelength on a galvanized sheet metal sample, which is usually a tough material to test the setup. The white light laser provides enough spectral power and spectral width to easily pass that test, demonstrating its profound capability for this task. It should even be possible to use the powerful multi-Watt white light laser beam to perform in-situ height measurements



03

Multiphoton image of the same neuroblast cell as in **(01)**. *The same details as in multicolor confocal linear miscropscopy are visible.* **(01)**–**(03)** *result from a fruitful collaboration with Prof. J. Käs, University of Leipzig.*

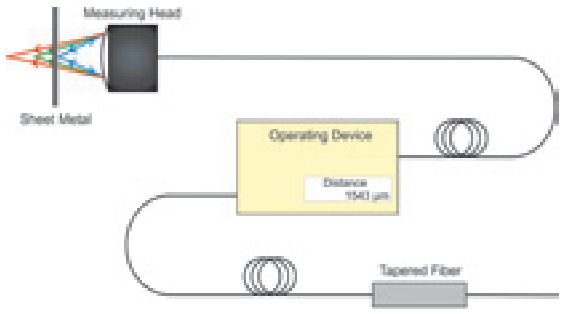


04

White light was generated in a 2,0 µm diameter tapered fiber with an average power of 330 mW. It was collimated using a 10x microscope objective and sent through a 40 nm wide interference filter at 450 nm. The remaining 8 mW of blue light are being focused through a 40x microscope objective onto a piece of rat liver. Moving the sample led to a vertical cut with a width of 1.5 µm. The images result from a collaboration with P.A.L.M. Microlaser Technologies AG, Bernried.

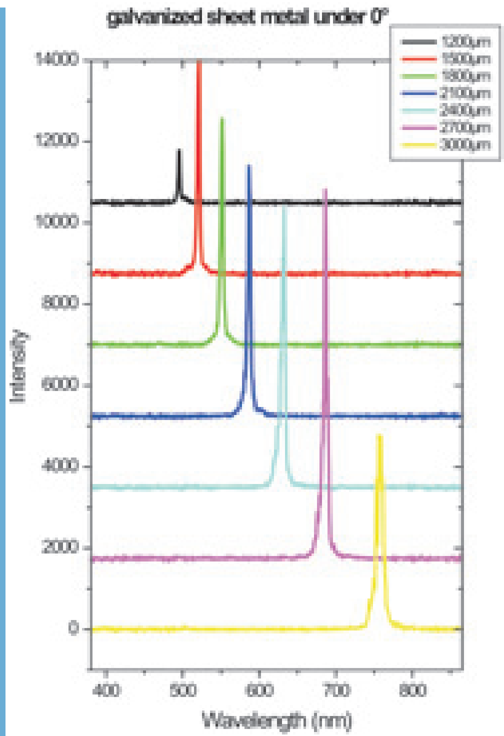
ZUSAMMENFASSUNG

Weißlichtlaser sind eine neue Klasse von Lasern, die nicht nur einfarbiges Licht aussenden, sondern einen weiten Bereich des Lichtspektrums abdecken. Es gibt bereits Weißlichtlaser, deren Spektrum vom Blauen über das Grüne, das Gelbe, das Rote bis in den Infraroten Spektralbereich reicht. Bis vor kurzem waren solche Laser noch undenkbar, und erst die Technologie der Ultrakurzzeitpulse hat solche Laser ermöglicht. Ihre kommerzielle Verwendung wurde bisher durch hohe Anschaffungskosten verhindert. Seit kurzem erlaubt diodengepumpte Festkörper-Lasertechnologie in Verbindung mit gezogenen Glasfasern, solche Weißlichtlaser kompakt und kostengünstig herzustellen. Wir stellen die wesentlichen Entwicklungen und eine Reihe praktischer Anwendungen vor.



05

Working scheme of the distance measurement: A 2.5 µm thick tapered fiber was pumped with 550 mW of Ti:sapphire light at 800 nm. The generated white light was reduced to 5 mW and sent into the operating device, which contains a beamsplitter. The white light is sent through a fiber to a chromatic lens, causing longitudinal chromatic aberration with a series of different colored foci. Reflected light is sent back into the operating device, being focused onto a pinhole and analyzed by a spectrometer. The measurements are the result of a collaboration with Precitec Optronik, Rodgau.



06

Distance measurement using galvanized sheet metal. The curves show the reflected spectra for different sample-measurement head distances. The signal-to-noise ratio is quite large.

directly in a laser welding arc, giving micrometer accuracy. We have also demonstrated that this method works at large angles up to 75° as well. A high signal-to-noise ratio is still achievable in this case. Once more, the superb white light laser beam allows high input coupling efficiency (especially when compared with a light bulb) and high spectral intensity in this difficult measurement environment. Also, the large spectral width of the white light allows for a superior distance range.

6. Application: Coherence radar

Coherence radar is a white-light Michelson interferometer technique, which allows the determination of the surface structure of objects which are several decimeters in diameter. Professor Häusler from Erlangen is specialized in this field and collaborated with us for these experiments.

The white light laser beam is split into two parts using a beam splitter. One part is reflected off a reference mirror, and the second part is sent to the object under investigation. The reflected light interferes with the reference light, and the resulting fringe pattern is evaluated as a function of distance of the reference mirror to the beam splitter. Equaling reference distance with measurement distance gives rise to strong interference effects, which in turn allow the surface relief measurement with submicron accuracy. This coherence radar technology had been demonstrated for centimeter sized objects, however, measuring objects from the automotive sector or turbine blades was out of reach up to now. The biggest obstacle was low light intensity, as the laser beam had to be expanded to decimeters in diameter.

The compact white light laser source with multi-Watt output power would be able to circumvent this problem. Record object diameters with submicron resolution were achieved. **(07)** shows an engine block which was measured using this method in a single scan.

7. Conclusion

Compact and reliable white light lasers have become available over the last few years, using diode pumped solid state laser technology in combination with tapered fibers. We have constructed such relatively inexpensive systems and demonstrated a variety of applications, ranging from biology (microscopy, laser cell cutting) to surface metrology (optical coherence radar). In the future, such sources will certainly gain spectral width, become more compact and even cheaper, and will find their way into a plethora of scientific and industrial implementations. •

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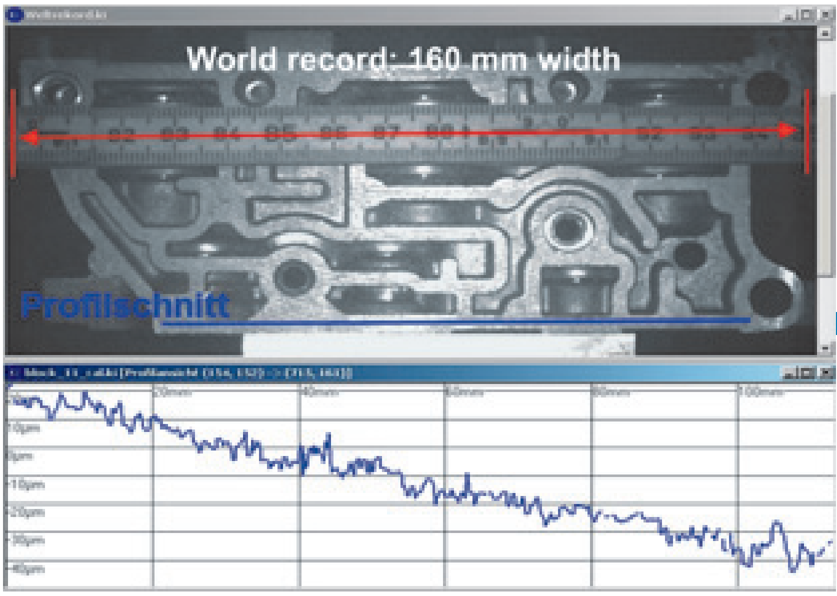

07

Three-dimensional coherence radar measurement of an engine. We used a white light fiber with 2.5 µm diameter and an output power of 375 mW. The width of the engine is 13 cm. The image is a result of a collaboration with Prof. Dr. Gerd Häusler of the University Erlangen-Nürnberg.

THE AUTHORS

Harald Giessen

got his Physics Diploma in Technical Physics from Kaiserslautern University (1992), working on optical properties of II–VI semiconductors. He was a J.W. Fulbright scholar at the Optical Sciences Center of the University of Arizona and obtained his M.S. and Ph.D. degrees in Optical Sciences in 1994 and 1995, respectively, working on ultrafast optical properties of semiconductor quantum dots. He was a post-doc at the Max-Planck-Institute for Solid State Physics in Stuttgart in 1995 and 1996, discovering coherent Rabi flopping in semiconductors. From 1997 to 2000, he held a C1 position at the University of Marburg, working on submicron spatial optical resolution and ultrafast photoionization dynamics of noble gases. In 2001, he became a C3 professor at the University of Bonn, focusing on ultrafast white light lasers and plasmonics. Since 2004, he has been head of the 4. Physikalisches Institut at the Universität Stuttgart, concentrating research on metallic optical metamaterials and applications of compact white light lasers.

Felix Hoos

is a Ph.D. student, building compact ultrafast diode-pumped solid state laser systems. He got his Diploma in Electrical Engineering from the University of Karlsruhe in 2004, utilizing white light from tapered fibers in ultrafast pump-probe spectroscopy.

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is a Ph.D. student, working towards his degree investigating applications of compact white light lasers. He got his Physics Diploma in 2002 from the University of Bonn, working on tapered fibers and their optical properties.

Jörn Teipel *(left) and* Felix Hoos *(right) at Hannover Messe 2005, presenting the compact white light laser.*

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