Three-dimensional laser lithography

A new degree of freedom for science and industry

In the last decades micro- and nanotechnology have made enormous progress. One of the key success factors is the continuous improvement of lithographic techniques which are the driving forces of innovation in many industrial areas. So far, lithography on the sub-micrometer scale has mostly been limited to planar objects. Trends towards further miniaturization and high-density integration call for disruptive developments of production standards. The next logical step is to go from planar two-dimensional lithography to the third dimension.

THE AUTHORS

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Dr. Michael Thiel studied physics in Karlsruhe where he also started his doctoral thesis. At the Institute of Applied Physics he investigated artificial 3D chiral photonic crystals fabricated by 3D laser lithography. He finished his thesis in 2010 in the group of Martin Wegener. Michael Thiel is a co-founder of Nanoscribe GmbH developing advanced DLW technology for science and industry.

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Martin Hermatschweiler studied physics in Ulm and Karlsruhe where he worked as a scientist at the Institute of Applied Physics investigating 3D photonic crystals fabricated by 3D laser lithography. His main assignment was the conversion of 3D polymer structures into silica and silicon under supervision of Martin Wegener. Martin Hermatschweiler leads the company as CEO since the initialization of the business idea in 2007.

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Three-dimensional (3D) direct laser writing (DLW) has the potential to be an additional key driver in laser lithography. DLW can be considered as 3D analogue of planar electron-beam lithography allowing for the fabrication of arbitrary 3D micro- and nanostructures with feature sizes on the order of 100 nm. Computer-aided exposure of a multitude of available photoresists and established 3D casting techniques turn DLW to a powerful platform for a large variety of applications in life sciences, (opto-)electronics, or photonics. Nanoscribe's "Photonic Professional" DLW systems are successfully in use in research labs in Europe, Asia, and North America. Industrial products are expected to be established via this innovation-enabling technique in the near future.

Principle of direct laser writing

Have you ever used a lens to focus sunlight onto a sheet of paper in your childhood? On a sunny day, the intensity in the focus is high enough to ignite the paper. Obviously, this is not the most virtuous form of using light in order to modify matter.

However, modern state-of-the art DLW systems operate quite similarly: Instead of sunlight, a near-infrared laser is focused. Instead of paper, a UV-curable photoresist is used – transparent at the wavelength of the laser, i.e., one-photon absorption does not allow for exposure. Due to very high intensities in the laser focus, though, the probability of a non-linear optical process called two-photon absorption is increased. This process is supported by femtosecond laser pulses with very high peak intensities (see laser textbox) and leads to a spatially confined absorption volume in the laser focus, hence triggering photopolymerization of a volume pixel ("voxel") of typically ellipsoidal shape (Figure 1). This voxel is scalable in size depending on the irradiated laser intensity and focusing optics and allows for features sizes down to 100 nm, i.e., much smaller than the irradiated wavelength of light. Absorption and eventually a post-exposure thermal treatment trigger a chemical crosslinking: Sufficiently crosslinked parts render insoluble in a subsequent developer bath whereas insufficiently or non exposed parts of the photoresist volume will be washed away in the developer bath. Therefore, the 3D exposed volume is revealed as a free-standing three-dimensional structure.

Computer-aided manufacturing

A photograph of the DLW system "Photonic Professional" allowing for computer-controlled exposure of UV-curable photoresists is shown in Figure 2. The user-friendly, intuitive software NanoWrite allows easy realization of structure designs which may be created as simple as with computer aided design (CAD) software. NanoWrite supports both the common STL and DXF data format. The DLW-system related native programming language GWL additionally provides access to all relevant writing parameters, giving total control of operation while keeping the language simple.

Once the data is loaded, a piezoelectric scanning stage continuously moves the chosen substrate relative to the kept-fixed focus generated by a high-NA objective lens. The mechanical movement is fully automated and synchronized with the laser source. Like a pen guided in three dimen-

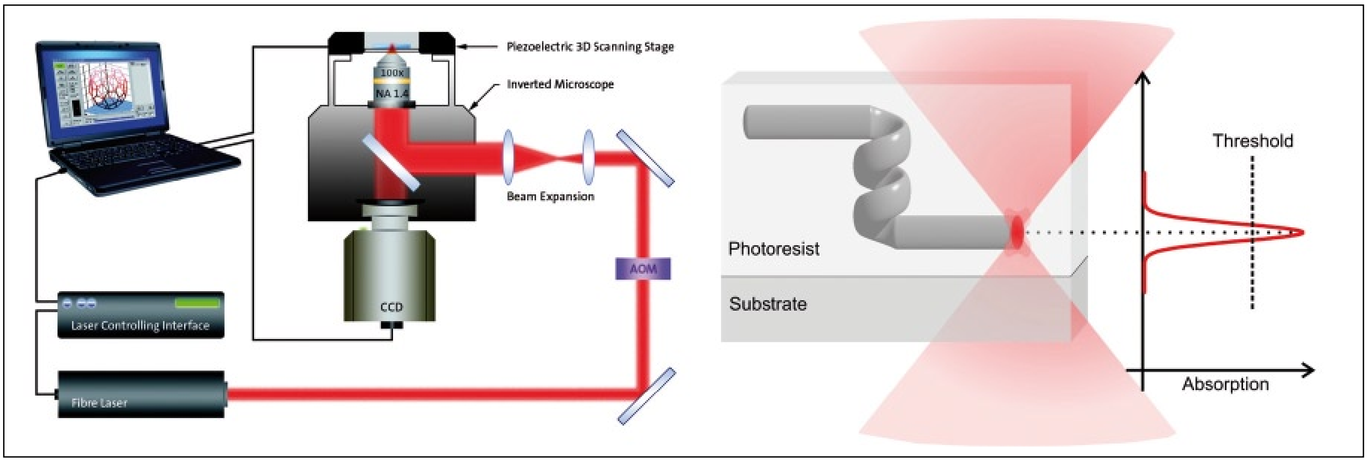

FIG. 1: **Left: Scheme of the DLW system "Photonic Professional". A pulsed near-infrared laser (see laser text box) is guided into an inverted microscope and tightly focused into a UV-sensitive photoresist. A piezoelectric stage moves the substrate relative to the kept-fixed focus in all three spatial dimensions. The DLW works computer-controlled and fully automated.**
Right: The resist shows high optical transparency at the laser center wavelength at 780 nm. Precisely in the focal volume, the photoresist is exposed by two-photon absorption when exceeding the polymerization threshold of the material. Scanning the sample relative to the focus enables the polymerization along arbitrary trajectories in 3D.

sions, micro- and nanostructures can now be "written" in 3D. Up to 300 µm x 300 µm x 300 µm volumes can be structured very precisely with the piezo in one step. Additional mechanical stages allow for large-area and vertical stitching of the piezo volumes. Glass slides, printed circuit boads, or silicon wafers may serve as substrates. Unconventional substrates like microfluidic channels and others have been evaluated.

A miniaturized Eiffel tower at a scale of 1:3,400,000 is shown in Figure 2 as an example. The freestanding object is manufactured in the resist IP-G on a glass substrate. All fine features of the CAD file have been translated into the polymer.

Photoresists and Casting

Many UV-curable photoresists have been successfully applied for 3D microfabrication. Among them, there are well-known resists like SU-8, ORMOCERE®, IP or AZ. Negative as well as positive tone resists can be used that distinguish as follows: When writing into a negative tone resist, the laser focus acts like a pen. Free-standing structures result. In a positive tone resist, the laser focus acts like an "eraser", breaking up chemical bonds allowing the solvent to "dig" into the resist along previously exposed volumes. After development in a solvent bath, 3D tubes, tunnels or moulds are formed.

Additionally to the broad spectrum of photoresists, researchers worldwide have developed molding and casting techniques for replication into other materials of interest. Several routes have been developed for the transfer into oxides, semiconductors and metals employing, e.g., atomic layer deposition (ALD), chemical vapor deposition (CVD) or galvanization known from the LIGA process (a German acronym for Lithography, Galvanization and Abformung (molding)). A very attractive possibility for industrial applications is the ability to fabricate closed surfaces that can be used as molds for repetitive replication by imprinting, hot embossing, injection molding and other techniques. By this, masters of complex shapes can be designed and replicated for inexpensive mass production.

Overview of applications

Flexible structuring on the sub-micrometer scale in all three dimensions enables novel applications in a variety of research fields. An overview is shown in Figure 3. In nanophotonics, periodic nanostructures like photonic crystals and metamaterials control the "flow of light". For photonic crystals, the importance of the third dimension was clear from the beginning. The younger field of metamaterials has just started to explore novel possibilities of 3D architectures

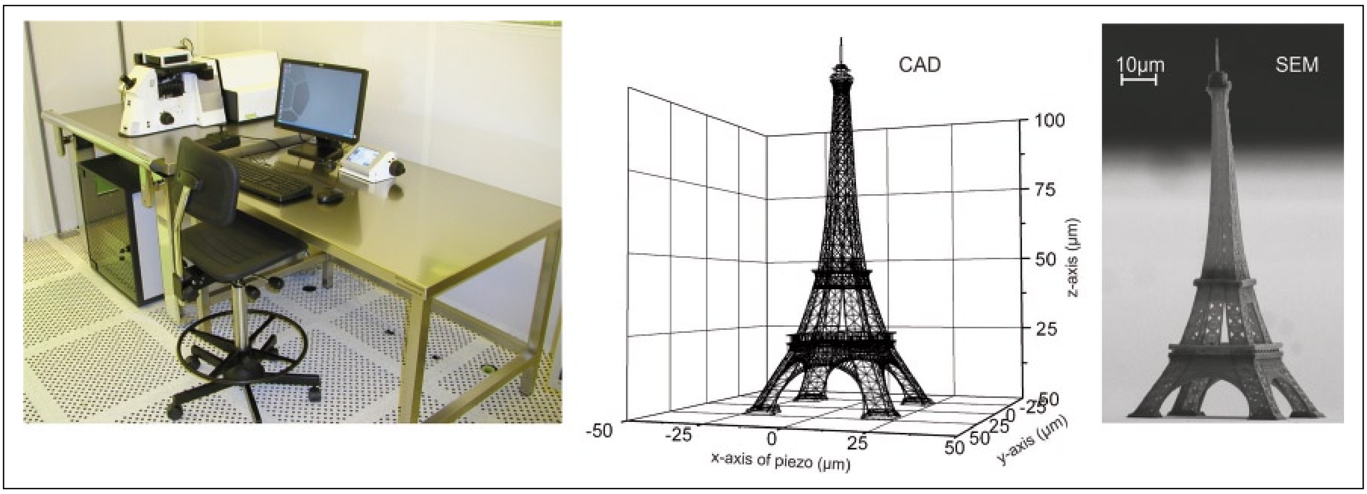

FIG. 2: **Left: Photograph of an installed DLW system "Photonic Professional" in a clean room environment. Right: Computer-aided design (CAD) versus scanning electron micrograph (SEM) of fabricated miniaturized Eiffel tower (scale of 1:3,400,000).**

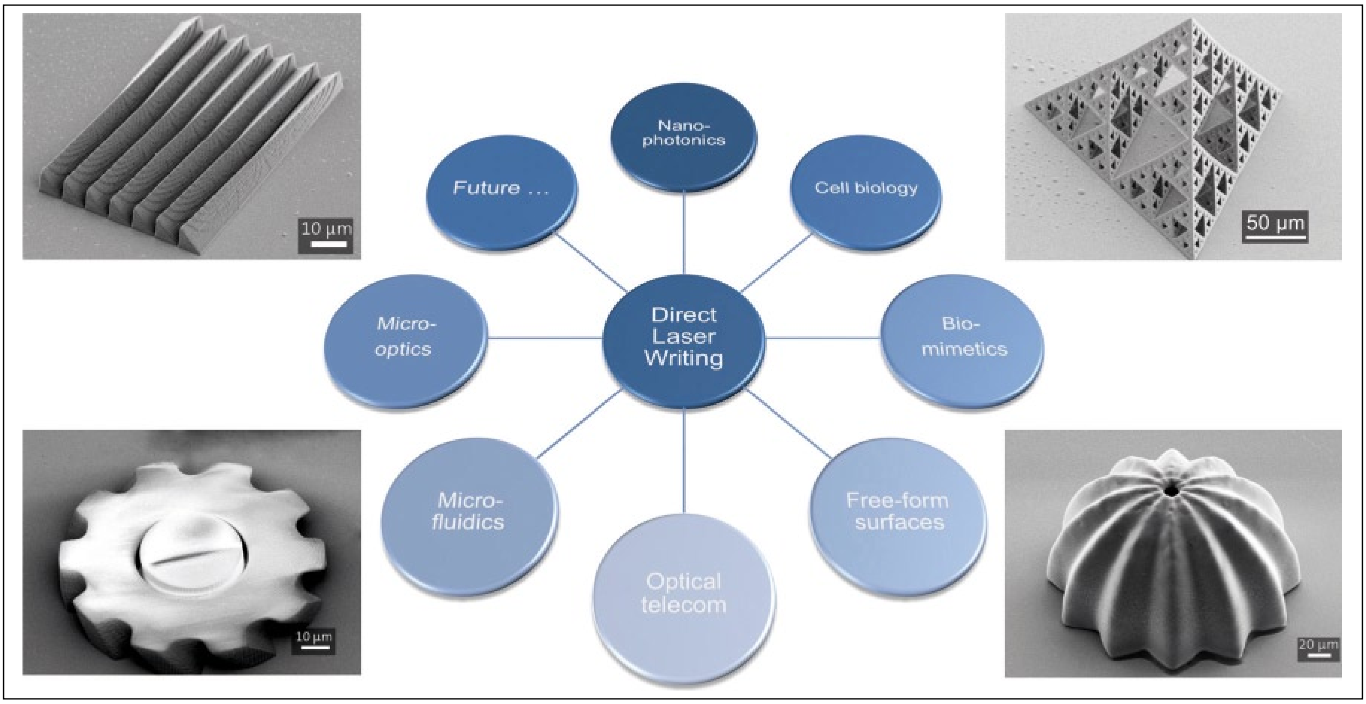

FIG. 3: **Overview of applications for 3D laser lithography and gallery of electron micrographs.**

(see next section). Other applications in optics and photonics are, e.g., distributed feedback lasers, photonic sensors, optical interconnects, diffractive/refractive optics, or mask manufacturing.

In life sciences, cell studies have long been restricted to 2D templates. Two-photon absorption allows for fabricating true 3D extra-cellular matrices for stem-cell differentiation, cell-growth and cell migration studies. Moreover, biomimetics studies of, e.g., the Gecko or Lotus effect need the ability to structure hierarchically in the third dimension.

Microfluidic devices control confined fluids on sub-millimeter scale and enable flow control with integrated pumps, valves, or sensors. Recently, high-density implementation of several functions in a lab-on-a-chip received considerable interest. DLW can provide patterning of ring resonator lasers or tailored 3D environments with sub-micron resolution acting as filters, mixers or sensor elements on commercial glass chips.

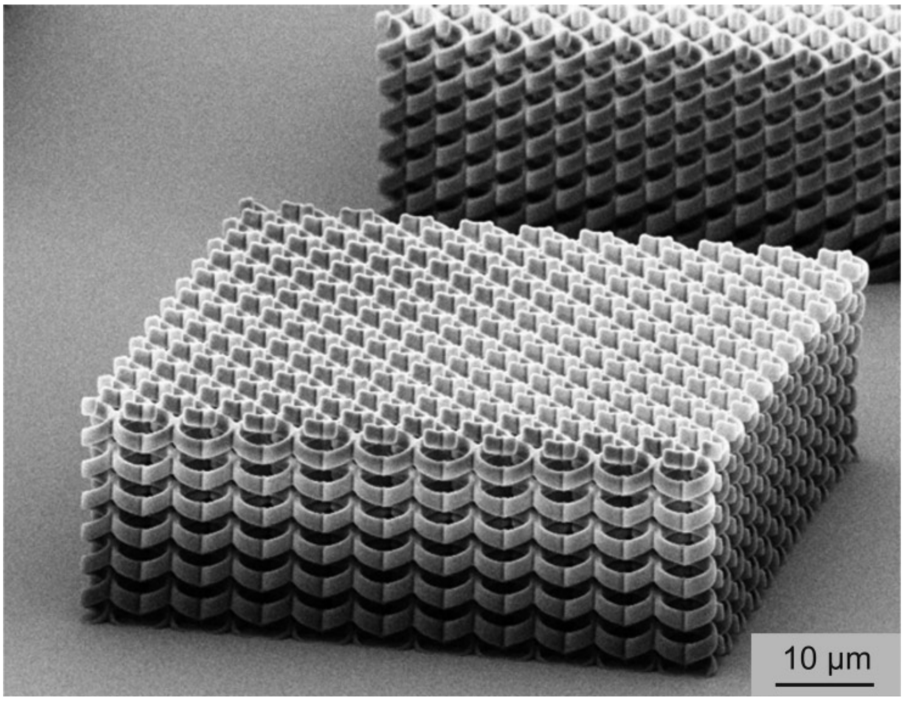

FIG. 4: **Artificial chiral structures as examples for photonic applications. The phases of the helices can be changed freely allowing the investigation of polarizing properties of these functional nanostructures.**

3D nanostructures for photonic applications: Photonic crystals and metamaterials

Laser lithography implies the manipulation of matter with light. Reversing the situation, the manipulation of light with matter has been investigated by many research groups all over the world. A multitude of successful examples of how to control light-matter interaction by using man-made nanostructures has been published. Laser lithography offers an additional degree of freedom in order to take advantage of novel opportunities to control light by means of 3D nanostructures for photonics.

Photonic crystals and photonic metamaterials are prominent examples for such man-made optical materials. They are (in most cases periodic) arrays of materials with different refractive indices. Lattice constants of these arrays are on the order of the wavelength of the interacting light in case of photonic crystals, as for metamaterials, the individual building blocks are less than a wavelength away from each other. For visible light, for example, the lattice constant does not exceed a few hundred nanometers explaining the high demands on fabrication techniques.

Chiral structures are a specific example of a distinct subgroup of 3D structures having a long history in optics and photonics starting with Louis Pasteur's ground-break-

INFO

Compact ultra-fast laser source

TOPTICA Photonics' frequency doubled Er-doped fiber lasers are optimized for 3D laser lithography. The heart of each FemtoFiber laser is an oscillator with SESAM technology for self-starting and reliable mode-locking. The femtosecond laser pulses are then amplified to high peak powers in a subsequent amplifier. This all-fiber configuration is manufactured with only polarization maintaining fibers, which guarantee environmental ruggedness. The DLW system "Photonic Professional" benefits from the outstanding high peak powers at the frequency doubled wavelength of 780 nm. In addition, TOPTICA's FemtoFiber lasers are compact, reliable and robust. Therefore, industrial 3D laser lithography profits significantly from these top performing and turn-key fiber lasers.

ing experiments in the 19th century. Objects are chiral if the mirror image cannot be superimposed with the original. This definition also implies that chiral structures are 3D. Knowing the importance of the handedness of the structure on the photonic properties, the computer-aided approach of DLW is the method of choice for the deterministic fabrication of artificial chiral material. Producing a twist on micron scale requires ultra-high structuring precision for all spatial coordinates: DLW meets these challenges.

Figure 4 shows an electron micrograph of a fabricated chiral photonic crystal. The helical building blocks of the structure have a diameter of about 3 µm and have been arranged in different configurations in order to investigate the underlying physics [1]. Besides the interesting physics, well-chosen parameters and materials allow for tunable broadband circular polarizers [2] – a true real-world application that can be fabricated using DLW.

Outlook

3D laser lithography is an innovation-enabling technology and already a standard for microfabrication in many research labs over the world. To date, there is no other 3D fabrication technique showing this impressive versatility on micro- and nanoscale. Numerous applications have been developed that may enter the industrial sector very soon. Giving the additional degree of freedom for science and industry, 3D laser lithography will have a bright future.

Thanks

Many scientists worldwide work in the field of 3D DLW. It is beyond the scope of this article to review all contributions and advances made by the scientific community. Dr. Thomas Hellerer, Senior Sales Manager of Toptica Photonics AG, has kindly provided the details of the FemtoFiber laser series of Toptica. The authors would like to express their gratitude to the group of Prof. Dr. Martin Wegener at the Karlsruhe Institute of Technology (KIT), the Center of Functional Nanostructures, and the Institute of Nanotechnology in Karlsruhe. We thank Anke Werner who organized the preparation of this article.

THE COMPANY

Nanoscribe GmbH, Germany

Nanoscribe is a spin-off company of the Karlsruhe Institute of Technology (KIT), founded in 2007, meanwhile being world market and technology leader in three-dimensional laser lithography. The Carl Zeiss invested company has been proposed for the highest ranked German innovation award "Deutscher Zukunftspreis" both in 2010 and 2011. Based on more than 10 years of experience in three-dimensional micro- and nanolithography, DLW systems of Nanoscribe enable the realization of nano- and microstructures for research and application. Nanoscribe's state-of-the-art 3D laser lithography systems are currently in use in many research institutes throughout Europe, the USA, China and Japan.

www.nanoscribe.de

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Exhibitions

Photonics West 2012,
San Francisco, USA
24–26 January 2012
Nanoscribe GmbH, Booth #4220
Toptica Photonics, Inc., Booth # 717