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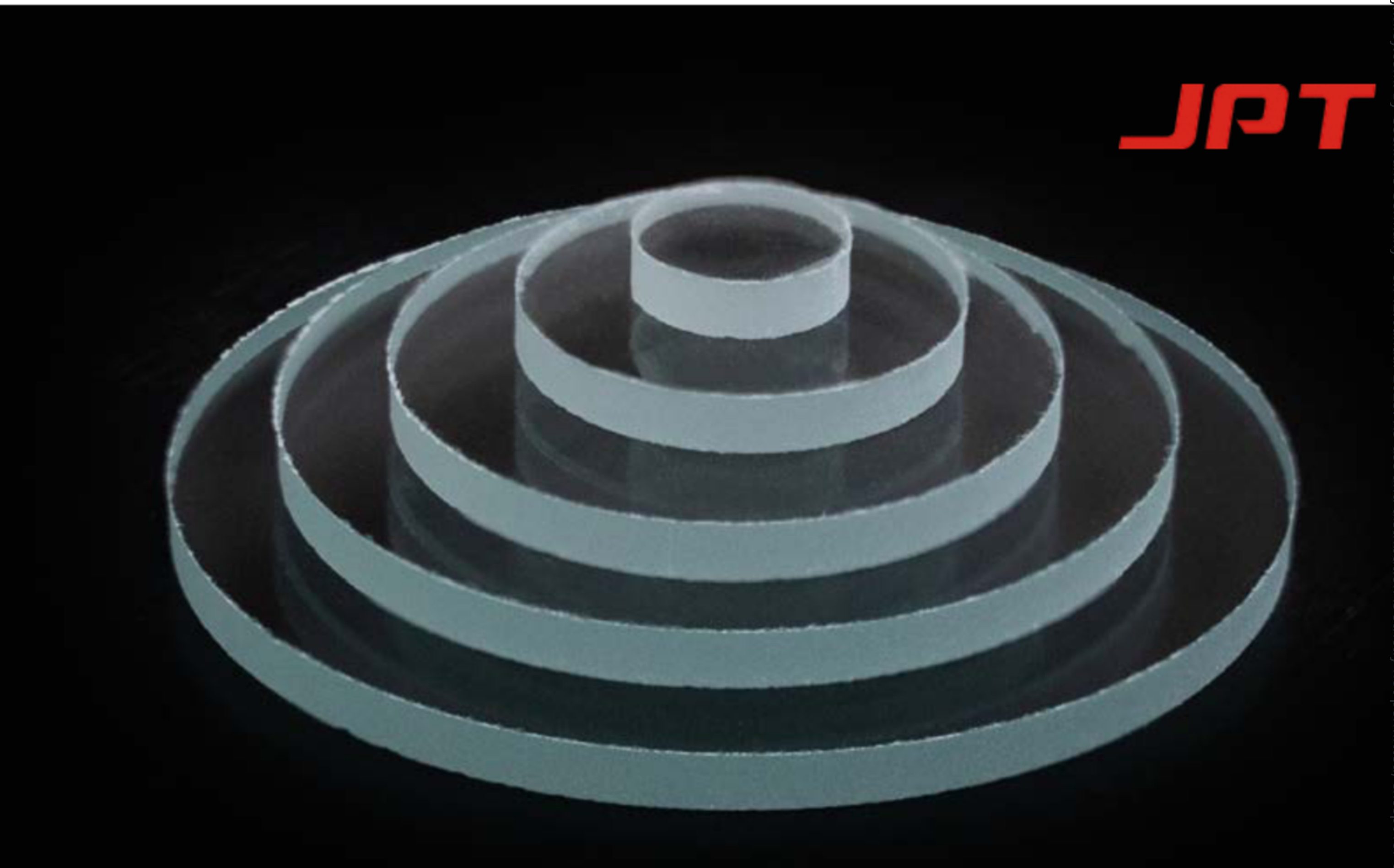

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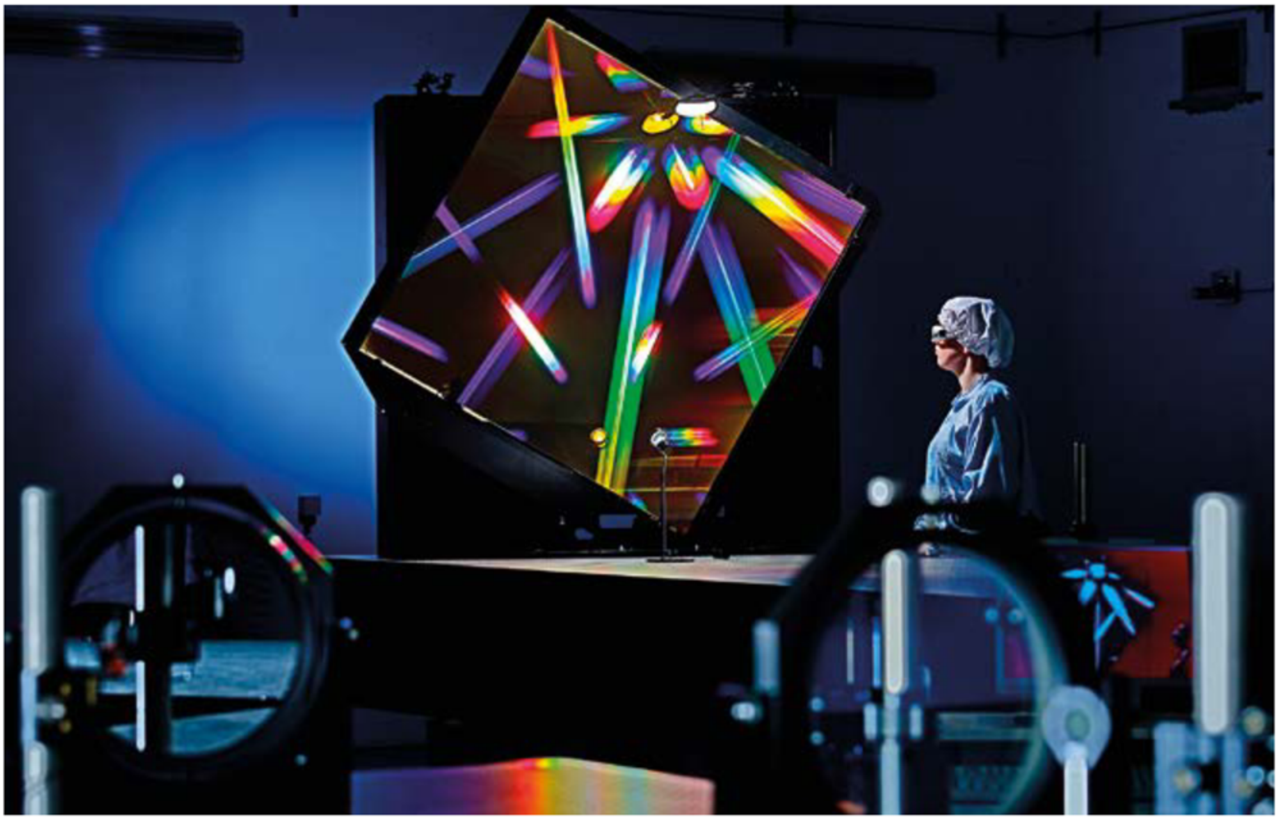
Resource-efficient generation of large-area micro and nanostructures

High-quality, large area diffraction gratings originated by diode laser-driven interference lithography

Benedikt Bläsi, Martina Müller, and Harald Rossmeier



Lasers are widely used in various manufacturing processes. In order to achieve sustainable production, it is important to reduce the environmental impact caused by the laser operation. One major improvement is the step from gas lasers to diode lasers.

▲ The large-scale interference lithography setup at the Fraunhofer Institute for Solar Energy Systems ISE (Source: Fh. ISE)

Replacing gas with diode lasers reduces the energy consumption of the light source by up to a factor of 1,000. Gas lasers usually also require substantial cooling, either wasting thousands of liters of water every operating day or increasing energy consumption when a closed cooling circuit is used. This article addresses large scale interference lithography as an important application, where gas lasers were the light source of choice until the arrival of solid-state lasers and novel diode laser solutions in recent years.

In interference lithography, high-end lasers are used to originate micro and nanostructures on areas up to the square meter scale [1, 4]. Large area gratings or engineered diffusers can be used in displays, LED lighting or in solar cells [2]. Lasers emitting at wavelengths <445 nm with extreme requirements of stability, beam profile, coherence and output power are needed for large area interference lithography.

For 3D AG, a tooling and industrial manufacturing company specialized in processing nano and microstructures, large area originations are needed to obtain seamless surface areas – both for research and for industrial clients. The laser used in the lithography setup is one of the core elements to produce high quality structures. The template originated by interference lithography in glass is later replicated by 3D AG using

Fig. 1 Toptica's TA-SHG pro system comprises a high-power, tunable, frequency-doubled diode laser, a high power semiconductor (TA) and an integrated frequency doubling stage (SHG pro) with digital control DLC pro (right). (Source: Toptica)

electroforming processes, and the nickel replicas serve as templates for industrial manufacturing processes. This first glass master is crucial for the high fidelity and functionality of the structure in subsequent steps and final products.

Experimental setup – interference lithography

Interference lithography is based on the superposition of two or more coherent waves on a photoresist-coated sample. Typically, a laser beam is split, expanded, spatially filtered and then superimposed on the sample. Therefore no mask is required and the achievable exposed size only depends on the beam diameter as long as the exposure stability can be maintained. In a subsequent wet chemical development step, the pattern recorded in the photoresist is transformed into a surface relief structure.

At Fraunhofer ISE, an L-shaped optical table with 10 and 12 m length enables beam expansion up to very large areas (up to 1.2 × 1.2 m). For such large area processes, the exposure times can reach up to five hours. The phase between the interfering waves needs to be kept stable during this time, which implies extremely high thermal and mechanical stability of the setup as well as high laser coherence and stability. As an example, vibration amplitudes or position changes of more than 20 nm over the exposure time would be detrimental [6]. In this work, we evaluated a Toptica DLC TA-SHG pro emitting at 390 nm with a single frequency output power of 1 W. No water cooling is required due to its high energy efficiency. This not only makes installation and operation easier, but also contributes to the overall stability. Large area structures for various applications such as diffraction gratings, solar cells and LEDs could be successfully originated using this laser system.

Versatile functionalities of structured large area surfaces

Large-area and seamless micro and nanostructures are needed for a wide range of applications. In display technology they can be used as diffusers or antiglare surfaces, as grating couplers or to polarize light. In lighting technology, surface structures lead to enhanced LED outcoupling or light steering. In the highest efficiency solar cells, gratings-based light trapping makes optimum use of the solar radiation.

If seamless and homogeneous large-area structures are needed in the product, the mastering technology must fulfil these requirements. High-end mastering technologies, such as electron beam lithography or extreme ultraviolet (EUV) lithography, are extremely expensive and not feasible for large areas. Interference lithography is very well suited for such requirements.

Companies

3D AG

3D AG is an independent full service company based in Switzerland with thirty years of experience in micro and nanotechnology. From designing banknote security features to the creation of tools for display manufacturing, 3D AG explored and acquired a wide knowledge in the processing of structures for various functionalities. 3D AG focuses on manufacturing durable molds by electroforming and has developed various in-house processes, such as a high precision step-and-repeat UV imprint technology. The 3D AG expertise is customized to upscale micro and nanostructures from the laboratory to industrial manufacturing.

https://3dag.ch

Toptica Photonics

Toptica has been developing and manufacturing high-end laser systems for scientific and industrial applications for more than twenty years. The portfolio includes diode lasers, ultrafast fiber lasers, terahertz systems and optical frequency combs. Toptica today has 450 employees in six commercial entities with a consolidated group revenue of 100 million euros (about $107M).

www.toptica.com

Institute

Fraunhofer Institute for Solar Energy Systems ISE

Fraunhofer ISE in Freiburg, Germany, is the largest solar energy research institute in Europe. The institute is committed to promoting sustainable, economic, safe, and socially just energy supply systems based on renewable energies. Its research provides the technological foundations to supply energy efficiently and on an environmentally sound basis in industrialized, threshold and developing countries. Focusing on energy efficiency, energy conversion, energy distribution and energy storage, the Institute develops materials, components, systems and processes.

www.ise.fraunhofer.de

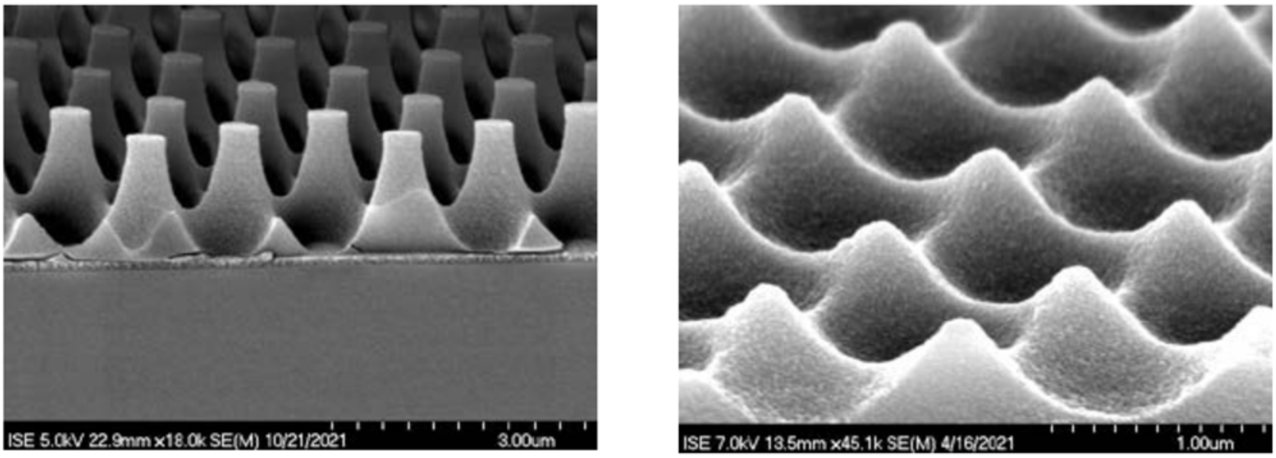


Fig. 2 Examples of large area structures fabricated during the evaluation. The left SEM image shows a diffraction grating designed to cause a very bright color appearance. The hexagonal grating in the right image is designed to trap light in triple-junction solar cells with efficiencies >35 %. (Source: Fh. ISE)

Microreplication techniques are typically used to integrate such functional structures into products. The basic idea is that firstly a master structure is researched and designed to then be originated – the origination being the initial and most important step to guarantee proper industrial replication in further processes. The quality and fidelity of the structure is crucial for a successful application. Clean room facilities are an elementary environment for a high performance laser interference setup, as provided by ISE using the Toptica DLC TA-SHG pro for the engineering of the experimental setup described here. A master origination not only needs true structure fidelity, but a defect-free surface because defects can hinder functionality or visually disturb the surface area.

3D AG has specialized in the later replication of masters to obtain high fidelity copies (nickel shims) of the master structure by electroforming. To make the glass surface conductive, a gold layer is sputtered onto the glass master at the ISE facilities. Electroforming nickel shims from such sputtered masters maintains the origination effort through the creation of a nickel shim family with multiple generations. The first copy is an Au-Ni alloy with a thickness of 300 µm ± 10 µm. This rigid tool, a precise replica of the glass master, serves as a template for multiple generations. Defect inspection can only be conducted in the reflective view of the sputtered surface or in the first Au-Ni master. As the process is very delicate and sensitive, the exposure is repeated multiple times. The best result is chosen to produce multiple pure nickel shims as tools for industrial replication of the structure.

One of these nickel tools is used as a stamper for further processes such as nanoimprint lithography for the industrial replication of the structure in other materials. Other industrial processes are roll-to-roll (R2R) or roll-to-plate (R2P) applications. Shims of various thicknesses can be made, mostly of 80 µm – 200 µm, depending on the chosen application. In many cases, the nickel templates can also be welded to sleeves to better facilitate high volume production.

Conclusion

The solid-state laser at 390 nm has proven to be a reliable modern tool to substitute legacy gas laser systems. Homogeneous high-quality structures can be originated seamlessly by interference lithography on large areas. Solid-state laser technology is therefore well suited for this type of high-end lithography process, paving the way to innovative products in display technology, lighting, or solar energy conversion.

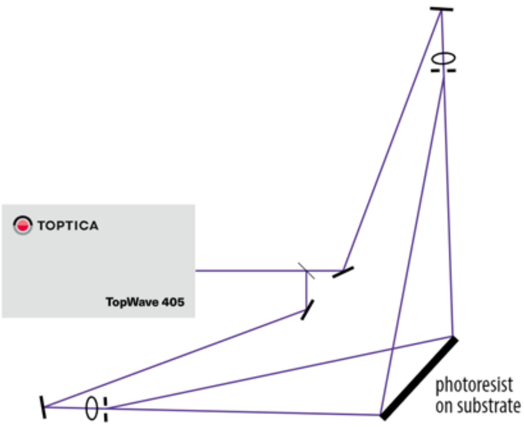


Fig. 3 Sketch of a large area interference lithography set-up (Source: Toptica)

relevant wavelength range	257 – 445 nm
wavelength stability	unlocked: typ. <5 pm drift in 8 hours locked: <0.003 pm drift in 8 hours (depending on reference)
coherence lengths	>>100 m
spatial mode, beam quality	TEM_{00} $M^2 \leq 1.2$
optical output power	0.5 – 3 W (depending on wavelength)
energy consumption	typ. <100 W

Table Characteristics of the laser system as discussed in the text

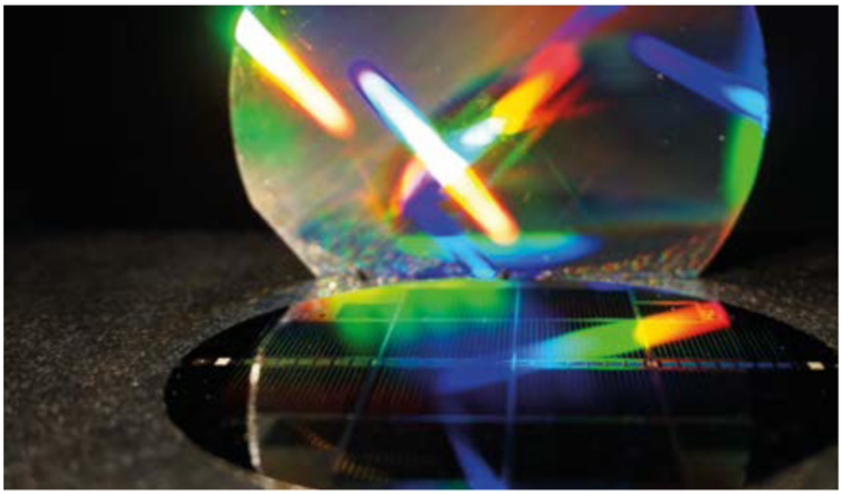


Fig. 4 Interference lithography-based diffraction gratings enable multijunction solar cells to achieve the highest efficiencies [5]. (Source: Fh. ISE)

The flexibility of modern solid-state lasers is seen as a plus for interference lithography as it opens up the accessibility of a great choice of wavelengths (VIS to DUV) and output power levels (see Table).

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Authors

Benedikt Bläsi received his MSc from University of Durham (UK) in 1995 and his PhD from Freiburg University (Germany) in 2000, for his work on interference lithography for optically-functional nanostructures. He is co-founder of Holotools GmbH (since 2014 part of Temicon). In 2004 he was a visiting fellow at University of Technology Sydney, Australia. Since 2005 he is head of the group 'cleanroom and microtechnology' at Fraunhofer ISE. Since 2019 he serves as an associate editor for the journal Optics Express. His main research focus is on photon management for photovoltaic systems, displays and lighting applications.

Martina Müller is owner and CEO of 3D AG, a 3rd generation family business specialized in optical and functional nanostructures, the development of high security features for banknotes, for product and brand protection, as well as the production of new products with optical elements, such as displays, smart glasses or biomimetics. Martina's educational background in chemistry, art and business enables interdisciplinary creativity, inspired by research and experienced in logical evaluation and strategy.

Harald Rossmeier began his career at Toptica in 1999 after graduating with an engineering degree in physics from the University of Applied Sciences in Munich. He played a leading role in the development of industrial OEM diode laser systems and later took over the role of product manager for this segment. In 2011, he moved to the US to drive the application and business development in Biophotonics and Semicon for Toptica. Since his return in 2014, he resumed the position of product manager OEM diode lasers, focusing on providing high-end solutions for industrial lithography and holography applications.

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