Q 9: Photonics (3D Print) (joint session Q/K)

Time: Monday 17:00–19:00 Location: HS V

Q 9.1 Mon 17:00 HS V

Lateral Shear Interferometry for Wavefront Measurements of 3D-Printed Micro-Optics — •Yanqiu Zhao, Lunwei Wang, Jan-Niklas Bauer, Leander Siegle, Julian Schwab, Florian Mangold, and Harald Giessen — 4th Physics Institute and Stuttgart Research Center of Photonic Engineering, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

3D-printed micro-optics offer distinct advantages in terms of precision and compact size, enabling them to navigate narrow human tissues, including arteries, to capture clear images of their surroundings. This capability necessitates a meticulous quality control process, not only of the lens shapes, but also of the propagating wavefronts.

Thus, we carry out such measurements on 3D-printed micro-optics to assess their quality comprehensively. Wavefront measurements provide a more holistic evaluation of the micro-optics performance when compared to conventional shape measurements. The micro-optics used in our study are fabricated using a Nanoscribe Quantum X and are printed directly on substrates or on optical fibers, also comparing simple 2-photon printing with 2-photon gray scale lithography.

We demonstrate consistent and precise wavefront measurements using a simple shear plate interferometer setup. Unlike direct wavefront measurements, shear interferograms reveal the spatial wavefront derivative. By analyzing the interferogram fringes, we extract wavefront information that can be fed back into the design process within an iterative loop. This process supports quality improvement for 3D-printed micro-optics.

Q 9.2 Mon 17:15 HS V

Complex light fields produced by 3D-printed computer-generated hologram on fiber — •Zihao Zhang[1], Leander Siegle[1], Pavel Ruchka[1], Daniel Flamm[2], and Harald Giessen[1] — [1]4th Physics Institute and Research Center SCoPE, University of Stuttgart, Germany — [2]TRUMPF Laser- und Systemtechnik GmbH, Ditzingen, Germany

Non-Gaussian beams are pivotal in numerous scientific and industrial applications, including multi-atom trapping and laser-based material processing. Holographic optical elements can be employed to generate beams with specific intensity distributions. For instance, multiple Gaussian foci can be precisely positioned within three-dimensional space for optical trapping, and the intensity distribution of a Gaussian beam can be modified into various forms for material processing. Despite their utility, many beam-shaping optics are often complex and bulky. Certain applications necessitate solutions that are not only compact and straightforward but also adaptable and capable of rapid adjustments. In this study, we leverage the state-of-the-art technology of two-photon grayscale polymerization (2GL) to create customizable and precise optical elements on a microscale. Here, we present a 3D-printed on-fiber beam shaper, whose design enables the efficient generation of a three-dimensional distribution of 30 foci along a trefoil optical knot using a highly flexible fiber device.

Q 9.3 Mon 17:30 HS V

Millimeter-sized 3D Printed Optics by Two-Photon Grayscale Lithography — •Leander Siegle and Harald Giessen — 4th Physics Institute, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

We demonstrate millimeter-sized optics for focusing and imaging applications fabricated by two-photon grayscale lithography (2GL). Typical sizes of 2GL 3D printed lenses have previously been limited to the sub-millimeter range. Using low-magnification objectives in combination with high photo-initiator density resists, we fabricate aspherical lenses with diameters of 1 to 5 mm. Compared to the typical two-photon polymerization fabrication process, 2GL offers better shape accuracy, while simultaneously increasing throughput. To showcase 2GL fabricated millimeter-sized lenses, we design, 3D print, and optimize high-numerical aperture singlet lenses for focusing and imaging in the visible and near-infrared. We determine the shape accuracy and analyze the optical performance. Furthermore, we investigate a singlet lens for imaging and examine the high-resolution performance with a USAF 1951 resolution test chart. 2GL 3D printed lenses offer toolless rapid prototyping for custom optical solutions in the micron to millimeter range.

Q 9.4 Mon 17:45 HS V

Near-infrared Laser damage in 3D printed microoptics — •Sebastian Klein, Pavel Ruchka, Tobias Steinle, and Harald Giessen — 4th Physics Institute and Research Center SCoPE, University of Stuttgart, Germany

In recent years, two-photon-polymerization (2PP) 3D printing has seen a significant rise in importance in the field of microoptics, delivering high precision free-form optics with a low manufacturing cost compared to conventional fused silica microoptics. Applications range from biomedical imaging systems such as endoscopes, to employment in compact high-power fiber-based laser systems and material processing using diffractive optical elements for customized beam shaping. For the latter, high reliability and performance even under high power densities are essential.

In this work, we quantify femtosecond laser-induced damage in the 2PP photoresists IP-S and OrmoComp by microscope imaging cube samples irradiated with different wavelengths and fluences. By incorporating the more sensitive differential interference contrast (DIC) imaging technique, we determine damage thresholds of these photopolymers in the NIR spectral range. Furthermore, we introduce a novel approach for damage detection surpassing the sensitivity of DIC microscopy. With this approach, the damaging effects of telecom C-band radiation after multiple hour exposures are studied, giving a first look at the long-time high-power stability of the polymers.

Q 9.5 Mon 18:00 HS V

3D printed high NA micro-optics for quantum applications — •Pavel Ruchka[1], Sara Jakovljevic[1], Nam Tran[2], Carlos Jimenez[3], Simone Luca Portalupi[2], Michael Jetter[2], Alois Herkommer[3], Stephan Reitzenstein[4], Sven Höfling[5], Caspar Hopfmann[6], Peter Michler[2], and Harald Giessen[1] — [1]4th Physics Institute and Research Center SCoPE, University of Stuttgart — [2]Institut für Halbleiteroptik und Funktionelle Grenzflächen and Research Center SCoPE, University of Stuttgart — [3]Institute for Applied Optics and Research Center SCoPE, University of Stuttgart — [4]Institute of Solid State Physics, Technische Universität Berlin — [5]Technische Physik, University of Würzburg — [6]Deutsche Telekom Chair of Communication Networks, TU Dresden

3D-printed micro-optics made with two-photon polymerization have revolutionized fields like imaging, sensing, and illumination. This method allows the creation of complex miniature freeform shapes for mechanical and optical uses with high precision, opening up new possibilities for advanced technology. In this work, we present a novel approach to 3D-printed high numerical aperture (NA) micro-optics on optical fibers, targeting applications such as quantum communication and trapped-atom quantum computing. We fabricate shape-optimized refractive and diffractive lenses with NA values as high as 0.8 and characterize their performance through beam profiling. Additionally, we demonstrate the successful coupling of quantum dots at wavelengths of 780 nm and 1550 nm to corresponding single-mode fibers, enabled by these high-NA 3D-printed micro-optics.

Q 9.6 Mon 18:15 HS V

3D printed micro-sized dark-field condenser by two photon polymerization — •Robert Horvat[1], Leander Siegle[1], Pavel Ruchka[1], Michael Schmid[2], Lukas Weseman[3,4], and Harald Giessen[1] — [1]4th Physics Institute, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — [2]Printoptix GmbH, Nobelstraße 15, 70569 Stuttgart, Germany — [3]School of Physics, The University of Melbourne, Victoria 3010, — [4]ARC Centre of Excellence for Transformative Meta-Optical Systems, School of Physics, The University of Melbourne, Victoria 3010, Australia

We demonstrate a miniaturized fully 3D printed dark field condenser for microscopy applications. Dark field microscopy is a simple but effective technique for contrast enhancement that allows imaging of transparent samples, useful in bio-medicine. Usually, microscope setups are bulky and costly. Our approach miniaturizes the system to the micro- and millimeter size, while allowing rapid prototyping and quick adaptation for individual system integration. We realise this by using two photon polymerization to 3D print two photoresists on both sides of a microscope glass slide. We first fabricate an annular ring aperture from a highly absorptive photoresist on one side of the glass slide with diameters between 300 and 2000 micrometers. Next we print a high numerical aperture lens within the same diameter range on the other side of the glass slide. We use the 3D printed dark field condenser to illuminate different samples, such as a USAF 1951 resolution test chart, and compare its performance to the typical bright field illumination.

Q 9.7 Mon 18:30 HS V

Broadband Mode Division Multiplexing of OAM-Modes by a Micro Printed Waveguide Structure — •Julian Schulz[1] and Georg von Freymann[1,2] — [1]Physics Department and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, 67663 Kaiserslautern, Germany — [2]Fraunhofer Institute for Industrial Mathematics ITWM, 67663 Kaiserslautern, Germany

To utilize the orthogonal mode space of OAM-modes to increase the amount of information throughput for optical fibers, an efficient and compact device to create, superimpose and to decompose OAM-Modes is needed We present as a proof of principle a waveguide structure, which transformations the eigenmodes from spatially separated single mode waveguides adiabatically into modes of a ring waveguide carrying $|\mathrm{OAM}| \leq 2$. In an adiabatic evolution, the population of the eigenmodes remains constant while the eigenmodes change according to the system. Two mechanisms are utilized to maintain the propagation constants of each individual mode consistently spaced during the propagation thou the structure: Individual waveguides are detuned by changing their radius and an artificial magnetic field is introduced by twisting the structure. The inherent tolerance of an adiabatic evolution allows our device to operate effectively across a wide spectrum of wavelength. Besides that, it can also be used as a demultiplexing structure, if the adiabatic evolution is run backwards. We demonstrate the capabilities of the structure with BPM-simulations and experiments with a polymer waveguide structure fabricated via direct laser writing. [*Advanced Optical Materials* **12**, 2302597, (2024)]

Q 9.8 Mon 18:45 HS V

Fiber-based femtosecond 3D printing — •Anton Hellstern[1], Claudia Imiolczyk[1], Pavel Ruchka[1], Marco Wende[2], Theresa Kühn[3], Moritz Flöss[1], Michael Heymann[3], Andrea Toulouse[2], and Harald Giessen[1] — [1]4th Physics Institute, University of Stuttgart, Germany — [2]Institute of Applied Optics, University of Stuttgart, Germany — [3]Institute of Biomaterials and Biomolecular Systems, University of Stuttgart, Germany

Ultrashort laser pulses are often used in medical applications, for instance for soft-tissue surgeries. However, the progress on using such laser pulses for additive manufacturing of tissue is rather marginal so far. Therefore, we aim to realize an endoscopic fiber-based femtosecond 3D printer to minimally invasively surgically repair organ damage on a micrometer scale. For this, high peakpower femtosecond laser pulses are required, in order to 3D print the desired geometries using two-photon-lithography. By combining a grating compressor, a singlemode fiber, and suitable 3D printed microobjetives directly on the fiber tip, we achieve subpicosecond pulse durations which are able to polymerize both commercial photopolymers as well as bioinks. We report on dose tests, the optimization of printing speed, laser power, pulse compression ratio and pulse duration, as well as slicing and hatching variation. We demonstrate solid cubes as well as connected lines, leading to 3D woodpile structures that represent scaffolds which ultimatively could be colonized by living cells. This direct printing of cell scaffolds by endoscopic 3D printing should allow in the future for example printing of bone tissue inside the body.