HIGH-PRECISION GRAYSCALE LITHOGRAPHY FOR MICRO-OPTICS

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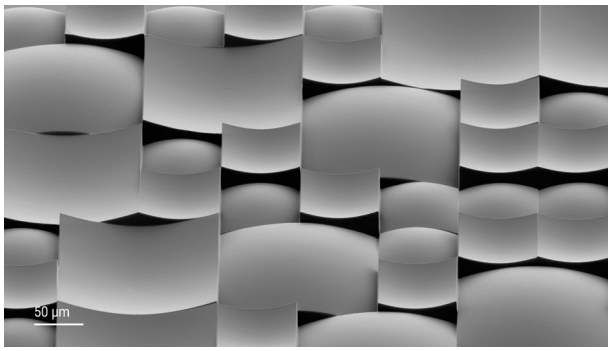


https://doi.org/10.1051/photon/202513476

Micro-optics are key components in a wide range of applications, including advanced imaging, sensing, and display systems. These applications require optical elements that combine a minimal form factor with outstanding optical performance. Two-Photon Grayscale Lithography, based on Two-Photon Polymerization, enables additive manufacturing of 2.5D microoptics with submicron resolution, high shape accuracy and broad design flexibility, making it a powerful technology for next-generation optical components.

Fast and versatile microfabrication technologies are driving the development of miniaturized optical elements that are essential to modern optical and photonic systems. Applications such as 3D sensing, display technologies, imaging systems, and AR/VR devices rely on optical components with increasingly smaller dimensions and ever-higher precision. As the trend toward miniaturization continues, the fabrication of microscopic optical structures presents growing challenges in nano- and microfabrication.

Two-Photon Grayscale Lithography (2GL®) addresses these challenges by enabling the rapid and precise fabrication of 2.5D micro-optical elements with freeform geometries, submicron resolution, and ultra-smooth surfaces. Based on Two-Photon Polymerization (2PP), 2GL combines the design freedom of additive manufacturing with the outstanding grayscale printing performance, known for its surface quality and shape accuracy required for advanced optics.

The Quantum X litho system implements this approach in a maskless lithography platform optimized for optics manufacturing. It enables the fabrication of refractive (figure 1), diffractive, and hybrid micro-optics with a shape accuracy of $S_a \leq 200$ nm (ISO 25178) and surface roughness below $R_a < 5$ nm. These characteristics make the system suitable for applications ranging from rapid prototyping and master template fabrication to wafer-level patterning for industrial manufacturing.

TWO-PHOTON POLYMERIZATION: PRINCIPLE AND APPLICATIONS

Two-Photon Polymerization (2PP) relies on the physical effect of two-photon absorption, where an atom or molecule absorbs two photons simultaneously to reach a higher energy state. Typically, this involves a photosensitive liquid resin that normally cures under UV light but is instead solidified by near-infrared (NIR) laser light when two photons are absorbed at once. This effect is confined to the laser's focal volume, where the light intensity is sufficiently high, enabling localized polymerization with submicron precision.

2PP is widely used for fabricating microoptics with high spatial resolution, optical-quality surfaces, and high shape accuracy. However, the printing process requires splitting of the structure design into numerous closely spaced layers to avoid staircasing effects and achieve smooth surfaces. As a result, fabricating micro-optical elements often implies long print times.

TWO-PHOTON GRAYSCALE LITHOGRAPHY: COMBINING PRECISION AND PRINT PERFORMANCE

Two-Photon Grayscale Lithography builds on the established principle of two-photon polymerization (2PP), extending it with dynamic voxel size control to significantly improve printing speed.

Unlike conventional layer-by-layer fabrication, 2GL continuously modulates the laser power during exposure to produce spatially varying voxel heights within a single scanning plane. A grayscale image serves as the input, translating into spatial variations in exposure dose. This allows 2.5D structures to be printed in one step, drastically reducing the number of layers and substantially shortening overall fabrication time by up to two orders of magnitude.

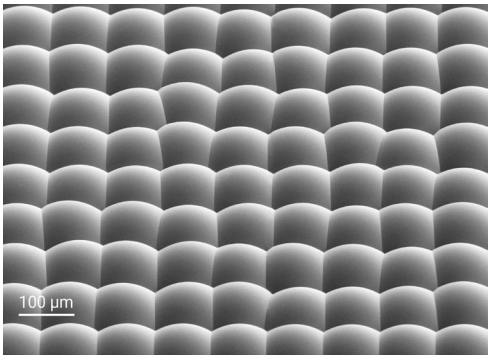


Figure 1: Densely packed microoptics in random microlens array for diffuser applications. The microlens array was fabricated by Two-Photon Grayscale Lithography and features a fill factor of 100%.

2GL offers broad design flexibility for freeform micro-optics, enabling the fabrication of complex refractive elements, sharp-edged geometries, and hybrid components that combine refractive and diffractive elements. The process produces smooth surfaces without slicing artifacts or voxel-induced distortions, making it well-suited for high-precision optical applications.

2GL provides a means to iterate and produce functional prototypes with optical-grade quality much faster than conventional Two-Photon Polymerization, and without the need for time-intensive mask fabrication. The combination of speed, submicron resolution, and design flexibility makes 2GL a practical approach for both rapid development and scalable manufacturing of advanced microoptical components. In addition, the ability to fabricate 2.5D nano- and microstructured patterns supports wafer-level production and the creation of master templates for subsequent ● ● ●

replication processes.

ALTERNATIVE MICROFABRICATION TECHNOLOGIES

Various microfabrication technologies are used to fabricate 2D and 2.5D micro-optical structures. This section presents an overview of lithography-based methods, both mask-based and maskless, and compares their capabilities and limitations with those of Two-Photon Grayscale Lithography.

2D UV LITHOGRAPHY

One-photon absorption underpins conventional photolithography, where light transfers geometric patterns from a photomask to a photosensitive material. In contrast, maskless technologies use direct laser writing to pattern structures without the need for masks.

Microlens arrays are commonly fabricated using a UV lithography combined with photoresist reflow. In this process, a photoresist is exposed to UV light to fabricate 2D microstructures, which are then thermally reflowed to create hemispherical or aspherical surface profiles. While this process is well-suited for large-scale production of simple microlens designs, it is limited in design complexity and in achieving high fill factors up to 100%. The design flexibility can be enhanced by transferring patterns into the substrate using reactive ion etching (RIE), although this adds process complexity and cost.

GRAYSCALE LITHOGRAPHY

Grayscale lithography extends binary photolithography by enabling fabrication of complex 2.5D microstructures with continuous height profiles. This capability is essential for producing advanced micro-optics such as those used in mobile devices, diffractive optical elements, hologram optics and structured surfaces.

Two main approaches exist in grayscale lithography: photomask-based lithography and direct laser writing, each suited to different applications.

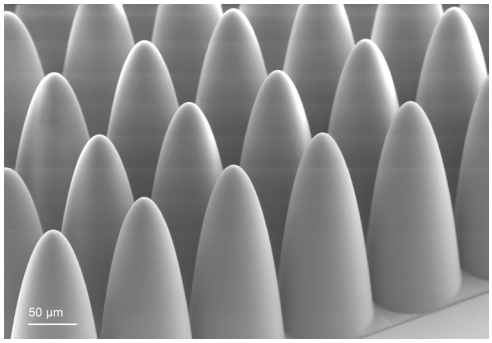


Figure 2: High aspect ratio microlens array fabricated using Two-Photon Grayscale Lithography, showcasing submicron shape accuracy and optical-grade surface quality.

While photomask-based lithography offers high throughput for large-area fabrication and high-volume production, direct laser writing enables fast iteration cycles for rapid prototyping.

MASK-BASED 2.5D GRAYSCALE UV LITHOGRAPHY

Photomask-based grayscale lithography uses specific masks to modulate exposure doses across a photosensitive resist, creating the desired topography after UV light exposure and development. The resulting 2.5D structures can then be transferred into the substrate via etching or replicated by thermal or UV molding.

Although this method allows rapid exposure of large substrates for high-volume production, it requires costly grayscale masks precisely tailored to resist characteristics. These masks are time-consuming and expensive to produce and iterate, which can take days or weeks. This limits their use in projects requiring rapid design iteration cycles.

MASKLESS 2.5D GRAYSCALE UV LITHOGRAPHY

Maskless grayscale lithography systems, such as those offered by Heidelberg Instruments, provide flexible fabrication of intricate 2.5D microstructures without the need for expensive masks. In this direct laser writing approach, spatially modulated UV light directly writes into a positive photoresist, with exposure dose variations encoding the desired structure depths. After development, the resulting 2.5D surface topographies are revealed. These patterns can then be transferred into optically relevant materials using replication techniques such as UV molding.

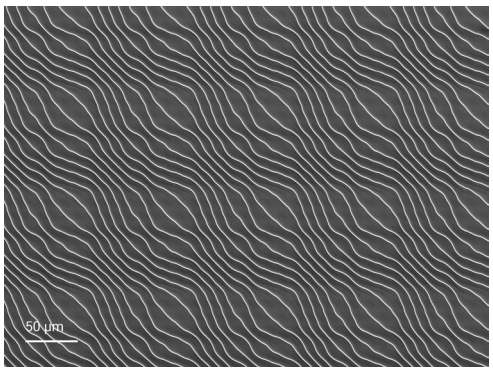
Unlike mask-based grayscale lithography, the maskless approach offers precise exposure control to compensate for nonlinear resist responses and batch-to-batch variations. However, achievable structure heights remain limited by the resist thickness, typically up to 60 µm. Recent studies using newly developed photoresists have demonstrated structure heights exceeding 160 µm, expanding the range of possible applications.

THE ROLE OF MATERIALS IN NANO- AND MICROFABRICATION

Printing material selection influences resolution, surface roughness, transparency, mechanical stability and long-term durability under varying environmental conditions. These properties are particularly critical in photonics and optics manufacturing, where optical performance is paramount.

Recent material innovations have introduced photopolymers with high transmission across the visible

Figure 3: Freeform diffractive optical elements with highest shape accuracy for high optical performance. Design by LightTrans International, print by Nanoscribe.



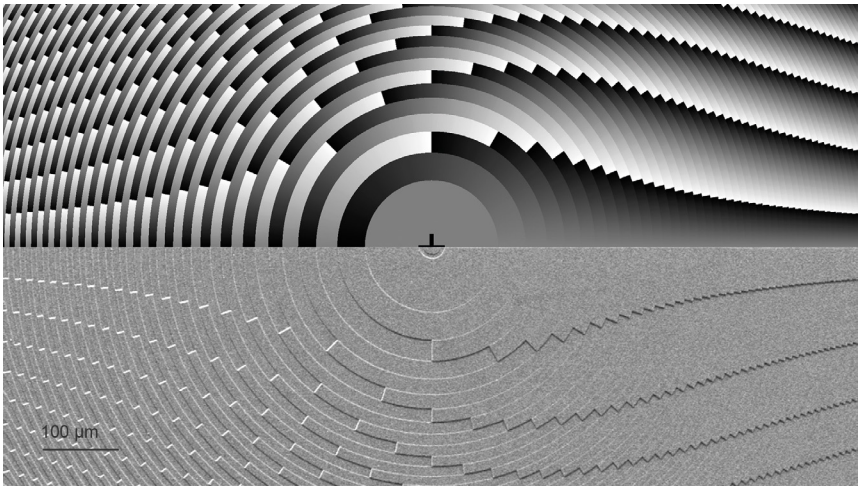


Figure 4: Grayscale design (top) and print of a Moiré lens (bottom). These diffractive lenses can be used to adjust the focus length.

spectrum and extending into the near-infrared and ultraviolet ranges, as well as photopolymers with different refractive indices and Abbe numbers. Both Two-Photon Polymerization and Two-Photon Grayscale Lithography support a wide range of such resins, enabling fabrication of micro-optical components precisely matched to diverse application requirements.

Two-Photon Grayscale Lithography utilizes liquid negative-tone resins, thus overcoming the height limitations imposed by Beer's law in one-photon grayscale lithography, where film thicknesses of positive resists typically restrict structure heights to around 60 µm. In contrast, 2GL enables fabrication of 2.5D microstructures with heights up to 1 mm and with high aspect ratios as exemplified by a 3D-printed microlens array in figure 2. Furthermore, the photoresists used in one-photon grayscale lithography are often highly sensitive to environmental factors, such as humidity and temperature, which can significantly affect process stability. Two-Photon Grayscale Lithography, however, offers robust processing conditions during preparation, printing, and development. In most cases, neither spin-coating nor pre- or post-processing steps are required.

Thanks to its robust process and the low proximity effect, 2GL does not require additional proximity correction tools, which helps reduce process complexity and simplifies data preparation workflows.

MARKETS AND APPLICATIONS

REFRACTIVE 2.5D MICRO-OPTICS

Two-Photon Grayscale Lithography expands design possibilities beyond classical optical geometries while maintaining submicron resolution. Applications include beam shaping, collimation, light homogenization, illumination, and imaging. The 2GL technology enables fabrication of almost any 2.5D shape, including spherical, aspherical, sharp-edged and freeform refractive optics. Both regular microlens arrays and random lens arrangements can be printed with fill factors up to 100% and high aspect ratios are also possible.

DIFFRACTIVE OPTICAL ELEMENTS

Diffractive optical elements (DOEs) are nanostructured surfaces that manipulate light based on the principle of diffraction (figure 3). By encoding spatial phase profiles into subwavelength or micron-scale surface reliefs, they can shape light to produce precise far-field intensity distributions, such as spot arrays, gratings and complex intensity or phase images. DOEs are used in applications that require precise beam shaping, such as holographic projection, laser beam homogenization, beam splitting in ● ● ●

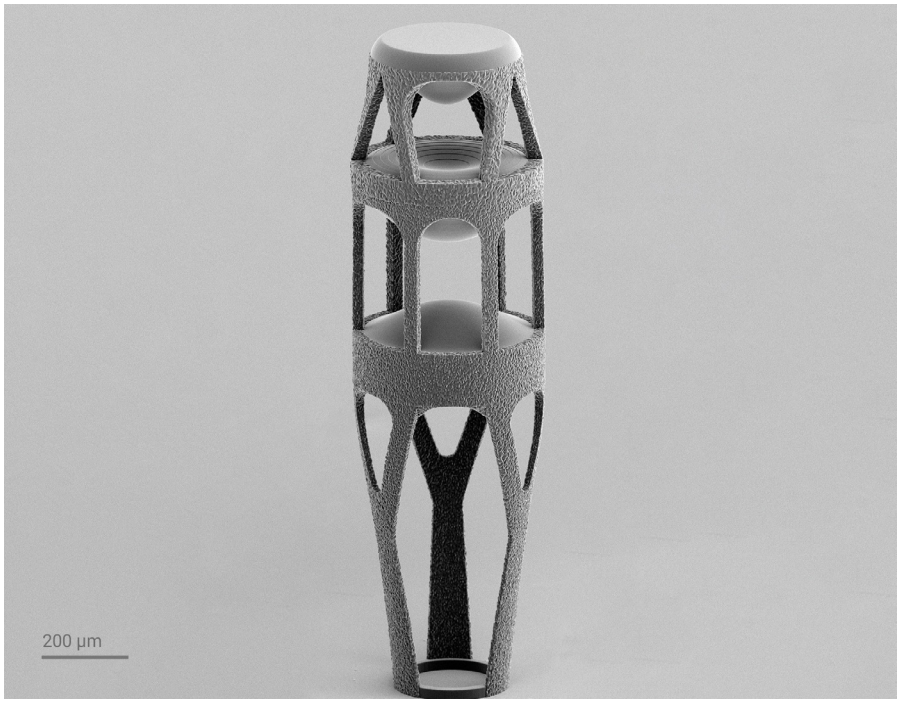


Figure 5: High-precision optics developed for a miniature endomicroscope. The stacked freeform lenses are 3D-printed by Two-Photon Grayscale Lithography. The three lenses are supported by a textured scaffold avoiding back-reflexes. All three freeform lenses have optical-grade surfaces on the top and bottom, integrating diffractive and refractive elements into one optical system and are printed in one pass. Lens design by Printoptix, manufacturing by Nanoscribe.

material processing, and structured light generation for 3D sensing. Their compact form factor and design flexibility make them especially valuable in systems where conventional refractive optics are limited by size, weight, or complexity.

Two-Photon Grayscale Lithography is well suited for the fabrication of multi-level and quasi-continuous DOEs, which require precise 2.5D surface topographies to encode phase functions. The technology offers the lateral and axial resolution needed to create DOE features with submicron precision and offers high shape accuracy and printing performance to print DOEs in reasonable time.

One example is a 256-level Moiré lens fabricated by 2GL with a lateral pixel size of 500 nm. Complex freeform DOEs, such as quasi-continuous DOEs shown in figure 4, further demonstrate 2GL's capability to produce highly accurate surface profiles that are essential for ensuring optical performance in far-field beam shaping or phase control applications.

HYBRID OPTICS

2GL enables the fabrication of hybrid micro-optics that combine refractive and diffractive features into one, continuous topography. This is particularly relevant for applications where complex wavefront shaping or chromatic aberration correction is required. While refractive elements offer high focusing efficiency, diffractive structures can compensate for dispersion or introduce precise phase control. Thus, combining both allows for compact, highly functional optical components.

2GL supports the direct fabrication of such hybrid elements with its ability to produce freeform 2.5D topographies at submicron resolution without multiple lithography or alignment steps. For example, hybrid microlenses designed for aberration-corrected imaging can be printed in a single printing step from grayscale input data, preserving design fidelity and ensuring high surface accuracy.

CONCLUSION AND OUTLOOK

Two-Photon Grayscale Lithography builds on the principle of Two-Photon Polymerization by enabling the fabrication of high-precision 2.5D micro-optics. Through dynamic voxel size modulation, 2GL produces freeform surfaces with optical-grade smoothness and submicron resolution, ideal for beam shaping, imaging, and light modulation applications.

The 2GL process integrates seamlessly into microfabrication workflows: from rapid design iteration based on grayscale input data to high-precision printing. Furthermore, 2GL can be combined with subsequent replication via nanoimprint lithography, hot embossing, or injection molding. This makes 2GL a viable bridge between prototyping and scalable manufacturing.

Looking forward, the optimization of printing material properties is enabling the development of photoresins tailored for specific applications. This advancement will continue to enhance the functionality of printed structures and improve their stability, both during integration into optical modules and throughout their operational lifetime. In addition, automated processes will further increase throughput and improve process repeatability.

While originally developed for 2.5D structures, the underlying grayscale modulation principle also enables the fabrication of complex 3D micro-optics. Three-dimensional geometries, such as stacked freeform lenses for microendoscopy (figure 5) illustrate how 2GL has evolved toward fully 3D optical components for next-generation applications in sensing, communications, displays, and integrated photonics.