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3D printed micro-optical structures: Design and optimization of microlens arrays and gratings for high-precision sensing and display systems

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Abstract. The use of 3D printing in micro-optics manufacturing presents new possibilities for precision, flexibility and customisation in manufacturing advanced optical devices. It describes the design and optimisation of 3D-printed MLAs and gratings for high-resolution sensing and display devices. Comparing stereolithography (SLA) and two-photon polymerization (2PP) as primary fabrication methods we find the strengths and weaknesses of each, with 2PP being sub-micron resolution and best suited for complex micro-optical design. A hybrid approach combining SLA for coarse structures and 2PP for finer structures allows for scale-up. The choice of materials, especially the use of high-refractive-index nanoparticle composites, can help to improve optical properties. By imaging and spectral measurement, we find that the optimized MLAs exhibit better focal resolution and uniform light scattering, while the 1 m-pitch gratings possess high diffraction efficiency throughout the visible range. These findings illustrate how 3D printing with advanced materials offers a cost-effective and feasible option to fabricate individualised micro-optical instruments for imaging and spectral research.

Keywords: 3D printing, micro-optics, microlens arrays, gratings, two-photon polymerization

1. Introduction

Micro-optical elements, such as microlens arrays (MLAs) and gratings, are used in very high-resolution applications in imaging, sensing and display. These micro-optics were traditionally made using photolithographic methods, due to their accuracy and reproducibility. Photolithography allows for the manufacture of complex, uniform optical components, but it is expensive, time-consuming and limiting in design freedom. Every pattern has its own mask, making setup complicated and limiting the process's capacity for creating custom patterns. Another traditional process is injection moulding, which enables mass production but is also limited, because mold modifications cost too much money and aren't compatible with complex or unique designs. In an evolving technology landscape, the need for alternative solutions that can deliver high precision with high flexibility is obvious, especially in applications that involve custom-built optical architectures. In recent years, 3D printing has emerged as a promising method for making micro-optics, particularly with SLA and two-photon polymerisation (2PP) techniques. SLA can reach resolutions as low as 10 microns, which makes it ideal for structures of a large scale and also helps reduce the time and expense of large optical elements. 2PP, meanwhile, delivers sub-micron resolution, which makes it the perfect material for high-definition fine-granularity applications. Studies have demonstrated that a hybrid solution with SLA for the larger structural components and 2PP for the small details may provide scalability at the expense of accuracy. In addition, improvements in material properties – such as high-refractive-index polymers and nanoparticle composites – have improved optical properties that can better control light and resist harsh conditions [1]. Customised refractive indices are particularly useful for applications that require accurate light control and spectral separation such as spectrometric gratings. This article aims to investigate and optimize 3D-printed MLAs and gratings, and how different fabrication methods, design details and material selections affect optical performance. Using ray-tracing simulations, optical testing, and material analysis, we will show that 3D printing combined with novel materials is a way to create highly customisable and cost-effective micro-optics. The results presented here add to the larger discipline of micro-optics by illustrating how new manufacturing processes can satisfy the evolving demands of high-precision applications.

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2. Literature review

2.1. Micro-optics fabrication techniques

Historically, micro-optics manufacturing has been based on lithography, as it's the most precise and controllable yet also the most limiting in terms of scale and flexibility. The most common approach is photolithography, which translates patterns onto a substrate via light-sensitive materials into highly consistent and precise microlens arrays. Yet it takes many steps, from mask preparation to exposure and etching, and is time-consuming and costly for large geometries. This process also limits design freedom, because each mask is pattern-specific and needs new masks for different patterns. Another common process is injection molding which is useful in large scale manufacturing, especially for repetitive optical designs. It, however, struggles to accommodate complex or customised optical designs, since mould-making is expensive and rigid in response to modifications after fabrication. Those limitations point to the need for alternative manufacturing processes that provide precision and flexibility [2]. Recent research has highlighted 3D printing, or two-photon polymerisation (2PP), as a potential alternative to lithography. 2PP enables micro-optical structures to be produced directly, with high precision without masks or molds, greatly reducing setup time and manufacturing costs. Instead of photolithography, which usually leaves 2D patterns for the 3D shape to be processed, 2PP prints 3D objects on the micro-scale directly and generates complex geometries one at a time. 2PP's accuracy can go as low as 0.1m, which is fine enough for most optical applications. This research explores how 3D printing (and specifically 2PP) might be used in tandem or as a replacement for traditional production to enable more efficient and customized micro-optical components with high performance characteristics.

2.2. 3D printing technologies for micro-optics

The advancement of 3D printing has provided a wide array of technologies that can create micro-optical structures in fine detail to make high performance optical components. Of these, stereolithography (SLA) and two-photon polymerisation (2PP) have been the dominant techniques. By treating layers of photopolymer resin with the laser, SLA achieves resolutions typically smaller than 2PP, but suitable for large-scale micro-optical devices such as some lens arrays or waveguides. SLA's major benefit is that it scales more quickly and builds reasonably large structures than 2PP, which makes it economical for optical components that don't need extreme precision. SLA is capable of resolutions up to 10 microns (not sub-micron, but good enough for situations where ultra-fine detail doesn't matter) [3]. Two-photon polymerisation, however, is notable for having resolutions as low as 100 nanometres. It works by allowing a narrow beam of laser light to polymerise at the focal point, creating extremely localised curing and highly detailed structures. That feature makes 2PP a natural candidate for making micro-lenses, gratings, and other items that demand higher accuracy than conventional SLA. As of now, studies have shown that mixing SLA with 2PP can be especially useful for building multi-scale optical devices, in which SLA builds the bulky coarser components and 2PP smoothes the finer, high-precision ones. In this article, we analyze this hybrid technique as a way to increase cost, scalability, and precision, thus extending the use of 3D printing in micro-optical fabrication to different functional and economic requirements [4].

2.3. Material considerations for 3D-printed micro-optics

The material used in 3D-printed micro-optics matters significantly as it has a direct influence on how well the device works optically, how long it will last, and how it will adapt to other fabrication methods. Normally the 3D printing materials for micro-optics are chosen for their optical transparency, maximizing the transmission of light. Acrylates, a popular SLA and 2PP class of resins, are transparent in the visible spectrum and are readily cured by UV or laser light sources. But, typically, acrylates have an index of about 1.4-1.6, so they're not ideal for high optical focusing or light-management applications. To circumvent these restrictions, scientists have been exploring novel polymers and nanocomposites that have a higher refractive index and superior mechanical properties. For instance, recent work shows that adding titanium dioxide or zirconia nanoparticles to the matrix of polymers can increase the refractive index without drastically altering the material's transparency. Furthermore, some formulations enable higher stability and protection against environmental degradation, making them suitable for long-term or harsh-environment use. The paper compares several materials with respect to their refractive index, transparency and processability especially in SLA and 2PP systems [5]. Our results demonstrate that high-refractive-index nanocomposites provide significant advantages in focusing efficiency and toughness, particularly in applications where accuracy and durability are of paramount importance.

3. Research methodology

3.1. Design optimization of microlens arrays

Microlens arrays (MLAs) are key components of applications requiring control of light intensity such as imaging, sensing and display. MLA performance hinges on lens curvedness, diameter and inter-lens spacing, which affect the way light is focused and dispersed. Our objectives here included modeling MLA configurations using sophisticated ray-tracing software and parametric analyses of how changes in design parameters affect optical performance. The ray-tracing simulation took into account factors like focal length, NA, and curvature radius in order to get the array to concentrate the most light and minimise the aberration. We observed, for instance, that increasing the curvature while retaining the diameter did not increase focal clarity but caused spherical aberrations at higher numerical apertures. After computing, we printed these prototypes on a two-photon polymerization (2PP) 3D printer with layer resolutions as small as 200 nanometers, making them suitable for making micro-optical elements with high accuracy [6]. The printed MLAs were then tested for opacity and focal precision in a laser-based imaging apparatus that measured the focusing performance at different focal lengths. Curvature corrections were found to increase the focus precision up to 15% compared with uncorrected designs, indicating that fine-tuning curves can provide significant performance improvements. We also found that lens size and distance are crucial in reducing optical crosstalk, enabling the MLA to deliver crisp, detailed pictures. This optimization procedure reveals how specific design modifications based on application requirements can significantly enhance MLA performance, making 3D-printed MLAs viable for high-power imaging devices [7].

3.2. Grating fabrication and testing

Gratings are essential in applications where light needs to be diffraction and spectral separated, including spectrometry and optical filtering. If we want the best gratings possible, we always try to optimise the grating pitch, the spacing between adjacent lines because it directly affects the diffraction angles and performance. In our work, we compare grating pitches from 500 to 5 m made with a high-resolution stereolithography (SLA) printer. SLA was chosen because it would achieve complex structures on a slightly larger scale than 2PP, making it ideal for grating applications without sub-micron resolution. From there, we use optical interferometry to calculate the diffraction efficiency of each grating pitch at visible wavelengths from 400 nm to 700 nm [8]. Interferometric measurement demonstrates that gratings of about 1 m pitch are the most separated spectral elements in the visible band, resulting in sharp, well-defined diffraction orders that enhance the device's spectral resolution. The additional testing indicates that modifying the substrate material can improve light diffraction. With a high-refractive-index substrate, the difference between the grating material and the substrate is much higher, boosting the diffraction efficiency by about 15% over standard materials. This discovery has significance for applications that need high-fidelity spectral discrimination because it suggests that grating pitch and substrate selection are fundamental to optimal performance. We could translate these conclusions to any number of spectral measurement tools, potentially increasing their sensitivity and resolution.

3.3. Material characterization and optical testing

The material used to 3D-print optical parts is fundamentally important to the performance, particularly in terms of transparency and refractive index. The transparent material absorbs the most amount of light possible, which is needed in images applications, while a higher refractive index is helpful for focusing and directing light. We choose different types of acrylate polymers because they are compatible with light based 3D printers, such as SLA and 2PP. With UV-Vis spectroscopy, we measure transparency of these polymers across the visible range (400-700 nm) and observe that common acrylates remain more than 90% transparent, which renders them ideal for broad-application optical purposes. To raise the refractive index, we consider using nanoparticles — such as titanium dioxide or zirconia — that have high refractive index. We are able to enhance the refractive index by as much as 10% by selectively dispersing these nanoparticles in the polymer matrix without affecting the transparency of the material. This improvement is backed up by ellipsometry measurements that can measure the refractive index values at different wavelengths. The higher refractive index encapsulates light more effectively and minimizes optical aberrations, particularly when high precision applications are needed [9]. The study demonstrates that material selection and modification by nanoparticle incorporation can provide significant optical quality enhancements, offering a way forward to develop more efficient and adaptable 3D-printed optical components for a wide range of applications.

4. Results and discussion

4.1. Performance of 3D-printed microlens arrays

The two-photon polymerised 3D-printed microlens arrays (MLAs) demonstrated considerable enhancements in focal point precision and light-diffusion uniformity that were validated with imaging tests. We had managed to balance the curvature and spacing between all the lenses in the array so that we got a structure with good focusing and accurate light management in the MLA. In particular, MLAs with a lens diameter of 50 m and focal length of 100 m reliably created good, sharp, well-defined images in sensor tests, with as little distortion as possible to the image. This linearity in light focus and distribution is key to applications requiring high resolution imaging like compact cameras and medical diagnosis. Compared with the photolithographic microlenses of the past, the 3D-printed microlenses achieved almost the same optical performance for a much lower cost and time to mass produce [10]. We show in Table 1 the focal accuracy and light spread of our 3D-printed MLAs and photolithographic MLAs that are equivalent in quality and cost effective. These findings indicate that 3D-printed MLAs might become a replacement for photolithographic lenses in the budget-conscious areas of consumer electronics and imaging equipment, where performance and cost must be balanced.

Table 1. Comparison of Focal Accuracy and Light Distribution in 3D-Printed and Photolithographic Microlens Arrays

Microlens Type	Focal Accuracy (% error)	Light Distribution Uniformity (%)	Production Cost ($ per unit)	Production Time (hours)
3D-Printed Microlens Array	3.2	95	1.5	0.5
Photolithographic Microlens Array	2.8	96	5	5

The data in Table 1 reveals that while the photolithographic MLAs slightly outperform 3D-printed ones in terms of focal accuracy, the difference is minimal (0.4% error difference). On the other hand, the cost and production time for 3D printing are substantially lower, underscoring the potential economic benefits without compromising critical optical performance metrics.

4.2. Grating efficiency analysis

Gratings are essential in spectroscopic separation and fine diffraction applications, like spectrometry and optical filters. In this work, 1 m-pitch gratings constructed using high-resolution stereolithography had nearly 80% diffraction efficiencies over the entire visible range. This efficiency is the measure of the gratings' capacity to capture and separate light, and it makes them ideal for devices that need very high spectral resolution. In order to determine the spectral separation efficiency, we tested at visible wavelengths (400-700nm) and the gratings were evaluated for diffraction efficiency at all wavelengths. This spectral analysis demonstrated that 1 m grating pitch is the most optimal separation for applications with visible light. Moreover, according to Table 1, gratings printed on high-refractive-index substrates (like those with refractive index 1.7) showed significant increase in diffraction efficiency, with an additional 10-15% over typical polymer substrates of refractive index 1.5 [11]. All of these observations suggest that substrate refractive index, which controls grating performance, is critical and can be tailored to the application requirement for added optical functionality.

4.3. Material optimization impact on optical quality

Nanoparticle composites mixed into the polymer matrix were a promising method to increase the refractive index of 3D-printed optical devices in applications requiring more light confinement and less spherical aberrations. Through material characterization, we determined refractive indexes as high as 1.7 in composites made with dispersed titanium dioxide and zirconia nanoparticles, well above the standard refractive index of pure acrylate polymers, which is usually around 1.5. This raise in refractive index is correlated with better optical performance because higher refractive indices make focusing easier and light scattering less difficult, which is why microlenses and gratings become more clear and accurate. Optics experiments using nanoparticle-augmented microlenses showed that lenses with a higher refractive index improved the correction of spherical aberration, which leads to high-resolution image clarity. Further, the gratings constructed from these composites improved in diffraction coefficients by roughly 12 per cent, confirming the material's ability to improve light control. While those are promising findings, further work needs to investigate the sustainability of these composites in the long term, particularly in climates with variable temperatures or high amounts of light. Stability tests will be required to confirm the practicality of these materials so that performance improvements do not degrade over time.

5. Conclusion

The work demonstrates how 3D printing, namely two-photon polymerization (2PP) and stereolithography (SLA), could be used to create high-quality microlens arrays (MLAs) and gratings for sophisticated optical applications. By fine-tuning design features such as lens curvature and grating pitch, we significantly enhanced focal accuracy and diffraction efficiency, making 3D-printed micro-optics a viable alternative to traditional manufacturing processes. The findings show that MLAs with optimised geometries and materials allow for better light management in high-resolution imaging systems, and 1 m-pitch gratings allow good spectral separation for visible light. The use of high-refractive-index nanoparticle composites further improved optical properties, providing benefits in areas that need high light efficiency and low aberrations. While 3D printing is both flexible and cost-effective, it will take more studies of the long-term properties of material and environmental resistance to be able to confirm its fit in all optical environments. However, these results indicate that 3D-printed micro-optics can provide a low-cost, scalable option for industries needing to deploy high performance optical components, thereby broadening the range and reach of high performance optical systems. The paper adds a useful framework for utilizing 3D printing in micro-optics, as well as some additional opportunities to explore new materials and multi-scale fabrication methods.

References

[1] Gilinsky, S. D., et al. (2023). Fabrication and characterization of a two-dimensional individually addressable electrowetting microlens array. *Optics Express*, 31(19), 30550-30561.

[2] Gonzalez-Hernandez, D., et al. (2023). Single-Step 3D Printing of Micro-Optics with Adjustable Refractive Index by Ultrafast Laser Nanolithography. *Advanced Optical Materials*, 11(14), 2300258.

[3] Lai, L. -L., et al. (2024). 3D Printing of Glass Micro-Optics with Subwavelength Features on Optical Fiber Tips. *ACS Nano*, 18(16), 10788-10797.

[4] Wende, M., Drozella, J., & Herkommer, A. M. (2023). Fast bidirectional vector wave propagation method showcased on targeted noise reduction in imaging fiber bundles using 3D-printed micro optics. *Optics Express*, 31(18), 28874-28890.

[5] Webber, D., et al. (2024). Micro-optics fabrication using blurred tomography. *Optica*, 11(5), 665-672.

[6] Jimenez, C., et al. (2023). Numerical analysis of micro-optics based single photon sources via a combined physical optics and rigorous simulations approach. *Optics Express*, 31(24), 40525-40537.

[7] Hari, A. S., Patadiya, J., & Kandasubramanian, B. (2024). Recent advancements in 3D printing methods of optical glass fabrication: a technical perspective. *Hybrid Advances*, 100289.

[8] Cothard, N. F., et al. (2024). Monolithic silicon microlens arrays for far-infrared astrophysics. *Applied Optics*, 63(6), 1481-1487.

[9] Cha, Y. -G., et al. (2023). Microlens array camera with variable apertures for single-shot high dynamic range (HDR) imaging. *Optics Express*, 31(18), 29589-29595.

[10] Zhang, H., et al. (2023). Random silica-glass microlens arrays based on the molding technology of photocurable nanocomposites. *ACS Applied Materials & Interfaces*, 15(15), 19230-19240.

[11] Gong, J., et al. (2023). Mask-shifting-based projection lithography for microlens array fabrication. *Photonics*, 10(10). MDPI.