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Arbitrary 2D GRIN lens fabrication in diffusive photopolymers

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ABSTRACT

We introduce a new method to make gradient index (GRIN) lenses in diffusive photopolymers with nearly arbitrary two-dimensional (2D) profiles. By modulating the 2D intensity pattern and power of the exposure with a deformable mirror device (DMD), the index profile of the GRIN lens can be controlled. Combined with the self-developing nature of the photophotopolymer, rapid on-demand printing of arbitrary micro-optics is enabled. We demonstrate the process by fabricating quadratic GRIN lenses, Zernike polynomials and multi-focal lenses.

Keywords: GRIN optics, photopolymer, optical fabrication

1. INTRODUCTION

Gradient index (GRIN) lenses and micro-optics are important devices in photonics and optoelectronics because they offer appealing form factors, simplified mounting and packaging for many applications, additional degrees of freedom in lens design and can enable aberration or lens element reduction. These attributes have driven applications in fiber optic communication, imaging systems, and optical medical devices.

Current methods to fabricate GRIN lenses[1] are neutron irradiation,[2] chemical vapor deposition (CVD),[3] ion exchange[4–6] and polymerization.[7] Neutron irradiation creates a GRIN distribution by changing the index of refraction of boron glass (ex. BK7 glass) by locally altering the boron concentration. The variation in the index of refraction is approximately linear to the neutron irradiation dose, enabling arbitrary and high fidelity GRIN recordings. However, large neutron doses are required to induce the index change and the fabricated GRIN pattern can disappear over time. The CVD technique fabricates GRIN lenses by sequentially depositing thin, homogeneous layers of glass materials onto a substrate. The GRIN pattern is produced by depositing glasses with different refractive indices as the volume is created, varying the refractive index distribution axially through the volume. However, CVD has limitations for large diameter lenses due to the step index formation by the deposition process and can only fabricate axial GRIN lenses. The ion exchange technique is the main technology used for mass production and creates GRIN lenses by diffusing ions from a bath of salt(ex. lithium bromide) into a glass substrate and replacing the ions originally residing in the glass. The ions have different densities and different refractive indices, resulting in a GRIN distribution in the glass matching the diffusion profile of the ions, with diameters ranging from 0.5 - 10 mm. However, ion diffusion profiles limit potential index profiles formed to Gaussian, Lorentzian or linear, making arbitrary GRIN distribution impossible to fabricate.

To reduce cost and increase GRIN lens performance several methods have been developed to fabricate GRIN lenses in polymers. Polymer GRIN lens rods have been fabricated through thermal treatment[8] and UV irradiation.[9] Large diameter polymer GRIN lenses, measuring over 50 millimeters in diameter, have been fabricated using multiple monomers and longitudinal diffusion to create the gradient index profile.[10] However, the fidelity of the polymer GRIN lenses fabricated with these methods were both poor and process intensive. High fidelity

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polymer GRIN lenses have been fabricated by exposing 100 μm - 1 mm thick samples with a de-focused Gaussian beam,[7] but the index profile was limited to a Gaussian profile.

In summary, the underlying physical principle of these methods limits their ability to fabricate high fidelity GRIN lenses with arbitrary index profiles. To overcome this limitation we propose and demonstrate a new form of GRIN lens fabrication that can print high quality polymer optical components with arbitrary control over the refractive index profile.

This new method makes polymer A-GRIN lenses by patterning optically driven diffusive photopolymer media with a deformable mirror device (DMD) and a light emitting diode (LED). The absorbed light induces polymerization and monomer diffusion, resulting in a permanent volume index change correlated to the total optical dose[11] without wet chemical processing. The DMD enables spatial control of the optical dose, which allows production of GRIN lenses with a complex index profile in a single step.

2. EXPOSURE AND METROLOGY INSTRUMENTATION

A deformable mirror device (DMD) is used to modulate the 2D intensity pattern and power of the exposure, to controllably pattern the index in the photopolymer, as shown in Figure 2. An LED with a center wavelength of 405 nm is used as the exposure source to optimize the absorption of the photo-initiator in the visible spectrum. The center wavelength of the LED can be changed to optimize photoinitiator absorption,

To determine the refractive index profiles of the fabricated structures, the samples are imaged onto a shack-hartman wavefront sensor, as shown in Figure 2(b). The refractive index is quantified by relating the measured optical path difference to the thickness of the sample under test.

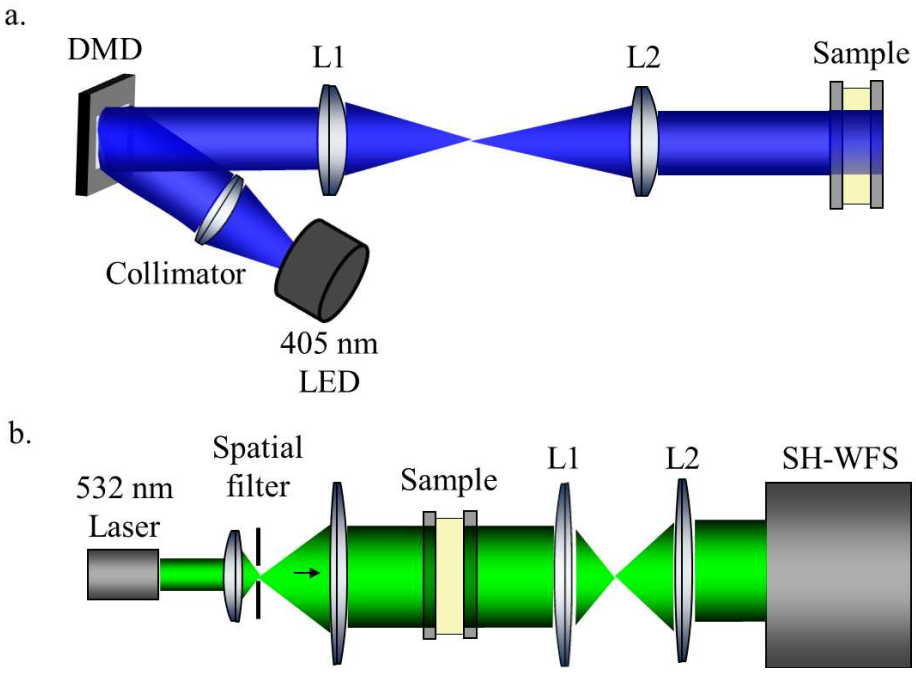

Figure 1. Exposure and metrology system. (a) Exposure system that uses a light emitting diode (LED) and deformable mirror device to modulate the 2D intensity pattern and power of the exposure. (b) Metrology system that measures the refractive index profile by imaging the sample under test onto a shack-hartmann wavefront sensor.

After exposure, the samples are kept in the dark at 60 degrees Celsius for five days, allowing polymerization and diffusion to continue. The elevated temperature accelerates the diffusion process, reducing the required development time. After the exposure and development processes have completed, a uniform optical exposure consumes the remaining photoinitiator and monomer, leaving a permanent, photoinsensitive part that requires

no additional processing. The combination of a software-controlled exposure and self-developing material makes this method ideal for rapid prototyping of complex GRIN lenses and micro-optics.

3. MATERIAL SYSTEM

Optically driven diffusive photopolymer media is an appealing material platform for GRIN lenses and micro-optics. It affords relatively high index contrasts and high sensitivity, in materials that are low cost, self-processing, widely tunable and environmentally robust.[12] The materials are synthesized in the liquid phase so the form factor is very flexible and encapsulation of additional optical or mechanical elements is possible. The media consists of two independent chemistries, a solid host, low-index matrix formed by a thermo-set polymer, followed by recording into a second (typically radical) high-index photopolymer.[13] Figure 2 elucidates how the refractive index distribution is modulated in the media.

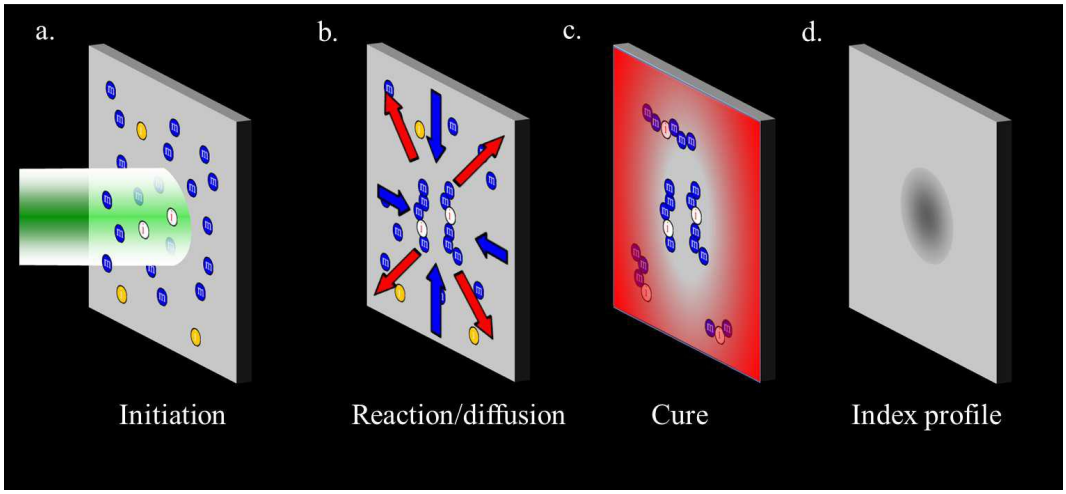

Figure 2. Description of the index modulation mechanism in optically driven diffusive photopolymer media. (a) Photons create radicals that initiate polymerization (conversion of writing monomer to polymer) at that location. (b) Replacement monomer diffuses into the reaction region and the matrix swells out of it. (c) An optical flood exposure consumes all remaining chemistry. (d) Segregation of writing polymer and matrix creates the index distribution proportional to the optical dose.

Structured light creates radicals that initiate polymerization proportional to the local optical dose. This creates a concentration gradient in the monomer that induces diffusion of replacement monomer into the reaction region. This causes the matrix to swell out of the reaction region, creating the index distribution through segregation of the matrix and recording polymer. Thus it is similar to ion exchange in that the refractive index profile is created through segregation and diffusion of materials with different refractive indices, however, this method enables optically structured diffusion profiles and thus index profiles only limited by the optical pattern that can be generated.

The photopolymer material formulation used[11] is similar to commercial two-chemistry media[14,15] which consists of a photolytic-ally inert urethane matrix and an acrylate and photoinitiator that comprises the writing chemistry. To reduce scatter in the exposed material, we experimentally determined the glass transition temperature, T_G, of the material had to be larger (approximately 20°C) than commercial diffusive photopolymer media. We attribute the reduction of scatter in high T_G materials to a reduction in the photopolymerization reaction rate and extended dark polymerization. These effects separate the reaction and diffusion dynamics, suppressing noise gratings.[16]

To increase uniformity of initiation in depth, and thus uniformity in the refractive index distribution through depth, a small concentration, .067%, of photoinitiator is used in the material. Unfortunately, this results in less sensitivity and spatially non-linear absorption that can result in poor recording fidelity if left uncorrected.

However, by adjusting the optical pattern to compensate for the non-linear response, high fidelity structures can be fabricated.

4. EXPERIMENTAL RESULTS AND DISCUSSION

High quality optical components can be fabricated in the material by compensating for the non-linear response to the optical exposure. Figure 3a (solid blue line) depicts the reduction in refractive index profile fidelity if the non-linear media response is not compensated for correctly. However, adjusting the optical pattern using equation 1 to compensate for the non-linear response, high fidelity structures can be fabricated, as shown in Figure 3a (dotted red line).

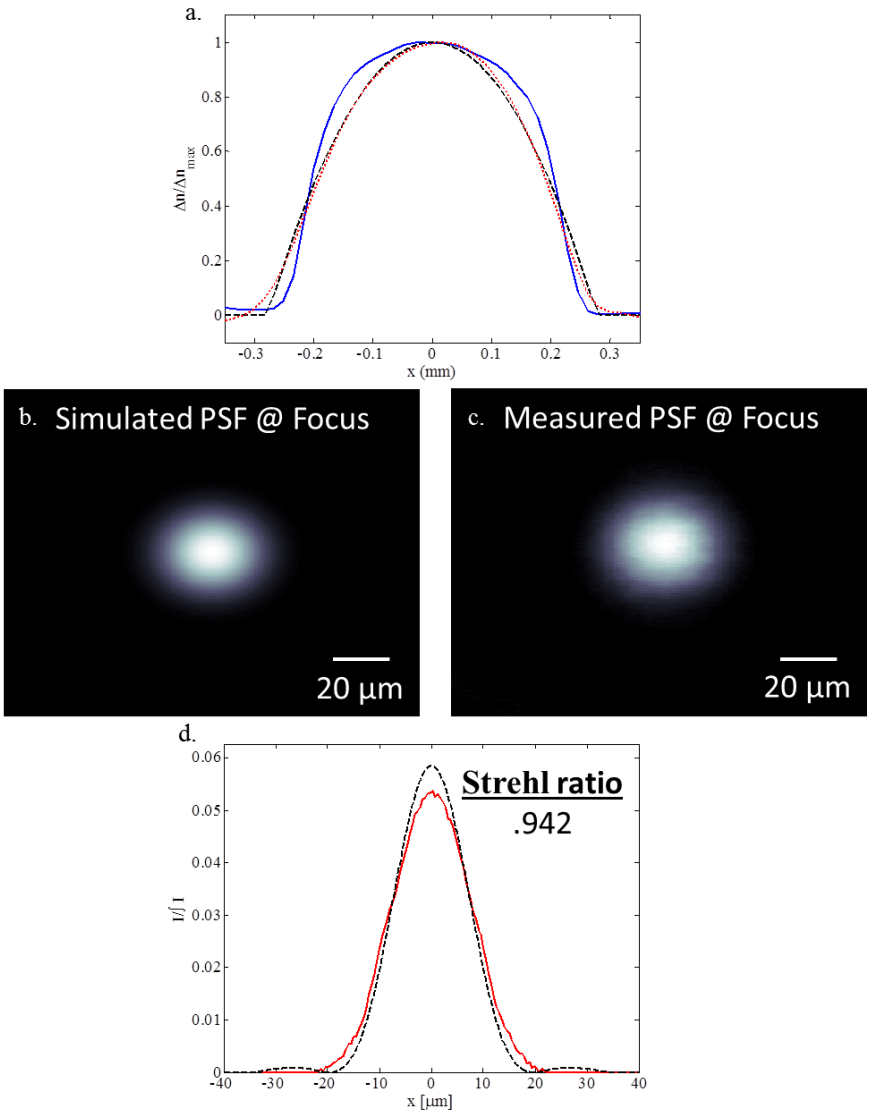

Figure 3. The imaging quality of the GRIN lenses. (a) The index profile of the intended (black dashed), uncorrected (solid blue) and corrected (dotted red) profile. (b) The simulated point spread function (PSF) at the focus of the lens. (c) The measured PSF at the focus of the lens. (d) Cross-section of the simulated (black dashed) and measured (solid red) PSF at the focus.

To demonstrate optical performance of components fabricated with this technique, a GRIN lens with a

quadratic profile was fabricated and its point spread function (PSF) at its focal plane, Figure 3c, and its phase profile, Figure 3a, were measured. The measured PSF was compared to simulated performance of a GRIN lens with an ideal phase profile, shown in Figure 3b&d. To compare how well the measured performance compared to expected performance, the root mean square (RMS) error between the measured and designed phase profile was calculated and converted to a Strehl ratio. The Strehl ratio of the PSF at focus was measured by a camera and compared to the Strehl ratio determined by measuring the phase. The measured 2D phase profile and PSF had a Strehl ratio .9548 and .942 respectively, demonstrating the quadratic pattern was recorded with high fidelity.

In addition to recording traditional GRIN lens function into the material, complex patterns and diffractive optical function can be recorded with high fidelity, as demonstrated by Figure 4. Figure 4a&d are Zernike coefficient profiles [3,3] and [-1,3] that we recorded into the material and Figure 4b&e are the measured refractive index profiles of those recordings. In addition to Zernike profiles, large diffractive structures, a Fresnel zone plate, was fabricated in the media with high fidelity, as demonstrated by the phase micrograph shown in Figure 4g&h.

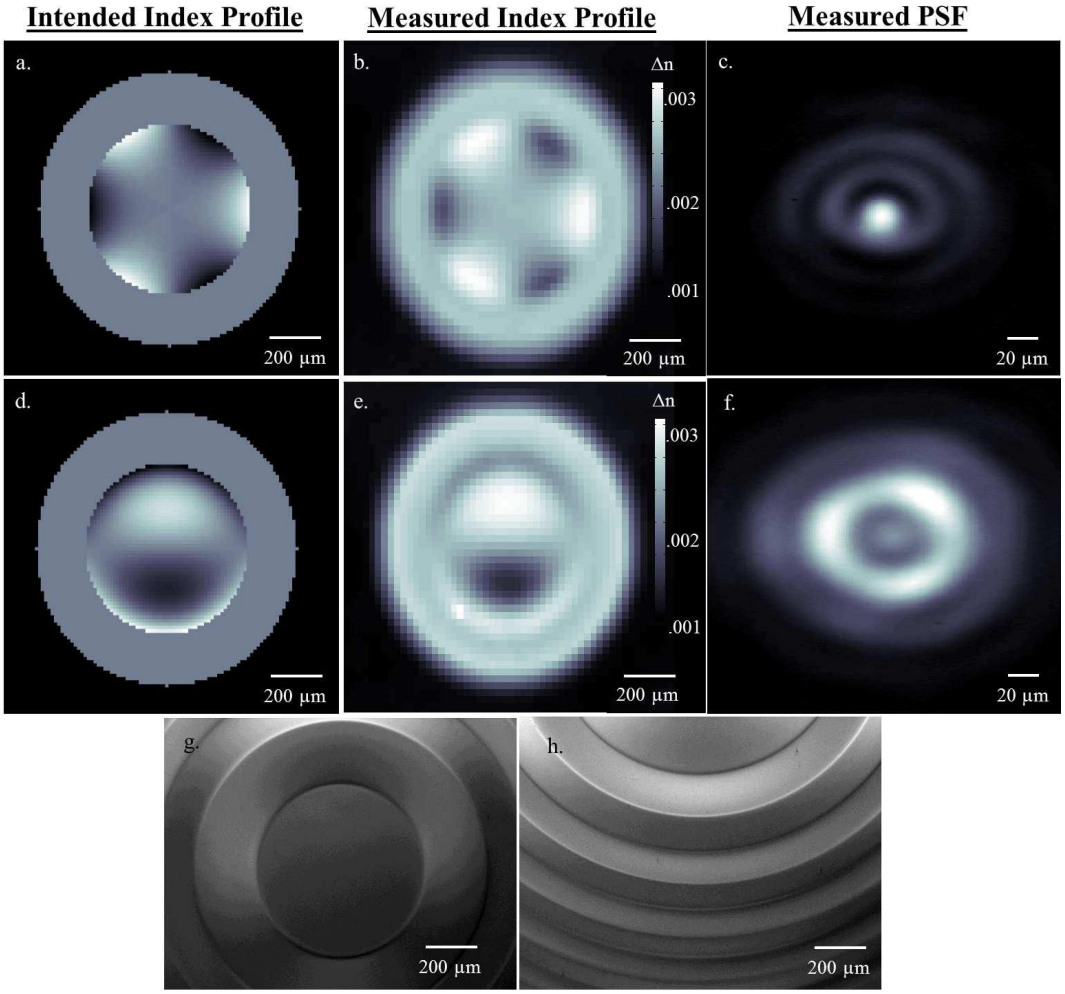

Figure 4. (a) Intended index profile of z[3,3]. (b) Intended index profile of z[-1,3]. (c) Measured index profile of z[3,3]. (d) Measured index profile of z[-1,3]. (e) Measured PSF of lens with a 25 mm focal length and sample shown in (c), 200 μm from focus. (f) Measured PSF of lens with a 25 mm focal length and sample shown in (d), 200 μm from focus.(h) Phase micrograph of the center and the (i) edge of the Fresnel lens.

The Zernike patterns written in the media had a .951 and .943 correlation coefficient with their designed profiles, respectively, as quantified by the Shack-Hartmann wavefront sensor software, demonstrating high recording

fidelity. To create more complex optical function or permanently remove aberrations in an optical system, multiple Zernike profiles can be multiplexed together[17] in the fabricated optic.

The complexity of the index profile of the A-GRIN optic is limited by the ability to generate the optical pattern required to create the desired index profile. One of the inherit trade-offs as a result of this is between the thickness of the A-GRIN optic and transverse resolution of the index profile. This will limit the amount of optical path delay that can be attained for a given transverse resolution. This can be somewhat negated by increasing the maximum index contrast of the material and potentially overcome by reducing layer thickness and stacking many high resolution layers.[18]

5. SUMMARY AND CONCLUSIONS

We have presented a method to fabricate A-GRIN optics by patterning optically driven diffusive photopolymer media with a deformable mirror device (DMD) and a light emitting diode (LED). The arbitrary index profile is created by modulating the 2D exposure pattern with the DMD and LED enabling . We demonstrated A-GRIN optic fabrication by creating quadratic profile GRIN lenses, Zernike polynomials and multi-focal diffractive lenses that had Strehl ratios larger than 0.95 and phase errors less than 5%.

The materials are synthesized in the liquid phase so the form factor is very flexible, enabling the fabrication of hybrid A-GRIN/refractive optical components by using a mold the form the refractive surface and exposing the lens in the mold.. A further benefit is that custom A-GRIN optics can be fabricated on demand, not unlike 3D printing technologies, bringing benefits of low cost small volume production, and quick turn custom and prototype components.

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