Liquid Deposition Photolithography for Photonic Device Fabrication

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Abstract: We describe a novel fabrication method, liquid deposition photolithography (LDP), for the creation of polymer photonic devices. We demonstrate LDPs ability to fabricate photonic devices by fabricating a waveguide array and gradient index lens.

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1. Introduction

Recently, it was realized that a material with a spatially changing refractive index through its volume, can bend light in almost any manner. This had lead to many applications for photonic devices, such as, extended depth of field lenses, photonic crystals, and volume computer generated holograms. Established methods for photonic device fabrication include multiphoton direct-write lithography at a scanning point, multilayer projection lithography of sequential two-dimensional (2D) planes or volume holography of entire three-dimensional (3D) volumes. While nanometer resolution is possible in all cases, throughput dramatically increases with dimensionality of the exposure, but at the cost of flexibility in the structure that can be fabricated.

Fabrication of 3D photonic devices requires precise manipulation of a material refractive index in three dimensions. One-photon, diffusive photopolymers [1] enable self-developing 3D patterning of up to cm thick solid volumes. These materials contain two monomers, in which the first monomer is thermally or optically gelled, providing a physical scaffold for index structures. Linear absorption of incident light polymerizes the second monomer, locally depleting it in the exposed region. This causes diffusional mass transport of unreacted monomer into the exposed region, resulting in an increased material density and index of refraction. A post-exposure optical flood cure bleaches remaining initiator and cross-links all remaining monomer, yielding stable, permanent index structures.

Here we show a new fabrication process, liquid deposition photolithography (LDP), to fabricate 3D index structures for photonic devices. The fabricated 3D index structures can have an index contrast up to 0.1, allowing greater flexibility in device fabrication.

2. Liquid Deposition Photolithography

Liquid Depostion Photolithography is a novel fabrication method [2], that can efficiently create mm^3 optical devices with programmable, gradient index of refraction with arbitrary feature size. LDP utilizes a one photon, initially liquid photopolymer in a process that produces patterned 3D volumes through repetitive layering, where each layer is structured by projection lithography. The use of a liquid photopolymer enables high throughput via micro-fluidic manipulation and rapid monomer diffusion. The process steps of LDP are shown in Fig. 1(a). First, liquid monomer is drawn through a microfluidic channel as the platform is lowered, producing a new material layer (i). Second, the liquid layer is patterned by 2D projection lithography, polymerizing and solidifying the monomer in the exposed regions (ii). Polymerization is suppressed just below the window via oxygen diffusion from the polydimethylsiloxane (PDMS) mold. Third, unreacted monomer diffuses from the adjacent layer of liquid monomer into the solid, increasing the index of refraction (iii). Finally, the entire layer is optically flood cured to a solid, cross-linked, photo-insensitive polymer (iv). Steps (i)-(iv) are repeated to fabricate complex 3D index structures.

In addition to full 3D control of index, processing time in LDP is reduced compared to multi-layered planar lithography because the material is self-developing, enabling the entire process to be completed on a single instrument. This eliminates the additional instruments in multi-layered planar lithography that are required for layer planarization and chemical and thermal processing. Similar to planar lithography, transverse resolution is a function of the projection optics, material response, and layer thickness, while axial resolution is determined by layer thickness. In LDP the layer

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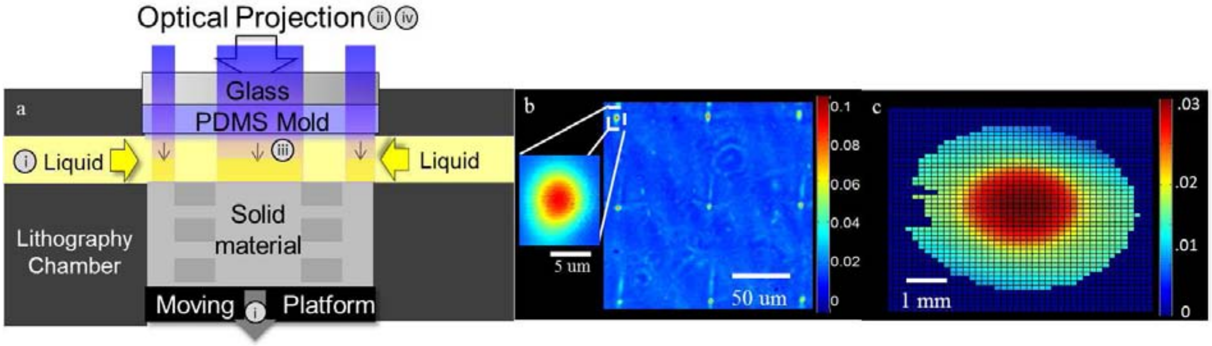

Fig. 1. (a) Process steps of liquid deposition photolithography (LDP). (b) Refractive index map of the waveguide array fabricated with LDP. (c) Refractive index map of the fabricated GRIN lens.

is not spin coated but, instead, fluid is deposited by the motion of a stage with nanometer resolution and planarized by the chamber window [see Fig. 1(a)]. The chamber window allows optical pattern access, and, through the use of a 125μm thick PDMS layer, provides a constant flux of oxygen at the liquid monomer boundary via diffusion. Oxygen is a strong radical inhibitor [3], so polymerization is prevented in the thin liquid monomer layer directly adjacent to the chamber window. The thin monomer layer provides a short diffusion path for the unreacted monomer, decreasing the diffusion time for the 3D volume and enabling rapid fabrication of thick, high axial resolution photonic devices.

3. Photonic Device Fabrication

To demonstrate LDPs ability to fabricate various 3D photonic devices, a 2D waveguide array and gradient index (GRIN) lens were fabricated using the process. To create a mm-thick rectangular waveguide array of 3000 waveguides, 100, 10 μm layers were sequentially patterned and stacked within the LDP chamber, a portion of which is shown in Fig. 1(b). The index contrast of the waveguide array was measured to be approximately 0.1, as shown in Fig. 1(b), through a spatially resolved measurement of Fresnel reflectivity. In order to fabricate large gradient index structures required for GRIN lenses and other equivalent devices, a deformable mirror device (DMD) must be used as the lithographic mask. To create a mm-thick GRIN lens, 100, 10 μm layers were sequentially patterned with a DMD and stacked within the LDP chamber, a refractive index map of the index change is shown in Fig. 1(c). In order to improve the fidelity of the GRIN recording, an unstructured cure to gel the layer prior that the gradient exposure is required. However, while this improves the fidelity of the recording, this also decreases the potential index contrast, because the full dynamic range of polymerization is no longer being used.

4. Conclusions

In summary, the LDP process enables efficient production of gradient index structures with arbitrary index feature size and shape not limited by out of focus exposure. By using a liquid, self-developing photopolymer that is manipulated through microfluidics and a chamber window that automatically planarizes each new layer, processing of multiple layers is done on a single instrument, minimizing fabrication time. This technique could be used to fabricate arbitrary 3D refractive index devices such as photonic crystal waveguides, diffractive elements such as volume computer generated holograms and 3D integrated photonic devices.

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