Three-dimensional waveguide arrays via projection lithography into a moving photopolymer

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ABSTRACT

We demonstrate a projection lithography method that induces optical index changes in a flexible polymer cable that is continuously translated through the image plane. We demonstrate that a static spot pattern generates a grid of waveguides along the cable length via a continuous extrusion process. Rotations or scaling of the optical spot array can fabricate image inverters or magnifying face plates in a single process step. The resulting polymer devices have applications in optical backplanes, endoscopes for medical applications and lightweight imaging systems.

Keywords: Holographic photopolymers, Holographic Recording Materials, Direct-Write Lithography, Integrated Optics

1. MOTIVATION

The two dimensional array of vertical cavity surface emitting lasers (VCSEL) is an attractive transmitter for ultra short-reach optical communication due to the potentially high bandwidth per unit area. To capitalize on this large bandwidth density, however, requires a mating waveguide array with pitch matching the VCSEL spacing, which is measured in 10s of µm. The waveguides in the array must be precisely arranged in a two-dimensional grid, making their fabrication difficult with traditional planar lightwave circuit processes.

One can extend 2D planar processes to create 3D arrays by repeating process steps to align and expose layers sequentially, though the tolerances on layer thickness and in-plane alignment make this approach challenging as the number of layers grows. Another approach is to fabricate each layer separately and then stack at the wafer scale followed by dicing of individual parts. Finally, nearly arbitrary 3D waveguide arrays can be formed directly in glass via femtosecond micromachining. This has the advantage of producing a single monolithic part with tight tolerances but the sequential, single-point exposure of waveguides may be too slow for industrial applications. In addition, glass substrates may not meet the cost requirements for high-volume optical backplanes, motivating the use of polymer hosts.

We propose and demonstrate a new form of 3D lithography that can form 3D polymer waveguide arrays in a single process step. The material is a highly sensitive volume photopolymer, enabling rapid processing with small total optical power. The lithography method can create nearly arbitrary 3D waveguide structures including rotations and fan-outs. We demonstrate the process with a 4 by 4 array on 60 µm centers deeply buried in a 4 mm by 4 mm substrate.

2. BACKGROUND

Materials

Traditional photopolymers such as photoresists are patterned by exposure and subsequent monomer removal via solvent wash, making them inappropriate for the fabrication of 3D index structures where solvent access is impossible. In contrast, thick polymers developed for holography require no thermal or wet processing. The process by which optical exposure causes development of index structures in these materials is an active area of research. In the simplified model, a bleaching initiator absorbs a photon with wavelength typically between ~350 and ~600 nm and

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initiates polymerization. This initiator starts growth of the polymer chain, which in turn locally depletes the monomer concentration. The monomer concentration is then refreshed by diffusion from the surrounding volume, locally increasing the density and index in the exposed volume. At the end of the process, a uniform incoherent exposure bleaches all remaining dye and polymerizes the entire sample, “fixing” the desired index change through crosslinking. By careful chemical design, this process occurs with less than 0.1% polymerization shrinkage, minimizing stress and dimensional changes.\(^5\) Index changes are comparable to inorganics at ~10\(^{-2}\) and this can be increased at the expense of greater shrinkage.

In this work we use HDS 3000, green-sensitive holographic photopolymer from InPhase Technologies. An advantage of this material is the separation of mechanical and optically-sensitive functions into two distinct polymer components, as shown in Figure 1. This enables the thermoset matrix polymer to be optimized for optical and mechanical properties independently of the writing photopolymer. The matrix material has high index uniformity and low scatter making it an ideal waveguide substrate. Finally, note that samples are fabricated via simple pour-and-set casting, and do not require spinning or blading.

**Figure 1.** Flexible photopolymer “rods” of 4 mm x 4 mm cross-section on a US quarter coin, fabricated by casting the liquid precursors into a slot mold. The top, clear, sample is matrix only (no photopolymer or initiator), while the bottom, colored, sample is fabricated from the complete, photosensitive mixture.

**Direct write of 3D waveguides**

Unlike most materials used in optical lithography, these diffusion-mediated photopolymers provide analog control over the index of refraction, enabling simultaneous waveguide shape and amplitude control, limited only by the possible 3D optical exposure. A popular fabrication method is to introduce a stationary focused beam at the boundary of a photopolymer volume, for example by embedding a fiber in the polymer.\(^{10,11}\) These “self-exposed” waveguides develop by a complex nonlinear process similar to soliton propagation that can not be directly controlled. Automatic alignment to the light source is attractive, but the light must have sufficient photon energy to initiate photochemistry, generally limiting the method to visible wavelengths and thus excluding use at infrared communication bands.

As shown in Figure 2, both limitations are overcome by scanning the focused point through the 3D photopolymer volume to directly write 3D waveguides.\(^{12}\) These waveguides can be aligned to fiber or other embedded components by machine-vision methods. In contrast to the “self-written” waveguide approach, the profile and amplitude of the waveguide index can be directly controlled by changing the focal spot size and power, respectively, during writing. Inherent absorption of the initiator tends to reduce the intensity on the back of the part; this can be compensated by appropriately compensating with variable writing power.\(^{13}\)
Figure 2. Direct writing of, micron-scale waveguides. The polymer is translated through the focus, parallel to the direction of optical propagation in order to create a straight, gradient-index waveguide of circular cross-section. The guide length is limited to be less than twice the working distance of the lens.

Typical results of this process are shown in Figure 3. The cm-thick polymer volume is transparent after the post-exposure bleaching step. In this case waveguides were written sequentially with 100 microwatts of 532 nm light moving with acceleration of 100 mm/s² (to compensate for absorption in depth). The process is thus similar to femtosecond laser micromachining of glass with the notable exception of the optical power levels required. Note that the linear absorption process results in well-confined, isolated waveguides.

Figure 3. Typical results for sequentially-written waveguides in cm-thick volumes, shown in lower left. The gradient-index cross section and slice along the guide are shown in the tomographic reconstructions, top.
micromted slices placed on a DIC phase microscope, as shown in lower right. Note that the DIC images are naturally the gradient of
the sample index, making this image appear to be a set of "bumps" on a flat plane.

The very low total power used in exposing each waveguide suggests that many can be created simultaneously via
appropriate projection optics. The process begins with a 2D optical pattern that describes the desired index distribution
at one particular slice of the array. This pattern is imaged 1:1 with a custom, symmetric lens system into a glass
projection chamber, shown in Figure 4. The pre-cast polymer blank (shown in Figure 1) is moved with constant velocity
through the optical image in the focal plane. Index-matching oil is used to make the glass chamber and the polymer
blank appear to be a single uniform optical block. The moving polymer responds to the optical intensity pattern with a
permanent increase in index as described previously. A static input image will thus record a 3D waveguide array. The
waveguide pattern can be changed along its length by changing the incident optical spot pattern via rotations, scalings or
interchanges. In the following sections, we describe the design and verification of the custom projection optics and
demonstrate their performance with a 4 x 4 waveguide array.

3. OPTICAL DESIGN

While an off-the-shelf lens is adequate for the sequential process shown in Figure 2, the additional field requirements of
the simultaneous exposure system demand a custom projection lens. An unusual requirement on this lens train is the
need to image deeply within the BK7 exposure chamber, which induces significant spherical aberration. A symmetric
lens design was chosen (see Figure 4) including a glass block of half the exposure chamber thickness in order to cancel
coma and distortion. To minimize cost and lead times, we designed this lens as an assembly of off-the-shelf lenses held
in a custom aluminum lens tube. The plots show the calculated energy distribution, revealing that the system should
reach a two micron spot diameter over a 1 mm polymer blank diameter and a ~6 micron spot diameter over a 4 mm part
diameter.

![Projection Monitor](image)

Figure 4. Geometrical optics model of exposure system showing both custom projection optics and the following monitor system
used for verification (top). The bottom plots show the "encircled energy" calculation which gives the energy distribution within the
spots at various positions within the waveguide array.

Since the image, by design, is buried within the exposure chamber, there is no direct method to verify the
performance of the custom optics. Thus an identical set of monitor optics is also implemented to re-image the spot array
in the polymer to an external plane for validation with a high magnification digital camera. As shown in Figure 5, a
mask with 10x10 square holes of 4 μm diameter on 39 μm centers was illuminated and imaged into the chamber which
was filled with index matching oil in place of the photosensitive polymer. The exposure plane was re-imaged by the
monitor optics and captured with a high-magnification and high-resolution digital camera. The “input image” shows a
small portion of the 2 by 2 mm pattern immediately after the mask and the “output image” shows the captured image at

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the monitor exit plane. We wrote image processing software to find all of the spots captured by the camera and to extract their width and height profiles. The averages of all such profiles are shown at the bottom of Figure 5. The calculated 1/e height and width of the spots in the input array is $(5.4 \pm 0.3) \times (5.3 \pm 0.2) \mu m$, consistent with the 4 \( \mu m \) hard apertures and finite capture NA. At the output plane, the spots are measured to have dimensions of $(6.1 \pm 0.2) \times (6.2 \pm 0.2) \mu m$. This is exactly the diffraction limit calculated in Figure 4, confirming that the illumination optics (not shown), mask, 16 lenses and 4 glass assemblies have all been aligned in all degrees of freedom to within the required tolerances.

Figure 5. Validation of projection lithography optics (Figure 4) via the insertion of a high-resolution spot array (middle left) and its reconstruction at the monitor port (middle right). Measurements of the input and output spot profiles (lower left and right) match the predicted performance.

4. DEMONSTRATION

A 4 by 4 array of optical spots at was generated from a collimated 532 nm laser using a computer generated hologram designed and manufactured by Tessera (formerly Digital Optics Corporation). These 16 coherent spots were relayed to the left-most surface shown in the optical layout of Figure 4. At the exposure plane, these spots are separated by 60 \( \mu m \), have a numerical aperture of approximately 0.04 and power per spot of 10 \( \mu W \) \pm 0.5 \( \mu W \).

The material used is a 4 mm cube of InPhase HDS 3000 Tapestry photopolymer. This material is optimized for roughly one mm thick films, so the concentration of photoinitiator was reduced to 50% to proportionally reduce the optical absorption in this thick volume. This volume is translated through the focal plane, surrounded by index matching oil to avoid aberrations, at a rate of one mm/second. This rate is only for experimental convenience and obviously can be increased at the expense of more than 160 \( \mu W \) total writing power.

To visualize the recorded structures, the part was microtomed and imaged with a DIC microscope, as shown in Figure 6. As desired, each spot has recorded a localized gradient-index waveguide. Given the length of the part and image NA, individual beams in this array have a diameter of \(~200 \mu m\) on one face of the polymer when focused on the opposite surface. However, these large overlaps (roughly the size of the total image in Figure 6) in combination with the one-photon initiation process clearly provide adequate spatial localization. The grid of lines between guides is due to the interference of the out-of-focus portions of the beams and can be removed by decohering the array, although they have minimal impact on the waveguide properties.
Figure 6. Phase image of the recorded index structure using a 4x4 spot array relayed into the polymer via the optical system of Figure 4. The DIC microscope presents the spatial derivative of the optical delay, making the image of the 20 \( \mu \text{m} \) thick, gradient-index polymer slice appear as a series of “bumps” on a flat plane. Lines on the image are due to interference of the out-of-focus portions of the beams.

5. CONCLUSIONS

We have shown that it is possible to fabricate deeply-buried, 3D waveguide arrays in a single, self-developing process step. The custom projection lithography system has 2 \( \mu \text{m} \) spot diameter over a mm part diameter and can accommodate an array length of roughly 7 cm, well in excess of that needed for on-board connectors. We have previously shown that such waveguides can be aligned directly to sources and written with 90° folds off of internal facets\(^\text{15} \), making them interesting for ultra-short reach, high bandwidth communications systems.

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