Single Mode 3D Diffusive Photopolymer Optics for Optical Integrated Circuits

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Abstract: We demonstrate single mode three-dimensional optics fabricated via direct-write lithography in diffusive photopolymers, including uniform waveguides, symmetrical waveguide tapers, 90⁰ sharp waveguide bends and waveguides through thin hybrid subcomponents.

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1. Introduction

We investigate the use of direct-write lithography with a µW laser focused into a one-photon photopolymer to form three-dimensional (3D) waveguides. The peak index and cross section of the waveguides are controlled along the guide path, providing additional degrees of freedom for novel optical circuits. We report novel test procedures for these small (D < 10 µm) and weak (δn < 0.01) 3D waveguides deeply-buried in thick (mm) polymers. Specifically, we show how to perform optical-quality cut-back in these rubbery polymers that cannot be cut or polished, which enables complete characterization of modal properties as a function of distance along the guide. We use this test procedure to show symmetric 3D tapered and uniform polymer waveguides and confirm that they are single-mode (SM) over length. Precise characterization of the mode profile allows the total measured loss to be separated into coupling and propagation loss. These measurements are used to verify the repeatability of uniform waveguide fabrication which in turn provides an accurate validation of the propagation loss measured via cutback. Finally, the initially-liquid photopolymer is used to encapsulate hybrid reflective and transmission optical elements, here a front surface mirror and thin glass windows. Direct write lithography is used to form single-mode waveguides that respectively reflect to form 90⁰ bends or transmit to form hybrid single-mode couplers.

2. 3D waveguide fabrication in diffusion-based photopolymer

Typical diffusive photopolymers[1] are flexible solids with active components consisting of an initiator that absorbs a fraction of the incident light to form radicals and a monomer that polymerizes by reaction with this photo-initiator. A localized illumination therefore creates high molecular-weight polymer in the illuminated region via the consumption of low molecular-weight monomer units. This local depletion of monomer causes monomer diffusion into the exposed region, resulting in an area of increased density and refractive index. After this mass transport has locally increased the refractive index, a uniform optical exposure is used to consume all the remaining initiator and monomer, rendering the polymer chemically and optically inert and thus environmentally stable. The diffusion-based photopolymer used in this work is InPhase Technologies Tapestry™ HDS 3000 modified for lower absorption by half the usual photoinitiator concentration.

Fig. 1 Optical layout of the direct-write lithography system. The logarithmic neutral density filter modulates the laser with large dynamic range naturally matched to exponential Beer-Lambert absorption of the material.

Direct-write lithography used in this paper for 3D waveguide fabrication is implemented by moving the polymer sample primarily parallel to the optical axis to create symmetrical guides from a symmetrical focus[2]. 3D waveguides are formed by focusing several µW of the 50-mW Coherent Compass 315M laser into the moving polymer, as shown in Fig. 1. Although the cm-thick polymer is optically thin, weak Beer-Lambert absorption naturally tapers the waveguide index if incident power is held constant. This taper can be controlled or eliminated by a logarithmic-variable neutral density (ND) filter, Thorlabs NDL-10C-4, moved synchronously with the sample.
via Newport PM500 stages. By varying the velocity of the ND filter relative to the velocity of the polymer, the incident writing power can be modulated proportional to $T_{\text{Eff}} e^{-z}$, where $T_{\text{Eff}}$ is the effective material transmittance and $z$ is the material depth to the focus in mm.

3. **Pseudo-cutback and active mode imaging for waveguide characterization**

Tapered and uniform 3D waveguides written into this diffusion-based photopolymer bulk are difficult to characterize as a function of length because polymer materials can be difficult to cut and polish, particularly the rubbery materials required for diffusion of the monomer. This difficulty can be overcome by exploiting the flexible nature of the polymer. First, individual polymer layers with thickness of 1 mm are cast between glass plates. These layers are separated from the glass molds and laminated into an optical-quality thick sample. Coherent confocal microscopy verifies that the laminate boundaries have less than 0.1% reflectivity, indicating intimate contact. Glass microscope slides are laminated to the front and back to act as optical windows. After waveguides are written and developed, the laminated stack is easily separated into optically-flat sections, avoiding the need to cut or polish the polymer.

After separation, the mode profile of the individual polymer layers can be individually tested to characterize taper performance. Each polymer layer is laminated to a front-surface metal mirror so that testing of the waveguide can be performed in reflection, as shown in Fig. 2(a). This reflection test method provides two advantages: the path length is doubled, helping to separate guided from radiation modes and only one alignment is needed, improving the repeatability of coupling loss measurement. Mode profiles versus thickness for single-mode 3D uniform and tapered waveguides are presented in Fig. 2(b). These waveguides are written at 1 mm/s using a focused spot of 4.36 $\mu$m 1/e$^2$ diameter. The writing power is 1.5 $\mu$W at the front surface, modified by three power profiles along the waveguide’s depth. The power profile with $T_{\text{Eff}} = 0.71$ yields a uniform waveguide with mode diameter of 5.2 $\mu$m, while the modes of waveguides written with $T_{\text{Eff}} = 0.73$ and 0.75 are parabolically tapered.

![Fig. 2 Characterization of the 3D waveguides. (a) Optical layout of the waveguide characterization system. The incident laser focus is aligned to the buried waveguide front face by maximizing power returned through the confocal filter. The filter rejects radiation modes and out-of-focus reflection to precisely characterize total round-trip loss. The magnified image of the guided mode is captured on a commercial beam profiler. A typical measured profile from a SM mode is shown in the inset. (b) Measured mode diameters of 3D waveguides. All the waveguides are confirmed to be single mode. The error bars are one standard deviation of seven samples at each point, demonstrating the repeatability of the process. Dotted lines are parabolic fit to show trends.](image)

This mode characterization along the guide length enables simple and accurate measurement of propagation loss of a single waveguide via calculation and subtraction of coupling loss. To confirm the accuracy of this measurement, we exploit the repeatability demonstrated in Fig. 2(b) to test individual waveguides with different lengths, shown in Fig. 3(a). Uniform waveguides are written with an exposure power of 1.5 $\mu$W and power profile $T_{\text{Eff}} = 0.71$ in three polymer slabs of thickness $L = 1$, 5, and 10 mm, respectively. Each slab is tested to obtain propagation loss for length $2L$ and coupling efficiency. Then, excess propagation loss was obtained by fitting the results of four experiments at each length to a line, as is standard for the cutback method, shown in Fig. 3(b). Excess propagation loss of four samples of each length yields 0.147 ± 0.009 dB/cm waveguide loss. The y intercept from the linear fit equation 0.393 ± 0.124 dB, close to the calculated coupling loss 0.413 ± 0.056 dB. This accuracy enables excess propagation loss measurement just from a sample of single length by subtracting the calculated coupling loss from the total loss of a 10-mm waveguide, yielding 0.140 ± 0.043 dB/cm, in good agreement with the line fit.
4. 90° sharp waveguide bends and waveguides through thin transmission optics

Sharp waveguide bends make integrated optical circuit compact[3] and provide convenient vertical coupling for optical circuits[4]. Here a 90° sharp waveguide bend is automatically formed by dragging a focused laser spot through a polymer triangular prism, shown in Fig. 4(a). The waveguide bend is characterized with the active mode imaging system, shown in Fig. 2 (a). The excess loss at 90° bending is measured to be 1.278 dB.

Transmission optical elements such as Faraday rotators, wave-plates or thin-film filters are difficult to integrate into integrated optical systems. Here, we illustrate perfectly-aligned waveguides formed across thin glass windows to illustrate the capability, as shown in Fig. 4(b). The coupling loss of the SM waveguide illustrated in Fig. 4(c) is tested with the system of Fig. 2 (a). The testing results, shown in Fig. 4(d), match theory to within 0.3 dB.

5. Conclusion

We demonstrate single-mode uniform and parabolically tapered three-dimensional waveguides fabricated via direct-write lithography in diffusive photopolymers. Modulation of the writing power is shown to compensate Beer-Lambert absorption in the single-photon initiator and to provide precise control of modal tapers. A laminated sample preparation is introduced to enable full 3D characterization of these modal tapers without the need for sample polishing which is difficult for this class of polymer. The accuracy and repeatability of this modal characterization is shown to allow precise measurement of propagation loss from single samples. These testing procedures are used to demonstrate single-mode waveguides with 0.147 dB/cm excess propagation loss and symmetrical tapers up to 1:2.5 using 1.5 microwatts of continuous write power. The coupling loss of SM uniform 3D waveguides through thin transmission elements is in good agreement with theoretical calculation. The measured loss at the SM 90° sharp polymer waveguide bends is 1.278 dB.

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