Mode profile imaging and loss measurement for uniform and tapered single-mode 3D waveguides in diffusive photopolymer

Chunfang Ye, 1 Keith T. Kamysiak, 1 Amy C. Sullivan, 2 and Robert R. McLeod 1, *  

1 University of Colorado, Boulder, CO 80309, USA  
2 Agnes Scott College, Decatur, GA 30030, USA  
* Robert.McLeod@colorado.edu

Abstract: We demonstrate single-mode uniform and parabolically tapered three-dimensional waveguides fabricated via direct-write lithography in diffusion-based 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.

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Introduction

Traditional optical waveguide circuits are planar devices with uniform thickness and discrete index profiles. In the past decade, there has been growing interest in three-dimensional (3D) waveguides whose path, peak index and cross section can all be controlled along an arbitrary guide path. These additional degrees of freedom enable novel optical circuits and may provide a platform for the interconnection of fiber and other traditional waveguide devices, including mode transformations.

Current approaches to 3D waveguide fabrication can be characterized by the lithography method (direct write vs. “self-written”) and the material photo-response (multiphoton vs. single photon). The most common technique is 3D scanning direct-write lithography with a femtosecond laser which undergoes multiphoton absorption at the focus to locally change the index of refraction of glass or polymer [1–3]. This method is popular because the lithography approach provides programmable 3D control over the waveguide path and the nonlinear absorption confines the response to the focal region. The primary disadvantages are low fabrication speed enforced by the small multiphoton cross section and difficulty in aligning the waveguides to other devices. The second common approach is to “self-write” waveguides in a one-photon sensitized photopolymer. Here, light from a stationary focus or embedded fiber is introduced directly into the photopolymer, forming a waveguide which propagates into the polymer in a soliton-like fashion [4]. The advantages of this approach are its simplicity and the automatic alignment of the self-written waveguide to an embedded or butt-coupled source. However this technique has limited control over the shape and direction of the resulting waveguides and single-mode operation has not yet been demonstrated over millimeter scale [5, 6]. Finally, nearly all studies of 3D waveguides to date have performed limited characterization because the deeply buried, gradient-index guide is not compatible with profilometry, prism coupling or other measurement methods designed for planar devices. This lack of characterization methods is particularly problematic for studies of nonuniform guides such as modal tapers [7–9].

In this work, we investigate the use of direct-write lithography, which provides control over the waveguide path and mode, with a one-photon photopolymer, which requires only a low-power continuous laser source. Specifically, we show that direct-write lithography with a μW laser focused into a one-photon photopolymer can form symmetric, single-mode, 3D waveguides. The power of the writing laser is varied to compensate for absorption and to create precisely controlled modal tapers.

Additionally, we report test procedures for deeply-buried polymer waveguides not compatible with existing techniques. The waveguides written are small (D < 10 μm), weak (δn < 0.01) and deeply embedded in thick (mm) polymers, defeating most index and modal characterization methods. Near-field techniques such as electron microscopy and profilometry
can provide precise index shape of ridge planar waveguides, but do not apply to embedded 3D waveguides. Phase microscopy such as differential interference contrast (DIC) microscopy [10] typically offers a qualitative, but not quantitative, index picture. Quantitative phase microscopy has been reported [11], but is limited to physically thin objects. Specialized methods for index profiling of 3D waveguides and fiber cores including modified optical diffraction tomography (ODT) [12], scanning transmission microscopy [13] and reflection scanning [14] do not provide a complete 3D measurement of the guide index. This incomplete characterization prevents the calculation of the critical waveguide properties including mode size, shape and loss.

An alternative is to forgo index measurement and instead to directly measure modal properties along the guide length. The prism-coupling method is commonly used for planar waveguides, but it is not applicable for deeply embedded 3D waveguides. The cutback method allows mode characterization of 3D waveguides including tapers but requires an optical-quality polish after each cut. While appropriate for inorganic glasses and crystals, this polishing step is often impossible for polymers, particularly those with low glass transition temperature as used here. This lack of index or modal test methods for 3D glass and polymer waveguides is reflected in virtually no reported characterization beyond total loss and end-facet mode profile.

Here, we introduce a procedure that enables optical-quality cut-back surfaces in polymers that cannot be cut or polished. Thick, optical-quality materials are first fabricated as laminates of a number of thin polymer layers. After waveguide lithography, the layers are separated and independently tested for modal properties. This provides complete characterization of modal properties as a function of distance along the guide.

We use this test procedure to show symmetric 3D tapered and untapered polymer waveguides and confirm that they are single mode 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.

**3D waveguides fabricated in diffusion-driven photopolymers**

Photopolymer offers several advantages over glass as a material platform for optical waveguides including greater optical sensitivity, widely tunable material properties and lower cost. However, polymers used for 3D waveguides must self-develop an index change in response to light, unlike 2D waveguides in which wet chemistry (e.g. solvents) can be used to develop structure [15]. For example, multiphoton absorption writing uses the increased index of the photopolymerized region at the focus [2, 3]. Unfortunately, the structure is only stable so long as one-photon or thermal processes do not cause the large remaining quantity of initiator and monomer to react. Since this assumption is not applicable for one-photon absorbers, an additional process is required to form permanent structures in 3D one-photon polymers.

Diffusive photopolymers, also referred to as volume or holographic photopolymers, were originally developed for holographic data storage (HDS) [16] and have recently been adapted for 3D optical interconnection [5, 17, 18]. Typical diffusive photopolymers consist of two chemical systems: one that forms a solid yet flexible matrix and the photo-active components consisting of an initiator that absorbs a fraction of the incident light to form radicals or other initiating species and a monomer that polymerizes by reaction with this photoinitiator. The matrix can be formed from the same monomer as the writing material [19] or from an initial catalyzed thermal reaction [20]. After this matrix formation, localized illumination of the photo-active components creates a high molecular-weight polymer in the illuminated region via the consumption of low-molecular-weight monomer. 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
diffusive 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.

Direct-write lithography for 3D waveguide fabrication can be implemented by moving the
polymer sample primarily perpendicular or parallel to the optical axis [17]. Perpendicular
writing tends to create asymmetrical guides, however beam shaping has been demonstrated in
multiphoton absorption to create symmetrical waveguides [2, 21]. Alternatively, parallel
writing automatically creates symmetrical guides from a symmetrical focus [17]. The parallel
write geometry is used in this paper, as shown in Fig. 1. 3D waveguides are formed by
focusing several µW of the 50-mW Coherent Compass 315M laser into the moving polymer.
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 $T_{Eff}^{z}$, where $T_{Eff}$ is the effective material transmittance and $z$ is the material
depth to the focus in mm. Beer–Lambert absorption is compensated at the focus when $T_{Eff}$
equals the pre-exposure transmittance of 1 mm of material.

**Pseudo-cutback method for 3D mode 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 as shown in Fig. 2.
First, the liquid polymer precursors are cast between flat glass plates separated by 1 mm
spacers. Room-temperature thermal polymerization solidifies the material into optical-quality
slabs which are then removed from the mold and laminated together to form multi-mm
samples. 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.
Fig. 2. Pseudo-cutback method developed for polymers that cannot be cut or polished. Step 1: Cast individual polymer layers. Step 2: Laminate the layers into a thick polymer sample. Step 3: Write guides through the laminated polymer sample. The material transmittance (dashed line), the incident power curve (dash-dot line) and power at the focus (solid line) along the depth are also shown. Step 4: Separate the individual layers. Step 5: Test individual layers.

After separation, the individual polymer layers have optical-quality faces and can be individually tested for mode profile 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. 3. 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.
Fig. 3. Optical layout of the waveguide characterization system. The incident laser focus with 2.6µm 1/e² diameter is aligned to the buried waveguide front facet by maximizing power returned through the confocal filter. This filter rejects radiation modes and out-of-focus reflections to precisely characterize total round-trip loss. Without the waveguide, the incident laser beam diffracts through the (at least) 1mm polymer slab, reflects at the mirror and (at most) 0.02% of light couples back to the detector. The magnified image of the guided mode is captured on a commercial beam profiler. A typical measured profile from a single-mode guide is shown in the inset, which is nearly perfect Gaussian in shape.

We show below that the measured mode profile enables calculation of coupling efficiency, allowing propagation loss to be extracted from total measured loss. However, this is only true if the guides support only a single mode. Since the mode image shown in Fig. 3 could be the sum of the fundamental and one or more symmetric higher-order modes, an independent test must be used to verify that only a single mode is present. Scanning the incident beam focus across the guide excites the fundamental and possibly higher-order antisymmetric modes. Coupling efficiency versus offset to these multiple modes will be broader than coupling to a single mode. This latter quantity can be calculated via the overlap integral of two displaced Gaussian fields as shown in Fig. 5(a) to be a Gaussian versus offset ∆y with a radius \( \sqrt{\frac{w_1^2 + w_2^2}{2}} \). As shown in Fig. 4, the measured coupling efficiency agrees well with the theoretical prediction. This confirms that the waveguides support only a single mode.

![Mode Profile](image1)

![Mode Imaging](image2)

Fig. 4. Verification of single-mode performance. (a) Test geometry. (b) Measured and theoretically calculated coupling efficiency as a function of offset in the y direction. The coupling efficiency is measured via the confocal filter to reject extraneous signals such as surface reflections and radiation modes.
Mode profiles versus thickness for single-mode 3D uniform and tapered waveguides are presented in Fig. 5. These waveguides are written at 1 mm/s using a focused spot of 4.36 µm 1/e^2 diameter. The writing power is 1.5 µW at the front surface, modified by three power profiles T_{Eff} along the waveguide’s depth. One example of these power profiles is shown as the dash-dot line in Fig. 2. The power profile with T_{Eff} = 0.71 yields a uniform waveguide with mode diameter of 5.2 µm, while the modes of waveguides written with T_{Eff} = 0.73 and 0.75 are parabolically tapered. The mode profiles are nearly Gaussian (Gaussian fit quality [22] ≥ 0.92) and symmetrical within measurement limits. The narrow error bars in Fig. 5 demonstrate the ability to write repeatable uniform and tapered waveguides.

The index profile of a waveguide is not uniquely determined by the mode profile. However we can estimate peak index change ∆n by assuming the index shape of the waveguide. For a single-mode waveguide with a Gaussian-shaped index profile \( n^2(r) = n_0^2 + NA^2 e^{-r^2/\rho^2} \), the field radius \( r_0 \) of the guided mode can be expressed as [23]:

\[
    r_0 = \frac{\sqrt{2} \rho}{\sqrt{(NAk_0\rho - 1)}}
\]

where \( \rho \) is the radius of the index profile, \( NA \) is the numerical aperture of the mode, \( n_0 \) is the bulk refractive index of the waveguide, and \( k_0 = 2 \pi / \lambda_0 \) is the vacuum wavenumber with \( \lambda_0 = 635 \) nm. Note that Eq. (1) differs from reference [23] due to different definitions of the mode filed. In reference [23], the mode field is defined as \( \psi(r) = \psi_0 e^{\frac{1}{2}i(r/\rho)^2} \), while in the mode profiler measurement it is defined as \( \psi(r) = \psi_0 e^{i(r/\rho)^2} \). Sublinear kinetics of radical photoinitiation [24] result in an index change proportional to \( P^\alpha \), where \( I \) is the writing beam intensity and \( \alpha \) is a single fit parameter [24]. We have previously shown the sub-linear kinetic parameter \( \alpha \) to be ~0.75 for this material [17]. Given \( I(r) = I_0 e^{-2r/w_0^2} \), where \( w_0 \) is the 1/e^2...
radius of the writing beam, the index profile is \( n(r) \propto e^{-2\alpha(r)/n_0} \), resulting \( \rho = \frac{w_0}{(\sqrt{2}\alpha)} \). Therefore, the calculated \( NA \) for the uniform waveguide shown in Fig. 5 is estimated to be 0.12. Since \( NA \) of a single-mode waveguide can be approximated as \( NA = \sqrt{(n_0 + \Delta n)^2 - n_0^2} \), where \( n_0 = 1.481 \), the estimated peak index change \( \Delta n \) is \( 4.64 \times 10^{-3} \), which is consistent with holographic recordings in the same material [16].

**Loss measurement for uniform single-mode polymer waveguides**

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. 5 to test individual waveguides with different lengths, shown in Fig. 6(a). Uniform waveguides are written with an exposure power of 1.5 \( \mu \)W and power profile \( T_{eff} = 0.71 \) in three polymer slabs of thickness \( L = 1, 5, \) and 10 mm, respectively. Each slab is tested as shown in Fig. 3 to obtain propagation loss for length \( 2L \) and coupling efficiency. 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. 6(b). Excess propagation loss of four samples of each length yields \( 0.147 \pm 0.009 \) dB/cm waveguide loss. The \( y \) intercept from the linear fit Eq. (0.393 \pm 0.124 dB, close to the calculated coupling loss 0.413 \pm 0.056 dB. This accuracy enables propagation loss measurement from a sample of a single length by subtracting the coupling loss calculated from the mode measurement from the total loss. For a 10-mm waveguide this yields an excess propagation loss of 0.140 \pm 0.043 dB/cm. This loss is in addition to bulk material absorption of 0.141 \pm 0.038 dB/cm due primarily to incomplete initiator bleaching. The characterization of mode size and single-mode condition versus length enables precise knowledge of the coupling loss even for tapered guides, which in turn permits measurement of propagation loss from a single sample length, avoiding the need for cutback loss measurement.

![Fig. 6. Experimental layout and results of loss measurement for the uniform single-mode waveguides. (a) Modified cutback method for loss measurement. Couple the incident laser beam into the waveguide and capture the maximum power in the guided mode on the mode profiler. By comparing the power in the guided mode to the measured power when the incident laser beam is focused at the front surface mirror, the material absorption and loss at the reflection surfaces are calibrated out. (b) Loss versus guide length.](image-url)

**Conclusion**

We have demonstrated uniform and parabolically tapered single-mode 3D waveguides in diffusion-based photopolymers and introduced methods to accurately measure mode profile and propagation loss along the guide length. Single-photon holographic photopolymers
developed for data storage are shown to be an attractive platform for 3D photonics due to their high sensitivity and self-developing index change. A logarithmic ND filter synchronized to the sample motion is shown to be a natural external modulator to compensate for Beer-Lambert absorption in order to fabricate uniform and tapered single-mode waveguides. A laminated sample fabrication method is shown to provide optical-quality surfaces for direct measurement of the evolution of the single-mode profile along the taper length. This precise and repeatable characterization enables coupling loss to be accurately calculated to find propagation loss from single sample measurements. The accuracy and repeatability of both the fabrication procedure and testing methods are verified by loss measurements for guides of 1 to 10 mm length which show excellent agreement. These results demonstrate single-mode waveguides with 0.147 dB/cm excess propagation loss and symmetrical tapers up to 1:2.5 using 1.5 µW of continuous write power.

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