3D Tapered Waveguides in Volume Photopolymers

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Abstract: We demonstrate tapered waveguides written in volume photopolymers using a three-dimensional (3D) direct-write lithography system. Cross sections of the tapered index profiles are measured using an optical diffraction tomography system.

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1. Introduction

Integrated optical circuits frequently require various forms of mode transformation, such as coupling from lasers to fibers, single mode fibers to multimode waveguides, and between single mode fibers with different mode sizes [1]. Tapered waveguides are required to adiabatically change from one mode size to another in order to reduce coupling losses [2]. Coupling into a larger waveguide and then converting to a smaller mode via a tapered waveguide can also reduce alignment tolerances when coupling to a single mode fiber [3]. We demonstrate tapered waveguides written in diffusion-mediated photopolymers for applications in integrated optical systems. Unlike in planar waveguide systems, where the waveguide tapers in only one dimension along its length, these waveguides have a cylindrically symmetric taper.

A three-dimensional (3D) direct-write lithography system that is capable of writing deeply embedded waveguides in diffusion-mediated photopolymers has recently been demonstrated [4]. These photopolymers have an analog response to the incident writing light, which allows us to write gradient index structures in all three dimensions. By varying the writing conditions, we can create waveguides that taper along their length. We demonstrate tapered waveguides written with this method. We also describe a measurement system capable of imaging the embedded index structures, which we use to characterize the taper.

2. 3D Direct-write Lithography

We use the direct-write lithography system described in [4] to fabricate tapered waveguides using the parallel writing geometry shown in Fig. 1. For the experiments described here, 4 mm x 10 mm x 45 mm disposable cuvettes are filled with InPhase Technologies media [5]. Since this photopolymer material is photoinitiated at 532 nm, a frequency-doubled Nd:YAG laser is focused into the material to write the waveguides. The green light is focused through an achromatic doublet lens operating at 0.1 NA in air to a calculated $1/e^2$ radius of $w_0 = 1.7 \text{ \mu m}$. The waveguides are written by focusing the light slightly behind the 10 mm length of the sample, opening a shutter, moving the sample away from the lens until the focus is slightly in front of the sample, and then closing the shutter. The waveguides presented here were written.
with 20 μW of incident green light and the stages were moved at a constant velocity of 2 mm/s. The resulting waveguides are 10 mm long and are cylindrically symmetric perpendicular to the beam propagation direction due to the cylindrically symmetric profile of the Gaussian beam. Because these samples are 10 mm thick along the propagation of the green light and the material has about 70% absorption in 5 mm, less writing light reaches the back of the sample than the front. This results in a waveguide that is stronger at the front of the sample and tapers to a weaker index guide at the back of the sample.

3. Results

Once the tapered waveguides have been written, measurements of these small, weak, deeply embedded index structures can be difficult. We use optical diffraction tomography to reconstruct two-dimensional cross sections of the index structures from a series of diffracted field measurements taken over a range of probe beam incident angles [6,7]. In the Born approximation, where the index perturbation is small enough that the probe beam is essentially undepleted, the Fourier transform of the index perturbation is directly related to the Fourier transform of the scattered field and can be reconstructed through backpropagation of this field. In general, this requires full amplitude and phase measurements of the scattered field, but for symmetric, smoothly varying index structures, the scattered field is real and so is equal to the square root of the intensity. Therefore, phase information is not required. We also overcome the low signal-to-noise problem of measuring weak index structures by optically ruling many equally spaced, identical waveguides, forming a grating with a diffraction efficiency that grows as the square of the number of illuminated lines [8]. The measured diffracted field will then be sampled at a spatial frequency of one over the grating period. As long as the line spacing is significantly larger than the size of the feature to be imaged, measurement of these discrete diffracted orders is sufficient to reconstruct the index of a single line, and the greater signal to noise allows us to more easily measure weak index changes.

The optical tomography system is implemented using a HeNe laser at 633 nm. We measure the index profile of the tapered waveguide by sending an approximately 1 mm diameter collimated beam through the sample and measuring the diffracted orders of the grating. These measurements are taken at 1 mm intervals along the length of the tapered waveguides. The diffracted intensity data is then backpropagated to reconstruct the index structure at different points along the length of the waveguide as shown in Fig. 2. The figure shows normalized cross sections of the index profile of the waveguide. The 0 mm position corresponds to the end of the waveguide that was closest to the lens during writing and consequently was exposed to the highest intensity. The index profiles decrease in amplitude along the length of the guide,
with the weakest index structure farthest from the writing lens as predicted. A Differential Interference Contrast (DIC) image of the tapered waveguide is shown in Fig. 3. The figure shows a set of 10x images stitched together to qualitatively show the change in amplitude of the index along approximately 5 mm of the length of the waveguide. Two waveguides, spaced 100 μm apart, are imaged with a 0.3 NA objective through a 4 mm thick polymer sample. The left side of the images shows the part of the waveguide that was closest to the lens during writing. Both figures show that the index profile of the waveguide decreases along the length, creating a tapered waveguide.

![Fig. 3. Differential Interference Contrast image of the tapered waveguide. Two waveguides are shown, spaced 100 μm apart. These images do not show the entire length of the taper, but show a qualitative picture of how the amplitude of the index changes along approximately 5 mm of the length of the waveguide. The side on the left of the picture was closest to the lens during writing and therefore has the stronger index change.](a166_1.pdf)

4. Conclusions

We demonstrate tapered waveguides written into photopolymers using a 3D direct-write lithography system. The parallel writing geometry combined with high material absorption creates waveguides that taper along their length. This changes the peak index of the waveguide without significantly altering the shape or size of the index structures. Varying the material absorption, writing beam size, or the speed or intensity of the beam during writing can be used to control the extent and the shape of the waveguide taper. We have also described an optical diffraction tomography system for producing high resolution images of the weak, deeply embedded waveguides. This allows us to accurately characterize the tapering index structure along its length.

References