Femtosecond laser fabrication of tubular waveguides in poly(methyl methacrylate)

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Femtosecond laser direct writing is employed for the fabrication of buried tubular waveguides in bulk poly(methyl methacrylate). A novel technique using selective chemical etching is presented to resolve the two-dimensional refractive-index profile of the fabrication structures. End-to-end coupling in the waveguides reveals a near-field intensity distribution that results from the superimposition of several propagating modes with different azimuthal symmetries. Mode analysis of the tubular waveguides is performed using the finite-difference method, and the possible propagating mode profiles are compared with the experimental data. © 2004 Optical Society of America

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Current techniques used for waveguide fabrication, such as photolithography, reactive ion etching, and high-energy ion implantation, are inherently planar technologies that require numerous processing steps and most often require the prior design and fabrication of a mask. By contrast, laser direct writing has the advantage of being maskless, allowing single-step, on the fly processing. Both UV and femtosecond lasers have been found to be effective as writing lasers. For UV irradiation the required refractive-index modification results from single-photon absorption, where the photon energy is near the material bandgap energy. The main limitation to UV-laser direct writing is the absorption of the glass, which restricts interactions to the penetration depth of the material (<1 mm). By contrast, femtosecond lasers operate at photon energies far below the material bandgap energy, permitting volumetric processing to a depth limited only by the working distance of the focusing element. In this case three-dimensional waveguides can be fabricated. Femtosecond lasers have also demonstrated better quality waveguides, lower insertion loss, and stronger refractive-index change in fused silica than UV lasers.[1] A large number of photonic devices have been successfully fabricated with femtosecond laser direct writing, including channel waveguides and Y couplers,[2] directional couplers,[3,4] gratings,[5] and active waveguides.[6]

Most studies in this field have concentrated on oxide glasses, most particularly, fused silica. Although the importance of fused silica as a substrate material is evident, other materials can be of importance for several applications. Polymeric materials offer a versatile, low-cost option for the fabrication and prototyping of waveguiding structures. In particular, poly(methyl methacrylate) (PMMA) is an inexpensive and widely used polymer for the cores of communications-grade polymer optical fibers. Although refractive-index gratings have been fabricated in this material with a femtosecond laser,[7,8] waveguide fabrication has been accomplished only with UV lasers and has suffered the limitations mentioned above. In this Letter we report, for the first time to our knowledge, volume fabrication of waveguiding structures in bulk PMMA with femtosecond laser radiation. We describe the writing technique, which uses a simple laser oscillator operating in the low-repetition-rate high-pulse-energy regime. We characterize the fabricated structures by measuring the near-field intensity distribution at the waveguide output, and we introduce a novel technique to resolve the refractive-index profile. Modeling of the propagating modes is performed by use of the finite-difference method.

The laser oscillator that is used for the writing process is an extended-cavity Ti:sapphire laser with a repetition rate reduced to 25 MHz and an ~40-nm spectral bandwidth centered at 800 nm that produces 20-nJ pulses with 30-fs duration and 4.5% pulse-to-pulse stability. The Gaussian laser output beam is focused by a 0.25-N.A., 10× microscope objective into a 12-mm-thick PMMA sample (Lucite L) that was translated parallel to the laser beam by a computer-controlled three-axis translation stage at 20 μm/s. The fabricated structures were examined with a difference interference contrast microscope [Fig. 1(a)]. This micrograph reveals that the structures exhibit a circular 25-μm-diameter cross section. Although difference interference contrast microscopy is not a quantitative technique, it can be inferred that the darker center region (Region I) and the lighter ring-shaped region (Region II) exhibit refractive-index changes of opposite sign. This can be interpreted as a result of thermal expansion at the point of focus of the laser during the writing process, which causes tensile

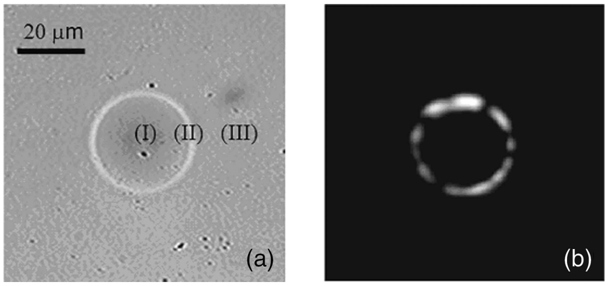

Fig. 1. (a) Difference interference contrast microscope image of the waveguide cross section. (b) Near-field intensity distribution at the waveguide output ($\lambda = 632.8$ nm).

and compressive stress at the center and in the surrounding regions, respectively. That is, the material in Region II is compressed against the intact material (Region III) and increases in density, resulting in an increase of its refractive index. This interpretation is supported by the near-field intensity distribution of a coupled He–Ne laser beam ($\lambda = 632.8$ nm) observed at the waveguide output [Fig. 1(b)].

Few techniques have been proposed so far that spatially resolve complex refractive-index profiles. The refractive-index contrast Δn in a laser-fabricated waveguide is usually estimated from the numerical aperture of the waveguide output.[3,6] Other techniques include interferometric measurement[5] or fitting a calculated mode profile to the measured near-field intensity.[1] However, these techniques have a limited accuracy and are unable to resolve complex index profiles. The refracted near-field (RNF) method is a more accurate technique[4,9] through which the refractive-index profile is obtained by moving a focused laser spot across the fiber end face and measuring the light intensity refracted sideways through the core boundary. Accuracies down to 10^{-4} are commonly achieved with sufficient spatial resolution to resolve complex profiles. However, this technique involves the use of high-cost equipment and requires specific sample preparation.[9] We have devised a rapid and cost-effective method through which the refractive-index profile across a waveguide buried in PMMA can be determined from its surface profile after it has been treated with a wet chemical etching process. With the assumption that Regions I–III all have a slightly different structure as a result of photoinduced and thermally induced stress, the solubility of each region to a given solvent, and therefore the etch rate, is expected to be different.

Selective chemical etching was performed on a surface transverse to the waveguide. The surface was polished (rms <10 nm) to eliminate laser damage resulting from the writing process and treated with Methyl Isobutyl Ketone for 60 min and cleaned with 2-propanol. The surface profile was then analyzed with a white-light interference microscope (Zygo NewView5000) that had 0.64-μm lateral resolution and 0.1-nm vertical resolution. As shown in Fig. 2(a), the different regions sustained different etch rates, measured to be 2.5 nm/min for Region I, 11.6 nm/min for Region II, and 5 nm/min for Region III. From the coupling properties of these structures, the high-refractive-index region (Region II) exhibits the fastest etch rate, giving rise to the depressed region in the surface profile. The relative refractive-index profile can therefore be obtained by reversing the surface profile illustrated in Fig. 2(a). The absolute refractive-index profile [Fig. 2(b)] can then be obtained after a one-time calibration by measuring the maximum refractive-index change $\Delta n_{\max}$ observed in Region II. The $\Delta n_{\max}$ value was separately measured to be 0.002 by use of a waveguide optical analyzer (EXFO OWA-9500) based on the RNF method.

The shape of the refractive-index profile determined by the selective etch profiling method was found to be consistent with the absolute profile measured with the RNF method [Fig. 2(b)]. This novel approach to estimating the refractive indices of waveguides in PMMA depends at present on the assumption of a linear dependence of etch rate and refractive-index change. This assumption is supported by the linearity between etch rate and refractive index found in similar studies[10,11] and by the strong correlation of the measured index profile with the results obtained with the RNF measurement. Separate studies of this dependence in PMMA are now under way.

This profile is characteristic of a tubular waveguide, in which guiding occurs within an annular core. In such waveguides a small local part of the large annular cross section is analogous to a transversely bent planar waveguide. This allows a relatively large total waveguide structure size (25 μm), yet with a guiding region of small dimensions (~5 μm wide). Refractive-index profiles of this type have been used to optically trap and manipulate micrometer-sized particles.[12] An analytical solution to the step-index annular-core fiber was proposed by Sarkar *et al.*[13] in the cylindrical polar coordinates (r, θ, z) by solving the Helmholtz equation

$$\nabla^2\psi + \frac{n^2}{c^2}\frac{\partial^2\psi}{\partial t^2} = 0\,, \tag{1}$$

where ψ is the electric field component along the propagation axis z. One can find a solution to Eq. (1) in the guiding region of index n_2 (Region II) by considering ψ to be harmonic in time t and space z coordinates. The solution can then be expressed by

$$\psi = \sum_v [a_v J_v(u_v r) + b_v Y_v(u_v r)]\exp(jv\theta)\,, \tag{2}$$

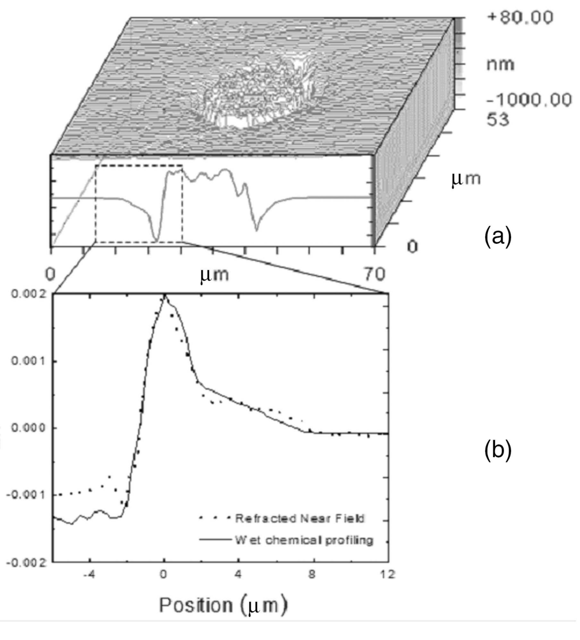

Fig. 2. (a) Three-dimensional cross-sectional surface profile after selective chemical etching, (b) corresponding refractive-index profile of a laser-written waveguide in bulk PMMA. The profile is centered on the waveguide core (Region II).

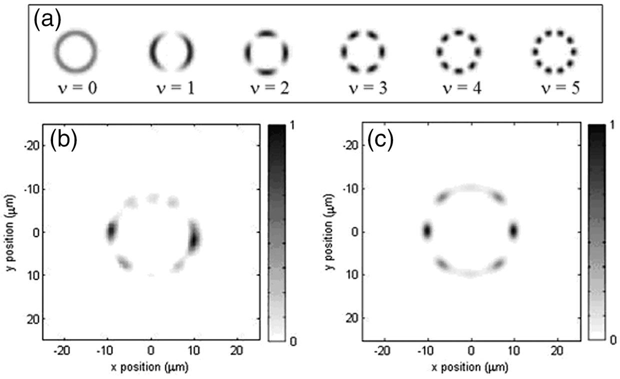

Fig. 3. (a) Numerical simulation of the intensity distribution for the possible modes. (b) Measured near-field intensity distribution at the waveguide output ($\lambda = 632.8$ nm). (c) Calculated intensity distribution of the mode superimposition.

where

$$u_v{}^2 = n_2{}^2 k^2 - \beta_v{}^2 ; \qquad (3)$$

v is the mode index (nonnegative integer), β_v is its corresponding modal propagation constant along z, and k is the free-space propagation constant. The field follows a Bessel function and a modified Bessel function along radial coordinate r and is expected to oscillate along azimuthal coordinate θ.

Numerical mode analysis was performed for the fabricated waveguides. We performed the modeling by solving the quasi-TE semivectorial representation of Eq. (1), using the finite-difference method for the refractive-index distribution described in Fig. 2(b). Because of the small radial width of the region, the waveguide was found to be single mode in the radial direction. By contrast, because of the large circumference of the waveguide, several modes exist in the azimuthal direction [Fig. 3(a)].

End-to-end coupling in the waveguides was performed with a He–Ne laser, and the output intensity distribution was captured in the near field with a CCD camera. For different coupling alignment configurations, the output intensity profile had different degrees of symmetry and appeared as a superimposition of several modes that were excited. Figures 3(b) and 3(c) show, respectively, an example of a measured output intensity profile and the calculated intensity profile corresponding to the superimposition of the modes corresponding to $v = 3$ and $v = 4$ in equal proportions, as predicted by the simulation.

In conclusion, buried tubular waveguides having an annular core have been fabricated in bulk PMMA by femtosecond laser direct writing. The refractive-index profile was obtained from selective etch profiling. Numerical calculation of the propagating modes in the waveguides was performed with a finite-difference method. Good agreement was found between calculation and measurement of the output distribution in the near field.

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