Demonstration of waveguide couplers fabricated using microtransfer molding

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Arrays of single-mode optical waveguides, couplers, and interferometers were fabricated from a UV curable prepolymer using microtransfer molding. The coupling between the waveguides was reproducible and consistent across the array and was controlled after fabrication by additional UV exposure. © *1997 American Institute of Physics.* [S0003-6951(97)01334-X]

This letter demonstrates that microtransfer molding (μTM)[1] can be used to fabricate arrays of polymeric optical waveguides, and the coupling between the waveguides can be adjusted after fabrication.

In μTM, the unclad polymeric waveguides are formed by filling the relief structure in the surface of a transparent, elastomeric mold with a liquid organic prepolymer, and then placing the filled mold in contact with a solid substrate (typically SiO_2). The liquid prepolymer can be crosslinked *in situ* by irradiating the system through the mold with a UV lamp. After crosslinking, the elastomeric mold is peeled away, leaving an array of quasi-rectangular polymeric structures on the substrate. These structures form the cores of the clad waveguides. The cladding layer is formed by covering the structures with the same liquid prepolymer. This cladding is crosslinked using a second exposure to the UV light. The index of refraction of the polymer increases with exposure time. Thus, the cores have a higher index of refraction than the cladding, since their integrated exposure to UV light is greater. The difference in index between the core and cladding can be controlled by the duration of the first and second exposures to the crosslinking UV light.

Waveguides are important components of sensors and switches. Waveguides have been fabricated from organic polymers using reactive ion etching,[2] UV laser[3] and *e*-beam[4] writing, induced dopant diffusion during polymerization (photolocking[5] and selective polymerization),[6] selective poling of electro-optically active molecules induced by an electric field,[7] polymerization of self-assembled prepolymers,[8] micromolding in capillaries (MIMIC),[9] and μTM.[1] We believe that μTM has a number of characteristics that might make it especially useful for the fabrication of optical waveguides, relative to methods previously used. First, it is exceptionally simple experimentally, and can readily be used to produce multiple copies of complex microstructures. Second, it is highly parallel, and is capable of forming waveguides over a large area. We have, for example, demonstrated the fabrication of an array of $\sim$1000, 3-cm long, $\sim$2-μm wide, and $\sim$1-μm high waveguides over a 0.8×3 cm^2 area in a single step taking only 5 min.[1] The parallelism of this procedure makes it a candidate for the fabrication of complex but low-cost integrated optical devices. Third, μTM can be used with a variety of materials: polyurethanes, epoxies, dye-doped polymers, and sol-gel silica. Fourth, μTM can be used to fabricate waveguides on virtually any optically smooth surface, including Si/SiO_2, glass, and reflective surfaces (e.g., Au and Ag) with which photolithography cannot be used. μTM can make waveguides on non-planar surfaces.[1] μTM can also make waveguides on flexible surfaces [e.g., poly(vinyl chloride) films], which can subsequently be deformed while guiding light. Fifth, since μTM can fabricate 3D structures, it can fabricate structures that incorporate gratings and other optical structures in a single fabrication step. Independent control over the composition and morphology of the waveguide, cladding, and substrate allows the performance of the waveguide to be tailored for a range of wavelengths and applications.

The optical properties of the materials for the waveguide core and the cladding made using μTM can be modified by selective UV exposure even after fabrication. In this letter, we demonstrate that the index difference between the core and the cladding can be gradually decreased with additional UV exposure time after fabrication. Chirped waveguides and waveguides covered with periodic structures may be fabricated using either 3D stamp morphology or patterned UV exposure.

Given the new capabilities that μTM appears to offer in the fabrication of polymeric waveguides, we wished to demonstrate the optical characteristics of these guides experimentally, and to establish simple optical functions such as coupling of parallel guides. Figure 1 outlines the fabrication of clad waveguides using μTM; this procedure is based on one used to fabricate unclad waveguides, and is described in detail elsewhere.[1] The whole process, except the crosslinking of the polymer, was conducted in a class-100 clean room. A poly(dimethylsiloxane) (PDMS) elastomeric mold[10] was cast from a photoresist pattern made in a standard photolithographic process.[11,12] The waveguide cores were formed by

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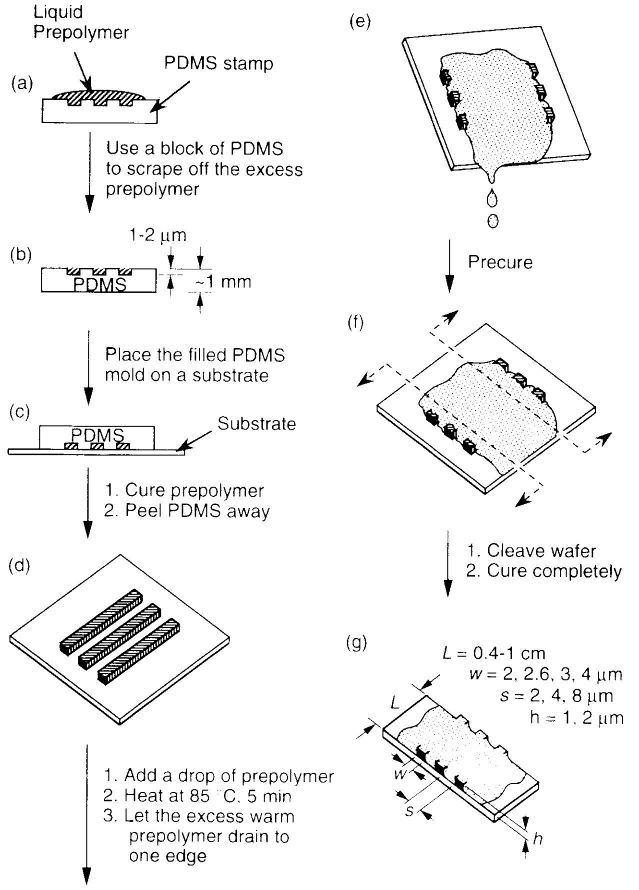

FIG. 1. Schematic diagram of the fabrication of an array of waveguides using μTM.

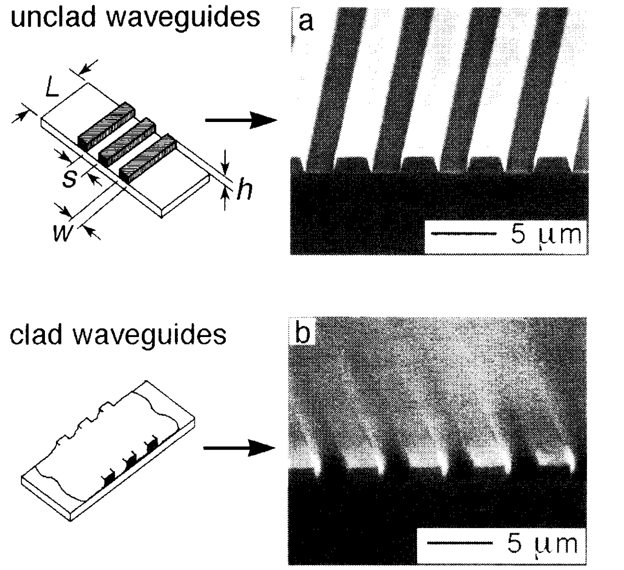

FIG. 2. SEMs of the ends of unclad (a) and clad (b) waveguides. The thickness (~1 μm) of the cladding layer shown in (b) is approximately the same as the height of the waveguides. The polymeric structures were coated with ~20 nm of gold before they were examined using scanning electron microscopy.

filling the relief structure in the elastomeric mold with a liquid prepolymer (a polyurethane, NOA-73, Norland Products, New Brunswick, NJ), and then placing the filled mold on a Si(100) wafer supporting a 2-μm thick layer of SiO_2. The prepolymer was crosslinked *in situ* by irradiating the system for 1 h at a distance of 1 cm from a 450 W medium-pressure Hg vapor lamp (Type 7825-34, Ace Glass, Vineland, NJ). After UV exposure, the elastomeric mold was peeled away, leaving an array of polymeric structures on the substrate [Fig. 2(a)]. The pattern used in these experiments generated waveguides with a variety of widths $w \approx 2.0$, 2.6, 3.0, and 4.0 μm, and spacings $s \approx 2.0$, 4.0, and 8.0 μm. All the waveguides made using the same mold have the same height h. The length L is determined by the points at which the wafer is fractured.

To make the cladding, a thick layer of the same liquid prepolymer (NOA-73) was applied to the waveguides [Fig. 1(e)], the surfaces of which had been slightly (10 min) oxidized in a UV-ozone cleaner (Models 135500 and 135500-2, Boekel Industries) to render them hydrophilic and improve adhesion. The system was heated to 85 °C on a hot plate to decrease the viscosity of the prepolymer, and the excess prepolymer was allowed to drain to one edge. The thin layer of prepolymer left on the surface was loosely crosslinked by a brief (1 min) exposure to UV light (365 nm) from a 4 W hand-held lamp (Blak-Ray UV lamp, Model UVL-21, UVP, San Gabriel, CA). The ends of the clad waveguides were squared by cleaving the substrate. After cleaving, the cladding was cured completely (30 s) with the 450 W medium-pressure Hg vapor lamp [Figs. 1(f)–1(g)]. This modification from the procedure described previously[9] allows the ends of waveguides to be cleaved when the cladding layer is still in the liquid phase, preventing the cladding from de-adhering from the guides. Figure 2(b) shows a scanning electron micrograph (SEM) of typical clad waveguides with $w \approx 2.6$ μm, $s \approx 2.0$ μm, and $h \approx 1.0$ μm.

Figure 3(a) shows a schematic diagram of the apparatus used to couple light into and out of the waveguides. Light from a He–Ne laser (633 nm) was first coupled into a single-mode optical fiber and then the optical fiber was butt coupled to the end of the waveguides using a precision three-dimensional translation stage. Using this apparatus, light could be selectively coupled into individual waveguides in the array, or into the cladding between or above the waveguides. The output light from the waveguides was imaged with a microscope objective and recorded on a CCD camera. The shapes and the intensities of the outputs of individual waveguides could easily be observed.[13] In Fig. 3(b), the trapezoids indicate the positions of the 3-μm wide waveguides with neighboring waveguides separated by 8 μm ($w \approx 3$ μm, $s \approx 8$ μm, $h \approx 1$ μm, and $L \approx 8$ mm). The shaded circle indicates the position of the optical fiber used to couple light into only one waveguide. Figure 3(c) shows an image of the single-mode output from this array where no evanescent coupling between adjacent waveguides was observed.

Figure 3(e) shows the output when light was coupled into a single waveguide of the same size ($w \approx 3$ μm, $h \approx 1$ μm, and $L \approx 8$ mm) as in Fig. 3(b), but with a smaller spacing ($s \approx 4$ μm) between neighboring guides [as shown in Fig. 3(d)]. The UV exposure time for Fig. 3(e) was the same as for Fig. 3(c). The 4-μm spacing was small enough to allow evanescent coupling between guides, and light was observed in five adjacent waveguides. In addition, as the

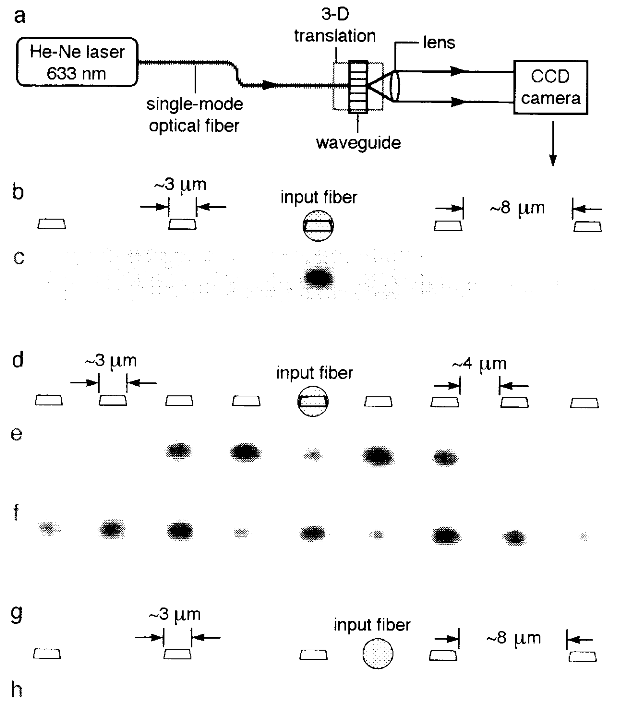

FIG. 3. (a) Schematic diagram of the optical coupling setup. (b) Schematic diagram of the end view of a waveguide array ($w \approx 3$ μm, $s \approx 8$ μm, $h \approx 1$ μm) with the position of the input optical fiber shown as a shaded circle. (c) Photograph of the waveguide output when light from a He–Ne laser was coupled into a single waveguide as shown in (b). (d) Schematic diagram of another waveguide array ($w \approx 3$ μm, $s \approx 4$ μm, $h \approx 1$ μm). (e)–(f) Photographs of the single-mode outputs of the waveguides shown in (d) when light was again coupled into a single waveguide. The UV exposure time for the waveguides used in (e) was the same as for those in (c). Photograph (f) shows a large increase in the coupling between the waveguides after an additional 20 s of UV exposure of the same array used in (e). (g) Schematic diagram of a waveguide array ($w \approx 3$ μm, $s \approx 8$ μm, $h \approx 1$ μm) with input optical fiber positioned *between* waveguides, and (h) photograph of the output of this waveguide array.

input optical fiber was moved to adjacent waveguides, this output pattern moved in register. The reproducibility and symmetry of this pattern established the uniformity of the coupling between the waveguides in the array. The low level of light at the exit of the central waveguide was caused by efficient coupling of light from the central waveguide into the adjacent waveguides.

Figure 3(f) demonstrates the ability to modify the coupling between adjacent waveguides by controlling the index difference between the guides and their cladding by manipulating UV exposure times. Figure 3(f) shows the output of the same waveguide array as in Fig. 3(e) after an additional 20 s exposure of the array (waveguides plus cladding) under the 450 W medium-pressure Hg vapor lamp. This exposure reduced the index difference between the core and cladding, and increased the coupling between the waveguides, as shown in Fig. 3(f), where light from a single waveguide was evanescently coupled into nine waveguides and many closed-path interferometers were formed.

Figure 3(h) shows the output of the array when light was coupled into the cladding *between* the waveguides shown in Fig 3(g) ($w \approx 3$ μm, $s \approx 8$ μm, $h \approx 1$ μm, and $L \approx 8$ mm). No waveguide output was observed when light was coupled into the cladding, and very little light was observed from the output end of the cladding. This experiment demonstrates that the excitation of multiple waveguides shown in Figs. 3(e)–3(f) is the result of coupling from propagating waveguide mode to propagating waveguide mode, not from cladding modes to waveguide mode. This interpretation is supported by numerical simulations.

We have also fabricated 2-μm high ($h \approx 2$ μm) clad waveguides with $w \approx 2.0$, 2.6, 3.0, and 4.0 μm, and $s \approx$ 2, 4, and 8 μm. These taller waveguides have cross sections approximately equal to the 3.3 μm mode diameter of the optical fiber, and give a coupling efficiency of approximately 35% for a 6-mm long waveguide. We have measured the propagation loss in these waveguides to be less than 0.6 dB/cm, which is the limit of our measurement uncertainty.

Using μTM, we have successfully fabricated clad waveguides with the cores and the cladding made from the same prepolymer. We have demonstrated evanescent coupling between single-mode waveguides in the visible region (633 nm), where the coupling can be tuned with UV exposure time. μTM has allowed us to fabricate arrays of waveguides of different sizes and spacings at the same time, so that single-mode guides and waveguides with different degrees of cross coupling can be made simultaneously with a single application of a PDMS mold. The coupling between waveguides in an array is consistent from waveguide to waveguide. Also, the coupling of light out of, and then back into individual waveguides in the array has been shown to form a network of closed-path interferometers.

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