Proton beam writing of low-loss polymer optical waveguides

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Proton beam writing is a direct-write micromachining technique capable of producing three-dimensional microstructures with straight and smooth sidewalls. Low-loss channel waveguides in SU-8, a chemically amplified negative tone resist, were fabricated using a focused submicron beam of 2.0 MeV protons with a dose of 30 nC/mm^2 and a beam current of approximately 2 pA. Propagation losses of approximately (0.19±0.03) dB/cm were measured at 632.8 nm wavelength. Waveguides of arbitrary design can be easily fabricated using proton beam writing, making the technique ideal for the rapid prototyping of optical circuits. [DOI: 10.1063/1.1606502]

Polymeric materials offer many advantages over traditional materials (e.g., lithium niobate, silicon, III–V semiconductors, etc.) used for optical waveguide fabrication. Some of their unique advantages are their low cost of production and ease of processing and fabrication. Polymeric materials may be easily engineered to obtain the desired optical parameters such as the bandwidth of transparency, high electro-optic coefficient values, and temperature stability for specific photonic applications.[1]

Some common techniques used for polymeric waveguide fabrication include photolithography and reactive ion etching,[2,3] photobleaching,[4,5] and high energy ion implantation.[6,7] These methods either involve numerous processing steps or make use of conventional mask-based techniques that require the design and fabrication of a mask before waveguides can be fabricated. Direct-write techniques such as laser direct-writing,[8] electron beam lithography,[9,10] and proton beam writing,[11,12] on the other hand, have the advantage of being maskless, allowing rapid and inexpensive prototyping.

In this letter, we report on the application of proton beam writing, a lithographic technique, to the fabrication of low-loss SU-8 channel waveguides. In proton beam writing, a focused submicron beam of high-energy protons is used to direct-write on suitable photoresists, such as SU-8 and polymethylmethacrylate (PMMA). The latent image formed is subsequently chemically developed. Three-dimensional, high aspect ratio microcomponents with straight and smooth sidewalls have been produced using this technique.[13] In this application, the cross-linked SU-8 forms the core of the waveguides, while an UV-cured resin, Norland Optical Adhesive 88 (NOA88) forms the cladding layer.

NANO™ SU-8 is a chemically amplified, negative tone photoresist from MicroChem Corporation (MCC), which has high sensitivity and provides high contrast. Upon exposure to actinic radiation (e.g., UV, electron-beam, x rays, or protons), it forms a ladder-like structure with a high cross-linking density and exhibits good chemical and thermal stability (T_g>200 °C). SU-8, ~5 μm thick, was first spin coated on a 4 in. Corning Pyrex® 7740 borosillicate glass wafer. The rms surface roughness of the Pyrex® substrate and the SU-8 photoresist, measured with an atomic force microscope (Digital Instruments, Dimension™ 3000 SPM), was 0.23 and 0.32 nm, respectively, over an area of 5 μm×5 μm. These surface roughness measurements show good optical qualities.

Proton beam writing is carried out using proton beams from the High Voltage Engineering Europa (HVEE) 3.5 MeV Singletron™ accelerator at the Center for Ion Beam Applications.[14] The waveguides were direct-written using a 2.0 MeV beam of protons with a beam spot size of ~0.3 μm and a beam current of ~2 pA. The 2.0 MeV protons penetrate the 5-μm-thick SU-8 resist layer, stopping well into the Pyrex® substrate. A combination of stage scanning and magnetic scanning was used to direct-write the SU-8 waveguides. The sample of dimensions ~1.5 cm×1.0 cm (i.e., length×width) was mounted on a three axis computer-controlled piezoelectric translational stage (Burleigh TSE-150HV Integral Encoder Stage).

The proton beam was magnetically scanned over a distance of 5 μm in one direction while, simultaneously the stage was traversed perpendicular to this magnetic scan direction at an optimal speed of 10 μm/s. The waveguides were direct-written with a dose of 30 nC/mm^2 (i.e., ~1.875×10^{13} particles/cm^2). A more detailed description of the magnetic scanning procedure and the dose normalization procedure can be found elsewhere.[15] The exposure time required for the waveguide fabrication was approximately 15 min for a length of 1 cm.

No postbaking of the SU-8 photoresist is needed after proton beam writing. The resist was chemically developed (i.e., the areas not irradiated are chemically removed) in propylenglygol-monoethylether-acetate (PGMEA) for 90 s and then rinsed in de-ionized water. Subsequently, a second

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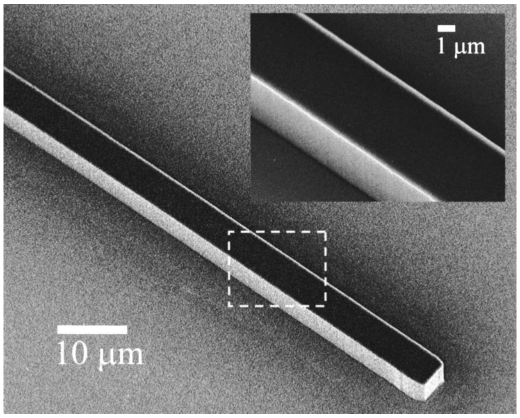

FIG. 1. Scanning electron microscopy image of a typical SU-8 waveguide fabricated using proton beam writing. Inset shows a close-up view of the straight and smooth sidewall of the waveguide.

rinse of the resist in PGMEA was performed for 30 s and followed by a final rinse in fresh de-ionized water. Channel waveguides with straight and smooth sidewalls, as shown in Fig. 1, are formed. This feature is crucial to minimizing scattering losses in optical waveguides.

NOA88, ~30 μm thick was then spin coated over these waveguides to form the cladding layer. In this same step, a piece of microscope glass slide was bonded with the NOA88 to form a protective cover. The NOA88 cladding was subsequently cured for 5 min using UV light at 365 nm wavelength and 200 W power. The waveguide sample was then baked at 50 °C for 12 h in an oven to improve the cladding's adhesion on both the Pyrex® and glass surfaces. A cross-sectional view of the resulting waveguide is shown in Fig. 2.

The optical properties of these SU-8 waveguides were characterized using various techniques. The bulk refractive index of the Pyrex® substrate, the refractive index of the irradiated SU-8 and that of the cured NOA88 cladding layer were measured using a Metricon 2010 prism coupler system. Their refractive indices at 632.8 and 1550 nm wavelength are given in Table I.

The waveguiding properties of these SU-8 waveguides were investigated using the end-fire technique. Figure 2 inset shows the mode profile of one of these waveguides at 632.8 nm wavelength. The propagation losses were determined by measuring the intensity of the scattered light (in the lateral direction) along the whole length of the waveguide using a charge coupled device camera. By averaging over 18 independent measurements, the propagation losses were found to be approximately (0.19 ± 0.03) dB/cm at 632.8 nm wavelength. Figure 3 shows a typical plot of waveguide propagation loss dependence as a function of waveguide length. Several authors have reported[10,16–18] propagation losses for polymer waveguides ranging from 0.08 to <1.5 dB/cm at wavelengths of 632.8–1550 nm. At 632.8 nm wavelength, the propagation losses for these SU-8 waveguides are lower than those reported[18] for Cytop™/Cyclotene™/Cytop™ and Cytop™/PMMA/Cytop™ waveguides (i.e., 0.51 and 0.65 dB/cm, respectively).

TABLE I. Refractive indices of the Pyrex wafer (the substrate), SU-8 (the core) and NOA88 (the cladding) at 632.8 and 1550 nm wavelength.

Material	Refractive index (632.8 nm)	Refractive index (1550 nm)
Pyrex® 7740	1.470	1.456
SU-8	1.596	1.575
NOA88	1.555	1.537

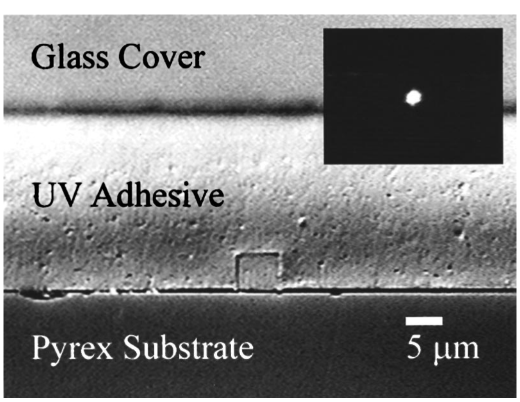

FIG. 2. Differential interference contrast micrograph of the cross section of the SU-8 waveguides. The waveguide core is approximately 5 μm×5 μm. Inset shows the mode profile of one of the SU-8 waveguides at a wavelength of 632.8 nm.

In conclusion, we have demonstrated the feasibility of using proton beam writing to fabricate low-loss channel waveguides in SU-8 with propagation losses of approximately 0.19 ± 0.03 dB/cm at 632.8 nm wavelength. Proton beam writing is a direct-write technique capable of fabricating waveguides with straight and smooth sidewalls in a single step process, thus an ideal technique for the rapid prototyping of optical circuits. Further work on the fabrication of optical waveguide components such as y-branching waveguides, directional couplers, and Mach Zehnder interferometers are currently in progress.

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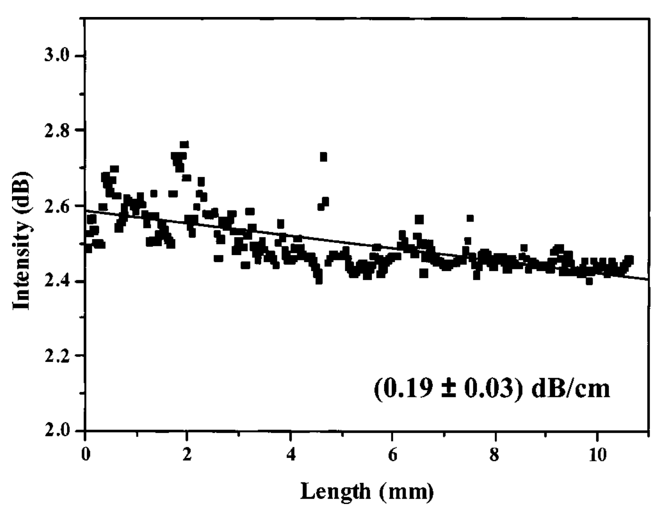

FIG. 3. Loss dependence of a typical SU-8 waveguide as a function of waveguide length at 632.8 nm wavelength.

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