Fabrication of buried channel waveguides in photosensitive glass using proton beam writing

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We report our results on the fabrication and characterization of buried, channel optical waveguides in photosensitive Foturan\textsuperscript{TM} glass using a high energy proton beam. Waveguides were fabricated with varying fluence, and the propagation loss and refractive index change were measured. Near-field mode data measured at 632.8 nm showed that waveguiding could be achieved for all fluences ranging from $10^14$ to $10^16$ protons/cm\textsuperscript{2}. The maximum positive refractive index change of $1.6 \times 10^{-3}$ was measured for the highest fluence. The waveguide propagation losses measured using the scattering technique were estimated to be in the range of 8.3–12.9 dB/cm, increasing with proton fluence. © 2006 American Institute of Physics. [DOI: 10.1063/1.2198798]

Foturan\textsuperscript{TM} is a photosensitive glass (manufactured by Schott Mikroglas) that can be directly patterned using conventional UV lithography,\textsuperscript{1} femtosecond lasers,\textsuperscript{2–5} and MeV protons.\textsuperscript{6–8} Unlike other glasses that require masking in order to allow for the formation of patterns, irradiated regions of Foturan\textsuperscript{TM} have a 20 times increase in etch rate after heat treatment.\textsuperscript{1} The ability to directly form microstructures in this glass along with its resistance to high temperature and corrosion\textsuperscript{1} has made it a particularly attractive platform for microfluidic applications such as microelectrochemical reactors.\textsuperscript{9–11} Furthermore, its high transparency and the ability to modify the refractive index of this glass make it equally attractive for the fabrication of micro-optical components such as waveguides,\textsuperscript{12} gratings,\textsuperscript{13} and micromirrors.\textsuperscript{3} Although femtosecond lasers are commonly used for waveguide fabrication in many types of glasses,\textsuperscript{14} only a limited number of studies have concentrated on the fabrication of waveguides in Foturan\textsuperscript{TM}.

An alternative and efficient technique that can be used for waveguide fabrication is proton beam writing.\textsuperscript{15} This technique utilizes a focused beam of MeV protons to direct-write structures in a material. The method relies on the fact that energetic ions lose most of their energy when they slow down in the form of collisions with target electrons, and by introducing atomic displacements. The cross section for both these processes increases with decreasing velocity of the incident ion resulting in most of the energy being deposited near the end of range, also known as the Bragg peak. The increased energy deposition at the end of range results in the formation of a region with altered refractive index that can be used for light guiding. Previous studies of proton beam irradiation for waveguide fabrication have concentrated on materials such as polymethylmethacrylate (PMMA),\textsuperscript{16,17} fused silica,\textsuperscript{18,19} and Er doped phosphate glass.\textsuperscript{20} In this study we apply the fabrication technique to Foturan\textsuperscript{TM} because it has the unique property of being a glass that can be both modified by irradiation to form waveguides and patterned to fabricate structures such as microfluidic channels. This makes Foturan\textsuperscript{TM} potentially an important material for microfluidic devices that have integrated optics for biosensing applications.

Commercial Foturan\textsuperscript{TM} samples were cut and mechanically polished along the edges to achieve an optical finish. The final polished samples were approximately $15 \times 7.5 \times 2$ mm\textsuperscript{3} in size with a residual root mean squared surface roughness along the polished edges of approximately 4 nm [measured using an atomic force microscope (AFM)]. The waveguides were fabricated using the proton beam writing facility at the National University of Singapore,\textsuperscript{21} where a beam of 2 MeV protons was used to direct-write waveguides over a length of approximately 7.5 mm. Seven waveguides were fabricated with fluences ranging from $1 \times 10^{14}$ to $1 \times 10^{16}$ protons/cm\textsuperscript{2}. During the irradiation, the proton fluence was monitored using an annular surface barrier detector mounted in the backward scattering direction. The SIMNRA software\textsuperscript{22} was used to fit the Rutherford backscattering spectra in order to confirm that the desired fluence was delivered to the sample. No postannealing was performed on the sample.

Figure 1(a) shows an optical differential interference contrast (DIC) microscope image of the sample end face. Also shown in Fig. 1(b) is the atomic displacement profile due to nuclear stopping in Foturan\textsuperscript{TM}, and the ionization profile due to electronic stopping simulated using the stopping and range of ions in matter (SRIM2003) software.\textsuperscript{23} The va-

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Density filters were used to attenuate the input light for ob-
taining distance objective and a 12 bit cooled charge coupled
device. Then the emerging light was imaged using a 50 times long work-
fiber was butt-coupled to the end face of the waveguides, and
laned into a single mode fiber that a majority of the atomic displacements that occur at the
end of range region that can be fabricated using
index change in Foturan™ is similar to that of fused silica,
more of the waveguide core region that can be fabricated using
waveguide fabricated with a fluence of $1 \times 10^{16}$ protons/cm$^2$ was measured to be 8.1 μm in the vertical and 8.6 μm in the horizontal
(1/e$^2$). This difference in the vertical and horizontal mode
field diameter is due to the way in which the waveguide is
fabricated. The horizontal profile can be controlled by chang-
ing the proton beam scan size, while the vertical profile is
largely dependent on the way in which the protons interact
with the sample via the nuclear and electronic stopping
powers.

A minimum of 20 near-field images were recorded for
each waveguide allowing us to average the output profiles
for refractive index reconstruction. The refractive index
profile was determined for the highest proton fluence
($1 \times 10^{16}$ protons/cm$^2$) using the propagation mode near-
field technique. This method allows one to determine the
change in refractive index from the mode profile and a
known refractive index for the bulk unirradiated material. We
measured the bulk refractive index of our sample to be 1.511
at 632.8 nm using a Metricon prism coupling system. Figure 3 shows an image of the light scattered
from the waveguide fabricated with the highest fluence ($1 \times 10^{16}$ protons/cm$^2$). (b) Recovered two-
dimensional 2D refractive index profile and line profiles through the center
of the mode along the (c) width and (d) depth of the sample.

Propagation loss measurements were performed using
the scattering technique. Laser light was launched into the
waveguides using the same single mode fiber, and the scattered
light was imaged using a stereo zoom microscope
mounted perpendicular to the waveguide. The loss values
were obtained by fitting the data to the equation $l = l_0 e^{-\alpha l}$,
where $l$ is the length of the sample, and $\alpha$ being the propa-
gation loss coefficient. The loss values retrieved from the
best fits were in the 8–13 dB/cm range, increasing with pro-
ton fluence. Figure 3 shows an image of the light scattered
from the waveguides, fabricated using the lowest and highest
fluences, and a graph showing the extracted loss results. For
these two waveguides we obtained loss values of 8.3 and

![Diagram](image-url)
12.9 dB/cm for the lowest and highest fluences, respectively. In the recent work of Bhardwaj et al., a maximum refractive index increase of $1.5 \times 10^{-3}$ was measured for waveguides fabricated using femtosecond laser modification at 800 nm. It was also noted that a positive index change could be induced by a femtosecond laser without heat treatment. It is known that if a two step heat treatment is applied could be induced by a femtosecond laser without heat treatment could be induced by a femtosecond laser without heat treatment.

Waveguides fabricated using an AFM. In our AFM studies of the surface of Foturan™ waveguides we observed no compaction for fluences ranging from $10^{14}$ to $10^{16}$ protons/cm². The root mean squared surface roughness we measured was between 2–3 nm. Further studies are therefore required to fully understand the mechanism for the refractive index change in Foturan™.

Typically the propagation loss of proton beam irradiated waveguides in fused silica before annealing is about 3 dB/cm for fluences of the order of $1 \times 10^{15}$ protons/cm², dropping below 1 dB/cm after thermal annealing. Waveguides fabricated in fused silica using femtosecond lasers also yield a loss of just over 1 dB/cm. Our results are higher, the minimum loss we achieved for unannealed Foturan™ was 8.3 dB/cm for a fluence of $1 \times 10^{14}$ protons/cm². Future annealing studies should enable us to lower the loss of our samples as well.

In conclusion we have successfully fabricated buried, channel waveguides in Foturan™ photosensitive glass using a high energy proton beam. Seven waveguides with fluences ranging from $1 \times 10^{14}$ to $1 \times 10^{16}$ protons/cm² were obtained, all of which were able to guide light. Optical characterization results at 632.8 nm yielded a propagation loss ranging from 8.3 dB/cm for a fluence of $1 \times 10^{14}$ protons/cm² to 12.9 dB/cm for a fluence of $1 \times 10^{16}$ protons/cm². The propagation mode near-field technique was used to measure a positive refractive index change of $1.6 \times 10^{-3}$ for a proton fluence of $1 \times 10^{16}$ protons/cm².

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