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Fabrication of optical waveguides using proton beam writing

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Abstract

Proton beam writing is a direct write lithographic technique that can be used to fabricate optical waveguides in a range of materials including polymer and glass. In this paper we demonstrate the proton beam writing method for fabricating waveguides in PMMA, and in Foturan photosensitive glass using a single step process of end of range refractive index modification. Both these materials are of considerable importance for bio and chemical sensing applications since they can both be directly micromachined either optically using photolithography or by using proton beam writing. The waveguides fabricated in these materials have been characterized optically to determine the propagation loss and the refractive index.

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Keywords: B1 Glasses; B1 Polymers; B3 Waveguides

1. Introduction

Optical waveguides are one of the basic building blocks of many microphotonic devices used in integrated optics ranging from optical amplifiers, optical switches, ring resonators and interferometers. Waveguides can be fabricated using a variety of lithographic and non-lithographic processes. Planar waveguides can be fabricated using coating or deposition techniques such as spin or dip coating, sputtering and chemical vapor deposition. In order to fabricate channel, ridge or rib waveguides however, one needs to use a process that allows you to define the optical pathways in three dimensions so that light confinement occurs both laterally and in depth. This can be achieved using masked processes such as photolithography either directly or in conjunction with reactive ion etching [1] or ion exchange [2]. Other direct write processes such as electron beam lithography [3] or laser direct write [4] can also be used to fabricate waveguides, however they tend to be much slower than the masked processes. The advantage of direct write techniques is that they can be used for rapid prototyping of almost any structure without the need for producing a mask which can add a significant cost to the device development.

Proton beam writing is an emerging direct write lithographic process that is capable of fabricating three-dimensional high aspect ratio nanostructures in polymer [5]. The technique can also be used to make metallic stamps that enable one to replicate structures using the nanoimprint lithography technique [6]. There are two methods of fabricating optical waveguides with the proton beam writing technique. The first is typically used to fabricate waveguides in polymers like PMMA and SU-8. The process involves directly micromachining the high refractive index core of a waveguide structure by proton beam writing. After development, the waveguide cladding is added by spin coating a lower refractive index UV curable polymer over the structure. This method has been previously used to fabricate optical waveguide cores in SU-8 with a cladding of NOA-88 UV curable adhesive [7]. The second method of producing optical waveguides using the proton beam writing technique requires only a single irradiation step. This method utilizes the end of range effects of ion implantation to produce a buried region of high refractive index. When an energetic ion impinges on a

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material it will loose energy due to interactions with target electrons (electronic stopping) or by colliding with target nuclei (nuclear stopping). This stopping process is strongly dependent on the velocity of the ion. As the ion slows down, the amount of energy that it loses to both electronic and nuclear interactions rapidly increases resulting in a region of high-energy loss at the end of range of the ion. This method can be used to define optical waveguides in many bulk materials such as polymer [8–10] and various types of glass [11–13].

In this paper we utilize proton beam writing to fabricate optical waveguides in poly methylmethacrylate (PMMA) and a photosensitive glass (Foturan). These two materials show a lot of promise for applications in bio and chemical sensing due to their biocompatibility, low cost and high transparency. It is important to develop methods of integrating optical structures such as waveguides in these materials. Waveguides can be used to provide a means of optically interrogating small volumes of material either by extracting fluorescent light for analysis, or to provide a localized laser excitation source for fluorescence.

2. Experiment

Optical waveguides were fabricated in PMMA and Foturan photosensitive glass using the proton beam writing facility at the Centre for Ion Beam Applications, National University of Singapore [14]. The facility allows for the fabrication of microstructures with a resolution better than 100 nm over magnetically scanned areas of about $800 \times 800\,\mu$m. For the fabrication of linear waveguides, the beam is scanned magnetically over a length of 3–5 μm perpendicular to a constant linear motion provided by an EXFO Burleigh inchworm UHV stage which moves at a speed of 10–50 μm/s over the length of the sample. Waveguides of up to a maximum of 2.5 cm can be fabricated using this method, limited by the stage travel. Before irradiation, both samples were mechano-chemically polished along the edges to achieve an optical finish.

In order to optically characterize the waveguides, mode profile and propagation loss measurements were performed. Optical mode profiles were measured using a 17 mW HeNe (632.8 nm) laser coupled into a 3 M single mode fiber (FS-SN-3224, core size 4 μm). The fiber was then butt coupled to the waveguides and the mode imaged using an infinity corrected 40× long working distance objective coupled to a 12 bit cooled charge coupled device (CCD) camera (Qimaging Retiga EXi). The high dynamic range and the low dark noise of this camera improves the image quality of the modes making it possible to use them in order to recover the refractive index of the waveguides using the propagation mode near field method [15,16]. Loss measurements were performed by imaging the light scattered out from the plane of the waveguide using a stereo zoom microscope [17].

3. Results and discussion

The depth at which the end of range occurs for protons can be controlled by varying the energy of the beam. The exact end of range depth can be predicted using a Monte Carlo simulation code known as Stopping and Range of Ions in Matter (SRIM) [18]. This code can simulate both the ionization profile (i.e. electronic energy loss) and the depth profile of the vacancies produced by the ion beam. The peak in the vacancy profile is located a few microns below the peak in electronic energy loss. This peak in vacancies is the predominant factor for the increase in refractive index in this region. In glasses and polymers the vacancies produced in this region result in re-ordering of the bonds usually resulting in a compaction of material [19]. For polymers the effect is even more pronounced and is usually accompanied by some out gassing of material, further increasing the compaction and refractive index [20]. Fig. 1 shows the SRIM simulation for 2.0 MeV protons in bulk PMMA and Foturan. The range of the proton beam along with the bulk density and the refractive index of

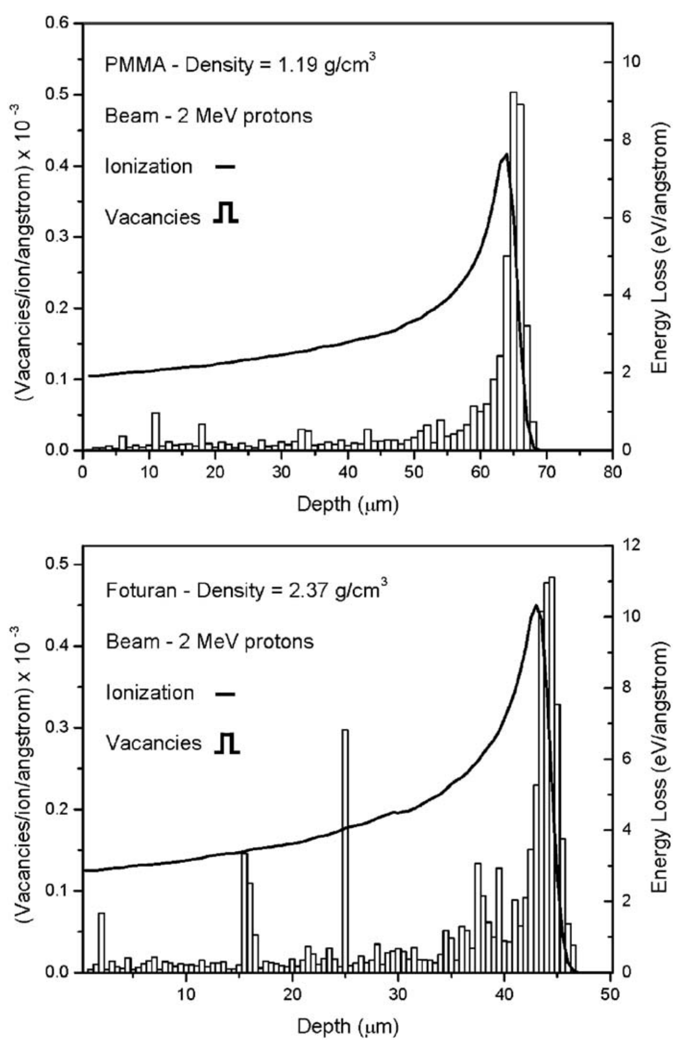

Fig. 1. SRIM simulation of the ionization and vacancy profile produced by a beam of 2.0 MeV protons in PMMA and Foturan.

Table 1
A comparison of the materials and optical properties of PMMA, Foturan and fused silica (GE 124)

Material	Density (g/cm^3)	Range of 2 MeV protons (μm)	Refractive index (632.8 nm)	Refractive index (1550 nm)
PMMA (Rohm GS233)	1.19	65	1.490	1.481
Foturan	2.37	45	1.511	1.497
Fused silica (GE 124)	2.20	46	1.457	1.445

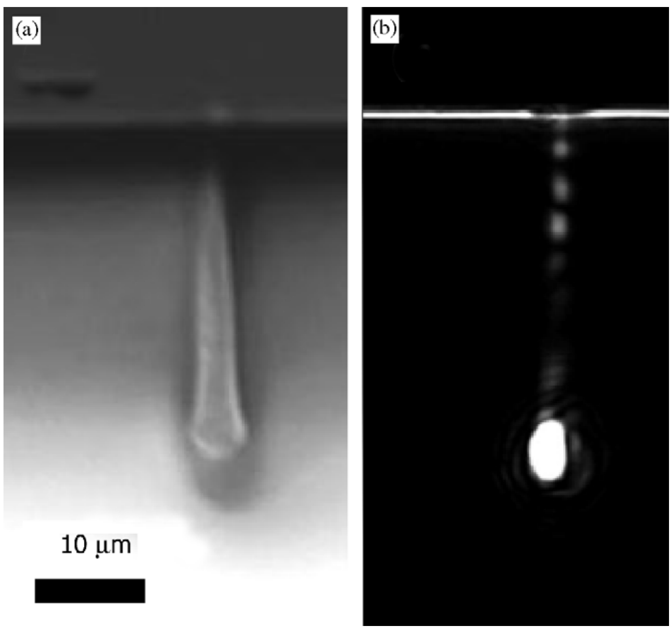

Fig. 2. Optical images of a waveguide fabricated in PMMA using a beam of 2.0 MeV protons. (a) DIC optical image of the edge of a PMMA waveguide sample showing the end of range region. (b) Optical image of a guided mode (HeNe—632.8 nm laser) in the same sample. A fluence of 2.2×10^{13} protons/cm^2 was used to fabricate this waveguide.

PMMA and Foturan are summarized in Table 1. Also shown for comparison is the properties of fused silica (GE 124). The values of the bulk refractive indices shown in this table for 632.8 and 1550 nm were measured using a Metricon 2010 prism coupler system. These values were used in the recovery of the change in refractive index at the end of range using the propagation mode near-field technique. The depth at which light guiding occurs for both sets of waveguides fabricated in this study agree with SRIM simulations.

An optical differential interference contrast (DIC) image showing the edge of one of the waveguides fabricated in PMMA is shown in Fig. 2. Also shown is an image of the guided mode produced using a fiber-coupled Helium Neon (632.8 nm) laser. Optical DIC images of a waveguide fabricated in Foturan are shown in Fig. 3. These images clearly show the end of range waveguiding region occurring approximately 45 μm below the surface of the sample. The DIC optical method allows one to easily image variations in refractive index. Optical images showing the modes supported by three waveguides fabricated in Foturan glass are shown in Fig. 4. A small amount light is observed in

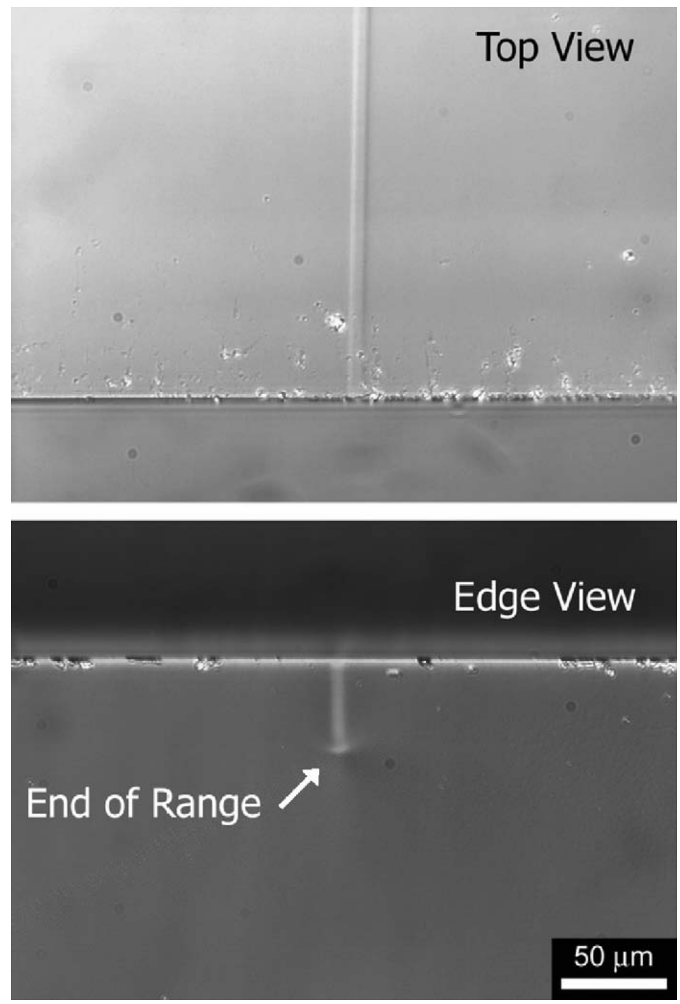

Fig. 3. Optical DIC images showing a waveguide fabricated in Foturan photosensitive glass using a beam of 2.0 MeV protons and a fluence of 1×10^{16} protons/cm^2. The side view of the sample clearly shows the end of range region.

regions above the end of range, this is most likely due to scattered light from the surface of the sample and is usually ignored when recovering the refractive index profile of the waveguide.

Polymers tend to be much more sensitive to radiation damage when compared to inorganic materials like glass. It was found that the fluence required to achieve light guiding was at least an order of magnitude lower for PMMA. In fact from our propagation mode near field estimates of the refractive index change for PMMA and Foturan, it was found that at least of 2–3 orders of magnitude more

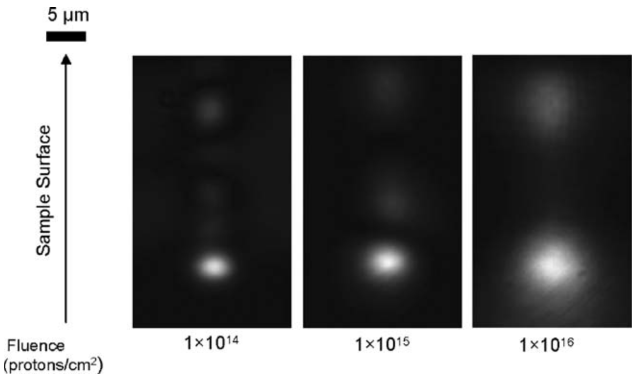

Fig. 4. Optical images in pseudo-color showing the modes supported by three waveguides fabricated in Foturan glass. The modes are shown for three different proton fluences.

protons were required to achieve that same refractive index increase. A refractive index increase of $\sim 3 \times 10^{-3}$ was measured for PMMA irradiated with a fluence of 5×10^{13} protons/cm^2 whereas it required at least 1×10^{16} protons/cm^2 to achieve a similar increase in Foturan. The refractive index profile as a function of depth for both PMMA and Foturan roughly follows the vacancy profile shown in Fig. 1. A Gaussian-like refractive profile occurs centered at the maximum in the vacancy profile with little or no refractive index change occurring above the end of range region. Laterally the profile is largely determined by the scan size used during the irradiation.

Due to the sensitivity of the PMMA to radiation damage, the beam current was maintained at about 1 pA or less to avoid blistering of the polymer. This blistering occurs if trapped gas produced by the proton beam cannot escape the material fast enough resulting in a gradual build up at the end of range. The propagation loss for the PMMA waveguides was between 1 and 2 dB/cm for a range of fluences between 2 and 5×10^{13}. This propagation loss is consistent with results obtained in other studies [9] and can be tolerated for small (less than 1 cm) integrated optical devices [21]. The Foturan sample yielded propagation loss values between 6 and 12 dB/cm for fluences between 1×10^{14} and 1×10^{16}. This is considerably higher than PMMA but only a factor of 2 higher than results obtained in fused silica before annealing [11].

4. Conclusion

In this study we have shown that it is possible to fabricate buried channel waveguides in both PMMA and Foturan photosensitive glass in a single step using proton beam writing. In the future such waveguides can be easily integrated in devices that use these materials for applications in biosensing [22,23]. The propagation loss of the fabricated waveguides was characterized and shown to be a lot lower for PMMA however the resistance to radiation damage of Foturan was considerably higher. Much higher proton fluence is required to achieve a similar refractive index change in Foturan when compared to PMMA. Depending on the device being fabricated, both materials are suitable for integrating optical waveguides.

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