Submitted to ECIO '03 2552

Integrated optical structures written in a polymer film by UV-induced refractive index modification

J. –S. Koo, C. B. E. Gawith, V. Albanis, S. P. Watts, G. D. Emmerson, R. B. Williams, and P. G. R. Smith
Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
jk@orc.soton.ac.uk

M. C. Grossel
Chemistry Department, University of Southampton, Southampton, SO17 1BJ, UK

Integrated optical devices are demonstrated in poly(methylmethacrylate/2-methacryloylethylmethacrylate) copolymers by direct UV writing. This new technique uses a UV-induced refractive index change without etching. Y-splitter junction losses of 0.4dB and splitting ratios of 50:50 ±1% were obtained.

Keywords: polymer waveguide, integrated optical devices, direct UV writing

Introduction

The expansion of high capacity optical transmission techniques into price-sensitive areas such as datacomms and access networks requires a major reduction in the cost of optical components. Polymer waveguides are promising for low cost devices, especially at shorter wavelengths, because of their easy processing, flexibility in design, and cost effectiveness [1]. In this paper we present UV-written integrated optical devices using a PMMA-based crosslinkable copolymer family [2].

Direct UV writing is based on a localised change in refractive index caused by short wavelength radiation and has been demonstrated in silica for writing devices such as channel waveguides, Y-splitters, and directional couplers [3]. While polymer-based waveguide devices such as Y-splitters and directional couplers have also been reported, these have previously been based on chemical wet etching processes to create buried channel waveguides [4]. Our novel approach has the significant advantage that it does not require photolithography, wet chemical developing or gas phase etching.

During our UV-writing process, waveguides are photowritten in a single step using a focused spot of UV laser light that increases the refractive index of a polymer film. Each UV-written waveguide is based on a thermally crosslinked polymer layer, which can be translated under the focused spot on computer controlled air-bearing stages to allow complex refractive index structures to be literally drawn into the photosensitive material. The translation system is capable of sub-micron positional control, making this a rapid and inexpensive mask-less process.

The copolymers used during these experiments were prepared from hydroxyethylmethacrylate (HEMA) and methylmethacrylate (MMA), to which we have introduced crosslinkable sites onto the hydroxyethyl side chains to create poly(methylmethacrylate/2-methacryloylethylmethacrylate) (P(MMA/MAOEMA)) [2]. These P(MMA/MAOEMA) copolymers have several distinct advantages for our process as they can be either thermally or UV crosslinked without the need for photochromic additives [5]. Even after thermal crosslinking these polymers remain photosensitive to allow further refractive index changes via UV-illumination, a characteristic which makes them highly suitable for direct UV writing.

To this end, these results describe our initial investigation towards the fabrication of integrated optical structures in P(MMA/MAOEMA) copolymers by direct UV writing. Initial structures based on channel waveguides, S-bend structures, and Y-splitters are described and characterized in terms of propagation, bend, and junction loss and UV-induced refractive index change. We also present our first results on a new minimal pre-bake technique designed to give enhanced photosensitivity and higher NA waveguides.

Polymer film preparation and waveguide fabrication

Fabrication of the polymer film was performed by spincoating a ~4μm-thick P(MMA/MAOEMA) [poly(methylmethacrylate/2-methacryloylethylmethacrylate)] layer onto a polished silica substrate, which was then thermally crosslinked at a temperature of 140°C for 2 hours [2]. Refractive indices for the polymer core and silica substrate layers were 1.498 and 1.457 respectively.

Direct UV writing into the polymer layer was performed using a frequency-doubled argon-ion laser operating at 244nm with a focused spot size of approximately 6μm diameter (Figure 1). UV writing powers of 1 – 10mW and scan speeds of 16 – 480 mm/min were investigated for the definition of channel waveguides in the polymer layer, resulting in a fluence range of between 0.4 and 4.6 J/mm^2. Straight channel waveguides were written by translating the sample in a straight line under the focused beam, while S-bends and Y-splitters were designed with cosine circular arcs in the curved waveguide region. This simple combination of structures provides the basis of many integrated optical devices, while allowing early evaluation of waveguide parameters such as propagation loss, bend loss, and mode profile, etc. From initial inspection it was found that a UV writing fluence of 1.6 J/mm^2 gave the best results in this material. The devices were completed by spincoating a polymer overcladding layer to form an ~8μm-thick layer of the same P(MMA/MAOEMA) material, which was again thermally crosslinked after deposition.

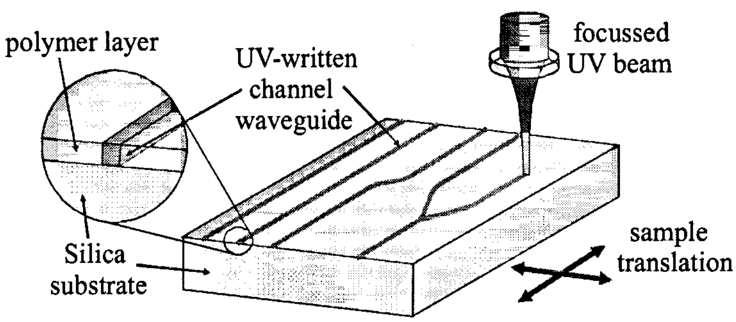


Figure 1. Direct UV writing of channel waveguide structures in a polymer layer.

Device characterization

For characterization, light from HeNe (633nm) and fibre laser (1310nm) sources were individually coupled into the waveguide with single-mode fibres for each respective wavelength. Transmission measurements were taken with an optical power meter and mode profiles were obtained using a silicon camera and computer-based evaluation software. From cut-back measurements the propagation loss in straight channel waveguides written with a fluence of 1.6J/mm^2 was found to be ~1dB/cm at 633nm, with a coupling loss of around 2 dB and loss difference between T_E and T_M modes of <0.1dB/cm. Mode profiles were largely independent of polarization with a single circular spot at both 633nm and 1310nm indicating single-mode operation at these wavelengths. The measured NA (at 633nm) of 0.05 (±0.01) corresponds to a UV-induced refractive index change of 1×10^{-3} in the core polymer layer.

The relationship between bend loss and radius of curvature was investigated by fabricating an array of S-bend channel waveguides with different bend radii in the range of 2 – 200mm (a process performed by changing the length of consecutive S-bends between 1 and 10mm while maintaining a consistent bend displacement of 125μm). Transmission results obtained from this array demonstrate that bend losses were minimized for radii of curvature greater than 50mm (Figure 2). Based on these results, Y-splitter structures designed for minimized bend loss in this material were fabricated with output arm separations of 250μm and 50μm and curved Y-junctions of 10mm-long, corresponding to radii curvatures of 200mm and 1000mm respectively. Direct UV conditions of 1mW power at a translation speed of 16mm/min were used to define each Y-splitting structure (corresponding to the same 1.6J/mm^2 fluence), and several straight waveguides were also written to allow direct comparison with the split channel waveguides in each sample. The two Y-splitter types were characterized at 633nm and 1310nm in terms of splitting ratio, branch loss and the shape of the mode profile. In each case the power-splitting ratio was measured to be 50:50 ±1% with symmetrical mode profiles typical of those given in Figure 3. It should be noted that the observed splitting ratios were near ideal, with no need for modification of the writing parameters between the two arms [6]. When compared with the S-bend insertion loss, it was found that Y-splitters featured an additional junction loss of less than 0.4dB at 633nm.

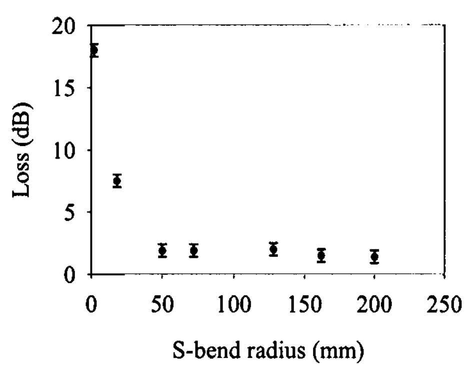


Figure 2. S-bend loss as a function of bend radius (λ = 633nm).

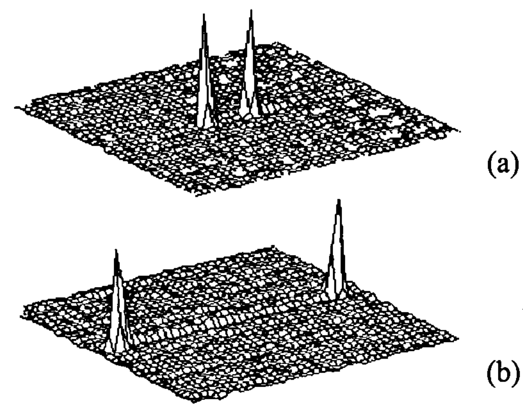
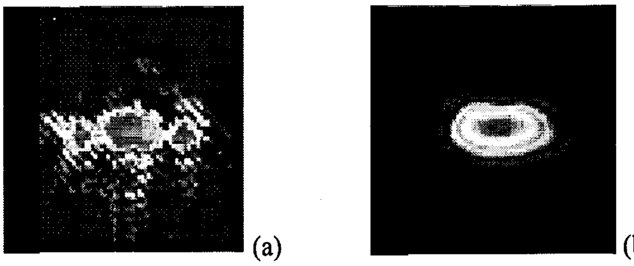


Figure 3. Mode profiles of 50:50 Y-splitters with an arm spacing of (a) 50μm and (b) 250μm (λ = 633nm).

Non-crosslinked pre-bake process for enhanced photosensitivity

Having achieved encouraging figures for Y-splitter junction loss we have continued to investigate new approaches towards obtaining a higher refractive index contrast in the channel waveguide structures. A new technique was developed which resulted in much higher NA waveguides, in which the polymer layers are pre-baked at a much lower temperature and shorter time (90°C for 10 min). Under these processing conditions, most of the solvent is removed but the polymer does not appreciably crosslink. Channel waveguides can then be written in the same way as before, but with optimised exposure conditions of 5mW power and scan speeds of 32 – 1024mm/min, corresponding to a fluence range 0.1 – 4.0J/mm^2. The sample is then crosslinked under normal conditions (140°C for 2hrs) and an overcladding layer applied.

Straight channel waveguides fabricated using this technique were characterized in terms of mode profiles and NA. It was discovered that channel waveguides written with a fluence between 0.3 and 1.1J/mm^2 supported multi-mode operation at 633nm but were single-mode at 1310nm (Figure 4). The NA of these waveguides was measured to be 0.10 (±0.01) at 633nm, corresponding to a much larger UV-induced refractive index change of ~3×10^{-3} in the core polymer layer.



(a) (b)

Figure 4. Mode profiles for channel waveguide structures UV-written into a non-crosslinked pre-bake P(MMA/MAOEMA) polymer film, as measured at (a) λ = 633nm and (b) λ = 1310nm.

Conclusions

In conclusion, we present a new technique for the definition of direct-UV-written integrated optical devices based on a UV-induced refractive index modification of PMMA-based crosslinkable copolymers, a process that eliminates the need for wet chemical developing and gas phase etching. Straight waveguides fabricated with this technique demonstrate propagation losses of ~1dB/cm, and a polarization dependent loss of <0.1dB/cm. Single-mode operation was obtained in channel waveguides with a NA of 0.05, and S-bend fabrication provided information on minimized bend loss for designing Y-splitters. Y-splitters with 200 and 1000mm radii provided symmetrical power distribution (splitting ratio 50:50%) and junction losses of less than 0.4dB. A new minimal pre-bake technique for preparation of the polymer films resulted in an enhanced photosensitivity and a larger channel waveguide NA of 0.1. These results demonstrate that direct UV writing provides a simple and versatile new solution for the fabrication of polymer integrated optical devices.

[1] B. L. Booth, *J. Lightwave Technol.* **7** (10), 1445-1453, 1989.

[2] J. –S. Koo, P. G. R. Smith, R. B. Williams, M. C. Grossel, and M. J. Whitcombe, *Chem. Mater.* **14** (12), 5030-5036, 2002.

[3] M. Svalgaard, *Elect. Lett.* **33** (20), 1694-1695, 1997.

[4] L. Xu, C. C. Eldada, K. M. T. Stengel, L. W. Shacklette, and J. T. Yardley, *J. Lightwave Technol.*, **14** (7), 1704-1712, 1996.

[5] A. G. Hallam, I. Bennion, and W. J. Stewart, *ECIO*, **201**, 26-28, 1981.

[6] K. Faerch and M. Svalgaard, *IEEE Photon. Technol. Lett.*, **14** (2), 173-175, 2002.