3566

Fabrication and characterization of planar and channel waveguides in bismuth-based oxide glasses

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ABSTRACT

This paper reports the fabrication of Bi_2O_3-based glass planar and channel waveguides using two techniques, respectively hot-dip spin-coating, and direct 244 nm UV-writing into the bulk glass. In the former, a 5 μm core glass film was achieved, which indicates a practical potential for realizing single mode operation channel guides. In the latter, the laser written structures obtained showed a positive refractive index change, estimated at 4×10^{-4} at 633 nm, and a loss of less than 4 dB/cm.

Keywords: Waveguides, Bi_2O_3, erbium, UV-writing.

1. INTRODUCTION

To increase the capacity in wavelength division multiplexing network (WDM) systems, there is an urgent need for optical amplifiers with a wide and flat gain spectrum in the telecommunication window. Also, a compact amplifier is required to meet low spatial and cost effective demand for metro use. Compact amplifiers such as erbium-doped planar waveguide amplifiers have been proposed. A novel oxide glass composition based on Bi_2O_3 has been developed, that can accept up to 13,000 ppm of Er with broadband emission and negligible concentration quenching [1-2]. A short bismuth erbium-doped fibre amplifier (Bi-EDFA) has already been demonstrated. Kuroiwa et al. have fabricated Bi_2O_3-based Er-doped fibres (Bi-EDF) with an Er concentration of 6,500 ppm and have reported that the Bi-EDF exhibited a net gain of 18 dB at 1560 nm and more than 9 dB in C + L band using only 22 cm-length [3-4]. A 1 cm Bi_2O_3-based waveguide has also been fabricated by sputtering and photolithography technology, but the propagation and insertion losses were high [5].

In this study, we report the fabrication of planar and channel waveguides in a Bi_2O_3-based glass. Erbium doped channel waveguides were fabricated using two different methods, direct laser writing into the bulk Er-doped glass, and hot-dip spin-coating followed by standard photolithography techniques and ion beam milling (IBM). Compared to the fabrication techniques involving photolithography, direct laser writing offers the advantages of a fast and low-cost way for engineering complex core/clad channel structures for integrated optic devices. The technique of hot-dip spin-coating allows the preparation of low-loss planar optical waveguides, which provide an ideal starting point for the fabrication of waveguide amplifiers. The process has been previously developed in the Optoelectronics Research Centre and has proved to be an efficient way to make low-loss (< 0.1 dB/cm) planar optical fluoride glass waveguides [6].

2. EXPERIMENTAL

The Bi_2O_3-based glass was provided by Asahi Glass Company.

2.1. Planar hot-dip spin-coated waveguides

First, a planar 3-layered glass sample (clad/core/overclad) was prepared by a two-stage hot-dip spin-coating process using the apparatus shown in figure 1. A polished Bi_2O_3-based glass substrate (disk of 2 mm thickness and 25 mm

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diameter) of refractive index 2.01 at 1550 nm, was preheated to its glass transition temperature (Tg) in an upper annealing furnace. A 200 g melt of Er-doped Bi_2O_3-based glass for the core film, or undoped Bi_2O_3-based glass for the overclad film, was heated up to 1250 °C in a separate furnace and then transferred into the lower furnace. When the temperature of the annealing furnace had stabilised, an Aerotech ATS0200 positioning system was used to transfer the molten glass between furnaces. Accurate control of the melt position resulted in the surface of the substrate being dipped a fraction of millimetre into the molten glass. The computer was used to synchronise the withdrawal and spinning of the substrate. The deposited slab waveguides were then annealed in the upper furnace at around Tg for one hour, followed by a slow ramp down to room temperature at 1 °C/min. The result is a slab waveguide consisting of a clad glass substrate, a spin-coated core film, and a spin-coated overclad film.

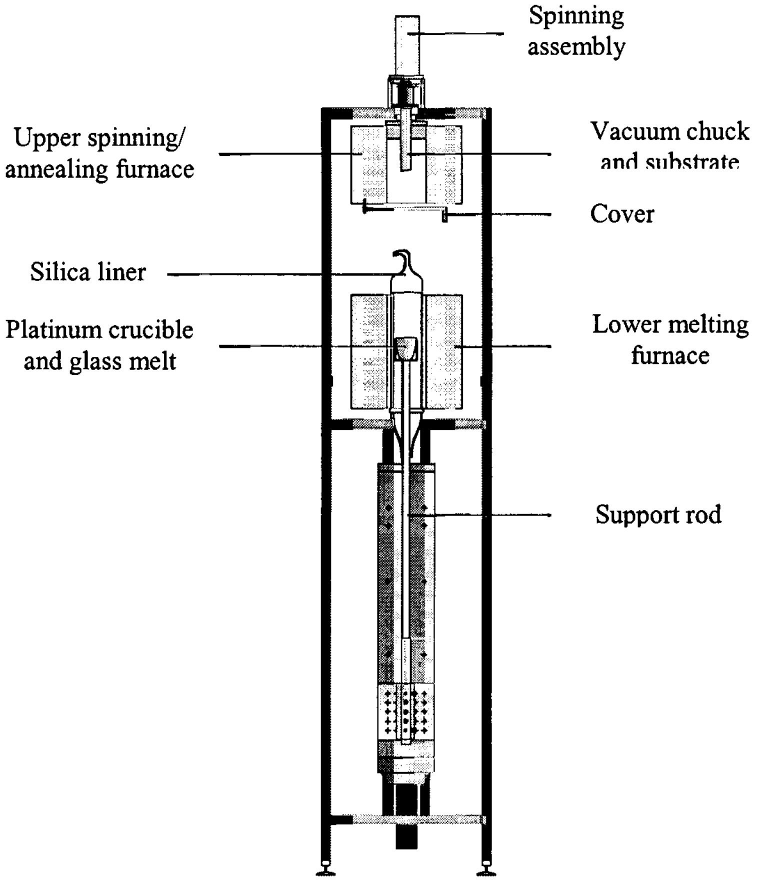

Figure 1: Apparatus for hot-dip spin-coating of waveguides using molten glass.

2.2 UV-written waveguides

The direct UV-writing apparatus consists of a frequency doubled Ar ion laser (Coherent FRED Sabre 500) with continuous wave output at 244 nm. The samples were positioned on a vacuum chuck connected to a computer controlled translation stage, which shifted perpendicularly to the incident UV laser beam at different speeds (figure 2).

Direct UV-writing was tried on three different samples: an undoped bulk glass, an Er-doped bulk glass, and a spin-coated Er-doped glass film (the film thickness was around 35 μm). Various fluences were used by varying the laser power and the writing speed to evaluate the behaviour of the glass for different conditions. Three series of fifteen exposures each were tested with a power of 10, 20 and 30 mW, and scan rates between 10 and 3000 mm/min. The spacing between the lines was 100 μm and between each set of fifteen 200 μm. The UV spot size was around 6 μm. The laser parameters are summarized in table 1.

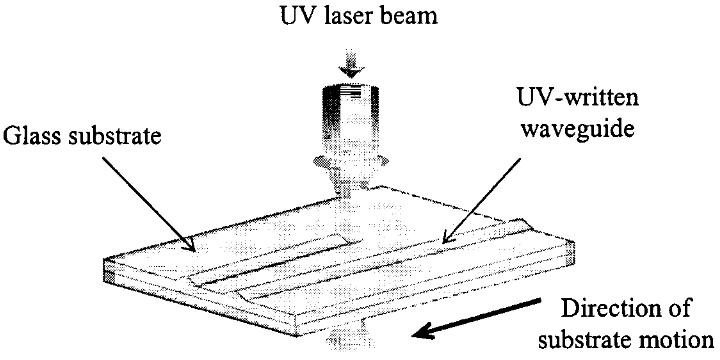

Figure 2: Scheme showing the direct UV-writing of channel structures in glass samples.

Table 1: Experimental conditions for direct UV-writing of waveguides.

Laser power (mW)	Exposure intensity (kW/cm^2)	Scan velocity (mm/min)	Exposure fluence (10 × kJ/cm^2)
10	35.3	10 … 3000	12.7 … 0.04
20	70.7	10 … 3000	25.4 … 0.08
30	106	10 … 3000	38.1 … 0.13

3. RESULTS

3.1 Planar hot-dip spin-coated waveguides

The 3-layered glass sample fabricated by hot-dip spin-coating was cut at two edges and the cross-sections were polished. Optical microscopy was used to examine the cross-section of the films.

The waveguides exhibited very good thickness uniformity over the central area, with only minor curvature of the surface observed at the border of the disc. The thickness of the core and overclad glass films is determined by temperature of the substrate and glass melt (viscosity) and the spinning speed and time [7]. The first deposited glass film undergoes a re-flow during the second spin-coating stage, thus reducing its dimensions. The final thickness of the two layers is very sensitive to the substrate temperature because of the fast quenching after dipping. Figure 3 shows an optical microscope picture of the cross-section of two 3-layered glass samples. Sample a) was prepared with a substrate temperature of 530 °C and sample b) with a substrate temperature of 580 °C in order to thin down the final core film thickness. A 5 μm core film thickness was achieved, which suggests a practical potential for single mode operation in the channel guides (figure 3).

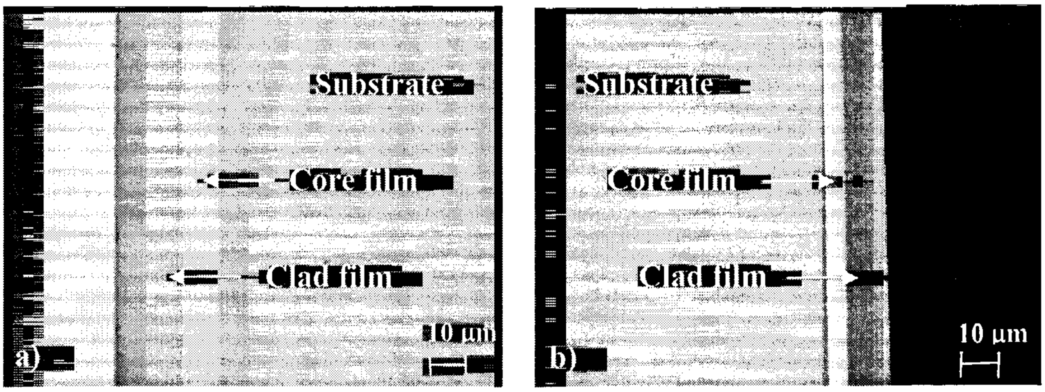

Figure 3: Cross-sectional optical microscope picture showing: a) a 22 µm core and 43 µm overclad, b) a 5 µm core and 22 µm overclad films thickness of two hot-dip spin-coated waveguide samples.

3.2 UV-written waveguides

The UV-written samples were observed under an optical microscope in order to check the surface and to identify visible effects of the UV beam on the glass. In figure 4 optical microscope images can be seen for channels written with different speeds of the translation stage. For all three UV-written samples, photostructural changes at the surface could be observed, as well as visible tracks for high fluences. Almost all the channels were discerned under the optical microscope, more clearly as the scan velocity decreased. For high fluences, physical damage and ablation of the glass occurred (figure 4), this effect was visible with the naked eye.

The dimensions of the written structures increased with decreasing scan speed for a given power. The optical micrograph of the cross-section of the undoped glass sample shows the surface roughness induced by the laser beam (figure 5). A dark, uneven glass region can be seen under the exposed area. This region is not guiding any light, whereas light confinement seems to occur from beneath this area, which suggests that the channel waveguides are buried and located several microns below the surface of the glass. From this picture, the dimensions of the damaged section produced by the highest fluence is around 20 µm wide and 10 µm deep. The guiding region itself appears to be much smaller.

Furthermore, surface profilometer measurements, using a Tencor Instruments Alpha-Step 200, were performed on the samples to quantify the surface relief caused from the UV-beam. The surface topography of the samples obtained from the Alpha-Step profiler confirmed the observations made under the microscope as it can be seen in figure 6. The scans show a variable effect on the glass surface that is depending on the write conditions. A surface scan that correlates the beam fluence with the type and height of the surface relief is depicted in figure 7. It can be generally noted that for high fluences, the UV beam generated a central ridge with ablated deposit on both sides, whereas for lower fluences, the resulting channel appeared smooth and uniform (figure 4). The structures size, measured from the surface scans, varied from 5 to 30 µm width and 15 nm to 1 µm height.

Both ends of all the samples were polished and light from a He-Ne laser (633nm) was launched into one end-face of the waveguide by coupling with a microscope objective lens or with a fiber, all the UV-written channels were found to guide light at wavelength of 633 nm. The modal intensity distribution at the other end-face was imaged onto a CCD camera using a microscope objective lens. In figure 8, TE waveguide mode profiles are depicted for two channels written with different UV-fluences. It can be observed that the waveguide produced with a low fluence showed an output mode that was more circular than the ablated channel.

Using the same optical experimental configuration, an upper bound on the loss was estimated to be 4dB/cm from the ratio of the output power of the waveguide to the incident power, assuming perfect input coupling. It is expected that the coupling loss between fiber and waveguide is usually of the order of 3db/cm, therefore we can safely expect that the propagation loss of the waveguides is of the order of 1dB/cm.

The next optical characterisation was performed measuring the numerical aperture of the waveguides. The far-field intensity pattern was obtained with a CCD camera at different distances from the end-face of the waveguides and the numerical aperture was calculated to be about 0.04. The change in refractive index was deduced from the NA through the trigonometric approximation. The refractive index change was calculated to be approximately 4×10^{-4} for a channel written with a laser power of 30 mW and a scan speed of 3000 mm/min.

Finally, the losses were measured as a function of wavelength. For the spectral attenuation measurement, white light from a tungsten lamp was launched in a fiber that was end-coupled to the UV-written waveguides. The output of the waveguides was then spectrally analysed using a monochromator. This experimental set-up was used to measure the Er absorption. A spectral attenuation graph is depicted in figure 9 for a direct UV-written waveguide in a spin-coated Er-doped Bi_2O_3-based glass film, in this graph the absorption of erbium at 1.5 μm can be observed. Furthermore, it can be deduced that the cut-off wavelength of the fundamental mode is above 1.6 μm.

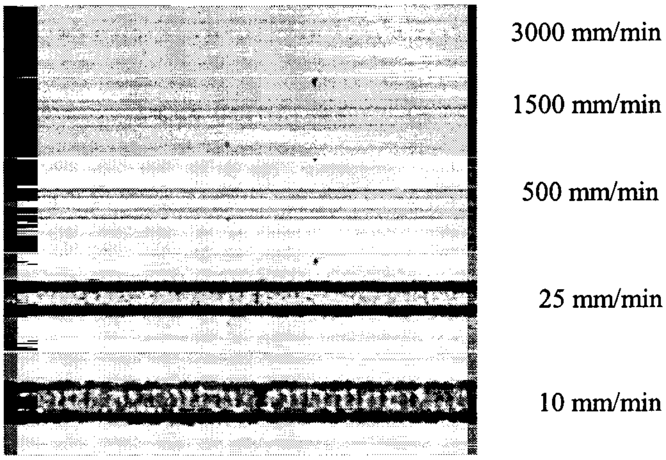

Figure 4: Optical microscope picture of the surface of a UV-written sample showing channel structures, with associated scan velocity (with a laser power of 30 mW).

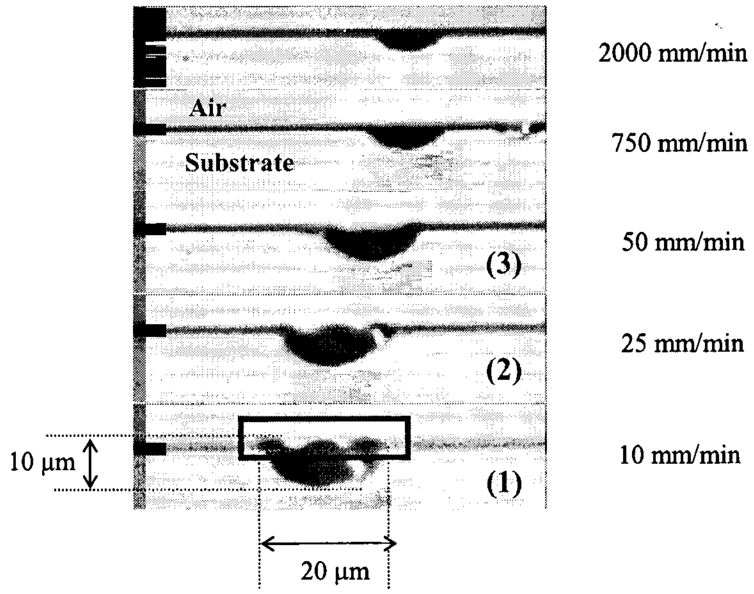

Figure 5: Cross-sectional optical microscope picture of a UV-written sample showing channel structures, with associated scan velocity (with a laser power of 30 mW).

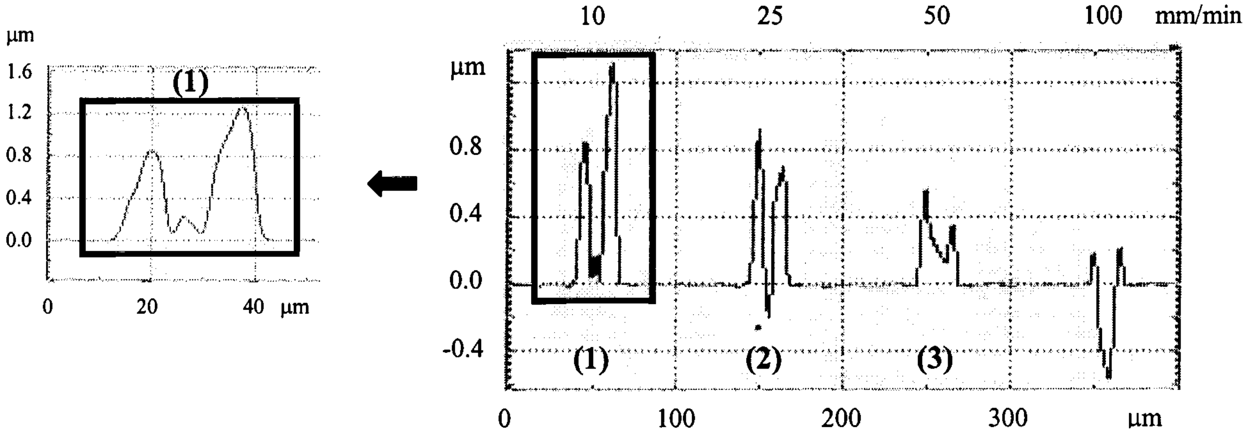

Figure 6: Surface profile of a UV-written sample. The peaks (1), (2) and (3) correspond to the channels (1), (2) and (3) of figure 5.

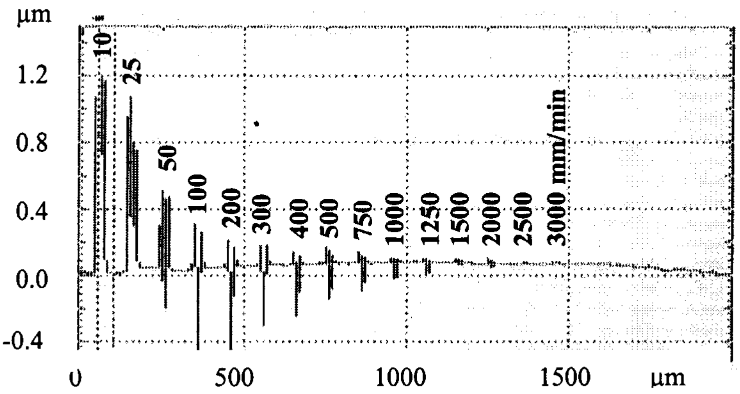

Figure 7: Surface profile of the UV-written Er-doped spin-coated film sample. The laser power is 30 mW and the scan velocity varies from 10 to 3000 mm/min.

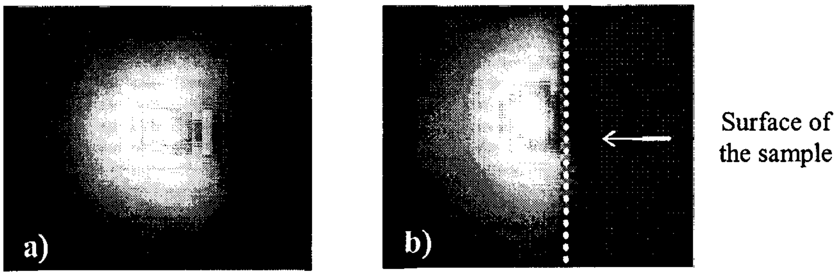

Figure 8: Near-field images of modal output for two waveguides: a) laser power of 20 mW and scan speed of 200 mm/min, b) laser power of 30 mW and scan speed of 25 mm/min.

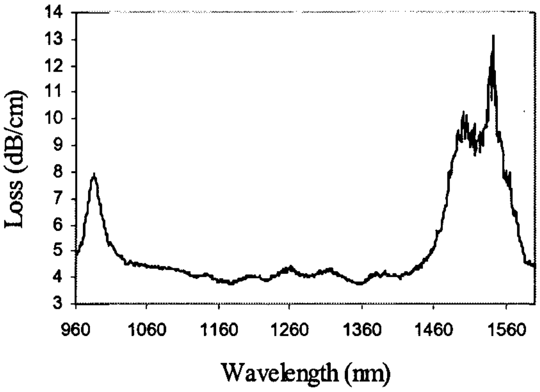

Figure 9: Loss of a direct UV-written waveguide in the spin-coated Er-doped film Bi_2O_3 glass with a laser power of 30 mW and a scan velocity of 1500 mm/min.

4. CONCLUSIONS

Planar Bi_2O_3-based glass films were successfully deposited on a glass substrate by hot-dip spin-coating, which will further allow their processing into single mode buried channel waveguides using standard photolithography techniques. Another approach to produce channel waveguides without photolithography is by direct laser writing. At the same time, a photoinduced permanent change in refractive index was demonstrated and direct laser written channel waveguides were realized into the Bi_2O_3-based glass. Using the fabrication techniques presented here, a short device integrated planar erbium amplifier will be fabricated and characterized.

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REFERENCES

1. S. Tanabe, N. Sugimoto, S. Ito and T. Hanada, "Broad-band 1.5 μm emission of Er^{3+} ions in bismuth-based oxide glasses for potential WDM amplifier", *Journal of Luminescence,* **87-89**, 670-672, 2000.

2. N. Sugimoto, "Ultrafast optical switches and wavelength division multiplexing (WDM) amplifiers based on bismuth oxide glasses", *Journal of the American Ceramic Society*, **85(5)**, 1083-1088, 2002.

3. Y. Kuroiwa, N. Sugimoto, K. Ochiai, S. Ohara, Y. Fukasawa, S. Ito, S. Tanabe and T. Hanada, "Fusion spliceable and high efficient Bi_2O_3-based EDF for short-length and broadband application pumped at 1480 nm", *Optical Fibre Communication*, Anaheim, California, 17-22 March 2001.

4. N. Sugimoto, Y. Kuroiwa, K. Ochiai, S. Ohara, Y. Fukasawa, S. Ito, S. Tanabe and T. Hanada, "Novel short-length EDF for C+L band amplification", *Optical Amplifiers and their Applications,* Quebec City, 2000.

5. Y. Kondo, T. Nagashima, S. Tanabe, T. Hanada, K. Kintaka and J. Nishii, "Fabrication of Bi_2O_3-based Er-doped waveguide for integrated optical amplifiers", *Optical Fiber Communication,* Anaheim, California, 17-22 March 2002,

6. D.W.J. Harwood, E.R. Taylor, C.T.A. Brown, D.P. Shepherd and D.N. Payne, "Novel fabrication technique for planar glass waveguides", *ECOC '98,* Madrid Spain, 20-24 September 1998.

7. D.W.J. Harwood, E.R. Taylor, Y. Rubin and G. Deflandre, "Numerical simulation of the hot-dip spin-coating process for the fabrication of glass optical waveguides", *XIX International congress on Glass*, Edinburgh, 1-6 July 2001.