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Femtosecond inscription of wavelength specific features in optical waveguide structures

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ABSTRACT

Using a femtosecond laser source waveguide, Bragg grating and waveguide-Bragg grating (WBG) structures have been written in fused silica and undoped phosphate glasses. The WBG devices are written using a slit focusing geometry and point-by-point grating inscription method. They demonstrate Bragg reflectivities at the design wavelength (1550 nm) and have been used as a new method for estimating the minimum refractive index change induced during the waveguide writing process.

Keywords: Direct write processes, photosensitivity, optical waveguide, femtosecond laser, fibre-Bragg grating, waveguide-Bragg grating.

1. INTRODUCTION

The use of femtosecond lasers in dielectric materials processing has expanded significantly in recent years due to the flexibility of this technique and the unique opportunities it presents in fields such as photonics. Of fundamental importance to the work presented here is the effect of a tightly focused femtosecond laser beam on media such as fused silica whereby the energy deposited to the medium can cause a permanent refractive index change that is localized at and around the laser focus [1]. Following this discovery the technique of direct writing of optical waveguides using femtosecond lasers has been applied to a range of passive and active media to create devices such as passive optical interconnects [2] and active gain volumes [3].

In another body of work femtosecond lasers have recently been used in the process of fibre-Bragg grating (FBG) inscription whereby the core of a single-mode optical fibre is rapidly translated through a tightly focused low repetition rate femtosecond laser beam [4]. In this point-by-point (PbP) method each laser pulse writes one period of the grating structure with the period of the grating being the ratio of the fibre translation speed to the laser pulse repetition frequency. We have studied both the processes of direct write laser waveguide fabrication and point-by-point FBG inscription in an effort to combine the two techniques and enable the direct writing of waveguide devices that include Bragg structures. Such devices could form the basis of wavelength selective splitters, de-multiplexers and miniature monolithic waveguide laser devices.

1.1. Direct write waveguides

Optical waveguides can be written in bulk glasses using two translation schemes, the waveguides are either written in a direction that is parallel or perpendicular to the laser beam direction. It is common practice to use a high quality microscope objective as the focusing lens. In the parallel writing geometry the maximum length of a waveguide is limited by the working distance of the focusing element however the advantage of this technique is that it automatically produces waveguides with a refractive index profile of cylindrical geometry. Where the laser beam is scanned in a transverse direction there is no limit to the length of waveguide achievable however the focal region of the writing laser beam (which ultimately describes the shape of the waveguide) is no longer circular in the direction of the waveguide's axis. The effect of the asymmetry of the laser focal region on the waveguide is such that, without

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mediation through other experimental techniques, a waveguide is produced with strong aspect ratio asymmetry. This asymmetry has a deleterious effect on the performance of the waveguide due to poor device mode-matching to the circularly symmetric mode profile from optical fibres used for input and output signal coupling and high transmission losses [5]. Several techniques have been used to modify the shape of the resultant refractive index region and to improve its symmetry. They include multi-passing of the writing laser beam over the written region in several slightly offset scans [6], using a very high magnification and numerical aperture (NA) objective such that each laser pulse produces a spherical modified region (of size that is defined by the diffusion of the laser pulse's energy into the glass matrix) [3] or by introducing an astigmatism into the writing beam before it enters the focusing objective [7]. We have employed another technique [8] formerly used in the fabrication of microfluidic devices [9] whereby a slit is introduced into the writing beam before the microscope objective. The effect of this slit, which is placed with its long axis parallel to the direction of the laser beam translation, is to expand the shape of the laser focus in one direction. This technique has several advantages over other methods of waveguide shape correction in that it is exceptionally simple, allows single pass writing and can be applied to objectives with long working distances allowing many layers of waveguides to be written above each other.

1.2. Point-by-point inscribed Bragg gratings

The process of stepwise inscription of fibre-Bragg gratings in optical fibres was initially reported by Malo [10] and has most recently been applied to femtosecond lasers for the inscription of gratings in standard telecommunication fibres [4] and active optical fibres [11]. This method of FBG inscription has several advantages over the more common phase mask method which typically uses the beam from an ultraviolet laser to modify the chemical structure of a photosensitive glass core. Using this methodology the length of the gratings are no longer limited by the length of an expensive phase mask, the grating writing process can be applied to any optical fibre with a transparent pathway to the core and it requires no core pre-sensitization (by doping or hydrogenation for example). Furthermore the design wavelength of the grating produced depends only on the effective refractive index of the core and externally controllable parameters. In a similar body of work we have demonstrated the effectiveness of this technique for writing gratings in optical fibres [12] with a view to its application in directly written waveguide structures.

2. METHODOLOGY

2.1. Waveguide writing technique

The experimental setup used to fabricate photonic devices is shown in Figure 1. Optical waveguides were fabricated using a regeneratively amplified, low-repetition rate Ti:sapphire femtosecond laser system (Hurricane) from Spectra-Physics. This system produced sub 120 fs, 1 kHz pulses and delivered an average power of 1 W. The femtosecond laser beam, operating at 800 nm, passed through a rotatable $\frac{1}{2}$ -wave plate and linear polarizer setup allowing fine control of the laser pulse energy to be achieved. Complementing this arrangement was a set of neutral density filters that further helped attenuate the amplified pulses to the required microjoule level.

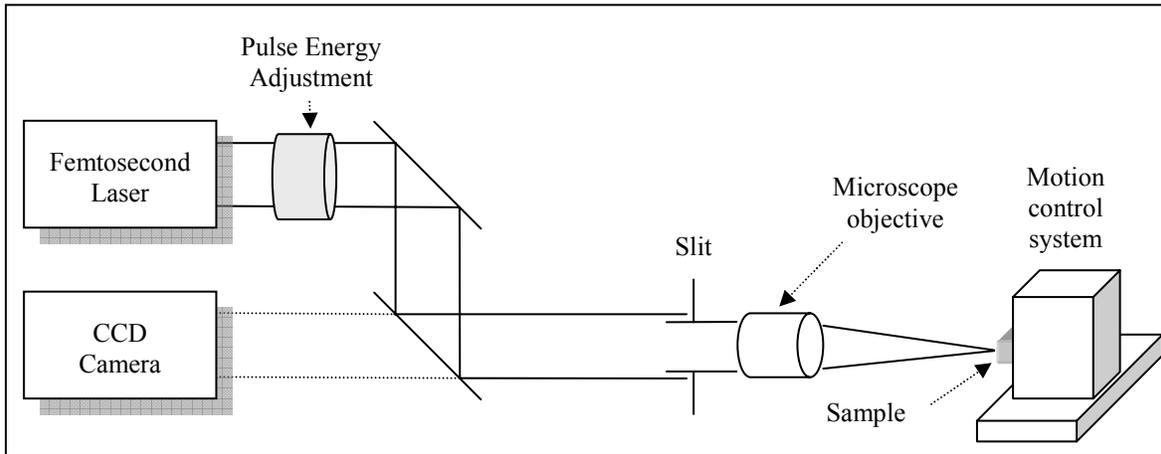


Figure 1: Waveguide writing setup. Note that the FBG and WBG writing setups are almost identical to this figure.

The laser pulses were tightly focused by a 20×0.46 NA microscope objective and injected into polished $12\times 10\times 3$ mm fused silica and phosphate glass samples. Using a computer controlled XYZ motion control stage samples were scanned in the x-direction with the laser focus approximately $450\ \mu\text{m}$ below the surface of the glass sample and at a speed of $50\ \mu\text{m/s}$ in the direction perpendicular to the laser beam propagation. A vision system consisting of a CCD camera and monitor were used to align target samples; the CCD camera made use of the view of the sample afforded through a dielectric turning mirror that was transparent to visible wavelengths of light.

In order to fabricate devices with symmetric cross sections, a horizontal slit aperture with a width of $520\ \mu\text{m}$ was inserted immediately before the focusing objective. The corresponding beam evolution and energy distributions at focus for this case are shown in Figure 2 (a) and (b). The effect of the slit is to expand the focal region in the y-direction giving rise to a near circularly symmetric writing beam. Pulse energies ranging from $0.5\ \mu\text{J}$ to $2\ \mu\text{J}$, after passing through the slit, were used in the formation of the optical waveguides.

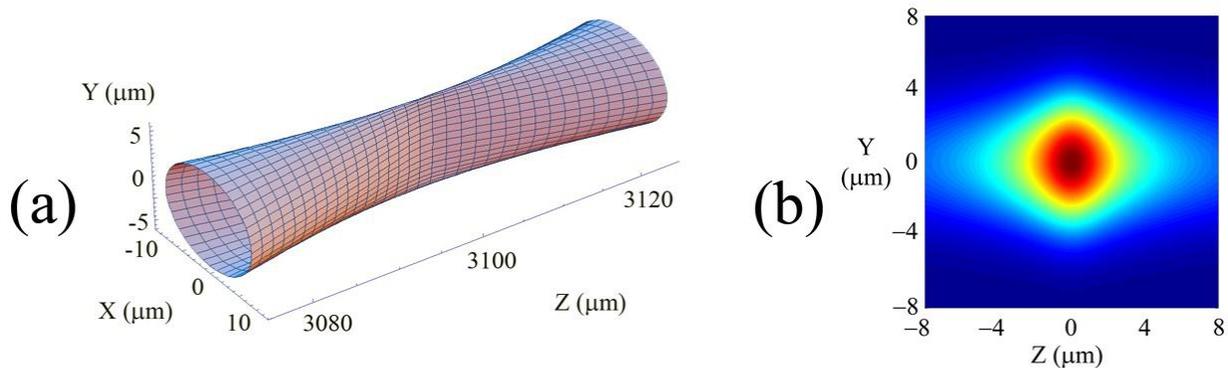


Figure 2: Modeled ray diagrams of the (a) laser beam focus and (b) energy distribution plot of the writing laser beam with the addition of the slit to the waveguide writing geometry.

Following the writing process the input and output faces of the glass sample were ground back and polished so as to remove the region of material where the writing beam was not fully submerged in the glass.

In order to characterize the fabricated waveguides, a fibre carrying either $635\ \text{nm}$ or $1550\ \text{nm}$ light was brought into close proximity with the polished input of the device. Near field and far field mode distributions exiting the device were captured using a $635\ \text{nm}$ wavelength probe, a microscope objective, a camera and beam profiler.

2.2. Fibre-Bragg grating inscription

The attenuated output from the femtosecond laser described in Section 2.1 was spherically focused into the core of an optical fibre using a 20×0.80 NA oil immersion microscope objective. The setup used is almost identical to that in Figure 1 however the slit is removed during the grating writing process and the use of an oil immersion objective removes the effect of the cylindrical input face of the optical fibre on the focusing objective. Optical fibre clamps are used in place of the bulk glass sample holder and the vision system was used to align the focus of the laser onto the centre of the core of the optical fibre.

During the writing process pulse energies between 150 and 450 nJ were used and second-order gratings were written at a translation speed of approximately 1.08 mm/s. Gratings of lengths up to 55 mm were produced using this method. As with most common FBG writing schemes the spectral characteristics of the grating can be monitored during the inscription process however given that the inscription process takes just a few tens of seconds the on-line grating diagnostic served only to confirm that the gratings written were of the desired wavelength and depth.

2.3. Waveguide-Bragg grating manufacture

The process of waveguide-Bragg grating (WBG) manufacture is a combination of the two processes described above. Using the same objective (20×0.46 NA) waveguides were written under conditions optimized for the glass type in use. The grating structure was written using the same objective but with the slit removed from the optical train and at a pulse energy more akin to that used during FBG manufacture. The order of the waveguide and grating manufacturing processes was alternated to investigate the effects on WBG performance.

3. RESULTS

3.1. Direct write waveguides

Highly symmetrical waveguides were fabricated in 10 mm long fused silica and phosphate glass blocks using the slit method. Under optical microscopy these devices exhibit excellent circular symmetry; Figure 3(a) & (b) show optical micrographs of the waveguide structures written in fused silica and phosphate glass respectively when illuminated from below.

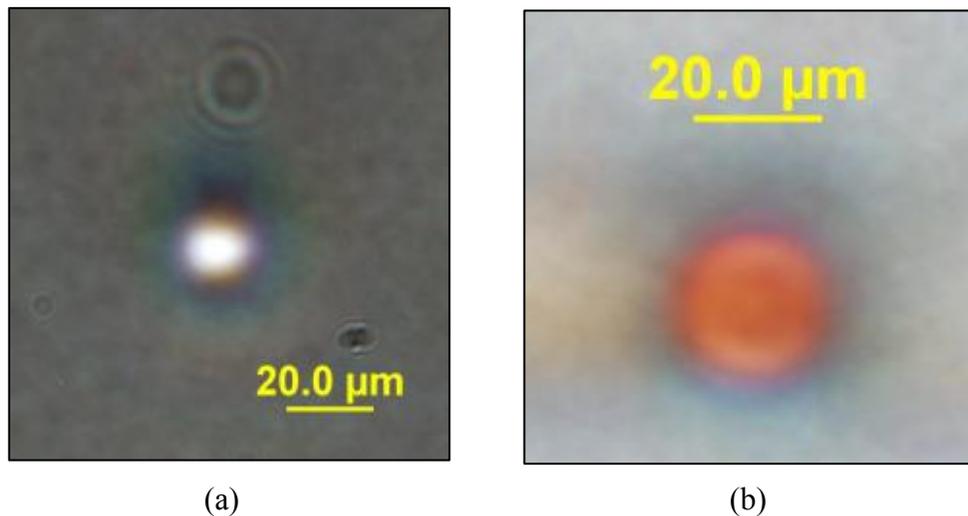


Figure 3: Microscope images of the optical waveguides written in (a) fused silica and (b) phosphate glass. The waveguide structures were illuminated from below hence the appearance of guided visible light through the device. The writing laser beam was incident from the right hand side of the figures.

Far-field and near-field images of the waveguide modes were taken for the waveguide written in phosphate glass. Using these mode profiles and knowledge of the waveguide diameter (taken from Figure 3(b)) an estimate of the refractive index change induced in the medium was derived using the BeamPROP software package from RSoft Inc. to best match the near field profile. From this fit the refractive index change in the waveguide is believed to be $+3.5 \times 10^{-3}$. Measurements of the losses in the phosphate glass waveguide have also been measured and are approximately 0.39 dB/cm at 1550 nm. Measurements of the loss characteristics of the fused silica waveguides have not been conducted at the time of writing.

3.2. Fibre-Bragg gratings

Fibre-Bragg gratings have been written in a range of passive and active non-hydrogenated single mode optical fibres. A typical passive device is shown here in Figure 4. This grating was written in Corning SMF-28e with a pulse energy of 0.37 μ J, it was 30 mm long and had a pitch of 1070.21 nm. The grating exhibited up to -53 dB peak insertion loss and the full-width half-minimum (FWHM) linewidth of the grating was 150 pm. Judicious selection of the writing power allows for minimization of the out of resonance insertion loss which in this device was 1.0 dB.

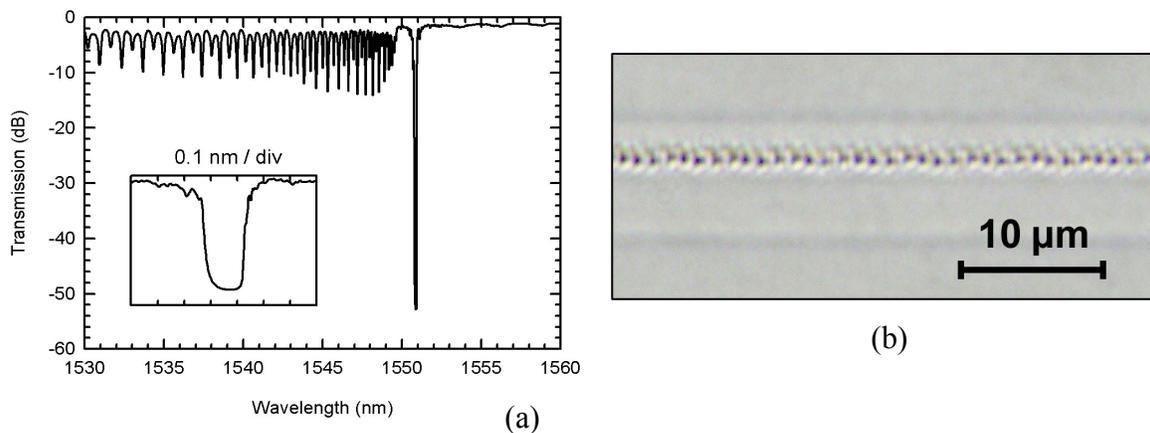


Figure 4: (a) Transmission spectrum of a typical PbP FBG, the inset shows the main rejection peak on an expanded abscissa. (b) Optical micrograph of the same FBG showing the individually inscribed grating periods overlapping the fibre optic's core.

The strong cladding mode structure that extends to the short wavelength side of the Bragg resonance peak is attributed to effective tilt introduced in the grating by writing slightly away from the core centre.

3.3. Waveguide-Bragg gratings

Waveguide structures that include Bragg grating reflectors in the entire length of the waveguide have been written in phosphate and fused silica glasses. Optical micrographs of an example fused silica WBG device and its components are shown in Figure 5. In these images the waveguides were written with pulse energies of 1.2 μ J, the gratings were written with pulse energies of 0.4 μ J and the waveguide and grating combination were written with the grating structure inscription preceding the waveguide inscription.

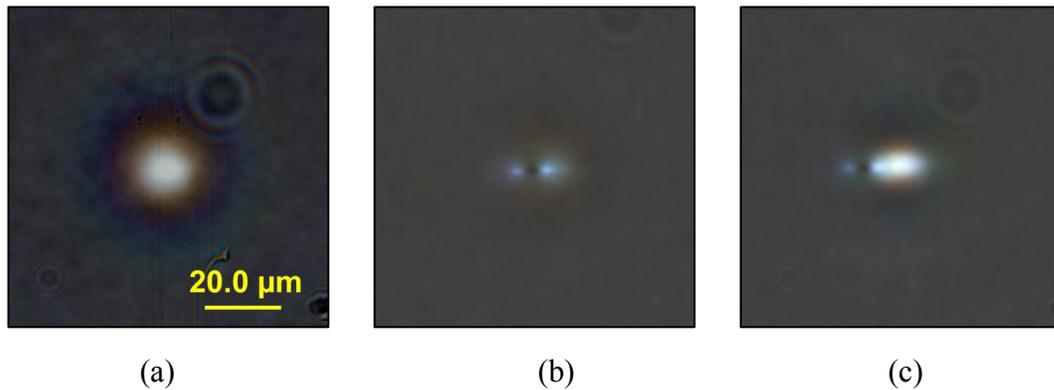


Figure 5: Optical micrographs of WBG components in fused silica observed under the same illumination and magnification conditions; (a) waveguide structure written alone (b) grating structure written alone (c) composite waveguide and grating structure. The writing laser beam was incident from the right hand side of the figures.

The characteristics of the waveguides written using the slit method have already been discussed in Section 3.1 however one should note that the waveguides in Figure 5(a) & (c) again exhibit excellent circular symmetry and are approximately 10 -15 μm in diameter. It is evident from Figure 5(b) that the grating structure consists of a central dark region where the modification of the fused silica has made the glass opaque. Surrounding this region to the left and right (in line with the writing beam's propagation path) are two regions that are seen to act as optical guides to the illuminating white light. In the composite waveguide and grating structure it is unexpected to find that the waveguide and grating do not overlap completely in the direction of the writing laser beam. This discrepancy is highly repeatable and not dependant on the order in which the waveguide and grating are written. It was expected that the waveguide and grating structures should overlap in space and this discrepancy may be due to the fact that the waveguides and gratings were written with different laser powers. It is conceivable that thermal or Kerr lensing in the optical elements or sample were responsible for the offset in positions.

The reflection and transmission spectral profiles of the fused silica waveguides, gratings and waveguides with gratings were measured in transmission and reflection using a swept wavelength system from JDS Uniphase. Because the rejection efficiencies of the spectral features were weak, reflection measurements were predominantly used in the characterization of the waveguides and gratings because this provides for higher sensitivity measurements. The waveguide structures written without a grating showed no evidence of any Bragg resonance reflections. Both the grating and the waveguide-with-a-grating structures exhibited distinct Bragg reflection peaks at wavelengths associated with the grating period and material refractive index. The gratings written were of second order period for operation at 1550 nm and slight discrepancies between the design and actual operation wavelengths arose due to uncertainties in the glass refractive indices and modification of the glass refractive index during the waveguide writing process. The spectral reflection profile of the written structures was observed to depend on the lateral position of the probing optical fibre relative to the grating or waveguide structures. Horizontal scans of the reflection profiles were obtained and plotted to further elucidate the behavior of the structures.

By measuring the peak in the reflection profile of the Bragg grating written with and without the presence of the waveguide structure a lower bound could be placed upon the change in refractive index induced during the waveguide writing process. Because the waveguide's guided mode resides partially outside of the waveguide structure the maximum induced refractive index is in fact higher than that 'measured' through the introduction of the grating.

The reflection profiles from the Bragg grating only and waveguide with grating are shown in Figure 6. Each graph contains two curves showing the reflection profile where the probing fibre is aligned on the centre of the structure and when aligned 12 μm from the centre. The reflection loss is plotted on a logarithmic scale relative to 0 dB which would represent 100% reflection.

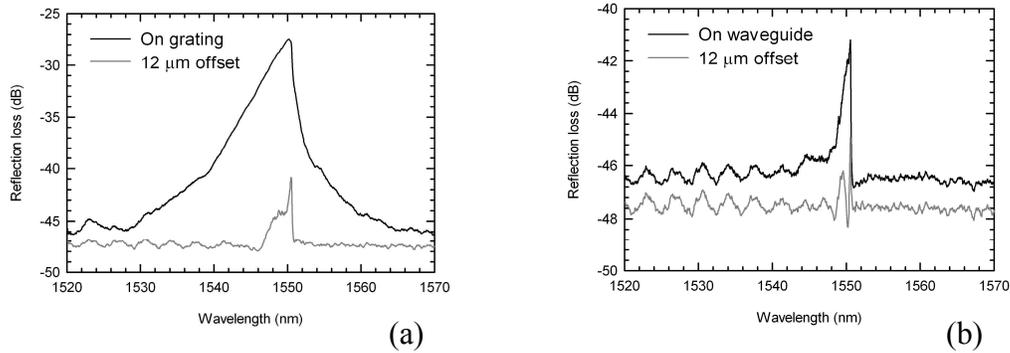


Figure 6: Reflection spectra from the (a) grating only structure and (b) waveguide with grating structure written in fused silica. Each plot shows two curves, the black curve represents the reflection profile from the centre of the structure where as the gray curve represents the reflection profile when the probing fibre is laterally offset from the structure centre by 12 μm .

The waveguide with a grating structure (Figure 6(b)) demonstrates a resonant Bragg reflection profile that is similar to that of fibre-Bragg gratings written with the PbP method. The grating only structure (Figure 5(a)) exhibits a much higher peak reflection efficiency however the width of the peak is very broad at approximately 15 nm. Away from the centre of the grating the reflection profile more closely assumes that of a typical Bragg grating structure with a narrow and well defined resonance peak. Complete plots of the reflection loss vs. lateral offset from the structure of interest are shown in Figure 7. These plots demonstrate how the width of the reflection peak from the waveguide with grating structure, Figure 7(b), remains narrow over a range of lateral probe positions. The greatest reflection efficiencies occur with a lateral position range of 10 μm which is comparable with the expected mode field diameter of the waveguide. By comparison, the grating-only structure exhibits a more narrow tolerance to lateral offset which is consistent with the lack of waveguide structure.

The reflection spectrum of the on-grating resonance depicted in Figure 6(a) is characterized by a broad Bragg resonance of approximately 15 nm full-width half-maximum (FWHM_x). Knowing that the physical period of the grating (Λ) is fixed, the broadening of this resonance ($\Delta\lambda$) cannot be attributed to a variation (Δn) of the effective refractive (n_{eff}) as dictated by Equation 1.

$$\Delta\lambda = \lambda_{Bragg} \frac{\Delta n}{n_{eff}} \quad (1)$$

For a grating bandwidth of 15 nm Equation 1 dictates that the variation in n_{eff} of the bulk material would have to be 1.2×10^{-2} , a value far greater than the refractive index change expected during the material processing step. It is more likely that the naturally divergent nature of the probing beam has limited the depth of grating that has been sampled. In this instance the broadening of the wavelength response is given by the Equation 2 for a weak grating (where κL is low) and the length of grating sampled by the light field is L .

Equation 1 however can be used to estimate the minimum refractive index change induced during the writing process. In Figure 6 the peaks in reflectivity of the Bragg grating only and WBG structures occur at 1550.11 nm and 1550.57 nm respectively. Using Equation 1 this implies that $\Delta n > 4.3 \times 10^{-4}$.

$$\Delta\lambda \approx \frac{\lambda_{Bragg}^2}{2n_{eff}L} \quad (2)$$

With a $\Delta\lambda = 15$ nm and n_{eff} of 1.44 the sampled length of the grating is implied by Equation 2 as being 500 μm . By way of a comparison, Figure 6(b) shows a significantly narrower Bragg resonance with a bandwidth of approximately 1 nm FWHM_x (indicative of an interaction length of 840 μm). Such an observation is consistent with the

additional confinement offered to the sampling probe beam by the waveguide structure. The significantly lower reflection efficiency of the waveguide-Bragg grating compared with the grating only case can be attributed to the poor overlap between the waveguide and grating region.

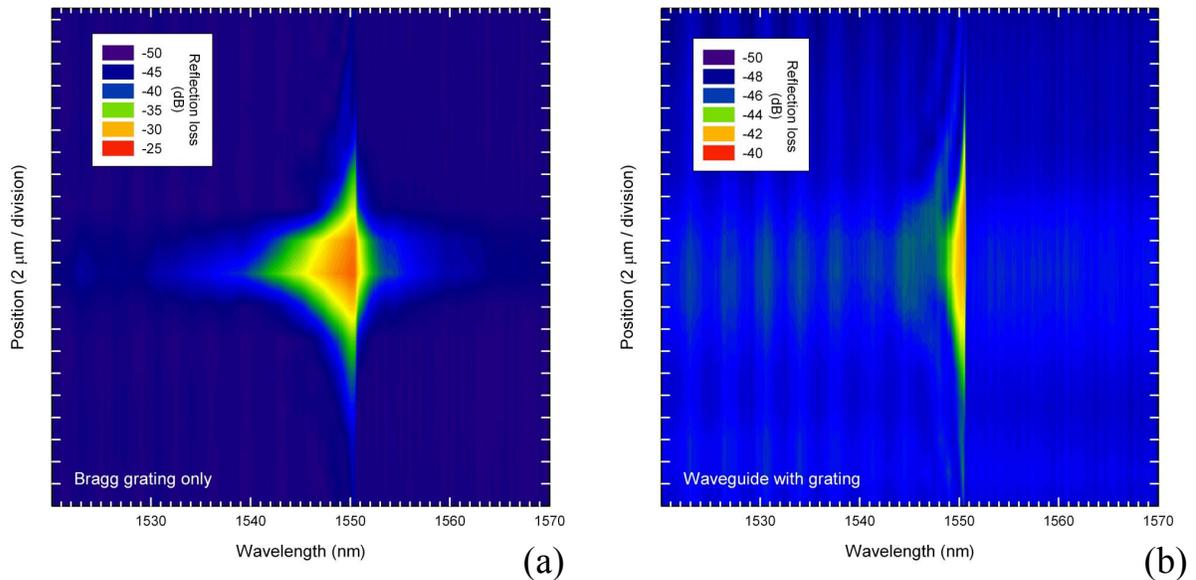


Figure 7: Contour plot of the reflection efficiencies of the (a) grating only and (b) waveguide with grating structures. Note that the plots have differing reflection loss (z -axis) scales.

Future improvements to the performance of these devices should be possible through optimizing the overlap between the grating and waveguide structures and by increasing the magnitude of the refractive index change written during waveguide manufacture. Several pathways exist towards achieving this latter goal including the optimization of waveguide writing conditions (by compensating for the self focusing or thermal lensing effects) and through the use of different glass hosts to increase the achieved Δn .

4. CONCLUSIONS

Using a simple slit beam shaping system we have written circularly symmetric optical waveguides in bulk glasses that include resonant Bragg grating structures added to the waveguides in a point-by-point inscription process. The characteristics of these waveguides, gratings alone and waveguide-Bragg gratings have been examined, primarily in reflection, and explanations for the spectral behavior of the devices are given. The waveguide-Bragg grating writing process is yet to be optimized and pathways for improving the performance of these devices have been offered. This work lays the foundations for the development of WBG structures in other passive and active host materials.

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REFERENCES

- [1] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," *Optics Letters*, vol. 21, pp. 1729-1731, 1996.

- [2] J. R. Liu, Z. Y. Zhang, S. D. Chang, C. Flueraru, and C. P. Grover, "Directly writing of 1-to-N optical waveguide power splitters in fused silica glass using a femtosecond laser," *Optics Communications*, vol. 253, pp. 315-319, 2005.
- [3] S. Taccheo, G. Della Valle, R. Osellame, G. Cerullo, N. Chiodo, P. Laporta, O. Svelto, A. Killi, U. Morgner, M. Lederer, and D. Kopf, "Er : Yb-doped waveguide laser fabricated by femtosecond laser pulses," *Optics Letters*, vol. 29, pp. 2626-2628, 2004.
- [4] A. Martinez, M. Dubov, I. Khrushchev, and I. Bennion, "Direct writing of fibre Bragg gratings by femtosecond laser," *Electronics Letters*, vol. 40, pp. 1170-1172, 2004.
- [5] A. Saliminia, N. T. Nguyen, M. C. Nadeau, S. Petit, S. L. Chin, and R. Vallee, "Writing optical waveguides in fused silica using 1 kHz femtosecond infrared pulses," *Journal of Applied Physics*, vol. 93, pp. 3724-3728, 2003.
- [6] J. R. Liu, Z. Y. Zhang, C. Flueraru, X. P. Liu, S. D. Chang, and C. P. Grover, "Waveguide shaping and writing in fused silica using a femtosecond laser," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 10, pp. 169-173, 2004.
- [7] R. Osellame, S. Taccheo, M. Marangoni, R. Ramponi, P. Laporta, D. Polli, S. De Silvestri, and G. Cerullo, "Femtosecond writing of active optical waveguides with astigmatically shaped beams," *Journal of the Optical Society of America B-Optical Physics*, vol. 20, pp. 1559-1567, 2003.
- [8] M. Ams, G. D. Marshall, D. J. Spence, and M. J. Withford, "Slit beam shaping method for femtosecond laser direct-write fabrication of symmetric waveguides in bulk glasses," *Optics Express*, vol. 13, pp. 5676-5681, 2005.
- [9] Y. Cheng, K. Sugioka, K. Midorikawa, M. Masuda, K. Toyoda, M. Kawachi, and K. Shihoyama, "Control of the cross-sectional shape of a hollow microchannel embedded in photostructurable glass by use of a femtosecond laser," *Optics Letters*, vol. 28, pp. 55-57, 2003.
- [10] B. Malo, K. O. Hill, F. Bilodeau, D. C. Johnson, and J. Albert, "Point-by-Point Fabrication of Micro-Bragg Gratings in Photosensitive Fiber Using Single Excimer Pulse Refractive-Index Modification Techniques," *Electronics Letters*, vol. 29, pp. 1668-1669, 1993.
- [11] Y. Lai, A. Martinez, I. Khrushchev, and I. Bennion, "Er:Yb Fiber Grating Laser Based On Femtosecond Laser Inscription Technique," presented at BGPP / ACOFT, Sydney, Australia, 2005.
- [12] G. D. Marshall and M. J. Withford, "Rapid production of arbitrary fibre Bragg gratings using femtosecond laser radiation," presented at IEEE LEOS Annual Meeting, Sydney, Australia, 2005.
- [13] M. Bass, J. M. Enoch, E. Van Stryland, and W. L. Wolfe, *Handbook of Optics*, 2nd ed: McGraw-Hill, 2001.