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Direct laser written waveguide coupler with an optically-tunable splitting ratio

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ABSTRACT

The femtosecond laser direct-write technique was used to create a 2x2 single-mode waveguide coupler in Yb-doped borosilicate glass. Initial modelling demonstrates that a reversible change in splitting ratio at 800 nm of more than 20% is possible (i.e. 50:50 to 30:70) if a shift in refractive index of the order of 1×10^{-4} can be induced. Such a shift is expected to be achieved through resonant optical excitation at 976 nm of the ytterbium ions, which increases the refractive index through heating and the direct pumping of a saturable optical absorption.

Keywords: Femtosecond laser, direct-write, tuneable, waveguide, coupler, ytterbium

1. INTRODUCTION

Significant attention has been directed to the use of femtosecond laser pulses for fabricating optical devices in transparent materials since it was demonstrated in 1996 that focussed femtosecond laser pulses can induce an increase in the refractive index of bulk transparent glasses at the point of focus[1]. This discovery led to the realisation of a variety of laser-inscribed waveguide devices, including evanescent couplers/splitters, waveguide Bragg-gratings, waveguide amplifiers and monolithic distributed-feedback waveguide laser oscillators[2-7]. The femtosecond laser direct-write technique also offers unique opportunities for the fabrication of three-dimensional photonic waveguide devices. Further advantages of the technique include rapid prototyping, compatibility with existing fibre systems, and freedom from lithographic masks and clean room fabrication environments. Here we report on the application of the femtosecond laser direct-write technique to create a 2x2 single-mode waveguide coupler with an optically-tunable splitting ratio.

2. BACKGROUND

In any absorptive medium the refractive index varies considerably in the vicinity of an absorption as a function of wavelength, and this variation in index is described by the Kramers-Krönig relations[8]. Furthermore, any change in the absorption of the medium will result in an associated change in refractive index. In rare-earth-doped glasses, the absorptions can be readily modified by pumping the glass at a suitable wavelength. For Yb^{3+}, the energy level structure consists of a single metastable state corresponding to an absorption at 976 nm, with the remaining states corresponding to absorptions in the UV and above. Tuning of the splitting ratio of a 2x2 coupler fabricated in a Yb-doped glass sample is thus achieved through resonant optical excitation at 976 nm of the ytterbium ions, which shifts the refractive index not only through the direct pumping of a saturable optical absorption (Kramers-Krönig causality) but also due to heating (thermo-optic effect)[9]. It is important to note that the index change is reversible and can also have a component due to the sum of contributions of a number of discrete UV transitions[10].

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3. MODELLING

3.1 2x2 evanescent coupler

Figure 1 (a) shows a beam propagation model (RSoft) of a simple 2x2 coupler fabricated in a Yb-doped borosilicate glass. When 800 nm light is injected into the left arm the coupler it can be seen that 50% of that light exits both of the coupler arms. The amount of light in each coupler arm is monitored in Fig. 1 (b). By varying the refractive index change in the coupler along the path that 976 nm pump light would follow (when injected into one arm) and monitoring the difference in the output splitting ratios, we demonstrate that a reversible change in splitting ratio of more than 20% is possible (i.e. 50:50 to 30:70) if a shift in refractive index of the order of $1x10^{-4}$ can be induced (Fig. 1 (c)). We believe that such a shift is achievable based on previous work in the literature. Low Yb-doped fibre literature indicates a $\Delta n \sim 2x10^{-6}$ can be achieved through resonant excitation of doped ions[10]. Our borosilicate glass has ten times more Yb ions by weight so we anticipate at least $\Delta n \sim 2x10^{-5}$ can be realised. Furthermore, our previous waveguide laser work suggests a pump induced temperature rise in the slow thermal regime (longer than 1 s) of 10-15^{o}C[11, 12]. This temperature rise translates into a $\Delta n = \Delta T(dn/dT) = 10x(3x10^{-6}) \sim 3x10^{-5}$ in borosilicate via the thermo-optic effect. Together these two effects should combine to shift the refractive index by enough of a margin such that a change in the splitting ratio at 800 nm can be measured.

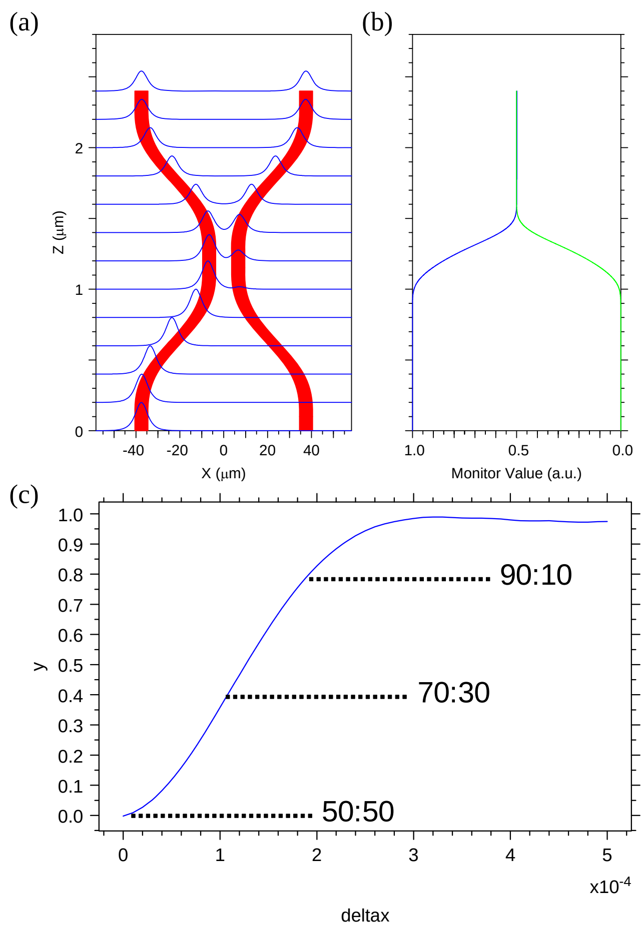

Figure 1. (a) Beam propagation simulation (RSoft) of a 2x2 coupler in Yb-doped borosilicate glass. (b) Monitored 800 nm light guided in each coupler arm along the device. (c) Difference in splitting ratio at the coupler's exit when the device's refractive index (deltax) is varied where 976 nm light propagates.

3.2 Mach-Zehnder interferometer

If a more sensitive device is required a Mach-Zehnder interferometer could be fabricated. The Mach-Zehnder interferometer (Fig. 2) is a particularly simple device for demonstrating interference by division of amplitude. A light beam is first split into two parts by a 50:50 evanescent coupler (beam splitter) and then recombined by a second 50:50 coupler. The distribution of optical powers at the two outputs depends on the precise difference in optical path lengths and on the wavelength of light being used. If the interferometer is fabricated precisely, the path length difference can be adjusted (e.g. in our case by shifting the refractive index of the device through resonant optical excitation and heating) so that for a particular optical frequency the second 50:50 coupler will split the beam with an efficiency between 0% and 100%, i.e. an optically tunable splitter can be realised.

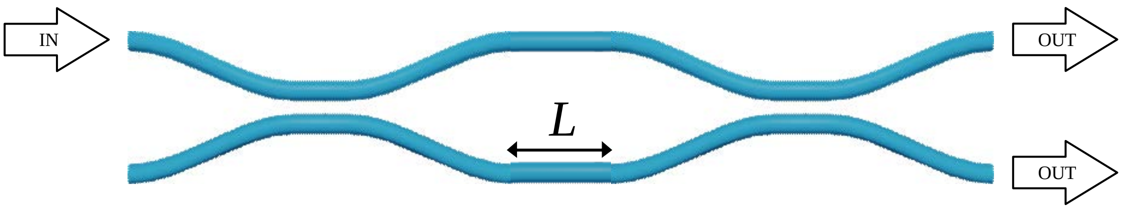

Figure 2. Schematic of a Mach-Zehnder interferometer incorporating two 50:50 splitters separated by a linear region of length *L*.

The phase difference between the light beams travelling in both arms of the Mach-Zehnder shown in Fig. 2 is given by

$$\Delta\varphi = kL\Delta n = \frac{2\pi}{\lambda} L \frac{dn}{dT} \Delta T \qquad (1)$$

where L is the portion of the device, in one arm, where the refractive index is shifted by the 976 nm pump light. For complete switching of the light exiting the device, a phase change of π is required over the length L. In our Yb-doped borosilicate glass, such a change at 800 nm requires $L\Delta T$=0.13. Once again assuming a pump induced temperature rise in the slow thermal regime of 10^{o}C, the length required to achieve complete switching is 13 mm. In terms of integrated devices, this length is quite significant and will result in a bulky device. Hence, there is a trade-off when considering a Mach-Zehnder as a switching device; sensitivity vs. device size. Furthermore, the longer the device becomes the harder it is to control the 976 nm pump absorption properties. For these reasons we concentrated our current efforts on a simple 2x2 evanescent coupler only.

4. EXPERIMENT & RESULTS

The femtosecond laser direct-write technique was used to create a 2x2 single-mode waveguide coupler in Yb-doped borosilicate glass (Fig. 3). The laser used to fabricate this device was a 1 kHz repetition rate, 120 fs pulse length, 800 nm regeneratively amplified Ti:sapphire laser that was focused into the glass sample using a 20x (NA 0.45) microscope objective. The coupler device was written 170 µm below the surface of a 15 mm long borosilicate glass sample with a nominal doping concentration (by weight) of 3% Yb. The glass sample was translated at a speed of 25 µm/s through the focused writing beam. The circularly polarised[13, 14] writing beam had a pulse energy of 1.2 µJ after passing through a 500 µm slit[15] and before being focussed. The coupler device was overwritten with five multiple passes.

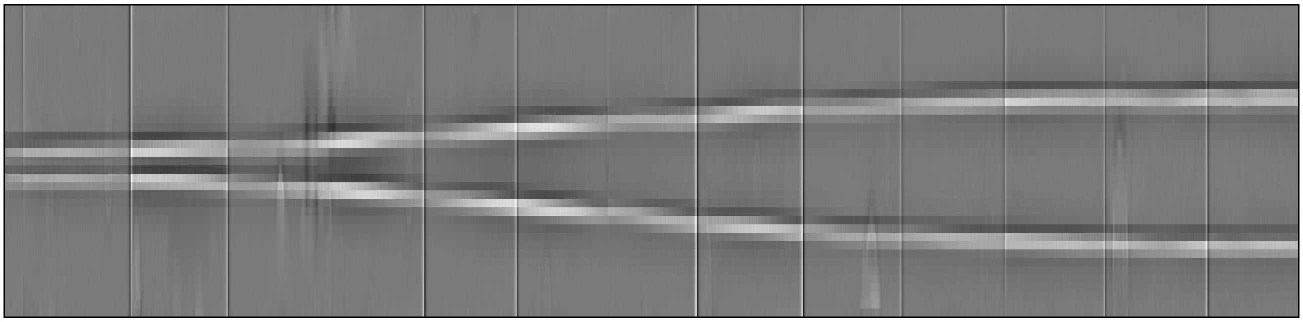

Figure 3. Transmission phase contrast micrographs stitched together showing half of a 2x2 evanescent coupler fabricated in Yb-doped borosilicate glass using the femtosecond laser direct-write technique. Image not to scale.

Characterisation of the fabricated coupler revealed a splitting ratio of 48:52 at 800 nm. This ratio was then monitored whilst injecting ~300 mW of 976 nm light into one of the couplers arms. In the slow thermal regime (longer than 1 s) we were unable to ascertain whether this splitting ratio underwent any change due to the introduction of the 976 nm light. We believe this is due to both arms in the interaction region of the coupler slowly heating up simultaneously. Measurement of the splitting ratio in the fast thermal regime (less than 3 μs) and on time scales close to the excited state lifetime of Yb (approximately 1 ms) should resolve this issue and is currently being investigated. Work into designing speciality glasses (doped glasses with higher thermo-optic coefficients) with our collaborators is also underway.

5. CONCLUSION

The femtosecond laser direct-write technique was used to fabricate a 2x2 single-mode waveguide coupler in Yb-doped borosilicate glass. The coupler had a splitting ratio of 48:52 at 800 nm. This ratio was not seen to change under 976 nm pumping in the slow thermal regime. Experiments monitoring the splitting ratio in the fast thermal regime are ongoing.

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REFERENCES

[1] Davis, K. M., Miura, K., Sugimoto, N. and Hirao, K., "Writing waveguides in glass with a femtosecond laser," Opt. Lett. 21, 1729-1731 (1996).

[2] Marshall, G. D., Ams, M. and Withford, M. J., "Direct laser written waveguide-Bragg gratings in bulk fused silica," Opt. Letters 31, 2690-2691 (2006).

[3] Gattass, R. R. and Mazur, E., "Femtosecond laser micromachining in transparent materials," Nat. Phot. 2, 219-225 (2008).

[4] Marshall, G. D., Dekker, P., Ams, M., Piper, J. A. and Withford, M. J., "Directly written monolithic waveguide laser incorporating a distributed feedback waveguide-Bragg grating," Opt. Lett. 33, 956-958 (2008).

[5] Ams, M., Dekker, P., Marshall, G. D. and Withford, M. J., "Monolithic 100 mW Yb waveguide laser fabricated using the femtosecond-laser direct-write technique," Opt. Lett. 34, 247-249 (2009).

[6] Ams, M., Marshall, G. D., Dekker, P., Piper, J. A. and Withford, M. J., "Ultrafast laser written active devices," Laser & Photon. Rev. 3, 535-544 (2009).

[7] Marshall, G. D., Politi, A., Matthews, J. C. F., Dekker, P., Ams, M., Withford, M. J. and O'Brien, J. L., "Laser written waveguide photonic quantum circuits," Opt. Express 17, 12546-12554 (2009).

[8] Hutchings, D. C., Sheik-Bahae, M., Hagan, D. J. and Van Stryland, E. W., "Kramers-Krönig relations in nonlinear optics," Optic. Quantum Electron. 24, 1-30 (1992).
[9] Williams, R. J., Jovanovic, N., Marshall, G. D. and Withford, M. J., "All-optical, actively Q-switched fiber laser," Opt. Express 18, 7714-7723 (2010).
[10] Arkwright, J. W., Elango, P., Atkins, G. R., Whitbread, T. and Digonnet, J. F., "Experimental and theoretical analysis of the resonant nonlinearity in ytterbium-doped fiber," J. Lightwave Technol. 16(5), 798-806 (1998).
[11] Dekker, P., Ams, M., Marshall, G. D., Little, D. J. and Withford, M. J., "Annealing dynamics of waveguide Bragg gratings: evidence of femtosecond laser induced colour centres," Opt. Express 18, 3274-3283 (2010).
[12] Little, D. J., Ams, M., Dekker, P., Marshall, G. D. and Withford, M. J., "Mechanism of femtosecond-laser induced refractive index change in phosphate glass under a low repetition-rate regime," J. Appl. Phys. 108, 033110 (2010).
[13] Ams, M., Marshall, G. D. and Withford, M. J., "Study of the influence of femtosecond laser polarisation on direct writing of waveguides," Opt. Express 14, 13158-13163 (2006).
[14] Little, D. J., Ams, M., Dekker, P., Marshall, G. D., Dawes, J. M. and Withford, M. J., "Femtosecond laser modification of fused silica: the effect of writing polarization on Si-O ring structure," Opt. Express 16, 20029-20037 (2008).
[15] Ams, M., Marshall, G. D., Spence, D. J. and Withford, M. J., "Slit beam shaping method for femtosecond laser direct-write fabrication of symmetric waveguides in bulk glasses," Opt. Express 13, 5676-5681 (2005).