Integrated Optical Devices

Fabrication of Multimode Interference Devices in Fused Silica by Femtosecond Laser Direct Writing

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Abstract: 1xN (N=2, 3, 4) MMI power splitters were fabricated in a fused silica substrate by laser direct writing, using a focused 515 nm amplified femtosecond laser beam, and characterized at 1550 nm. To accomplish this, several low loss waveguides were fabricated side by side to form a multimode waveguide with the output in a polished facet of the substrate, while a single low loss waveguide was fabricated to inject light in the centre of the multimode waveguide. The performance of the fabricated devices was optimized by testing three different designs.

1 INTRODUCTION

Multimode interference (MMI) devices are very important integrated optical components that can be used for several applications. Such devices can be used, for instance, as optical power splitters (Hosseini, 2011), couplers (Soldano, 1992), wavelength division (de)multiplexers (Porque, 2000), and switches (Al-hetar, 2002; Yu, 2011). MMI devices have clear advantages over other power splitters, such as directional couplers and Y-junctions. The ability to yield 1xN power splitting with a single device, without the need for cascading directional couplers or Y-junctions, enables a higher compactness which is key in the fabrication of integrated photonic circuits.

MMIs are usually composed by an input single-mode waveguide, connected to a multimode waveguide, and output single-mode waveguides. Light propagating in the single-mode waveguide arrives at the multimode waveguide where a large number of modes is excited, due to an increase in normalized frequency. The excited modes will then interfere between them as they propagate in the multimode region, since now each one has a slightly different phase velocity. Due to this fact, constructive interference occurs in certain locations, depending on the multimode waveguide parameters.

These devices are usually fabricated by Planar Lightwave Circuit technology (PLC), however, to achieve them, many fabrication steps and a cleanroom environment is required. Femtosecond laser direct writing changed the way integrated optical devices can be fabricated, eliminating many of the problems found in planar technology. This technique already enabled the fabrication of buried waveguides (Eaton, 2005), Bragg gratings (Zhang, 2007), directional couplers (Eaton, 2006), Y-junctions (Liu, 2005), integrated lasers (Calmano, 2010), among others. In 2005, Watanabe et al. (Watanabe, 2005) reported the fabrication of MMI devices with a longitudinal geometry inside synthesized silica. The longitudinal geometry involves the translation of the sample in a direction parallel to the incident laser beam yielding very symmetrical cross-sections, while being limited by the objective working distance and very simple device geometries. In 2008, Da-Yong et al. (Da-Yong, 2008) also reported the fabrication of MMI devices, but this time using a transversal geometry. The transversal geometry relies on the translation of the sample perpendicularly to the direction of the incident beam, where only the depth of the fabricated devices is limited, while several device geometries can be implemented. Despite the greater fabrication freedom, Da-Yong et al. used a low

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aperture objective to create the multimodal device in a single pass, thus somewhat eliminating this freedom in the fabrication of MMI devices.

The previous works only served as a proof of concept, since the devices were only functional for visible light. The work presented in this paper serves the purpose of fabricating MMI devices with a configurable design, working at the telecommunication wavelengths.

2 FABRICATION

The femtosecond laser system used in the fabrication of these devices was a Satsuma HP fibre amplified laser. The second harmonic beam at λ = 515 nm with an approximate 250 fs pulse duration was focused inside the fused silica substrate 50 µm below the surface with a 0.55 NA aspheric lens, as seen in figure 1.

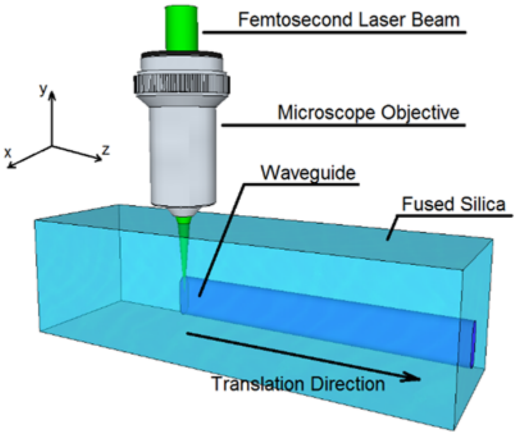

Figure 1: Schematic of device fabrication using the transverse writing geometry.

The conditions determined to be optimal for low loss optical waveguides were used: the writing beam polarization was oriented to be parallel to the scanning direction, a pulse energy of 250 nJ (at 500 kHz) was used, and a sample scanning velocity of 400 µm/s utilized. These exposure conditions yielded waveguides as seen in figure 2 (a), with total insertion losses of 1.1 dB, for 2.5 cm long waveguides, and a mode diameter of 12.3 µm x 7.1 µm (see figure 2 (b)), resulting in coupling losses of 0.37 dB per facet and propagation losses of 0.14 dB/cm.

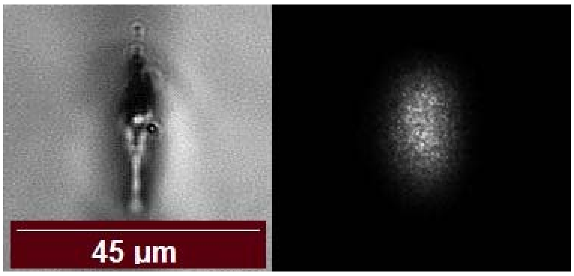

Figure 2: Cross-sectional image (a) and mode field distribution (b) of the fabricated waveguides.

A schematic of the fabricated MMI devices is shown in figure 3 (a). Three designs were tested in this work, two where the MMI is written longitudinally (figure 3 (b)) and one where the MMI is written transversely (figure 3 (c)). In the case of the longitudinal MMIs the first design is based on the writing of longitudinal waveguides from border A to B with a given waveguide separation, while the second is based on the writing of the longitudinal waveguides from border A to the fifth waveguide from the centre, followed by the ones from border B to the fifth waveguide from the centre and then writing the central waveguides alternately from the closest to the borders until the centre is reached. For the transversal MMIs the waveguides are written from border A to B in sequence, from the input to output with a given separation distance. It should be noticed that the number of waveguides in this last design is far superior to the ones required in longitudinal designs. All MMI devices were fabricated in a way that the output plane is placed exactly on the polished facet of the substrate.

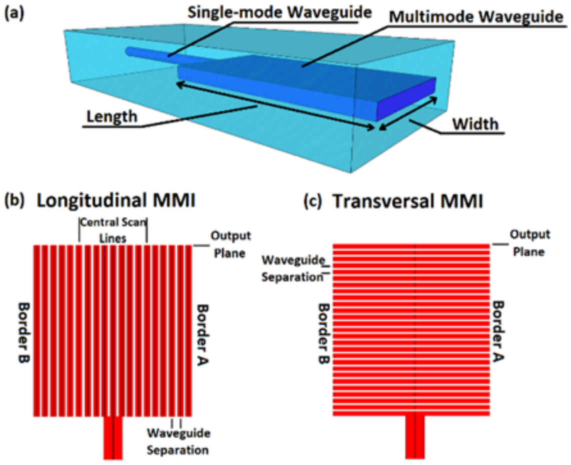

Figure 3: Schematic of the fabricated devices (a), as well as the longitudinal (b) and transversal (b) fabrication designs employed to optimize the device behaviour.

3 EXPERIMENTAL RESULTS

For higher splitting ratios it is normal that wider

MMI devices are required in order to separate the lobes. With this in mind, 50 μm wide MMIs were studied in this work. Since these devices behavior is highly dependent on width and femtosecond laser direct writing has a finite resolution, it is to be expected that while doing N writings with a given waveguide separation S the total width is larger than NxS. To compensate the final devices were written with 47.5 μm.

Another variable that can change the device performance is the refractive index distribution inside the multimode waveguide. The BPM simulations made in this work to support the device fabrication were obtained with a uniform refractive index distribution, and, as such, the separation between fabricated waveguides was controlled in order to obtain, as close as possible, the simulations refractive index distribution. In figure 4 longitudinal and transversal MMI devices with a waveguide separation of 1 μm are displayed. From the figure it is possible to observe that with a waveguide separation of 1 μm the modification is not uniform since individual writing tracks are still observable. Due to this fact the separation between fabricated waveguides was reduced to 0.5 μm.

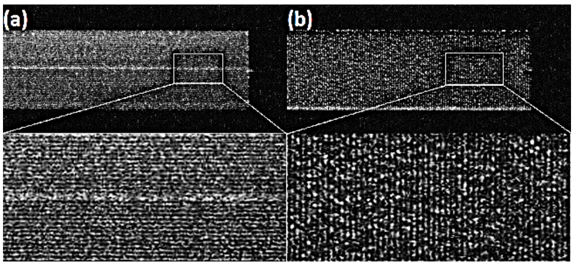

Figure 4: Dark field microscopy image of a longitudinal (a) and transversal (b) MMI device fabricated with a waveguide separation of 1 μm.

To fabricate power splitters with multimode waveguides three values are required, namely multimode waveguide width, length, and working wavelength (device refractive index is also important but not critical). The width was set to 50 μm, working wavelength to 1550 nm, but device length is an unknown for the different splitting ratios. To determine the device length BPM simulations were made with Rsoft (see figure 5 (a) to (d)) using a 2D model and a $7x10^{-3}$ refractive index difference. In this work 1x4, 1x3 and 1x2 power splitters were investigated and the device length was found to be, through simulation, roughly 690, 900 and 1350 μm, respectively. With the fabrication parameters set above, several MMI devices were fabricated using the three designs specified in section 2. All these designs were tested in an effort to improve the device symmetry and decrease stresses originated by the fabrication process. The first longitudinal design and the transversal design showed very similar results in terms of modal distribution (first longitudinal design results are displayed in figure 5 (e) to (g)), while the second longitudinal design did not show the simulated behavior but rather random distributions. It should be noted that the CCD from which the modal distributions were measured does not have a uniform sensitivity over its area, explaining why unequal distribution is observed.

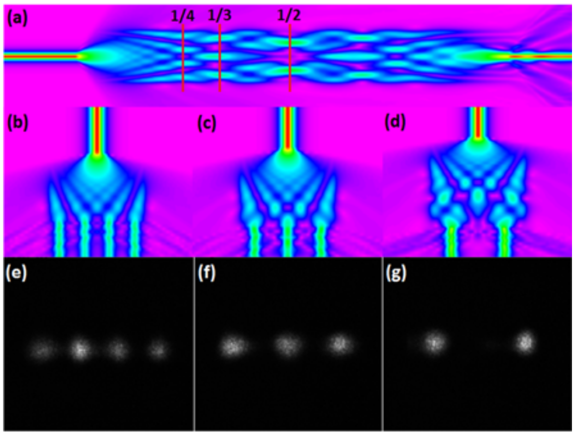

Figure 5: Figure showing the simulated behaviour and the results obtained with the first longitudinal design for 50 μm width devices. First the 1:1 MMI behaviour is simulated (a) and the 1:4 (b), 1:3 (c) and 1:2 (d) simulations obtained for a length of 690, 900 and 1350 μm respectively. From these simulated lengths the 1:4 (e), 1:3 (f) and 1:2 (g) behaviour was obtained experimentally.

These results can be explained by the microscope images in figure 6. From the top view images, in bright and dark field, it is possible to see that the second longitudinal design is not as uniform as the others. In the cross section view this becomes obvious since the guiding region is much more irregular. Apart from this, it is also interesting to notice that the other two designs have problems. In the first longitudinal design all MMI devices fabricated had a crack in the corner of border B (last waveguide to be written). This probably happens due to stress accumulation on this corner, resulting from the fact that waveguides were written from border A to B. On the transversal design some problems can also be identified by the dark field image. This design was implemented since it avoids the stress build-up but another problem arises due to hardware communication times. At border B more light is visible than at border A due to the laser being

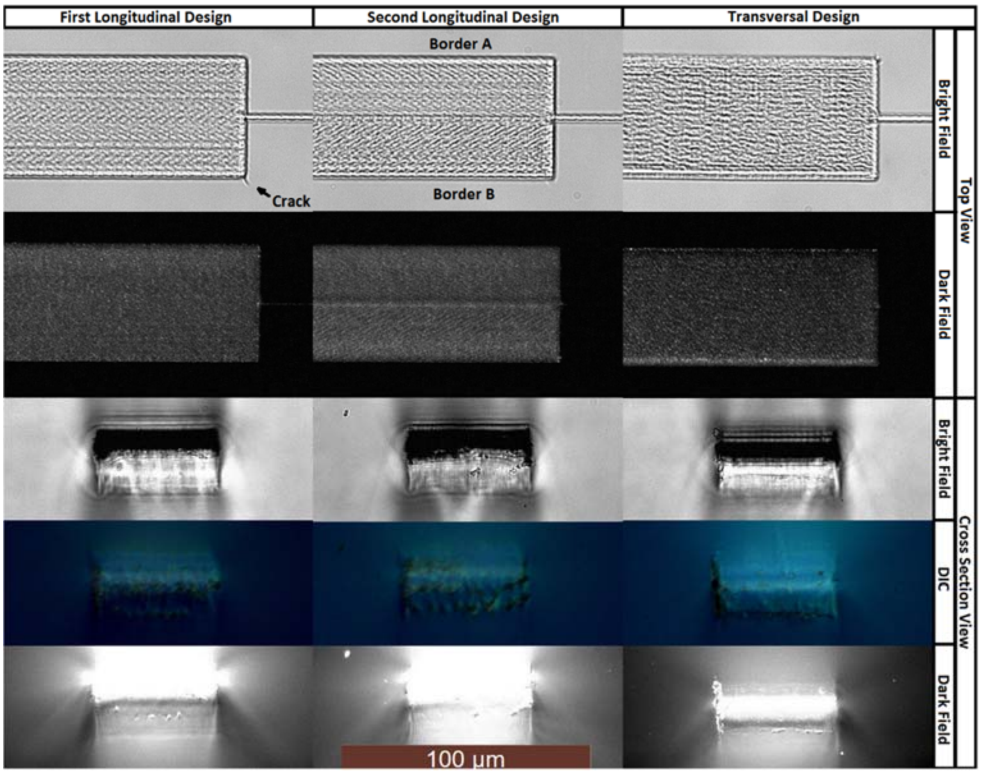

Figure 6: Top and cross section view microscopy images of the fabricated longitudinal and transversal MMI devices with a waveguide separation of 0.5 µm.

ON while decelerating, which causes an increased alteration of the local properties. Another interesting fact is the stress concentration on the top region of the MMI device, seen in the Differential Interference Contrast (DIC) images, and also the higher light scattering in this region for the longitudinal design when compared with the transversal design.

4 CONCLUSIONS

The fabrication of multimode interference devices, working at 1550 nm, was shown to be possible in fused silica with the femtosecond laser direct writing technique. Power splitting was achieved with experimental results proving to be in good agreement with BPM simulations. Splitters with a splitting ratio of 1x4, 1x3 and 1x2 were fabricated with a 50 µm width and a length of the multimode section of 690, 900 and 1350 µm, respectively.

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REFERENCES

Hosseini, A, Kwong, D, Zhang, Y, Subbaraman, H, Xu, X & Chen, R 2011, '1xN multimode interference beam splitter design techniques for on-chip optical interconnections', *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 17, no. 3, pp. 510-515.

Soldano, L, Veerman, F & Smit, M 1992, "Planar Monomode Optical Couplers Based on Multimode Interference Effects", *Journal of Lightwave Technology*, vol. 10, no. 12, pp. 1843-1850.

Porque, J, Coudray, P, Charters, R, Kribich, K, Etienne, P & Moreau, Y 2000, 'WDM based on multimode interferencecoupler built in an organic-inorganic material', *Optics Communications*, vol. 183, no. 1, pp.

45-49.

Al-hetar, A, Supa'at, A, Mohammad, A & Yulianti, I 2008, 'Multimode interference photonic switches' *Optical Engineering*, vol. 47, no. 11, pp. 112001.

Yu, F, Yamamoto, K, Piao, X & Yokoyama, S 2011, 'Multimode interference waveguide switch of electro-optic polymer with tapered access waveguides', *Physics Procedia*, vol. 14, pp. 25-28.

Eaton, S, Zhang, H & Herman, P 2005, 'Heat accumulation effects in femtosecond laser-written waveguides with variable repetition rate', *Optics Express*, vol. 13, no. 12, pp. 4708-4716.

Zhang, H, Eaton, S & Herman, P 2007, 'Single-step writing of Bragg grating waveguides in fused silica with an externally modulated femtosecond fiber laser', *Optics Letters*, vol. 32, no. 17, pp. 2559-2561.

Eaton, S, Chen, W & Zhang, L 2006, 'Telecom-Band Directional Coupler Written With Femtosecond Fiber Laser', *Photonics Technology Letters*, vol. 18, no. 20, pp. 2174-2176.

Liu, J, Zhang, Z, Chang, S, Flueraru, C & Grover, C 2005, '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.

Calmano, T, Siebenmorgen, J, Hellmig, O, Petermann, K & Huber, G 2010, 'Nd:YAG waveguide laser with 1.3 W output power, fabricated by direct femtosecond laser writing', *Applied Physics B*, vol. 100, no. 1, pp. 131-135.

Watanabe, W, Note, Y & Itoh, K 2005, 'Fabrication of multimode interference waveguides in glass by use of a femtosecond laser', *Optics Letters*, vol. 30, no. 21, pp. 2888-2890.

Da-Yong, L, Yan, L, Yan-Ping, D, Heng-Chang, G, Hong, Y & Qui-Huang, G 2008, 'Transverse Writing of Multimode Interference Waveguides inside Silica Glass by Femtosecond Laser Pulses', *Chinese Physics Letters*, vol. 25, no. 7, pp. 2500-2503.