Femtosecond laser fabrication of birefringent directional couplers as polarization beam splitters in fused silica

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Abstract: Integrated polarization beam splitters based on birefringent directional couplers are demonstrated. The devices are fabricated in bulk fused silica glass by femtosecond laser writing (300 fs, 150 nJ at 500 kHz, 522 nm). The birefringence was measured from the spectral splitting of the Bragg grating resonances associated with the vertically and horizontally polarized modes. Polarization splitting directional couplers were designed and demonstrated with 0.5 dB/cm propagation losses and -19 dB and -24 dB extinction ratios for the polarization splitting.

OCIS codes: (130.3120) Integrated optics devices; (130.5440) Polarization-selective devices; (140.3390) Laser materials processing.

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1. Introduction

Since the discovery of induced refractive index modification of transparent material using femtosecond laser exposure [1], many devices have been demonstrated, including directional couplers [2], Bragg grating waveguides [3], waveguides in active materials [4], and integrated lasers [5]. This method of forming waveguides opens up the prospects of producing three-dimensional integrated optical circuits in a single writing step [6, 7]. The possibility of three dimensional integration of directional couplers has been demonstrated in [8] while directional couplers with a low polarization dependence have been demonstrated in Eagle2000 borosilicate glass [2] where heat accumulation effects have been shown to yield low birefringence waveguides [9].

In fused silica, however, heat accumulation effects do not occur for the same laser writing conditions found to be optimum in borosilicate glass, leading to less symmetric waveguides where stresses have been found to affect the birefringence and the loss in such waveguides [10,11]. Further, waveguides fabricated in fused silica show birefringence that depends strongly on both the polarization of the writing laser and the intensity of the writing beam [12], and has been correlated with the orientation of laser-induced nanogratings that contribute a strong form birefringence effect [13, 14].

Fused silica is the material of choice for telecommunication and other optical applications for its high transmission and stability. Hence, understanding and controlling the formation of nanogratings is essential if we are to exploit polarization control in three-dimensional integrated

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circuits. Such strongly induced birefringence has already been explored in bulk glasses for the formation of computer generated holograms [15,16], polarization diffraction gratings [17], and birefringent elements [18].

Integrated beam splitters in fused silica and borosilicate glass have been used to demonstrate the potential for femtosecond written optical components to measure entangled photons [19,20] that may be essential in quantum computation and other application areas such as quantum key distribution [21] and differential polarization phase-shift keying for optical communication systems [22]. A key requirement for that objective is the development of highly stable polarization splitting optics that can be integrated into three dimensional optical circuits. To this end, the present paper exploits the birefringence found in femtosecond laser written waveguides in fused silica to create a polarization splitting directional coupler with spectral responses designed for wavelength-division multiplexing (WDM) operation in the C and L Telecom bands.

A schematic of the directional couplers developed for this investigation is shown in Fig. 1. The coupling ratio r of a directional coupler is defined as:

$$r = \frac{P_1}{P_1 + P_2} \tag{1}$$

where P_1 and P_2 are the powers measured at the output ports of the input arm and the arm opposite of the input arm, respectively. The coupling ratio calculated in Eq. (1) follows the relation for symmetric coupling:

$$r = \sin^2(KL + \phi) \tag{2}$$

where K is the coupling coefficient, ϕ is the phase accumulated in the bending region of the directional coupler and L is the length of the coupling region. K and ϕ are both wavelength and polarization dependent, therefore, r will also depend on the wavelength. To develop a high extinction ratio polarization beam splitter, one desires a large difference between the coupling ratios of the orthogonal polarization modes which is assessed here by a polarization splitting contrast factor, $\Delta r = |r_V - r_H|$. Using Eq. (2), this contrast factor expands to:

$$\Delta r = \sin[(K_V - K_H)L + \phi_V - \phi_H] \sin[(K_V + K_H)L + \phi_V + \phi_H] \tag{3}$$

where, r_V and r_H are the coupling ratios for vertical and horizontal polarized light, respectively. Suitable values for L and λ can be found to maximize the polarization splitting contrast factor in Eq. (3) once appropriate values for the vertical polarization (K_V, and ϕ_V) and horizontal polarization (K_H, and ϕ_H) coupling coefficients have been engineered in the waveguide writing procedure.

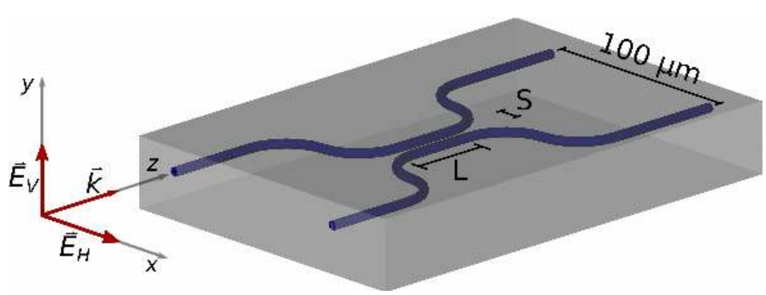

Fig. 1. Schematic diagram of the polarization beam splitter. E_V and E_H indicate the electric field orientation of Vertical, V, and Horizontal, H, polarized light, respectively.

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2. Fabrication

The femtosecond laser system used for the waveguide fabrication was a Yb-doped fiber chirped pulse amplified system (IMRA America μJewel D-400-VR), with a center wavelength of 1044 nm and repetition rate of 500 kHz. A second harmonic beam of $\lambda = 522$ nm wavelength and 300 fs pulse duration was generated in a lithium triborate (LBO) crystal to take advantage of a larger refractive index change found in fused silica than when using the fundamental wavelength [23]. The 522 nm beam was focused into fused silica glass to a 1.6 μm spot diameter ($1/e^2$ intensity) at a position 75 μm below the surface with a 0.55 NA aspheric lens. Low loss optical waveguides were generated with a 150 nJ pulse energy while scanning the sample at a constant speed of 0.27 mm/s using an air-bearing motion stage (Aerotech ABL1000) with a resolution of 2.5 nm. The polarization state at the focus was linear and oriented to be parallel or perpendicular with respect to the scanning direction by using a half wave plate. These exposure conditions yielded a mode field diameter (MFD) of 9.6 μm x 9.0 μm for polarization parallel to the scanning direction, which closely matches the circular MFD of a single mode fiber (10.4 μm), yielding very low loss (0.06 dB) due to mode mismatch for fiber-to-facet coupling when using index matching oil. The insertion losses are therefore mostly due to the waveguide propagation loss.

Following prior work in borosilicate glass [24], the directional couplers in fused silica were studied with waveguide center-to-center separation distance, S, varied between 5 μm and 15 μm and coupling lengths, L, varied between 0 mm and 20 mm. The waveguide S-bends were designed for 100 mm radius of curvature that yielded negligible loss when compared to the loss of straight waveguides.

To accurately determine the birefringence in these waveguides we measured the difference in Bragg resonance wavelength for Vertical and Horizontal input polarizations. Within each set of waveguides a Bragg grating waveguide was written with periodicity of 540 nm using an acousto-optic modulator operating at 500 Hz, as described in detail in [3].

3. Characterization methods

After fabrication, the coupling ratio of the directional couplers was characterized by free space end-fire coupling of a broadband unpolarized source (Agilent 83437A, 1300 nm to 1600 nm) into one waveguide arm of the coupler with an aspheric objective lens (New Focus, 30X, 0.4 NA). A broadband polarizer (Thorlabs LPNIR) was used in the free space region to excite vertically or horizontally polarized modes as designated by V (along the y-axis) and H (along the x-axis), respectively, as shown in Fig. 1.

The power at both output ports (P_1 and P_2) was measured for both vertical and horizontal polarizations as a function of wavelength with an Optical Spectrum Analyzer (OSA, Ando 6317B) set to a resolution of 2 nm. The resulting power spectra were used in Eq. (1) to calculate the coupling ratio as a function of the wavelength for each polarization. The intensity profile of the modes propagating in the waveguides at 1560 nm were measured by coupling the light from a tunable laser (Photonetics Tunics-BT) with a single mode fiber (SMF) to the waveguides and imaging the output onto a CCD camera (Spiricon SP-1550M) by a 60X magnification lens. In this way, the mode mismatch loss between the waveguide mode and the SMF mode was accounted. Lastly, spectral splitting of the V and H modes in BGWs was used to infer the waveguide birefringence with the OSA set at 0.01 nm resolution for a broadband ASE light source (Thorlabs ASE-FL7002).

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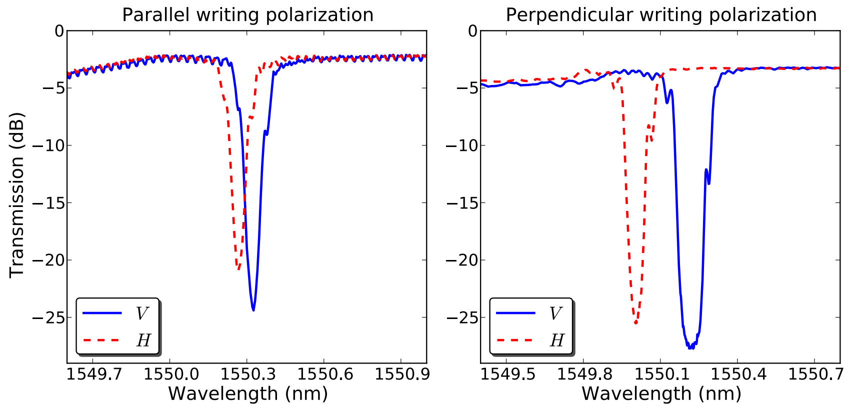

Fig. 2. Transmission spectra of two BGWs written with parallel (along z-axis) polarization (left) and perpendicular (along x-axis) polarization (right). Vertical polarized (– blue solid line) and horizontal polarized (- - red dashed line).

4. Results

Figure 2 shows the transmission spectra of two BGWs written with parallel (along z-axis) and perpendicular (along x-axis) polarization of the writing laser and spectrally probed with vertical (along y-axis) and horizontal (along x-axis) input polarized light. The shift in the Bragg wavelength between the two orthogonal polarizations directly yields the birefringence, Δn_{eff}, present in the waveguides according to Eq. (4), where $\Delta\lambda_B$ is the observed polarization shift in the Bragg wavelength and $\Lambda = 540$ nm is the grating period.

$$\Delta n_{eff} = \frac{\Delta\lambda_B}{2\Lambda} \tag{4}$$

Birefringence values of $(5.2 \pm 0.5) \times 10^{-5}$ and $(2.1 \pm 0.1) \times 10^{-4}$ where found at 1550 nm wavelength for parallel and perpendicular writing polarizations, respectively, for the case of isolated waveguides. Higher birefringence could result for waveguides in the coupling region from the additional asymmetric stresses induced by a nearby parallel waveguide. Birefringence values also vary ($\pm 30\%$) with the strength of the BGW and further depend on wavelength and on other exposure condition such as energy per pulse. The higher birefringence associated with perpendicular writing also corresponds to a higher loss of 1.2 dB/cm. In the following we have concentrated on the parallel polarization writing condition which produces lower losses of 0.7 dB/cm.

The measured coupling ratio of directional couplers fabricated with $S = 8\,\mu$m waveguide separation is shown in Fig. 3 as a function of interaction length. The data were fitted to Eq. (2) for each wavelength using a Levenberg-Marquardt least square algorithm to generate the coupling parameters K and ϕ that are shown as a function of the wavelength in Fig. 4 for both H and V polarization. The average difference between the K values for the two polarizations indicates an approximately 5% polarization difference on coupling coefficient.

The experimentally determined values of K and ϕ were used to calculate the polarization splitting contrast factor (Eq. (3)) as a function of the interaction length and wavelength for each waveguide separation tested. Values of Δr are shown in Fig. 5 for two sets of couplers with waveguide separation of $5\,\mu$m and $8\,\mu$m. For $15\,\mu$m waveguide separation, weak coupling would have required excessively long coupling lengths to achieve polarization splitting.

By analyzing Fig. 5, it is possible to find values for the coupling length that offer very high

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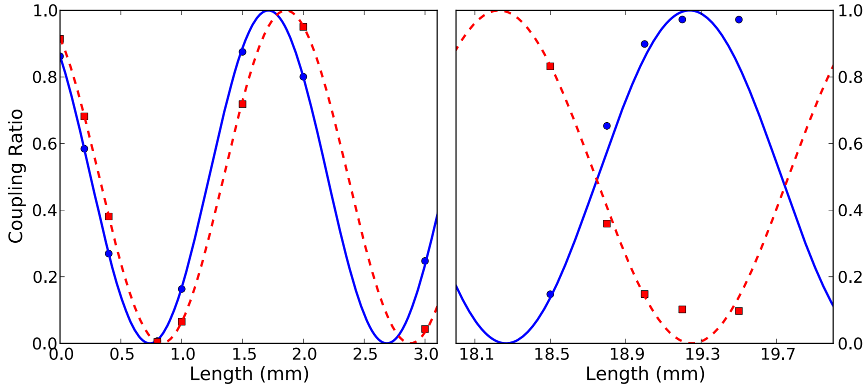

Fig. 3. Measured coupling ratio, r, as a function of coupling length for vertical polarized (● blue circle) and horizontal polarized (■ red square) modes together with calculated fits (solid and dashed lines).

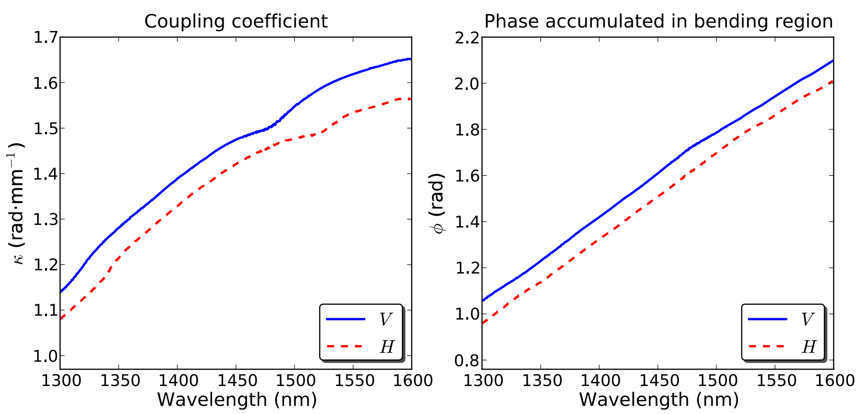

Fig. 4. Calculated K and ϕ as a function of wavelength for vertical polarized (– blue solid line) and horizontal polarized (- - red dashed line) modes and $S = 8\,\mu\text{m}$ waveguide separation.

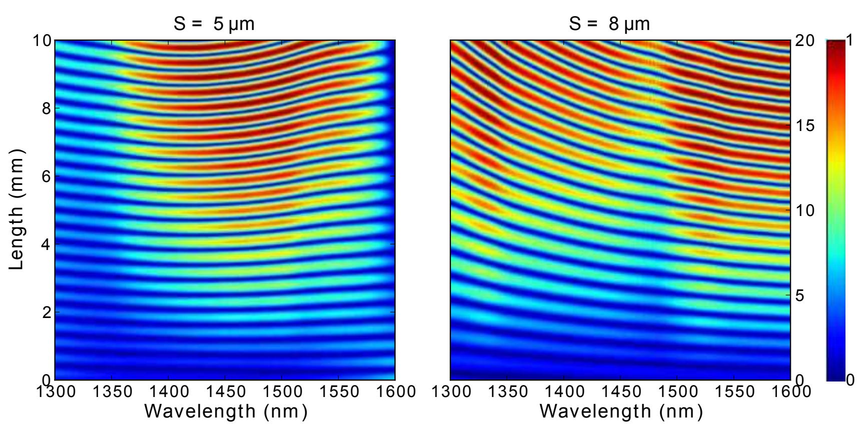

Fig. 5. Splitting contrast factor, Δr, for directional couplers with $5\,\mu\text{m}$ waveguide separation (left) and $8\,\mu\text{m}$ waveguide separation (right).

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polarization splitting contrast factor, Δr, of greater than 95% for several wavelengths. For a coupler with 5 µm waveguide separation and longer than 7 mm interaction length it is possible to find relatively strong polarization splitting for specific wavelengths in the range of 1400 nm to 1550 nm. For 8 µm waveguide separation, an interaction length of more than 12 mm is necessary for find strong polarization slitting at select wavelengths between 1300 nm and 1600 nm. However, because the fringes in Fig. 5 are not perfectly horizontal, the polarization splitting occurs in a narrow bandwidth. For example, a greater than 15 dB polarization extinction ratio is available across ≈10 nm bandwidth at 1478 nm with a polarization splitter of 5 µm separation and 9.5 mm interaction length or at 1505 nm for a directional coupler of 8 µm separation and 19 mm interaction length.

As a practical demonstration, Fig. 6 shows a plot of the power measured at both P_1 and P_2 output ports as a function of the input polarization angle for a wavelength of 1484.00 nm $\pm$ 0.05 nm in a device with a coupling length of 19.2 mm and a waveguide to waveguide separation of 8 µm. Aligned with the polarization angle, one also sees images of the output beam profile at both ports (P_1 and P_2) oscillating with this angle and yielding maximum polarization contrast at the $\frac{\pi}{2}$ radian and π radian positions for horizontally and vertically polarized light, respectively.

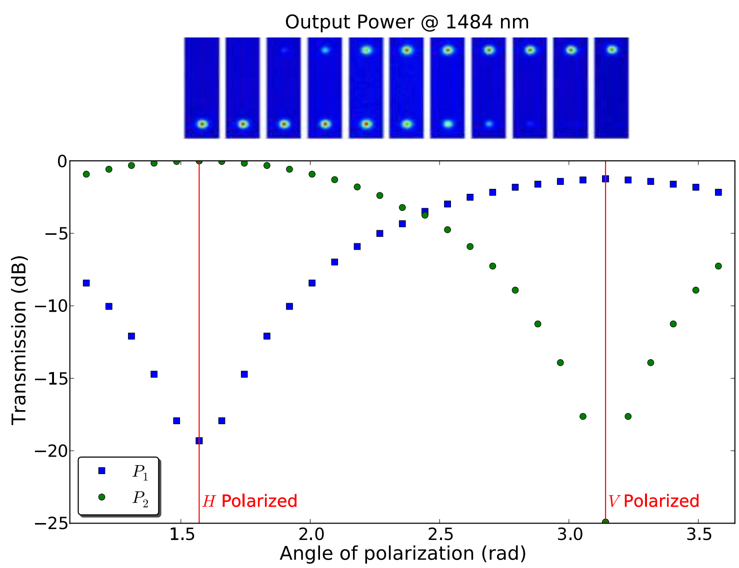

Fig. 6. Output power and mode profile as a function of the angle of polarization at 1484 nm, for the same arm as the input (P_1, ● green circle) and opposite arm as the input (P_2, ■ blue square).

5. Discussion

For a coupler device with a waveguide to waveguide separation of 8 µm and an interaction length of 19.2 mm, the results in Fig. 6 show that moderately high extinction ratios of -19 dB and -24 dB are possible for the H and V polarizations, respectively. The analysis of the coupling ratio data shown in Fig. 5 further permits one to find multiple combinations of wavelengths and coupler lengths for a given waveguide separation that offer high polarization extinction ratios in narrow spectral bands. Furthermore, extending these splitters to other waveguide separations offers additional degrees of freedom for controlling K and ϕ spectral values for offering wide spectral coverage across the full Telecom band tested here. One can further optimize the bending radius of the directional couplers in the same way as performed in todays planar light circuits in order to produce polarization beam splitters with even wider broadband response. Extending the bandwidth of the present polarization beam splitters may also be possible with this femtosecond laser writing technique by following the same design principles described in [24, 25].

The present polarization splitting coupler was based on the lower birefringence waveguides ($\Delta n_{eff} = 5.2 \times 10^{-5}$ for parallel polarization writing) that offered the lowest propagation loss of 0.7 dB/cm with Bragg grating response or 0.5 dB/cm without Bragg response. The strong polarization extinction of 19 dB to 24 dB seen here together with the 10 nm bandwidth for $\approx$ 15 dB polarization contrast are comparable to the results reported for polarization splitting in PCF optical fiber [26] or in planar lightwave circuits [27]. However, the present laser approach required long coupling lengths of up to 20 mm to enable complete separation of the polarization modes. An alternative approach that exploits the 4-fold higher form-birefringence in waveguides fabricated with perpendicularly polarized laser light promises more compact polarization beam splitters. Here, a shorter waveguide length may compensate against the additional propagation loss found for such highly birefringent waveguides (i.e. 0.5 dB/cm additional loss in BGWs fabricated with perpendicular versus parallel laser writing polarization) that may be developed by the same design and analysis methods presented in this paper.

Developing new laser processes that can lower birefringence in the present waveguides would, on the other hand, enable the fabrication of polarization insensitive waveguides which may allow the single step fabrication of both polarization free and polarization dependent devices for highly functional integration onto the same circuit platform. It may be possible that higher repetition rates can be used in femtosecond laser writing in fused silica to drive heat accumulation effects similar to the ones observed in borosilicate glass to reduce waveguide birefringence [9]. Despite the 5.2×10^{-5} birefringence observed in the present fused silica waveguides, polarization independent beam splitters can also be developed by using very short or zero-length directional couplers as demonstrated in [20]. Lastly, tuning the radius of S-bend waveguide region offers further latitude in shaping the spectral response of both the high and low polarization splitting waveguide couplers for specific application requirements.

6. Conclusion

Femtosecond laser induced birefringence in fused silica waveguides was harnessed here for the first time, to the best of our knowledge, to demonstrate polarization beam splitting in buried optical circuits. Moderately strong extinction ratio of up to -24 dB was noted for 2 cm long devices. The polarization beam splitters are sufficiently wavelength selective to be attractive for WDM application and promise to open new directions for creating polarization dependent devices in three dimensional optical circuits. However, the means to extend the bandwidth for such polarization splitting will require further design and laser process development.

The integration of the present polarization splitters inside bulk glass defines a highly attractive platform for creating stable and highly functional polarization-dependent optical circuits required today in optical communication and quantum entanglement systems.

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