Femtosecond laser direct fabrication of integrated optical wave plates in fused silica

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Abstract: Femtosecond laser fabrication of optical waveguides in bulk silica glass is extended to integrated optical waveplates. Polarization retardation was controlled by laser exposure, providing for trimming of waveguide birefringence between 10^{-5} and 10^{-4}.

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

1. Introduction

Femtosecond laser technologies have enabled many interesting developments in the processing of optical circuits that offer the prospect of full 3D integration of compact and highly functional optical devices. Studies have shown that, under certain condition, birefringence is produced in waveguides formed in fused silica glass by femtosecond laser pulses exposure [1,2], enabling the fabrication of birefringent elements [3]. Through careful tuning of the laser exposure parameters, mainly laser pulse energy and polarization, the waveguides birefringence can be controlled in order to fabricate polarization dependent devices. A polarization splitting directional coupler has already been demonstrated [4] using this approach. The present paper extends this laser exposure control to integrate polarization retarding wave plates inside laser-formed waveguides for the 1200 nm to 1700 nm spectral band. Such polarization devices expand our current component toolkit for fabricating highly functional 3D integrated optical circuits that are attractive for possible application in quantum encryption or quantum entanglement [5] and differential polarization phase-shift keying in optical communication.

The waveguides were fabricated with a frequency doubled Yb:fiber chirped pulse amplified system (522 nm, 400 fs, 150 nJ) operating at 500 kHz repetition rate. The beam was focused with a 0.55 NA lens 75 µm inside a fused silica sample while being translated at 0.27 mm/s in an air-bearing stage with 2.5 nm resolution. The polarization of the writing laser was tested in both perpendicular and parallel orientation to the forming waveguides, thereby manipulating the form birefringence induced by the laser generated nanograting. The polarization state of the waveguides are defined as Vertical (*V)* and Horizontal (*H)* with respect to the sample as shown in Fig. 1, and represent the slow axis and fast axes, respectively.

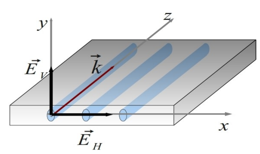

Fig. 1. Birefringent waveguides in a fused silica subtract with proper polarization axis Vertical and Horizontal.

The waveguide birefringence was measured by two techniques that both use free space coupling of broadband light into the end facet of the waveguide. First, weak Bragg Grating waveguides (BGW) of $\Lambda = 536$ nm period were fabricated with the method described by [5]. Polarization splitting of the Bragg resonances, $\Delta\lambda_B$ was recorded by collecting the output light of the waveguides into an Optical Spectral Analyzer (OSA) with 0.01 nm resolution, while the input polarization of the light was controlled by a linear polarizer to launch V or H polarizations. The birefringence in the waveguides followed the relation $\Delta n = \Delta\lambda_B/(2\Lambda)$. For the second technique, a cross polarizer arrangement positioned the sample between two polarizers adjusted to have a 45° launch angle against the V or H waveguide axis. The output light power collected with the OSA after passing through the analyzer with an angle of 45° or -45° with respect to the same proper axis is given by:

$$I_p = \frac{I_i}{2}(1+\cos\delta) \qquad I_c = \frac{I_i}{2}(1-\cos\delta) \qquad (1)$$

where I_p is the output intensity when the analyzer is at 45°, parallel to the input polarizer, and I_c is the output intensity when the analyzer is at -45°, perpendicular to the input polarizer. Discounting waveguide loss, the total power is $I_i = I_p + I_c$. The birefringence can be calculated from the retardance, δ introduced by the waveguide as $\delta = 2\pi \Delta n L/\lambda$, where λ is the wavelength and L is the waveguide length. The indetermination of the absolute retardation phase in multiples of 2π is resolved by the absolute birefringence measured with the Bragg gratings.

2. Results

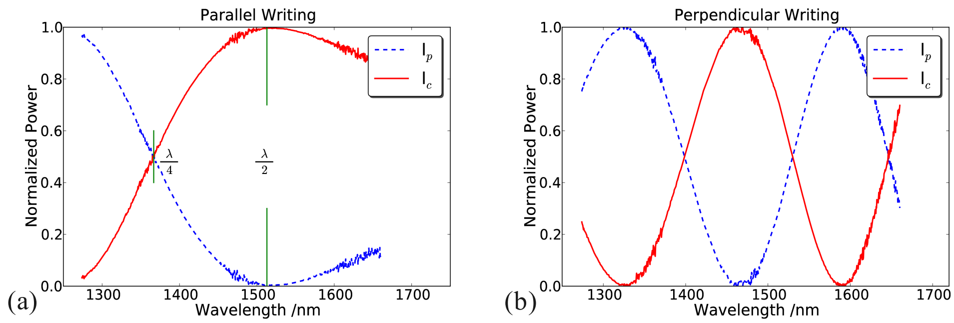

Fig. 2. Power as a function of the wavelength for the parallel polarizer and crossed polarizer configuration, and for parallel and perpendicular polarization of the writing laser.

Fig. 2 shows the transmitted waveguide power as a function of the wavelength measured with crossed polarizer technique. The point where both, I_p and I_c have the same value defines where the waveguide operates as a quarter-wave plate (λ/4 in Fig. 2a at 1365 nm) and the point where I_p is close to 0 and I_c is close to 1 is where the waveguide operates as a half-wave plate (λ/2 in Fig. 2a at 1513 nm).

The I_p and I_c powers for each of the quarter-wave and half-wave points marked in Fig. 2 were measured as a function of the analyzer angle and plotted in Fig 3a. Perpendicular polarization for writing shows a birefringence 4 to 10 times greater due to strong form birefringence in this nanograting orientation. The birefringence varies from 1.6×10^{-4} to 2.2×10^{-4} for the perpendicular writing and 1×10^{-5} to 5×10^{-5} for the parallel writing as shown in Fig. 3b.

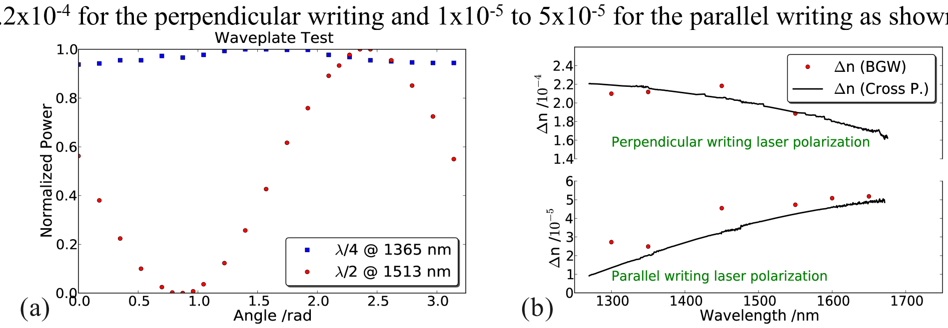

Fig. 3. (a) Power as a function of the angle of the analyzer; (b) Birefringence as a function of the wavelength for perpendicular and parallel polarization of the writing laser measured with the cross polarizers technique and with the Bragg Grating technique.

3. Conclusions

Two techniques for measuring the birefringence in laser-formed waveguides were demonstrated, verifying the quarter-wave and half-wave plate operation for the first time. The polarization isolation was -35 dB of contrast for the half-wave plate while there was a 5% variation for the quarter-wave plate. These new polarization control elements serve an objective to make integrated optical systems suitable for quantum entanglement experiments and other on-a-chip quantum optics applications.

4. References

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