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Tunable and rotatable polarization controller using photonic crystal fiber filled with liquid crystal

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We design and fabricate a compact tunable and rotatable polarization controller using liquid crystal photonic band gap fibers. The electrically and thermally induced phase shift in the Poincaré sphere and corresponding birefringence change are measured. The direction of the electric field is managed by connecting four electrodes in different electrode configurations, and the thermal tunability is controlled by on-chip heaters. According to the results, a quarter-wave plate and a half-wave plate working in the wavelength range of 1520–1600 nm are experimentally demonstrated. © *2010 American Institute of Physics*. [doi:10.1063/1.3455105]

Controlling the state of polarization (SOP) has become an important consideration in fiber-optic communication and optical sensing systems. Some methods for achieving polarization transformations have been developed, such as mechanical squeezing of fibers,[1] rotating wave plates,[2] electro-optic crystal waveguides,[3] and liquid crystal (LC) retarders.[4] With the recent development of photonic crystal fibers (PCFs), SOP control was proposed by using thermal tuning of the refractive index of a polymer partially infiltrated in some of the air-holes of PCF.[5] Taking advantage of the large thermo-optic and electro-optic effects of LCs as well as the fast response time,[6] the presence of the air-holes in PCFs makes them good hosts for LCs.[7–9] In this letter, we design and fabricate a compact tunable and rotatable polarization controller based on electrically and thermally tunable LC photonic band gap (LCPBG) fiber. Under an applied electric field, the circular symmetry of a LCPBG fiber is broken due to the reorientation of LC molecules. The guided modes in eigenstates experience a different phase delay when they are propagating through the device. Therefore, electrically induced phase shift and corresponding birefringence change between the orthogonal polarizations in the LCPBG fiber device as a function of driving voltage are measured at different temperatures using on-chip heaters. Compared to the previously reported results, we explore an alternative mechanism on a compact platform to control the SOP by electrically and thermally changing the birefringence of the LCPBG fiber.

The cross section of the LCPBG fiber device is illustrated in the inset of Fig. 1. The all-in-fiber device assembly is mainly based on the compact on-chip design.[10] The LC used in this work is MLC-6608 (Merck, Germany), which has a wavelength dependent ordinary and extraordinary refractive index of $n_o = 1.4768$ and $n_e = 1.5595$ at 589 nm. The fiber is a large mode area (LMA) PCF with a solid core surrounded by five rings of air holes arranged in a triangular lattice (LMA-13, NKT Photonics A/S, Denmark). The air-hole diameter, interhole distance, and outer fiber diameter are 4.3 μm, 8.5 μm, and 125 μm, respectively. The LC MLC-6608 is infiltrated for 20 mm of the length of the fiber by using capillary forces, and then mounted between two silicon v-grooves. Two single mode fibers are then placed in the grooves at each end of the LCPBG fiber to couple light in and out of the device by SU-8 fiber fixing structures which are used to obtain a high fiber coupling quality. These SU-8 structures with the thickness of 84 μm also act as the spacers between the top and the bottom chip along the whole device to avoid tilting the electrodes. The electrodes and heaters are patterned by using thick photoresist coating and two-step exposure.[11] The assembly is sealed with epoxy, and the top and bottom sides of the device are electrically grounded. The transmission spectra of the device for different temperatures are shown in Fig. 1. The insertion loss of the device at 1550 nm is around 2.8 dB. The notch in the transmission spectrum is caused by a cladding mode crossing through the band gap, forming a so-called "avoided-crossing" with the core mode of the band gap.[12]

When an electric field is applied to the LCPBG fiber, the LC reorients depending on the direction and strength of the applied voltage. Using four electrodes it is possible to control the direction of the electric field in the transversal direction with different electrode configurations (ECs) corresponding to three directions of the electric field (EC1: 0°, EC2: 45°, and EC3: 90°) as the dotted lines in Fig. 1, and thereby the transversal orientation of the LC molecules. The

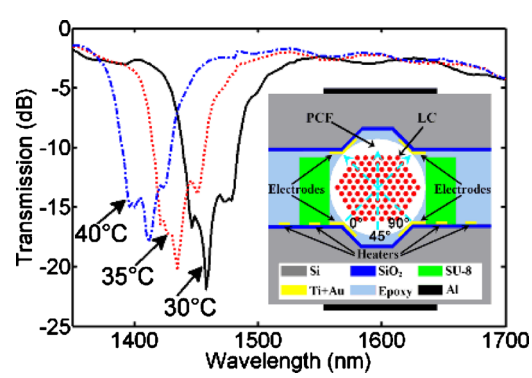

FIG. 1. (Color online) Transmission spectrum of the device by varying the temperature from 30 to 45 °C. Inset shows the cross section of the LCPBG fiber device. Dotted lines show the direction of electric field effectively applied to the LCPBG fiber.

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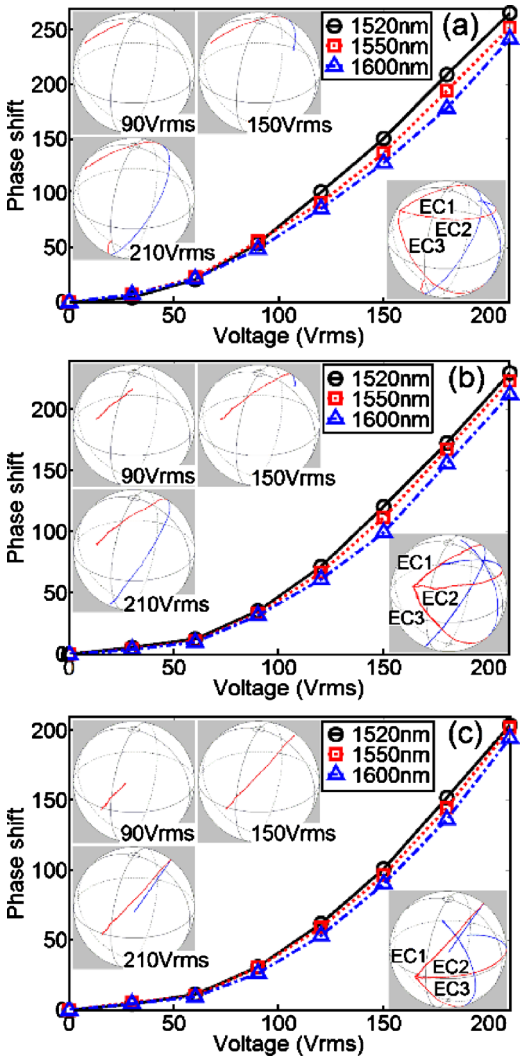

FIG. 2. (Color online) Electrically induced phase shift in EC1 as a function of driving voltage at (a) 30 °C, (b) 35 °C, and (c) 40 °C. Insets show the polarization states in the Poincaré sphere when a driving voltage from 90 to 210 V_{rms} is applied.

two orthogonally polarized guiding modes in LCPBG fiber experience different refractive indices compared to the case in which the field is off and this introduces a phase shift between them. To measure the electrically induced phase shift and corresponding birefringence change, a polarized and tunable laser source operating from 1520 to 1620 nm is used. A polarization analyzer launches the light in the LCPBG fiber device and resolves the output light into the Stokes parameters, which are plotted on the surface of the Poincaré sphere. Actively controlled phase shift between the orthogonal polarizations in the device results in a corresponding rotation in the sphere. To achieve a tunable device with low activation loss when the electric field is applied, we consider 210 V_{rms} as the maximum driving voltage and the maximum activation loss of 0.45 dB is found. The top insets of Fig. 2(a) show the phase shift in the Poincaré sphere for EC1 when a driving voltage from 90 to 210 V_{rms} is applied to the device at 30 °C by launching 1550 nm polarized laser light. The trace in the Poincaré sphere represents the continuous change of the polarization state, which starts from the near part of the sphere and ends on the opposite side of the sphere. Figure 2(a) plots the electrically induced phase shift in the device as a function of driving voltage for different

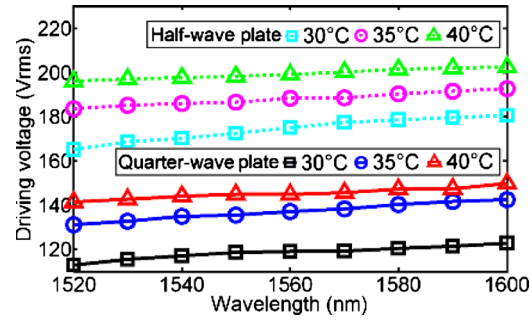

FIG. 3. (Color online) Driving voltage of EC1 as a function of wavelength for realizing quarter and half wave plates at different temperatures.

wavelengths (λ) at 30 °C. A phase shift (φ) of 266.2° for 1520 nm is obtained by applying 210 V_{rms}, which gives a birefringence (Δn) of 5.62×10^{-5} by the relation $\Delta n = \varphi\lambda/2\pi L$, where L is the length of the LC filled section. Less phase shift and birefringence are observed when an input signal with a longer wavelength is launched, e.g., a phase shift of 252.6° and 242.3°, and the corresponding change in birefringence of 5.44×10^{-5} and 5.38×10^{-5} are obtained for 1550 nm and 1600 nm, respectively. When the direction of the electric field is effectively rotated by connecting the four electrodes in different ECs, the reorientation of LC changes subsequently. Therefore, the input light with a fixed polarization state can experience dissimilar response when it propagates through the device. The bottom inset of Fig. 2(a) shows the phase shift in the Poincaré sphere for EC1, EC2, and EC3 with the driving voltage of 210 V_{rms}.

The same measurement has been taken for 35 and 40 °C. Figures 2(b) and 2(c) plot the electrically induced phase shift as a function of voltage for different wavelengths at 35 and 40 °C, and the corresponding phase shift in the Poincaré sphere with the driving voltage from 90 to 210 V_{rms}. When the temperature increases, the electrically induced phase shift decreases. This is because the birefringence of LC decreases as a function of temperature until it becomes zero at the clearing temperature.

These results demonstrate that the device can find use as a continuously tunable polarization controller but also can act as a quarter-wave plate with 90° phase shift and a half-wave plate with 180° phase shift. Since the electrically induced phase shift is wavelength dependent, small variations in the driving voltage are required to develop high performance polarization controllers or wave plates in the whole working wavelength range. Figure 3 plots the driving voltage as a function of wavelength for keeping the device as a quarter-wave plate and a half-wave plate at different temperatures among the wavelength range of 1520–1600 nm. At 30 °C the maximum driving voltage variation of 10.1 and 15.5 V_{rms} are observed when the device performs as a quarter-wave and a half-wave plate. However, only 6.3 and 8.3 V_{rms} variations are found to achieve a stable performance at 40 °C.

In conclusion, we demonstrate a compact tunable and rotatable polarization controller using LCPBG fibers in the wavelength range of 1520–1600 nm. This device has the potential applications as a polarimeter (a rotating wave plate and a polarizer architecture with a single detector) for

analyzing the SOP[13] or as a low-cost polarization stabilizer for optimizing the performance of polarization dependent systems or devices.[14]

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