Acousto-optic polarization-dependent mode coupling in a dual-mode hollow optical fiber

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We demonstrated unique polarization dependence in acousto-optic coupling in a two-mode hollow optical fiber (HOF). Local deformation of circular HOF induced by traveling acoustic wave resulted in highly birefringent optical transmission characteristics, which were experimentally analyzed for various central air-hole sizes. Potential applications for polarization-dependent devices such as polarization-dependent loss compensators and broadband polarization controllers are discussed. © 2007 Optical Society of America

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In recent optical fiber communication systems and sensors, the issue of polarization control has growing significance as a decisive factor for overall performance, especially in high-data-rate long-distance transmission and high-resolution interferometric sensory signal paths. Fiber-optic components having a polarization-dependent loss (PDL) or polarization mode dispersion can give rise to erroneous results. Thus, dynamic PDL management and fast polarization control to suppress those polarization-related errors would be highly appreciated.

Recently, there has been an effort to dynamically adjust the PDL by acousto-optic mode coupling in polarization-maintaining (PM) fibers. The coupling strength depended on the angle between the birefringence axes and the bending direction, and the 3 dB bandwidth was relatively narrow due to the beat-length dispersion between the coupled modes in the PM fibers.

In polarization control, a hollow optical fiber (HOF) based liquid crystal (LC) polarization controller has been reported, where a unique three-layered waveguide structure of HOF has been adapted as a nematic LC cage. Segmented electrodes imprinted on the HOF–LC composite could adjust the direction of LC molecule to result in polarization control. Acousto-optic coupling in HOF has been reported by the authors in an adiabatic taper from single-mode fiber (SMF) to HOF, where the spectral bandwidth of coupling was tunable in a broad range near 1.5 μm due to unique beat-length dispersion between the fundamental and the first excited modes of HOF.

In this Letter, we report an experimental analysis of highly polarization-dependent acousto-optic mode coupling along a dual-mode HOF for various optical waveguide parameters, for the first time to the best knowledge of the authors. In addition, we could control the polarization state of the beam in HOF by utilizing the birefringence induced by an acoustic wave.

Schematic diagram of the proposed device is shown in Fig. 1(a). The measurement setup is similar to those of prior well-established SMF acousto-optic tunable filters. The acoustic wave along the fiber generates microbending and consequently results in a periodic refractive index perturbation along the HOF. The HOF was designed and fabricated to guide
only two core modes, the fundamental and the first excited mode, whose modal characteristics were theoretically reported in Ref. 7. The modal intensity distribution and the direction of electric fields of the fundamental and the first excited mode are shown in Fig. 1(b).

It is predicted by theory and confirmed by experiment that the mode coupling induced by flexural wave on a fiber is inherently polarization dependent.\(^2,6,8\) For a piezoelectric transducer (PZT) vibrating in a direction, the index perturbation caused by the flexural wave is asymmetrical with respect to the vibration direction. Breaking the circular symmetry in HOF by an asymmetric acoustic deformation, there will be a considerable difference in the propagation constants between the \(x\)- and \(y\)-polarization LP modes. Therefore, the mode coupling, i.e., \(\beta_\text{01x} \rightarrow \beta_\text{11y}, \beta_\text{01y} \rightarrow \beta_\text{11x}\), becomes polarization dependent,\(^8\) which gives splitting in the transmission spectrum of the device. Due to the large refractive index contrast between the central air hole and the Ge-doped silica ring, a larger birefringence is expected compared with that of conventional solid core fibers.\(^7\)

The transmission spectra of the proposed device were measured for various input polarization states using a linear polarizer and a white light source. To ensure that the input beam was guided with only the fundamental mode, a mode stripper was used. Here we maintained the RF frequency of \(285\ \text{kHz}\) with a peak-to-peak voltage of \(10\ \text{V}\). The HOF had a central air-hole diameter of \(4.5\ \mu\text{m}\) and a Ge-doped ring core diameter of \(17.5\ \mu\text{m}\). The ring core had a refractive index higher by 0.005 than that of silica outer cladding similar to conventional SMFs.

In Fig. 2(a), we could clearly observe two polarization-dependent resonances near 1480 and 1620 nm. As the linear polarizer angle, or equivalently the relative direction of the incident linear polarization against the PZT oscillation plane, was varied continuously, the two peaks showed a reciprocal evolution; the peak near 1480 nm waxed as the 1620 nm peak waned, and vice versa. In these spectra in Fig. 2(a), we assigned the resonance near 1480 nm as \(x\)-polarization coupling and the other near 1620 nm as \(y\)-polarization coupling. The spectral spacing between the two orthogonal polarization peaks was 140 nm, an order of magnitude larger than that of conventional solid core SMFs.\(^8\) The geometrical ellipticity of the HOF was less than 3%, thus the wide separation between the polarization modes could be attributed to two factors: the local deformation of the HOF ring core by acoustically driven microbending and the polarization nature of HOF higher-order modes. In comparison with SMF, HOF has a modal field further extended into the cladding region, which makes the HOF more bend sensitive.\(^7\) Therefore the effect of a flexural acoustic wave, which is mostly guided by the cladding, is assumed to be enhanced in HOF to result in high polarization sensitivity.

For 1480 nm resonance, we could obtain 8 dB suppression of the \(x\)-polarization over a 3 dB bandwidth of 20 nm while keeping the high transmission in the \(y\)-polarization with a less than 0.64 dB loss as in Fig. 2(b). In the meantime, we could obtain 8 dB suppression of the \(y\)-polarization over a bandwidth of 21 nm while keeping the high transmission in the \(x\)-polarization with a less than 0.24 dB loss as in Fig. 2(c). Note that the 3 dB bandwidths of these polarization-dependent coupling resonance cover the S and L bands of the optical communication window for the peaks at 1480 and 1620 nm, respectively. Prior tunable PDL elements based on PM fibers given in Ref. 6 showed the 3 dB bandwidth to be less than 4 nm, yet the extinction ratio was 16 dB. Experimental observations in this study strongly imply that we can achieve a wideband polarization-selective transmission type device such as a PDL compensator that can cover the whole spectral range of one of the communication bands.

These polarization-dependent acousto-optic couplings were found to be highly dependent on the air-hole size. The spectral positions of the resonance for two orthogonal polarizations are plotted as a function of the driving acoustic frequency in Fig. 3. Two types of HOFs having different dimensions were tested. The air-hole and the ring core diameters of the first type of HOF were 4.5 and 17.5 \(\mu\text{m}\) and those of the second type were 5.9 and 18 \(\mu\text{m}\), respectively. The resonance peak was shifted with a quasi-linear slope (4.67, 5.6, 10.78, and 12.82 nm/kHz, respectively) in a broad wavelength range from 1100 to 1700 nm, as shown in Fig. 3. A larger wavelength splitting was observed when the HOF had a larger air-hole diameter.

By utilizing the birefringence induced by the acoustic wave, we have tried to implement an electronically controllable polarization controller. To
have high efficiency, we fabricated a HOF with a rather large air-hole diameter of 10.8 μm and a ring core diameter of 18.5 μm. The RF frequency was intentionally detuned away from the exact phase-matching conditions to avoid the strong coupling to other modes and isolate the impact of the acoustic wave on the state of polarization (SOP) of the guided fundamental mode, LP₀₁. The HOF length of 0.67 m was adiabatically tapered with a 10 mm taper length and then spliced to conventional SMF. Throughout the experiments the total insertion loss of the devices could be maintained at less than 1 dB. The output SOP was measured at 1550 nm with an automated polarization analyzer (Agilent 8509C). A tunable laser diode was used as the light source. The trace of the output SOP was measured in terms of the RF frequency and the voltage and represented in the Poincaré sphere as shown in Fig. 4.

Figures 4(a) and 4(b) are the SOP traces measured with fixed RF frequencies, 76 and 78.75 kHz, respectively, but with varying voltages. The SOPs at zero RF voltage coincide for both cases, but as the voltage increased to 56 V, the SOPs became totally different. The accumulation of the SOP traces measured with sweeping frequency from 73 to 83 kHz and varying voltage from 0 to 56 V is depicted in Figs. 4(c) and 4(d). At each RF voltage, the frequency sweeping was made in 1 min. As can be seen in Figs. 4(c) and 4(d), over 95% of the entire Poincaré sphere was covered by the trace. As reported in the LC-filled HOF, where the polarization state of the guided optical signal was controlled by an electric field, the experimental observations in Fig. 4 strongly suggest that the SOP throughput can be controlled by changing two parameters, the RF frequency and voltage. It is assumed that the anisotropic undulation of HOF and its sequential stress distribution induced by a nonresonant traveling acoustic wave resulted in versatile control of the SOP.

In conclusion, from the inherent characteristics of the phase-matching condition and the polarization property of a HOF under the acousto-optic interaction between the fundamental and the first excited mode, the HOF-acousto-optic tunable filter showed tunable broadband polarization-dependent coupling, which can be directly applied as a PDL compensator of 3 dB bandwidth over 20 nm and as extinction ratio of 8 dB. Efficient polarization control of the guided fundamental mode in HOF by changing the amplitude and frequency of the nonresonant flexural acoustic wave was also achieved. Over 95% of the whole Poincaré sphere was accessible with the proposed scheme sweeping the RF frequency and voltage from 73 to 86 kHz and from 0 to 56 V, respectively.

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