Suppression of polarization dependence in a two-mode-fiber acousto-optic device

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We present a theoretical and experimental analysis of the polarization dependence of a two-mode-fiber acousto-optic device, taking into account the residual stress in the fiber and the ellipticity of the core. We successfully demonstrate the suppression of the polarization dependence by relieving the residual stress, using thermal annealing.

Two-mode-fiber (TMF) acousto-optic devices have been shown to be efficient and practical for use as optical switches, frequency shifters, and tunable filters.[1–3] In these devices, a flexural acoustic wave propagates along a TMF and generates a traveling antisymmetric modulation of the optical path length with a period equal to the acoustic wavelength. When the acoustic wavelength matches the beat length of the fundamental LP_{01} mode and the second-order LP_{11} mode, complete coupling takes place between them. Advantages of the TMF devices' all-fiber configuration include low insertion loss and backreflection relative to their integrated-optic counterpart.[4] Moreover, if spatial-mode coupling rather than polarization-mode coupling as in integrated-optic devices is used, the TMF device can function for arbitrary input polarization. However, the TMF devices demonstrated so far have shown a small but nonnegligible polarization dependence in that the phase-matching acoustic frequency for complete coupling depends on the input polarization state.[2,3] This feature is often detrimental, for example, in a tunable filter, where it causes an unwanted passband wavelength shift in response to polarization drift. The suppression of the undesirable polarization dependence is essential for making the device practical, and one needs a thorough understanding of the polarization dependence to realize this. In this Letter we analyze the origin of the polarization dependence in a TMF acousto-optic device and present a simple solution for the suppression of the effect.

A schematic of the experimental TMF acousto-optic tunable filter is shown in Fig. 1. The device was fabricated with the same configuration as that described in detail in Ref. 3. A coaxial acoustic transducer excites a flexural acoustic wave at ~3-MHz frequency in a 10-cm-long unjacketed part of the TMF. The fiber had a depressed-step-index profile with a normalized index difference between the core and the cladding of $\Delta \approx 0.32\%$. The outer diameter of the TMF was 136 μm, and the diameter of its nominally circular core was estimated to be ~9.7 μm from the measured mode-field diameter.[5] A small ellipticity of the core, $\epsilon \approx 1.6\%$, was also estimated from the mode-field measurement, where the ellipticity is defined as the difference between the semimajor and the semiminor axes normalized by the semimajor axis.

The polarization dependence of the device was measured with polarized Nd:YAG laser light at the 1.064-μm wavelength, where the TMF supported the LP_{01} and the LP_{11} modes. The light was launched into the device in the LP_{01} mode through the first mode stripper, MS1. The second mode stripper, MS2, removed the LP_{11} mode coupled from the input LP_{01} mode by the acoustic wave. The coupling efficiency of the device was determined from the measurement of transmitted optical power. A polarization controller, PC, was used to vary the input polarization state. We could also choose the direction of acoustic displacement along the major or the minor axis of the core by rotating the TMF inside the coaxial acoustic transducer.

We have found four distinctive coupling behaviors corresponding to the two input polarization states for each of the two directions of acoustic displacement. Figure 2(a) shows the experimental results when the acoustic displacement is in the direction of the major axis (x axis) of the core. Curves A and B were obtained for input polarization aligned to the x and the y axes, respectively. The phase-matching acoustic frequencies were ~3.104 MHz (A) and ~3.112 MHz (B). Curves C and D of Fig. 2(b) are the experimental results when the acoustic displacement was oriented parallel to the minor axis (y axis) of the core. The phase-matching frequency for curve C was ~3.214 MHz, corresponding to input polarization along the y axis, and that for curve D was ~3.224 MHz for x polarization input. The separation of the phase-matching frequency for the two input polarization states represents unwanted polarization dependence that causes variations in the coupling wavelength and (or) the coupling efficiency. The optical modes involved in each coupling were identified by examination of their far-field diffraction patterns and polarization states without mode stripper MS2.

From the experimental results we deduced a level diagram of the modal propagation constants as shown in Fig. 3. The level spacings marked A, B, C, and D were

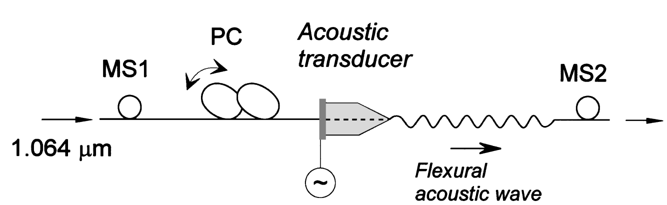

Fig. 1. Experimental setup used to measure the coupling efficiency of the TMF acousto-optic device.

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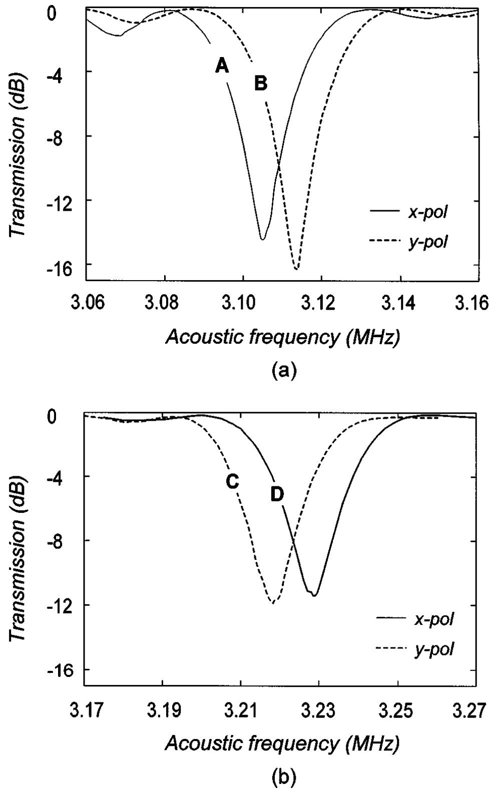

Fig. 2. Measured normalized transmission as a function of the acoustic frequency. Polarization dependence is shown for the transverse acoustic displacement as being (a) parallel to the semimajor axis (x axis) or (b) parallel to the semiminor axis (y axis) of the core.

calculated from the acoustic wavelengths corresponding to the phase-matching frequencies of coupling A, B, C, and D, respectively.[6] The spacing $\Delta\beta_{01}$ was obtained from the measurement of the polarization beat length of the LP_{01} mode (~160 cm) by a cutback method with an ambiguity in sign. Assuming that the major axis of the core was the slow axis for the LP_{01} mode, as is usually the case, we summarized the experimental results in Table 1. The well-known waveguide theory[7] explains that the large splitting $\Delta\beta_{e,o}$ between the LP_{11}^{even} and the LP_{11}^{odd} modes is due to the ellipticity of the core ($\epsilon \approx 1.6\%$). However, the theory predicts that the values of $\Delta\beta_{\mathrm{even}}$ and $\Delta\beta_{\mathrm{odd}}$ should have negative signs, contrary to our experimental observations.

To solve the discrepancy, we had to take into account the refractive-index change induced by the residual stress originating from the difference in thermal-expansion coefficients of the core and the cladding.[8,9] The stress-induced effect was obtained by use of a perturbation method applied to the eigenmodes of an elliptical core fiber[7] that includes the effect of electric polarization-induced charge. The perturbation method involves an overlap integral of the modal fields with the refractive-index changes caused by the stress field. The values of fiber parameters used in the calculation are summarized in Table 2. The results of the calculation, summarized in Table 1, show good agreement with the experimental results. Also shown in Table 1 for comparison is the theoretical prediction made without taking into account the residual stress but still considering the ellipticity of the core and the polarization-induced charges in the core–cladding interface. This is a pure geometric effect. The role of the residual stress in a circular-core fiber has been discussed.[11]

Because the polarization dependence of the device originated from the unequal values of $\Delta\beta_{01}$ and $\Delta\beta_{\mathrm{even}}$ (or $\Delta\beta_{\mathrm{odd}}$), it is inferred by the above analysis that the polarization dependence of the device can be eliminated if the stress-induced effect cancels the geometric effect. We can, in principle, eliminate the polarization dependence by reducing the residual stress. To verify the prediction and to realize a polarization-insensitive device, we used the thermal annealing method for stress relief.[12] A 6.5-cm-long unjacketed part of the TMF was heated in a furnace for ~30 min at a temperature of ~1200 °C and then cooled slowly to room temperature. When the annealed TMF was used in the acoustic device, the coupling of A and B in the original fiber [Fig. 2(a)] merged and shifted in frequency to 2.837 MHz, as shown in Fig. 4. The shift of the

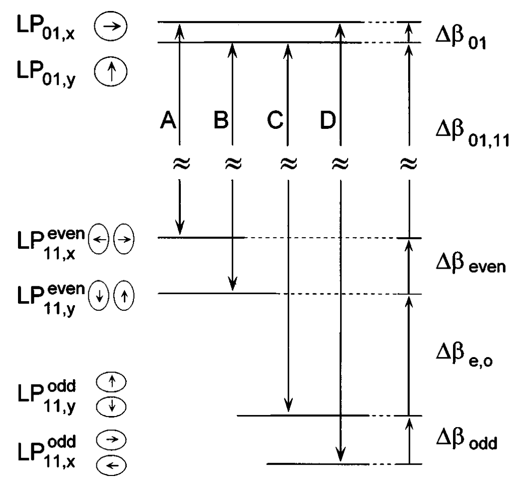

Fig. 3. Schematic diagram of the modal propagation constants in the slightly elliptical-core TMF.

Table 1. Experimental and Theoretical Values (in radians per centimeter) of the Propagation Constant Differences

	$\Delta\beta_{01}$	$\Delta\beta_{01,11}$	$\Delta\beta_{\mathrm{even}}$	$\Delta\beta_{e,o}$	$\Delta\beta_{\mathrm{odd}}$
Experiment	0.04	110	0.22	2.1	0.16
Theory	0.029	111	0.223	1.87	0.148
Geometric effect	0.004	115	−0.11	2.15	−0.1

Table 2. Parameters Used in the Calculation

Index profile	Depressed step index
Core index (germanium doping)	1.46396
Cladding index (fluorine doping)	1.45927
Core ellipticity	1.58%
Effective core diameter	9.7 μm
Effective V value	3.36
Differential thermal expansion coefficient[a]	1.7×10^{-7} °C^{-1}
Temperature change[a]	970 °C

[a]Refs. 9 and 10.

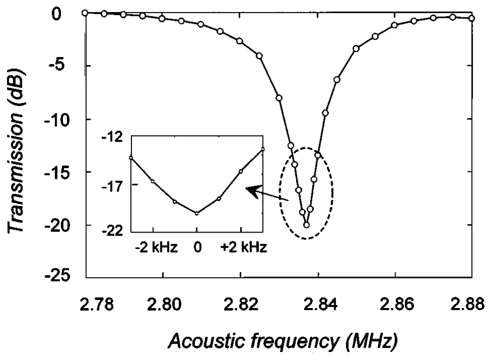

Fig. 4. Coupling characteristics of the acousto-optic device made with a stress-relieved fiber.

phase-matching frequency by ~270 kHz is attributed to the increase of the core radius by 2.5% because of the dopant diffusion during the annealing process.[13] At the frequency of 2.837 MHz, the minimum transmission was always smaller than −17 dB, even when the input polarization was changed arbitrarily. This implies that the difference of the phase-matching frequency for each polarization state was reduced to less than 2 kHz, which is a remarkable decrease from the ~8-kHz difference before annealing. A similar result was obtained for the other coupling at the frequency of ~2.950 MHz, which corresponds to coupling of C and D in the original fiber [Fig. 2(b)].

In summary, we have measured and analyzed the polarization dependence of a TMF acousto-optic device. We demonstrated the suppression of polarization dependence by relieving the residual stress in the fiber, using thermal annealing. We believe that the results are useful for fiber designs especially aimed at polarization-insensitive TMF devices.

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