

Apodization of elliptical-core two-mode fiber acousto-optic filter based on acoustic polarization control

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We propose and demonstrate a novel apodization technique for an elliptical-core two-mode fiber acousto-optic filter by twisting the fiber and adjusting the acoustic polarization. The sidelobe suppression in the filter spectrum was improved from -9.7 to -15.5 dB. A theoretical analysis that includes acoustic birefringence explains the experimental results with good agreement. © 2005 Optical Society of America

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As a key element of various all-fiber wavelength filters and optical switches, an all-fiber acousto-optic tunable filter (AOTF) has shown advantages such as low insertion loss, wide tuning range, and fast switching speed.^{1,2} However, practical applications of the fiber AOTF have been limited by large sidelobes (~ -10 dB) on both sides of the main filtering band. Such sidelobes may introduce interchannel cross talk between neighboring wavelength channels in wavelength-division-multiplexed systems. Acoustic amplitude apodization techniques used for integrated-optic AOTFs^{3,4} cannot be easily applied to fiber counterparts due to the difficulty in controlling the acoustic wave amplitude profile along a free-standing fiber. In this Letter, we propose and experimentally demonstrate a novel apodization technique for an elliptical-core (e-core) two-mode fiber (TMF) AOTF based on twisting the fiber and adjusting the acoustic polarization. We successfully explain the experimental results by using a theoretical model that includes the effect of acoustic birefringence caused by fiber cladding ellipticity. The sidelobe suppression ratio was improved by 5.8 dB.

A TMF AOTF uses a flexural acoustic wave to induce acousto-optic (AO) coupling between the LP_{01} and the LP_{11} modes guided in the core of the TMF.² TMFs with an e-core have been preferred to those with a circular core because the lobe orientation and the polarization state of the LP_{11} mode are preserved during propagation.⁵ Typically, an e-core TMF is designed to guide the LP_{11} mode whose lobe orientation is along the major axis of the core ellipse (even LP_{11} mode), while the LP_{11} mode with lobe orientation along the minor axis of the core ellipse (odd LP_{11} mode) is cut off over the wavelength range of interest. In this case, since an acoustic flexural wave couples the LP_{01} mode to the LP_{11} mode with the lobe orientation parallel to the acoustic vibration direction, when an acoustic wave is launched along the e-core TMF, only the acoustic amplitude component parallel to the major axis of the core ellipse contrib-

utes to LP_{01} - LP_{11} mode coupling. This means that the coupling coefficient can be modified as a function of the position in the fiber by controlling the angle between the acoustic vibration direction and the major axis of the core ellipse, even for constant acoustic amplitude over the interaction region. Therefore, one can realize filter apodization by the simple method of twisting. This principle applies even when the odd LP_{11} mode is not cut off as long as the acoustic frequencies required for coupling to even and odd LP_{11} modes are widely separated, as was the case for our experiment.

Figure 1 shows the scheme used to achieve sine apodization by manipulating the angle between the acoustic oscillation direction and the major axis in the AO interaction region. Assuming that the acoustic oscillation direction is maintained in the interaction region, the optimal apodization effect can be achieved by twisting the fiber 180° and launching an acoustic flexural wave to oscillate along the minor axis of the core ellipse at the input stage. In this case, the AO coupling efficiency becomes zero at both ends of the interaction region, with a maximum in the middle. However, as will be described below, the experimental result for the optimum twist angle deviated from 180° , which was attributed to a change in the acoustic polarization in the interaction region. Since most practical fibers would have acoustic birefringence, it is necessary to take its influence into account. For the small twist angle in this experiment,

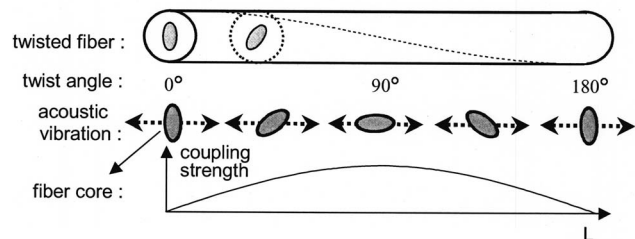


Fig. 1. Proposed sine apodization of the e-core TMF assuming that there is no acoustic birefringence.

two optical eigenpolarization states are maintained in the fiber frame because of the large phase mismatch in polarization coupling.

It has been known that the main source of the acoustic birefringence in a fiber is the ellipticity of the fiber cladding, which creates a phase velocity difference between two orthogonal linearly polarized flexural acoustic waves. The eigenaxes for acoustic birefringence are aligned with those of the fiber cladding ellipse (acoustic linear birefringence).⁶ For a complete analysis of acoustic birefringence in a twisted fiber, we need to investigate the effect on the acoustic circular birefringence that is produced by the twist-induced stress. We experimentally confirmed that torsional stress does not produce the acoustic circular birefringence within our experimental error. For the experiment, we used a highly circular cladding (Corning SMF-28) whose ellipticity was less than 0.1%. Therefore, the acoustic birefringence in a twisted fiber with greater cladding ellipticity could be determined by considering only the rotation of the acoustic linear birefringence axes. For simplicity of calculation, we used a reference frame that rotates along with the fiber cladding ellipse. In this case, the evolution of the acoustic polarization state, $\mathbf{A}(z)$, along the twisted acoustically linearly birefringent fiber can be expressed as⁷

$$\mathbf{A}(z) = \begin{pmatrix} A_x(z) \\ A_y(z) \end{pmatrix} = \exp\left(i\frac{2\pi}{\Lambda_a}z\right) \times \begin{pmatrix} \cos X - i\frac{\Delta\beta_a z \sin X}{2X} & -\tau z \frac{\sin X}{X} \\ \tau z \frac{\sin X}{X} & \cos X + i\frac{\Delta\beta_a z \sin X}{2X} \end{pmatrix} \times \begin{pmatrix} A_x(0) \\ A_y(0) \end{pmatrix}, \quad (1)$$

where $X = z(\Delta\beta_a^2/4 + \tau^2)^{1/2}$, $2\pi/\Lambda_0 = \beta_0 = (\beta_a^x + \beta_a^y)/2$, and $\Delta\beta_a = \beta_a^y - \beta_a^x$.

Here, A_x and A_y are the components of the acoustic amplitude along the minor (x) and major (y) axes of the core, respectively; $\Delta\beta_a$ is the propagation constant difference between the two orthogonal acoustic linear polarization modes, β_0 and Λ_0 are the average acoustic propagation constant and wavelength; z is the propagation distance; and τ is the twist angle per unit length. For e-core fibers, the eigenaxes of the cladding ellipse are typically parallel to those of the core owing to the manufacturing process, which we experimentally verified using a fiber geometry analyzer. As a result, only the y component of the acoustic amplitude contributes to the AO interaction, and the coupling strength, $\kappa(z)$ is

$$\kappa(z) \propto A_y(z) = \exp(i2\pi z/\Lambda_0) \left[\tau z \frac{\sin X}{X} A_x(0) + \left(\cos X + i\frac{\Delta\beta_a z \sin X}{2X} \right) A_y(0) \right]. \quad (2)$$

When the fiber is twisted ($\tau \neq 0$) and the acoustic oscillation direction is parallel to the minor axis at the input, [$A_y(0) = 0$], $\kappa(z)$ becomes

$$\begin{aligned} \kappa(z) &= \kappa_0 \exp(i2\pi z/\Lambda_0) \frac{\tau z}{X} \sin X \\ &= \kappa_0 \exp(i2\pi z/\Lambda_0) \frac{\tau z}{z[(\Delta\beta_a/2)^2 + \tau^2]^{1/2}} \\ &\quad \times \sin\{z[(\Delta\beta_a/2)^2 + \tau^2]^{1/2}\}, \end{aligned} \quad (3)$$

where κ_0 is the magnitude of the coupling coefficient when the acoustic polarization is parallel to the major axis. It can be seen in Eq. (3) and the coupled-mode equations for the optical modes that the phase-matching condition is $2\pi/L_B = 2\pi/\Lambda_0$, and the coupling strength changes sinusoidally along the propagation length, z , where L_B is the optical beat-length between the LP_{01} and the LP_{11} modes. The optimized sine apodization effect with a minimum side-lobe level is obtained when the parameter $X = l[(\Delta\beta_a/2)^2 + \tau^2]^{1/2}$ becomes 180° at the end of the interaction region, where l is the total interaction length. Note that, to prevent significant reduction of coupling efficiency, $\Delta\beta_a/2$ must not be much larger than τ in Eq. (3). On the other hand, as a special case, when the fiber is not twisted ($\tau = 0$) and an acoustic wave parallel to the major axis [$A_x(0) = 0$] is launched at the input stage, the coupling coefficient is expressed as

$$\kappa(z) = \kappa_0 \exp(i2\pi z/\Lambda_0 + i\Delta\beta_a z/2) = \kappa_0 \exp(i\beta_a^y z). \quad (4)$$

As expected, the coupling coefficient is constant throughout the interaction region and the phase-matching condition is $2\pi/L_B = 2\pi/\Lambda_0 + \Delta\beta_a z/2$, which is different from the case of $\tau \neq 0$.

Figure 2 shows a schematic of the experimental setup. We fabricated an AO filter that consisted of an acoustic transducer with two piezoelectric transducer (PZT) sections, an e-core TMF (with a core diameter of $8 \mu\text{m} \times 12 \mu\text{m}$ and a NA of 0.16), and a mode-selective coupler (MSC).² The input acoustic polarization state was controlled by tuning the amplitude and phase of the two PZT sections. Both ends of the filter were mounted on rotation stages and could be twisted by an arbitrary angle. The TMF used in the experiment was designed to guide two modes around 1300 nm, where the experiment was carried out. Broadband light from a 1300 nm LED was launched into the LP_{01} mode of the TMF, and the phase-

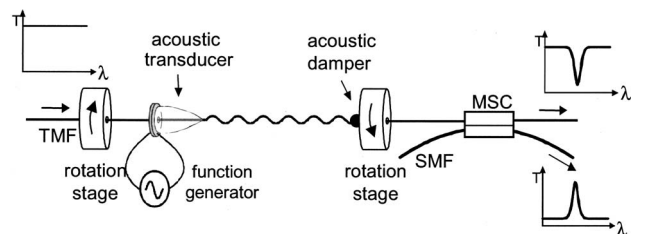


Fig. 2. Schematic of the experimental setup.

matched wavelength components were converted to the even LP_{11} mode by an AOTF. The AO interaction length and the applied acoustic frequency were 15.5 cm and 3.4 MHz, respectively. The signal in the LP_{11} mode was then coupled to the single-mode fiber (SMF) arm of the MSC, and the remaining signal continued to propagate along the TMF arm. The coupling efficiency of the fabricated MSC was 80%, and the unwanted coupling between the LP_{01} modes of the two fibers was -20 dB.

To estimate the magnitude of the acoustic birefringence, we measured the cladding ellipticity of the e-core TMF used in our work. Here, the cladding ellipticity was defined as the ratio of the diameter difference between the major and the minor axes to the average diameter, which was found to be $0.5 \pm 0.05\%$. This is expected to result in a phase velocity difference of $0.21 \pm 0.02\%$ between two acoustic linear polarization states at the applied acoustic frequency of 3.4 MHz.⁸ An experimental measurement of the phase velocity difference by directly measuring the evolution of acoustic polarization yielded $0.21 \pm 0.01\%$, in good agreement with prediction. With these parameters, we calculated the amount of acoustic phase retardation $\Delta\beta_a l$, and its value was $246 \pm 12^\circ$. Therefore, the theoretical optimum twist angle πl between the two ends of the fiber was $131 \pm 7^\circ$, which satisfies the condition $X=180^\circ$ in Eq. (3). Theoretical analysis also predicts that the magnitude of the sidelobe decreases from -9.5 to -17.5 dB as a result of optimized sine apodization. Further sidelobe suppression can be achieved by passing the light through the device twice using a reflection configuration.⁹

For demonstration of filter apodization, we measured the magnitude of the largest sidelobe in the output filter spectrum as a function of the twist angle in the range 40 – 180° . As can be seen in Fig. 3, the optimum twist angle for the minimum sidelobes was 135° , which agrees well with the theoretical prediction. The output spectra at the SMF port of the unapodized AOTF [$\pi l=0^\circ, A_x(0)=0$] and the apodized AOTF [$\pi l=135^\circ, A_y(0)=0$] are shown in Figs. 4(a) and 4(b), respectively. The magnitude of the largest sidelobe was reduced from -9.7 to -15.5 dB, which compares well with the theoretical predictions for sine apodization. The acoustic power needed for 100% coupling in the apodized AOTF was measured to be 3.7 ± 0.9 times bigger than that for the unapodized device. This agrees well with the theoretical prediction [from Eq. (3)] of a factor of 4. The 3-dB bandwidth broadening of 40% in Fig. 4(b) compared with 4(a) can be explained by the reduced effective interaction length in Fig. 4(b). The resonant wavelength shift of 3.4 nm, from 1296.8 nm in Fig. 4(a) to 1300.2 nm in Fig. 4(b), is due to different phase-matching conditions in Eqs. (3) and (4). Using an approximate empirical formula relating an e-core TMF to an equivalent circular core TMF for the dispersion relation between the LP_{01} and the LP_{11} modes,¹⁰ we expect the wavelength shift to be 2.4 ± 0.12 nm. This discrepancy is under investigation. Over the wave-

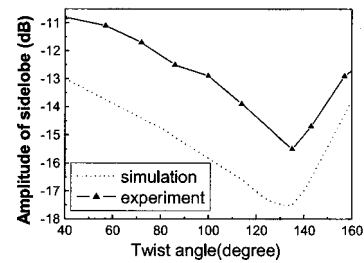


Fig. 3. Magnitude of the largest sidelobe as a function of the twist angle.

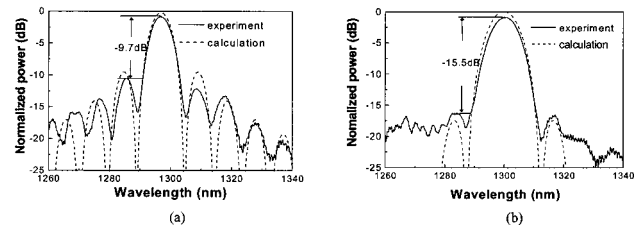


Fig. 4. Transmission spectra of an e-core TMF AOTF at the SMF port (a) without apodization, (b) with 135° twist apodization.

length tuning range of our interest, 100 nm, the acoustic phase retardation $\Delta\beta_a l$ varies by 1.4%, which is negligible.

We have successfully demonstrated an apodization technique for an e-core TMF AOTF based on the alignment of the input acoustic polarization and a twisted TMF. The influence of the acoustic birefringence induced by the ellipticity of the fiber cross section was theoretically and experimentally analyzed. The twist angle of the fiber and the initial acoustic polarization were adjusted to achieve a sidelobe reduction of 5.8 dB. The experimental results were in good agreement with the theoretical predictions.

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