Polarization-coupling all-fiber acousto-optic tunable filter insensitive to fiber bend and physical contact

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Abstract: We show that an all-fiber acousto-optic tunable filter based on polarization mode coupling using torsional acoustic wave is immune to the fiber bend and physical contact in the acousto-optic interaction region. We also propose and demonstrate a novel strain-free and size-reduced tunable filter with a 4-m-long fiber acousto-optic interaction region looped into a 5-cm-diameter coil.

OCIS codes: (060.2310) Fiber optics; (230.1040) Acousto-optical devices.

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1. Introduction

Tunable wavelength filters are key components for optical sensors and communication systems. The fundamental requirements for these optical filters include low loss, small form factor, and environmental stability. In particular, all-fiber acousto-optic tunable filters (AOTFs) with simple device structure have attracted considerable interest because of their advantages such as low insertion loss, wide and fast wavelength tuning, and variable attenuation via simple electronic control [1-4]. The all-fiber AOTFs are based on wavelength selective acousto-optic (AO) mode coupling by traveling flexural [1-3] or torsional acoustic wave [4-7]. In these devices, the acoustic waves produce the resonant coupling between two spatial modes in the optical fiber (for flexural wave) or between two polarization modes in a highly birefringent (HB) fiber (for torsional wave).

The torsional mode AOTF cannot use conventional single-mode fibers as in the case of the flexural wave counterpart, but has some important advantageous features. While it is relatively difficult to divide or combine the spatial modes in the optical fiber, the polarization modes in the HB fiber can be easily manipulated using various components commercially available. As an example, the all-fiber torsional mode AOTF can be switched between a notch type and a bandpass type filter by simply adjusting the angle of the output polarizer [4]. In addition, the torsional mode AOTF does not exhibit the coupling resonance shift or the deterioration in the filter spectrum due to the axial non-uniformity of the outer fiber diameter, because the acoustic dispersion of the torsional mode is independent of the fiber diameter [5, 7]. It should also be noted that a small non-circularity of the fiber cross-section introduces acoustic birefringence for flexural wave that results in complexity in output filter spectrum [8]. These advantageous features of torsional mode AOTFs are important for realizing robust and high-performance optical devices for practical applications. Effects of external perturbations are also important considerations for practical devices and we recently reported the influence of axial strain on the filter performance [9].

In this paper, we report our new findings in that the optical and acoustic properties of the torsional mode AOTF are surprisingly insensitive to fiber bending and physical contact in the AO interaction region. This is in great contrast to the case of the flexural mode AOTF, for which the bending and the physical contact of the fiber result in significant deterioration of the output filter spectrum and coupling efficiency [10-13]. The insensitivity to bending and physical contact can lead to new AOTF configurations that were not possible with flexural mode AOTF. As an example, we propose and demonstrate a novel strain-free and compact all-fiber torsional mode AOTF by coiling the fiber in the AO interaction region.

2. Perturbation effects in all-fiber torsional mode AOTF

As mentioned earlier, the mode coupling in the torsional mode AOTF is realized between two non-degenerate polarization modes of the same core mode propagating in the HB optical fiber. Since the bend-induced fiber birefringence is about two or three order of magnitude less than the typical birefringence in the HB fiber, the two optical polarization modes are well defined and very stable even in a bent fiber [14, 15]. The propagation properties of the first-order torsional acoustic wave are stable against the axial non-uniformity of the fiber diameter, the asymmetry of the fiber cross-section, the fiber bend, and the physical contact. The optical and acoustic insensitivity to these imperfections and perturbations makes it possible to realize long interaction length with a clean filter spectrum, compact packaging capability, and new device configuration as discussed in the following sections.

Figure 1(a) shows the experimental setup used for the measurement of filter performance under the fiber perturbations in the all-fiber torsional mode AOTF. The device is composed of a torsional acoustic transducer, two polarizers, and a HB fiber. The cross-section view of the HB fiber with an elliptical core of 2 μm × 4 μm dimension used in this experiment is shown in

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the inset of the Fig. 1(a). The outer diameter of the HB fiber and the polarization beatlength near 1550 nm were 80 µm and 1.36 mm, respectively. The AO coupling efficiency between two polarization modes is inversely proportional to the square of the fiber diameter for the same acoustic amplitude [4, 5]. The input polarization state of the light is aligned with one of the eigen polarizations of the HB fiber using an in-line fiber polarizer. The torsional acoustic wave was generated by the combination of two shear mode lead zirconate titanate (PZT) plates attached to wider end of an acoustic horn using an epoxy adhesive. The two PZT plates were arranged so that they oscillate 180 degrees out of phase, as shown in the inset of Fig. 1 illustrating the rear view of the transducer. When a radio frequency (RF) electric signal is applied, they oscillate in opposite direction to effectively twist the horn. The generated torsional acoustic wave was coupled to a bare section of the fiber bonded to the central hole in the acoustic horn. After propagating the designated length of 82 cm, it was absorbed by an acoustic damper (sticky tape) at the end of the interaction region. The torsional acoustic wave perturbs the input (horizontal) polarization and causes the energy transfer to orthogonal (vertical) polarization at resonant wavelength satisfying the phase matching condition [4, 7]. The uncoupled light in horizontal polarization is removed by a polarizer at the end of the interaction region, leaving only the coupled light with a spectral band centered at the resonant wavelength. For applying a line contact to the fiber for the perturbation test, a metal plate was positioned at the bottom of the fiber in the AO interaction region as shown in Fig 1(b). For the testing of the fiber bend effect, the 82 cm-long fiber section was coiled with the diameter of 5 cm as shown in Fig 1(c). The coiled fiber was laid on the optical table allowing physical contact.

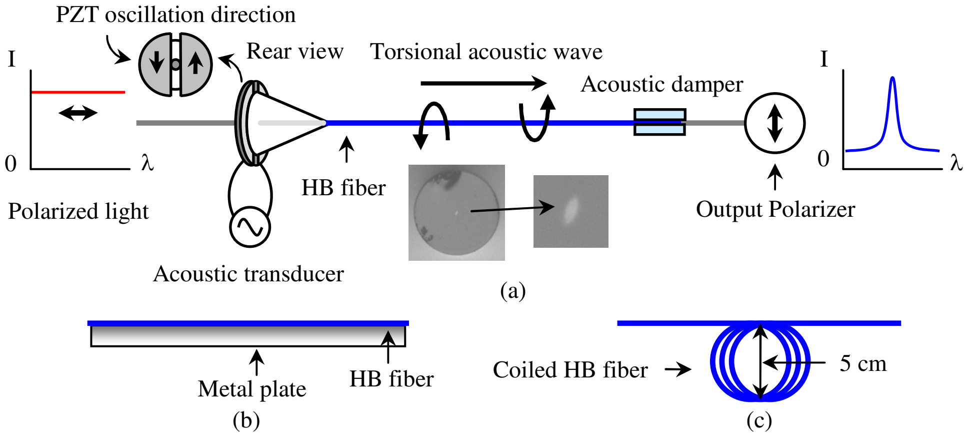

Fig. 1. (a) Schematic of the experimental setup used for measuring the fiber perturbation effect in the all-fiber torsional mode AOTF. The physical fiber perturbations of (b) line contact and (c) bending of AO interaction region. The inset of the Fig. 1(a) shows the cross-section of the elliptical core HB fiber used in this experiment.

Figure 2(a) shows the measured transmission spectra of the all-fiber torsional mode AOTF without and with the fiber perturbations of the line contact and the bending of the AO interaction region. The applied acoustic frequency was 2.748 MHz. In case of no perturbation, the fiber in the AO interaction length was maintained straight with minimal tension making the axial strain effect negligible [9]. It is surprising to see that the AO coupling is not significantly affected by the line contact and even the coiling of the fiber. The variation of the applied RF voltage required to maintain 100% coupling under the perturbations was less than 3% throughout the experiment. The center wavelength shift by the fiber bending was 0.2 nm, which is believed to be caused by the small bend-induced change in the birefringence of HB fiber. Any nonlinear chirping or deterioration in the filter spectrum was not observed, which confirms the ideas mentioned earlier.

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Next, we performed a test with another perturbation as shown in Fig 2(b). A small water drop, which is an effective damper for flexural acoustic wave, was applied over the fiber at different locations in the AO interaction region. The water drop has a shape of a hemisphere with the diameter of 1 cm and the height of 0.5 cm, as illustrated in the inset of Fig. 2(b). In order to observe the acoustic attenuation due to the water drop, the sticky tape damper was removed and the position of the water drop was varied between 1 and 10 cm from the horn tip. If the water drop effectively attenuates the traveling acoustic energy, the AO interaction length is defined as the distance between the horn tip and the water drop, and therefore, the filter spectrum will dramatically change with the variation of the water drop position. Figure 2(b) shows the transmission spectra for the different positions of the water drop. The negligible change in the spectra suggests that the water drop does not attenuate the torsional acoustic wave at all. We are currently investigating the attenuation and the reflection properties of various candidates for the torsional acoustic dampers, and the preliminary results show the torsional wave can be effectively attenuated in a liquid with a high viscosity.

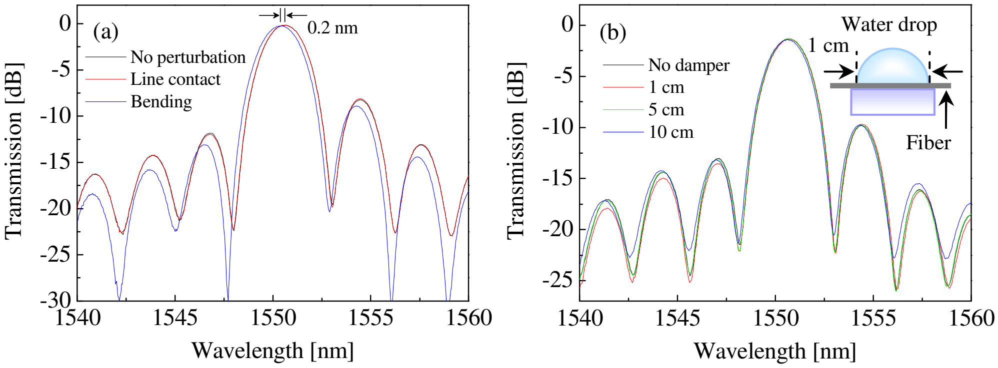

Fig. 2. Measured transmission spectra of the all-fiber torsional mode AOTF under the fiber perturbations of (a) the bending, the line contact, and (b) the partial contact in the AO interaction region of the filter. The cases of no perturbation (black line) and line contact (red line) in Fig. 2(a) has a complete overlap. The inset of the Fig. 2(b) illustrates the perturbation by water drop on the optical fiber.

3. Strain-free, long length and compact all-fiber torsional mode AOTF

As discussed above, the immunity of the torsional mode AOTF to bend, physical contact, and fiber imperfections allows a long interaction length for high efficiency and narrow linewidth with compact size when the fiber is coiled. Figure 3 shows the schematic of a proposed device. Here we used a 4 m-long bare fiber section for the AO interaction. The fiber was coiled with diameter of 5 cm and laid on an optical table allowing physical contact. The axial strain in the fiber is zero, and thus any complicated packaging for the strain management is not required. However, a bare fiber having physical contacts with other objects will not provide necessary long-term reliability against the fiber breakage. This problem can be resolved by using a fiber with very thin coating that does not interfere with acoustic wave propagation. Possible coating materials may be thin films of metal or carbon.

Figure 4(a) shows the measured transmission spectra of the 4-m-long AOTF operating as a notch filter. The measured 3-dB bandwidth was 0.89 nm, which is larger than the theoretical value of 0.45 nm calculated from the equation in reference [16]. The increased filter bandwidth is considered to be due to the non-uniformity in the optical birefringence in the fiber [7]. The bandwidth is also proportional to the slope of the dispersion curve shown in Fig. 4(b), and thus the dispersion management as well as the birefringence uniformity of the HB fiber will help reduce the filter bandwidth further.

The measured center wavelength of the filter is plotted in Fig. 4(b) as a function of the acoustic wavelength, which shows a linear relationship. The center wavelength of the filter can be continuously tuned between 1520 and 1620 nm (limited by the light source) for a 5%

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change in acoustic wavelength from 1.34 mm to 1.42 mm. This results shows that the polarization coupling by torsional acoustic wave is also useful to measure the polarization beatlength at various wavelengths.

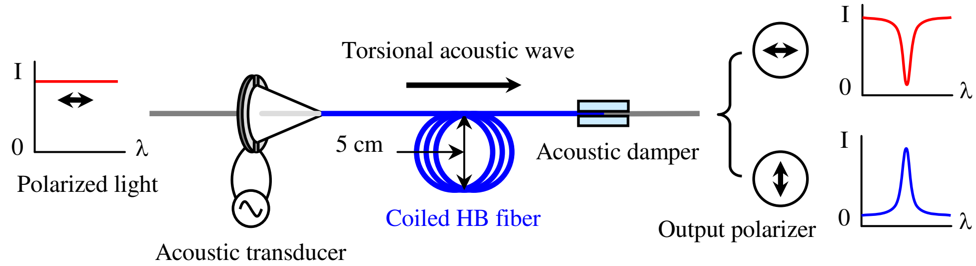

Fig. 3. Schematic of a proposed strain-free and size-reduced all-fiber torsional mode AOTF. The 4 m of AO interaction length is coiled to 5 cm in diameter.

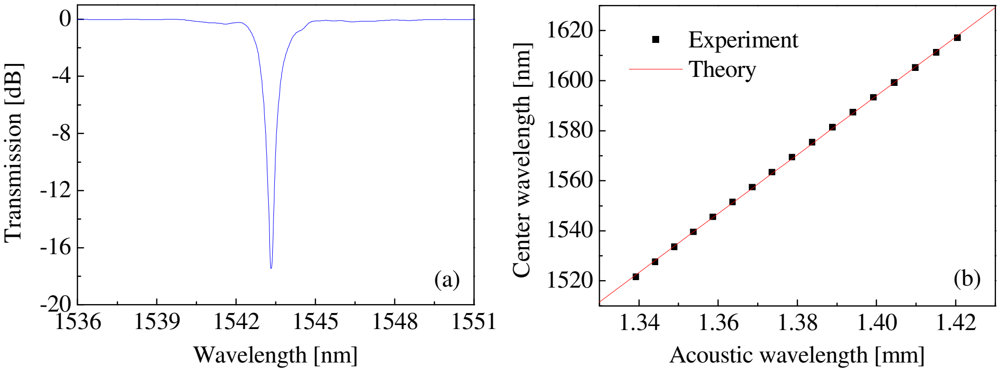

Fig. 4. (a) Measured transmission spectra of the all-fiber AOTF for the AO interaction length of 4 m and (b) the center wavelength of the all-fiber AOTF as a function of the acoustic wavelength.

4. Conclusion

In conclusion, we reported the stable mode coupling immune to fiber perturbations in all-fiber torsional mode AOTF. Both the coupling efficiency and the spectral shape of filter transmission were insensitive to the physical contacts or the bending of AO interaction region. We could successfully demonstrate a novel strain-free and size-reduced all-fiber AOTF. By coiling the AO interaction region of the filter, the 4-m-long device dimension could be reduced to less than 10 cm. The stable operation under the various fiber perturbations is unique property of the torsional mode AOTF, which provides new possibilities in many practical applications.

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