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Polarization-Independent All-Fiber Acousto-Optic Tunable Filter Using Torsional Acoustic Wave

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***Abstract*—The intrinsic polarization dependence of an all-fiber tunable wavelength filter based on polarization coupling by torsional acoustic wave is eliminated by employing a fiber loop configuration. In the fiber loop, two orthogonal polarizations split from input light propagate the single acousto-optic interaction region in opposite directions before being recombined to produce a polarization-independent filter spectrum. The polarization-dependent loss was estimated to be less than 0.1 and 0.3 dB within passband in bandpass and notch type filters, respectively.**

***Index Terms*—Acousto-optic (AO) filters, optical fiber devices, optical fiber polarization, tunable filters.**

I. INTRODUCTION

TUNABLE optical filters are in common use in optical communication and sensor systems. The fundamental requirements for these optical filters include low loss, negligible polarization dependence, 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, low polarization dependence, wide and fast wavelength tuning, and variable attenuation via simple electronic control [1]–[5]. The all-fiber AOTFs are based on wavelength-selective acousto-optic (AO) mode coupling by traveling flexural [1] or torsional acoustic wave [2], [3]. 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 recently developed torsional mode AOTF has some potentially important advantages above the flexural wave counterpart [2], [3]. First, since manipulation of polarization modes in an optical fiber is much easier than that of spatial modes, the torsional mode AOTF can be switched between a notch type and a bandpass type filter by simply adjusting the angle of the output polarizer. Second, the torsional mode AOTF does not suffer from wavelength shift or deterioration in the filter spectrum due to nonuniform acoustic properties of the fiber such as axial variation of fiber diameter, ellipticity of fiber cross-section, or fiber bending. Based on these advantageous features of torsional mode AOTFs, we recently demonstrated a novel strain-free compact-size device with long fiber coils in AO interaction region [3].

However, the torsional-mode AOTF based on polarization-mode coupling exhibits intrinsic polarization dependence. The device requires a polarizer at the input so that the input polarization is always aligned to an eigen axis of the HB fiber, and therefore, any input signal with its orthogonal eigen polarization is completely rejected. This kind of polarization dependence can be eliminated if one places a polarization splitter to separate the input light into two orthogonal polarizations and uses two identical AOTFs to process each polarization independently, before recombining the two output signals using another polarization splitter. However, the approach is impractical since it requires two AOTFs with identical filter responses.

In this letter, we show that fiber loop configuration enables the same polarization diversity operation with single torsional mode AOTF and single polarization splitter. The input light is split into two orthogonal polarizations, and they pass through the single AO interaction region in opposite directions. The two polarization components after AO coupling are recombined by the same polarization splitter resulting in polarization-independent output.

There have been several approaches to achieve the polarization independence, especially in all-fiber flexural mode AOTFs. They used a special fiber with specific stress profile in the fiber cross section [1] or double-pass device configurations [4], [5]. In [5], two flexural acoustic waves with different frequencies were used in double-pass device configuration, which independently provided phase-matched couplings for each eigen-polarization state. Reference [6] demonstrated that the polarization-dependent loss (PDL) can be compensated when a device is placed in a Sagnac loop interferometer with a half- wave plate. It should be noted that those schemes do not work in case of the torsional-mode AOTF, since our device is based on coupling between two polarization modes, not between the spatial modes. A multiwavelength comb filter utilizing a polarization diversity

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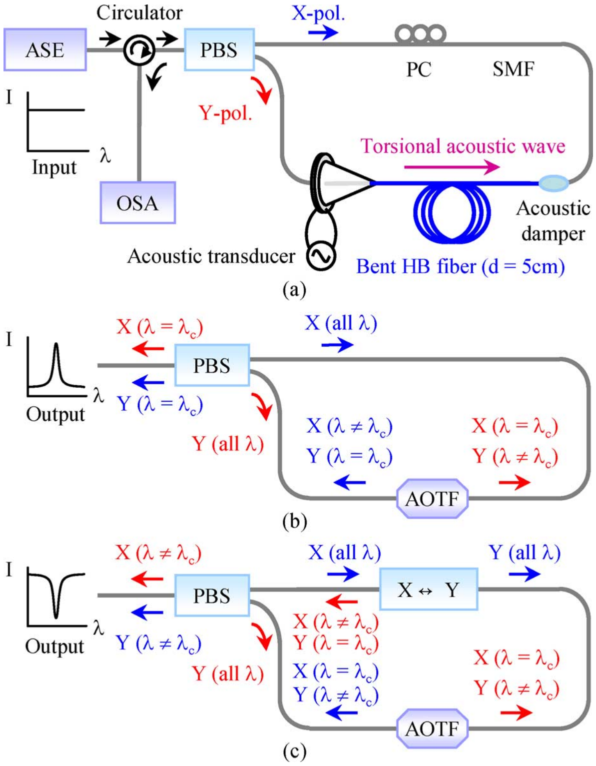

Fig. 1. (a) Schematic of a polarization-independent all-fiber torsional mode AOTF. Device operation in cases of (b) bandpass type, and (c) notch type. The bandpass/notch type is selected through adjustment of the PC. OSA: optical spectrum analyzer.

loop was also reported in [7], but the filter was based on interference between two polarization modes rather than actively tunable resonant coupling between the two polarizations.

II. EXPERIMENT AND DISCUSSION

Fig. 1 shows the schematic of the proposed all-fiber torsional mode AOTF. The device is composed of a torsional acoustic transducer, a circulator, an in-line fiber polarization beam splitter (PBS)/combiner, a polarization controller (PC), and an HB fiber. The PC and a single-mode fiber (SMF) were used for the polarization alignment, which should be substituted for an axis-aligned single HB fiber in practical applications. The torsional acoustic wave was generated by the combination of two shear mode lead zirconate titanate (PZT) plates [2]. The 82-cm-long bare fiber for AO interaction was necessary for narrow bandwidth ($\sim$2 nm) of the filter, which was coiled in the diameter of 5 cm, as shown in Fig. 1 [3]. The torsional acoustic wave provides complete coupling between two eigen polarizations at a resonant wavelength satisfying the phase matching condition [2]. The HB fiber had an elliptical core of 2 μm$\times$ 4 μm. The outer diameter of the HB fiber was 80 μm and the polarization beatlength near 1550 nm was 1.36 mm. A broadband amplified spontaneous emission (ASE) from an erbium-doped fiber amplifier (EDFA) with the wavelength range of 1520–1620 nm was used as an incoherent and unpolarized light source.

The polarization-independent bandpass filtering is achieved when the PC is set so that light transmits the SMF section without polarization change, as illustrated in Fig. 1(b). The unpolarized light launched from the ASE source is divided into two orthogonal polarizations by the PBS, and they propagate the single AO interaction region in opposite directions. Each polarized light in resonant wavelength (λ_c) is converted to the other polarization state by the torsional acoustic wave, and passes through the PBS to be coupled back to the original fiber. The lights out of the resonance in each polarization state are not affected by the acoustic wave, and finally removed at the PBS because the polarization axes of the PBS and the uncoupled lights are perpendicular to each other. This operation is identical for both clockwise and counterclockwise light, and thus results in the bandpass filtering at the resonant wavelength which is independent of the input polarization. Fig. 1(c) shows the device operation when the PC is adjusted so that polarizations are swapped between X and Y in the SMF section. Now all the lights after their round-trip in the fiber loop have opposite polarization directions as compared to the previous case. The polarized lights with resonant wavelength are removed at the PBS, and nonresonant lights are collected back to the original fiber, resulting in the notch type wavelength filtering as indicated in Fig. 1(c).

Note that AO interaction is accompanied with a frequency shift in the coupled (or diffracted) light by the amount of the acoustic frequency [9]. The optical frequency shifts up or down depending on both the input polarization mode and the optical propagation direction with respect to the acoustic wave. It should be guaranteed in this device that the frequency shift occurs with the same signs for the two orthogonal input polarizations; otherwise the output light will have a beating between the polarization components. In the bandpass type configuration of Fig. 1(b), both X- and Y-polarizations undergo same frequency shift since they go through the device in opposite directions, and result in no beating in the output signal. In case of the notch type filtering in Fig. 1(c), the frequency-shifted components are removed at the PBS and the output signal retains its original frequency.

Fig. 2 shows the measured transmission spectra of the all-fiber torsional mode AOTF operating in the bandpass type [Fig. 2(a)] and the notch type [Fig. 2(b)] at the applied acoustic frequency of 2.748 MHz. The resonant wavelength and the transmitted power of the filter could be tuned by adjusting the frequency and the magnitude of the applied electric signal, respectively. The achieved maximum coupling efficiency between two polarization modes was higher than 99% and the measured 3-dB optical bandwidth was 2.2 nm when the center wavelength was around 1550 nm. To estimate the PDL of the device, we compared the filter spectra (solid curve) for the unpolarized input with those (dashed curve) for the x-polarized input. The polarized input was obtained by inserting a linear polarizer in front of the ASE source. Each pair of the spectra in Fig. 2(a) and (b) showed a very similar profile, which confirms the ideas mentioned above. From this data, the PDL (loss difference for X- and Y-polarizations) was estimated to be less than 0.1 dB within the 3-dB passband in Fig. 2(a), and less than 0.3 dB outside the rejection-band in Fig. 2(b). The spectral mismatch found in sidelobes can be explained by the finite extinction ratio (22 dB) of the PBS and the wavelength dependence of the PC composed of SMF loops.

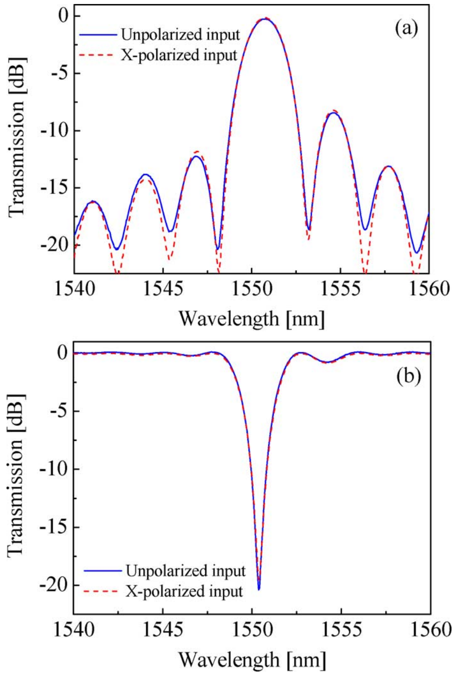

Fig. 2. Measured transmission spectra of the proposed all-fiber AOTF at 2.748 MHz operating as (a) bandpass type and (b) notch type.

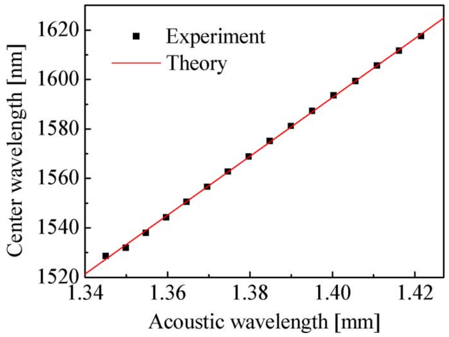

Fig. 3. Center wavelength of the all-fiber torsional mode AOTF as a function of the acoustic wavelength.

The asymmetry in the sidelobe spectra is caused by the small axial nonuniformity in the optical birefringence [10]. The total insertion loss of the device was about 2.8 dB, including 0.6 dB at the circulator (Photonic Technologies), 0.6 dB at the PBS (General Photonics), and the splicing loss of 1.6 dB (0.8 dB × 2) between the HB fiber and the SMF. In order to minimize the insertion loss and simplify the device, the set of the PBS and the circulator can be replaced by a four-port PBS in the practical applications.

The measured center wavelength of the filter is plotted in Fig. 3 as a function of the acoustic wavelength, which shows a linear relationship. The center wavelength of the filter could be continuously tuned between 1530 and 1620 nm (limited by the light source bandwidth) by the frequency tuning from 2.788 to 2.638 MHz, which corresponds to a 5% change in acoustic wavelength.

III. CONCLUSION

We have demonstrated the polarization-independent all-fiber torsional mode AOTF by employing a single torsional acoustic wave and a polarization splitter in a fiber loop. The remaining PDL will be further suppressed by use of a polarization splitter with a high-extinction ratio and a wavelength-independent PC. The result suggests a practical solution for the intrinsic polarization dependence of the torsional-mode AOTF based on polarization coupling. We believe that the torsional mode AOTF with superior features to the flexural mode AOTFs will find many applications in optical communication and sensor systems.

REFERENCES

[1] K. J. Lee, D.-I. Yeom, and B. Y. Kim, "Narrowband, polarization insensitive all-fiber acousto-optic tunable bandpass filter," *Opt. Express*, vol. 15, pp. 2987–2992, 2007.
[2] K. J. Lee, H. C. Park, and B. Y. Kim, "Highly efficient all-fiber tunable polarization filter using torsional acoustic wave," *Opt. Express*, vol. 15, pp. 12362–12367, 2007.
[3] K. J. Lee, I. K. Hwang, H. C. Park, and B. Y. Kim, "Polarization-coupling all-fiber acousto-optic tunable filter insensitive to fiber bend and physical contact," *Opt. Express*, vol. 17, pp. 6096–6100, 2009.
[4] D. A. Satorius, T. E. Dimmick, and G. L. Burdge, "Double-pass acoustooptic tunable bandpass filter with zero frequency shift and reduced polarization sensitivity," *IEEE Photon. Technol. Lett.*, vol. 14, no. 9, pp. 1324–1326, Sep. 2002.
[5] S. H. Yun, D. J. Richardson, D. O. Culverhouse, and T. A. Birks, "All-fiber acoustooptic filter with low-polarization sensitivity and no frequency shift," *IEEE Photon. Technol. Lett.*, vol. 9, no. 4, pp. 461–463, Apr. 1997.
[6] C.-S. Kim, B. Choi, J. S. Nelson, Q. Li, P. Z. Dashti, and H. P. Lee, "Compensation of polarization-dependent loss in transmission fiber gratings by use of a Sagnac loop interferometer," *Opt. Lett.*, vol. 30, pp. 20–22, 2005.
[7] Y. W. Lee, K. J. Han, J. Jung, and B. Lee, "Polarization-independent tunable fiber comb filter," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2066–2068, Sep. 2004.
[8] D. Östling and H. E. Engan, "Narrow-band acousto-optic tunable filtering in a two-mode fiber," *Opt. Lett.*, vol. 20, pp. 1247–1249, 1995.
[9] B. Y. Kim, J. N. Blake, H. E. Engan, and H. J. Shaw, "All-fiber acousto-optic frequency shifter," *Opt. Lett.*, vol. 11, pp. 389–391, Jun. 1986.
[10] K. J. Lee, K. S. Hong, H. C. Park, and B. Y. Kim, "Polarization coupling in a highly birefringent photonic crystal fiber by torsional acoustic wave," *Opt. Express*, vol. 16, pp. 4631–4638, 2008.