Polarization Properties of an Acousto-optic Photonic Crystal Fiber Filter

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Abstract. We investigate the polarization dependent characteristic of an acousto-optic filter in an endlessly-single-mode photonic crystal fiber and find that polarization dependence is high. The maximum wavelength shift due to polarization is ~ 2.25 nm and the polarization dependent loss is ~4.00 dB. The wavelength shift direction is different for different resonant dips in the acousto-optic filter when a polarized broadband light source is used as the input source, which is different largely compared with an acousto-optic filter based on a conventional single-mode fiber.

1. Introduction

Photonic crystal fibers (PCFs), also called microstructured optical fibers or holey fibers are a new class of optical fiber that emerged in recent years [1, 2]. Typically these fibers incorporate a number of air holes that run along the length of the fiber, and have a variety of different shapes, sizes, and distributions. A number of possible applications have been demonstrated because of their unique optical characteristics that cannot be achieved readily by conventional fibers [3, 4]. In recent years, many reports have been made for acousto-optic (AO) devices based on PCFs with interesting filter properties [5-10]. AO mode coupling has been observed in birefringent PCF [7], solid-core photonic bandgap fiber [8], and also hollow core PCF [9]. By utilizing a two-mode PCF that supports two core modes over a broad wavelength range, an all-fiber acousto-optic tunable filter (AOTF) with a wide tuning range as 1000 nm is achieved [11]. However, in a flexural-wave-induced fiber AO filter (AOF), only asymmetrical modes are excited because of the asymmetrical index perturbation profile. Several nearly degenerated constituent modes consist, which have different propagation constants. This leads to a polarization mode splitting effect, and the resonant wavelength of the filter shifts with the input state of polarization. In this letter, we investigate the polarization dependent characteristic of an AOF in an endlessly-single-mode photonic crystal fiber (ESM-PCF) in detail. Experimental results show that polarization properties of the AOF based on the ESM-PCF are different largely compared with that of an AOF based on a conventional single-mode fiber. The wavelength shift direction is opposite for two different resonant dip groups in the AOF based on the ESM-PCF when a polarized broadband light source is used as the input light. The maximum wavelength shift of the AOTF in the ESM-PCF at different polarized light as an input source is ~2.25 nm, and the polarization dependent loss (PDL) is as high as 4 dB.
2. Experimental setup
The schematic diagram of the AOF in the ESM-PCF is shown in Figure 1. The AOF consists of an ESM-PCF, an acoustic horn and a thin piezoelectric transducer (PZT) attached to the horn. When driven a sinusoidal electric signal, the PZT vibration excites a shear mode, which energy is focused at the center and transferred to the fiber by the horn. The flexural acoustic wave propagates along the fiber and results in periodic micro-bends that cause coupling between the two modes at a phase matching wavelength. The period of the micro-bends equals to the acoustic wavelength of the flexural wave in the PCF. Thus, when we tune the acoustic wavelength by changing the frequency of the driven electrical signal, we get a tunable filter. The acousto-optic interaction takes place within length L defined from the tip of the acoustic horn to an acoustic damper where the acoustic wave is absorbed. Transmission spectra of the AOF are measured by using a broadband light source and an optical spectrum analyzer (OSA) with a spectral resolution of 0.05nm.

The ESM-PCF used in our experiments is purchased from Crystal Fiber A/S, and the cross-sectional scanning electron micrograph is also shown in Fig. 1. The mode field diameter is ~6.4 μm, the spacing between the holes is ~7.78 μm, and the diameter of the holes is ~3.55 μm. The diameter of the entire holey region is ~ 60 μm, and the outer cladding diameter of the PCF is 125 μm. The total length of the PCF is about 25 cm, and both ends of the PCF are fusion spliced to single-mode fiber (SMF) by using a regular splicing machine (Erisson FSU975). The loss for each splice is about 0.5 dB. The acousto-optic interaction length L is about 16 cm.

3. Experiment and results
Figure 2 shows the transmission spectrum of the AOF. The frequency and voltage driven on the PZT are 4100 kHz and 60 V, respectively. The transmission dips are about 1507 nm and about 1540 nm which are due to the fundamental core mode coupling to two different cladding modes. But the dip around 1540 nm is not clear. The acousto-optic coupling is affected strongly by a circumferential angle of initial acoustic vibration on the PCF cross-section [10]. When the vibration direction of the acoustic wave is adjusted by rotating the PCF, the transmission spectrum of the AOF is changed, as shown in Figure 3, in which the dip around 1540 nm becomes deep. It is clear that the dip around 1540 nm splits to two dips, 1535nm and 1541 nm, respectively. The splitting of transmission spectra is caused by the acoustic and optical birefringence and the angular misalignment between the two birefringent axes [10]. In our experiment, we observe the polarization properties of this state in detail.
To test the polarization dependent characteristics of the AOF based on the ESM-PCF, a broadband light source with a polarizer is used to provide a polarized broadband source. Figure 4 shows the transmission spectra of the AOF at horizontal and vertical polarization states of the broadband light source. As shown in Fig. 4, the AOF in the ESM-PCF is polarization dependent strongly. The resonant wavelength at around 1507 nm shifts to shorter wavelength when the polarized broadband light source is horizontal (x-polarized) with the vibration direction of the acoustic wave applied on the ESM-PCF, while the two splitting resonant wavelengths around 1535 nm and 1541 nm shift to longer wavelength. When the light source is vertically polarized (y-polarized) with the acoustic wave vibration, the phenomenon is opposite as shown in Figures 5 and 6. The wavelengths of three resonant dips in different light states are given in Table 1. For the resonant wavelength around 1507 nm, the wavelength shift is about -1.05 nm between the light states with x- polarization and non-polarization, and is about 1.2 nm between the y- polarization and the non-polarization light states, respectively. The maxim wavelength difference caused by the polarization is about 2.25 nm. This phenomenon is very different compared with an AOF based on a conventional single-mode fiber.
Table 1. Wavelength of different resonant dips at different polarization states of the input light source.

| Resonant dip | Non-polarization state | x-polarization state | y-polarization state |
|--------------|------------------------|----------------------|---------------------|
| dip 1        | 1507.7 nm              | 1506.75 nm           | 1508.9 nm           |
| dip 2        | 1535.15 nm             | 1535.36 nm           | 1534.95 nm          |
| dip 3        | 1541.25 nm             | 1543.15 nm           | 1541.1 nm           |

The corresponding polarization dependent loss (PDL) versus wavelength for the AOF in the ESM-PCF is also measured by using an All-parameter-measurement equipment of Agilent Com.. Figure 7 shows the largest PDL is as high as 4.0 dB.

In an AOF, periodic micro-bends formed by the flexural acoustic wave propagating along the fiber cause coupling between the fundamental core mode to some cladding modes and lead to some dips in the transmission spectrum at wavelengths that satisfy the resonant condition. The phase matching condition of an AOF can be expressed as [12]:

\[
\lambda = (n_{co} - n_{cl}) \Lambda
\]  

where \( \lambda \) is the resonant wavelength, \( \Lambda \) is the period of the micro-bends and equals to the acoustic wavelength in the ESM-PCF, and \( n_{co} \) and \( n_{cl} \) are the effective indices of the fundamental core mode, and one of the forward-propagating cladding modes, respectively. At a fixed acoustic wave frequency, the resonant wavelength is shorter for a coupling between the core mode and a lower-order cladding mode due to a larger effective index of the low-order cladding mode.

Since the asymmetrical index perturbation due to the flexural-wave leads to a polarization mode splitting, the resonant wavelength of the filter shifts with the input state of polarization. The resonant dip 1 (at around 1507 nm) shifts to shorter wavelength when an x-polarized light inputs, in the contrast, the resonant dip 1 shifts to longer when a y-polarized light inputs. This means that

\[
(n_{co}^x - n_{cl1}^x) > (n_{co}^y - n_{cl1}^y) > (n_{co}^x - n_{cl1}^y)
\]  

Where \( n_{co}^x, n_{co}^y \), and \( n_{co}^x \) are the effective indices of the core mode, the x-polarization core mode, and the y-polarization core mode, respectively. And \( n_{cl1}^x, n_{cl1}^y \), and \( n_{cl1}^y \) are the effective indices of the low-order cladding mode, and the corresponding x-polarization and y-polarization mode, respectively. Thus, we deduce (2) to
Then, we can get

$$n_{x}^{c_{0}} - n_{y}^{c_{0}} - (n_{x}^{c_{0}} - n_{x}^{c_{l1}}) > 0 \quad (3)$$

Relation (4) shows that birefringence of the core mode is larger than that of the low-order cladding mode. By the same method, we can also get

$$n_{y}^{c_{0}} - n_{x}^{c_{0}} > (n_{y}^{c_{l1}} - n_{x}^{c_{l1}}) \quad (4)$$

where $n_{x}^{c_{l2}}$, $n_{y}^{c_{l2}}$, and $n_{x}^{c_{l2}}$ are the effective indices of the high-order cladding mode, and the corresponding x-polarization and y-polarization mode, respectively. Through the theoretical analysis, the experimental phenomenon will appear when birefringence of the core mode ($\Delta n_{c_{0}}$), the low-order cladding mode (corresponding to the resonant dip 1, $\Delta n_{c_{l1}}$), and the high-order cladding mode (corresponding to the resonant dips 2 and 3, $\Delta n_{c_{l2}}$) is satisfied with $\Delta n_{c_{l2}} > \Delta n_{c_{0}} > \Delta n_{c_{l1}}$. The origin of this polarization property of the AOF based on the ESM-PCF may be from the ellipticity in the fiber core and the irregularity in the air-hole lattice on the fiber cross-section that results birefringence of the core mode and two cladding modes is different. However, the further studies on the origin are needed.

4. Conclusion

The polarization properties of the AOF based on the ESM-PCF are different largely compared with that of an AOF based on a conventional single-mode fiber. The wavelength shift direction is opposite for two different resonant dip groups in the AOF based on the ESM-PCF when a polarized broadband light source is used as the input light. The reason may be due to the different birefringence of the core mode and two cladding modes of the ESM-PCF which is caused by the ellipticity in the fiber core and the irregularity in the air-hole lattice on the fiber cross-section. This work is very important to understanding the acousto-optic interaction in the PCF deeply, and the properties may be applied on an optical fiber sensor based on polarization.

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