1000 nm tunable acousto-optic filter based on photonic crystal fiber

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We report an all-fiber acousto-optic tunable filter based on a two-mode photonic crystal fiber. The properties of photonic crystal fiber allow us to demonstrate a notch filter tunable from below 700 to 1700 nm with a single acoustic transducer. The extreme dynamic range coupled with small insertion loss and fast response time ($\sim 100\ \mu s$) makes this device promising for ultrawideband optical systems. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2806198]

All-fiber acousto-optic tunable filters (AOTFs) have attracted interest owing to their advantages such as fast wavelength tuning and variable attenuation with simple electronic control.[1,2] Practical AOTFs for various applications, such as optical switches and wavelength tuning devices, have been demonstrated.[3] In the case of the wavelength tuning device, dynamic range or tuning range is a crucial factor that determines the capacity of current spectroscopy, telecommunication, optical signal processing, and sensor systems.[4–7] Emergence of photonic crystal fiber has opened a new possibility for ultrawide bandwidth optical systems by demonstrating single-mode guidance for entire optical wavelengths.[8,9] However, realization of such a system strongly demands subsequent advancement in optical devices that can function over this wide wavelength range.

In this paper, we report an all-fiber AOTF that can be tuned over an extremely wide wavelength range from below 700 to 1700 nm. The AOTF is based on acoustically induced mode coupling in a two-mode photonic crystal fiber (TM PCF) that supports two core modes over a broad wavelength range.[10,11]

Our all-fiber AOTF consists of a TM PCF, an acoustic horn and a thin piezoelectric disk (lead zirconate titanate, or PZT) attached to the horn [Fig. 1(a)]. A small hole is made at the center of the horn and the disk to allow for the unjacketed TM PCF to go through and be glued to the center of the horn. A sinusoidal electric signal excites a shear mode of the PZT vibration, of which energy is focused at the center and transferred to the fiber by the horn. The excited flexural acoustic wave traveling along the fiber results in periodic microbends that cause coupling between the two modes at a phase matching wavelength given by[12,13]

$$L_B(\lambda) = \Lambda_a, \tag{1}$$

where L_B is the wavelength dependent modal beat length and Λ_a is the acoustic wavelength of the flexural wave in PCF, which is the same as the period of the microbends. The acousto-optic (AO) interaction takes place within length L defined from the tip of the acoustic horn to an acoustic damper where the acoustic wave is absorbed.

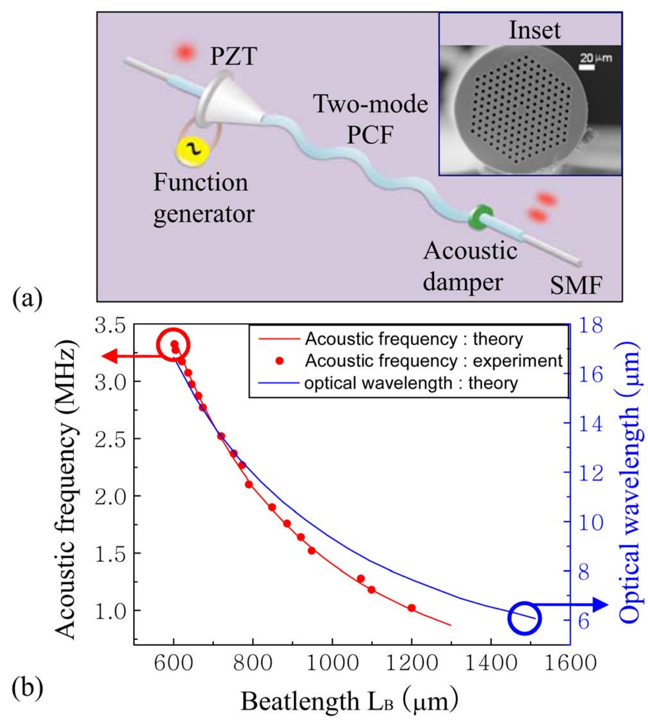

FIG. 1. (Color online) AOTF based on TM PCF. (a) Basic configuration; the PCF is the LMA-15 provided by Crystal Fiber A/S[11] and the cross section of the PCF is shown in the inset; SMF represents single mode fiber. (b) Acoustic frequency and optical wavelength as functions of modal beat length between LP_{01} and LP_{11}. The beat length equals to the acoutic wavelength under the phase matching condition (Eq. (1)).

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When broadband light is launched into the fundamental core mode of the TM PCF, the phase-matched wavelength (λ) component will be coupled to the second-order core mode, which can be removed by aligning the TM PCF precisely to the center of an output single-mode fiber or by bending the TM PCF after AO interaction. A notch filter with a center wavelength of λ is then realized. The important advantage of the AO device is its tunability. The acoustic wavelength and the amplitude can be adjusted to change the center wavelength and the depth of the notch by tuning the frequency and the amplitude of the electrical signal applied to the PZT. The above principle has been applied to make AOTFs with conventional fibers;[12–14] the dynamic range is, however, limited to $\sim$200 nm due to the limited two-mode range and nonmonotonic wavelength dependence of the modal beat length,[1,14] which cause mode coupling at multiple wavelengths and large variation of the filter linewidth dependent on the center wavelength. Such a limitation is dramatically removed by the use of a properly designed TM PCF. The inset in Fig. 1(a) shows the SEM cross-sectional image of the PCF used in our experiments. The average values of the relative hole diameter (d/Λ) and the spacing (Λ) between the holes are measured to be 0.492 and 9.689 μm, respectively. We studied the modal properties of the PCF by using a freely available simulation package adapting the plane-wave basis method and found that the PCF guides two core modes for any wavelength below 2.1 μm.[15,16] The modal beat length as a function of wavelength is shown in Fig. 1(b). Note that the curve has negative slopes everywhere and, hence, only one resonant wavelength is matched to a given beat length unlike the case of conventional fibers. This feature comes from the unusually strong dispersion of the photonic crystal cladding, and results in a single notch in the transmission spectrum of our device. There are possibilities of coupling to asymmetric cladding modes such as the LP_{12} and LP_{13} modes. However, we evaluated the coupling efficiencies between LP_{01} core mode and LP_{1m} ($m \geqslant 2$) cladding modes by calculating the mode overlap integrals between them under a phase distortion[1] induced by the microbends, and found that they are, under a constant microbend magnitude optimized for LP_{01} to LP_{11} coupling, less than 4% of that between LP_{01} and LP_{11} over the wavelength range from 532 to 1700 nm. Hence, we expect a single notch due to AO coupling between LP_{01} and LP_{11} over this entire wavelength range.

To relate the frequency of the electrical signal applied to PZT to the filter wavelength, we studied the relationship between the acoustic frequency (f_α) and the acoustic wavelength (Λ_a) in the PCF. The results are also shown in Fig. 1(b). The solid curve was the calculated results for a solid rod with the same diameter as the PCF,[17] and the dots were measured results from the TM PCF with an optical fiber vibrometer.[18] The good agreement between the calculated and measured results verified that the existence of air holes has little effect on the acoustic dispersion relationship.

Experimental investigations were conducted with the setup shown in Fig. 1(a) with an AO interaction length of $L = \sim 15.5$ cm. We firstly investigated the guided modes of the PCF by launching light with wavelength 532, 633, 980, and 1550 nm into the PCF with various lateral offset and launching angles, and found that the PCF indeed supports two core modes for these wavelengths. We then studied the AO coupling at various optical wavelengths as functions of acoustic frequency. Figures 2(a) and 2(c) show, respectively, the far-field output intensity profile from the end of TM PCF without splicing with SMF when 532 nm and 1550 nm lasers were launched into the LP_{01} mode of the fiber. When the acoustic signal with suitable magnitudes and frequencies (0.571 MHz for 532 nm and 2.998 MHz for 1550 nm) that satisfy the phase matching condition were applied, the output mode patterns were switched to LP_{11}, as shown in Figs. 2(b) and 2(d). No other core and cladding modes were observed when the acoustic frequency was varied from 0.571 to 3.33 MHz, indicating significant mode coupling only occur between LP_{01} and LP_{11} modes. The mode field distributions are well confined in the core region as expected from calculated results. These observations verified that the PCF used here guides two and only core modes (LP_{01} and LP_{11}) for wavelength from 532 to 1550 nm, and efficient AO coupling can be achieved at these wavelengths.

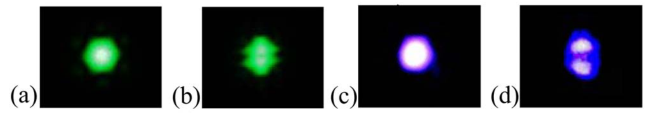

FIG. 2. (Color online) Far field patterns recorded at the output of the TM PCF. (a) and (c) are intensity profiles when acoustic signals are off, showing the patterns of LP_{01} modes. (b) and (d) are intensity profiles when acoustic signals are on, showing the coupled LP_{11} mode patterns. (a) and (b) are for wavelength of 532 nm and (c) and (d) are for wavelength of 1550 nm.

The tuning characteristics of the AOTF were then examined with two broadband sources: a KOHERAS Superk™ supercontinuum source with output spectrum from 700 to 1700 nm and a broadband source made by combining the outputs from two light emitting diodes (LEDs) with center wavelengths of 1300 and 1500 nm. The supercontinuum source has pulsed output with a repetition rate of $\sim$28 kHz, a pulse width of $\sim$1.3 ns, and a maximum output power of $\sim$100 mW. Light from the sources was firstly coupled into a SMF28 fiber, which is aligned and spliced to the input end of the TM PCF AOTF; the output end of the filter was aligned and spliced to a second SMF28 fiber that is connected to an optical spectrum analyzer. Figure 3(a) shows the measured transmission spectra of the TM-PCF AOTF for various acoustic frequencies. Only one significant resonant notch is observed in the output spectrum for each acoustic frequency and no additional notches due to coupling to cladding modes were observed. The relatively large ripples from 700 to 1200 nm are mainly due to the instability of the supercontinuum source. The spectra from above 1200 to 1700 nm were obtained with the LED sources and hence have much smaller ripples.

Figure 3(b) shows the relationships between the center wavelength, the 3 dB linewidth of the notch, and the acoustic frequency. The center wavelength was tuned from 700 to 1700 nm when the acoustic frequency was varied from 0.89 to 3.33 MHz. The experiments were limited by the spectral bandwidth of the broadband sources available in our laboratories. In fact, we have observed strong mode coupling at 532 and 633 nm, as shown in the proceeding paragraphs, indicating that the dynamic range can be extended down to 532 nm and further. This suggests a possible dynamic range of over 1150 nm. The 3 dB linewidth of the resonant notch changed from 5 to 6 nm for optical wavelength ranging from 700 to 1700 nm. The measured data agree well with the theoretical calculations based on the wavelength-dependent beat

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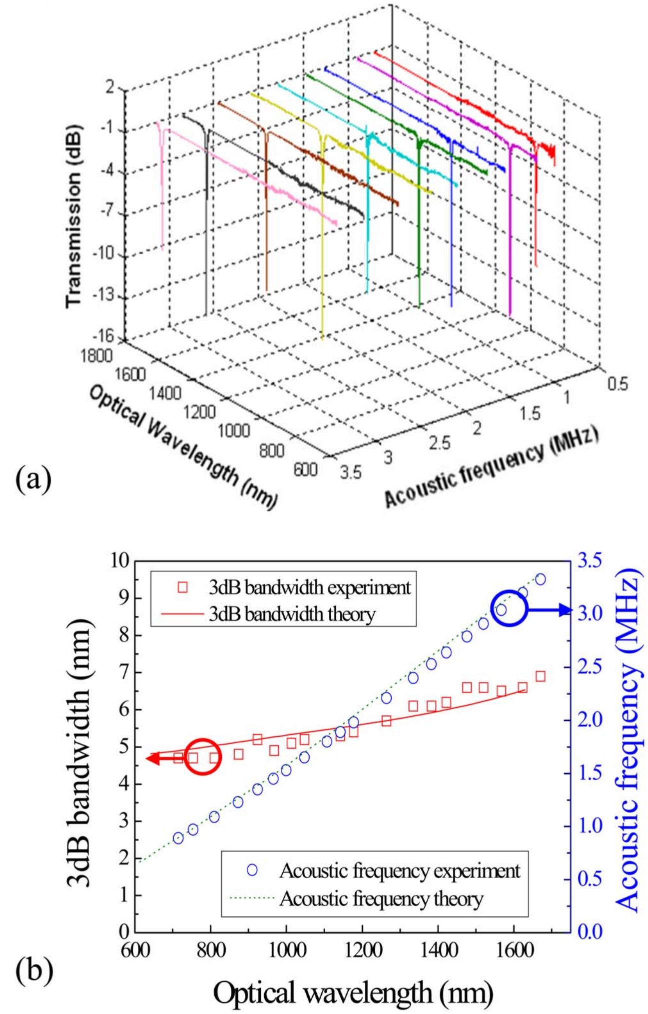

FIG. 3. (Color online) Tuning characteristics of the AOTF. (a) Wavelength tuning from 700 to 1700 nm, the ripples from 700 to 1200 nm are due to the instability of the supercontinuum source, and coupling to cladding modes cannot be observed. (b) Relationships between the center wavelength, the 3 dB linewidth of the notch and the acoustic frequency, lines (calculation) and symbols (experiment). The optical wavelength-acoustic frequency curve was calculated by using the results shown in Fig. 1(b) and phase matching relationship $L_B = \Lambda_a$.

length and the AO interaction length.[13] The small variation of the notch linewidth makes a striking contrast to that of AO devices based on conventional fibers, where the linewidth broadens by several times at the normalized frequency of $V \sim 3$.[19] The notch linewidth may be further reduced by optimizing PCF design to increase group-index difference between the two modes and/or increasing the interaction length.

The insertion loss of our AOTF may be estimated by considering the loss due to AO interaction and the joint loss with pigtail fibers. Assuming that the AOTF is spliced, at both ends, to endlessly single-mode PCF with $d/\Lambda = 0.4$ and $\Lambda = 9.132\ \mu$m, with perfect lateral and angular alignments, the joint loss due to mode-field mismatch was theoretically estimated to be below 0.01 dB per joint over a wavelength range from 500 to 1700 nm. Considering the very small (<0.1 dB) (Ref. 19) loss due to AO interaction, we expect that overall device loss to be very low.

The response time of the filter is determined by the transit time of the acoustic wave traveling through the interaction region. The velocity of the flexural acoustic wave through the fiber can be estimated from Fig. 2(a) to be $v_a = f_a \Lambda_a \approx 1600$ m/s, which gives a response time of 15.5 cm/(1600 m/s) $\approx 100\ \mu$s.

In conclusion, we have demonstrated an all-fiber AOTF employing a TM PCF. A tuning range of from below 700 to 1700 nm was achieved by using a single PZT. Although a notch filter is demonstrated here, it may be converted into a bandpass filter by using a mode converter just after the AO interaction region.[20] A properly designed chirped and appodized static long period grating in TM PCF would be able to convert LP_{11} to LP_{01} and vise versa over a broad wavelength range.[21] The PCF tunable filter may be extended to infrared wavelength by using fibers based on other materials such as chalcogenide glass.[6] The extremely wide tuning range coupled with the advantages of small insertion loss and fast response time of the all-fiber AOTF will allow a wide range of applications in spectroscopy, telecommunication, tunable lasers, optical signal processing, and sensing.

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