Acoustooptic Tunable Gap-Type Bandpass Filter With a Broad Stopband

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Abstract—We demonstrate a novel all-fiber gap-type tunable bandpass filter configuration that consists of a broadband hollow optical fiber (HOF) acoustooptic tunable filter (AOTF) concatenated with a narrowband single-mode fiber (SMF)-AOTF. Owing to the unique mode coupling properties of HOF-AOTF and SMF-AOTF, a narrow passband channel of a full-width at half-maximum (FWHM) of ~4 nm could be formed in a broad stopband platform of a 90-nm FWHM successfully. In this scheme, the center wavelength and rejection efficiency of both passband and stopband were found to be flexibly tunable by adjusting the frequency and the voltage of radio-frequency signals applied to individual acoustic transducers.

Index Terms—Acoustooptic mode coupling, bandpass filter (BPF), optical fiber devices.

I. INTRODUCTION

TO DATE, several all-fiber bandpass filter (BPF) schemes have been proposed and experimentally demonstrated for applications in fiber amplifier, laser, and dense wavelength-division multiplexing (WDM) optical communication systems [1]–[7]. In fiber Bragg gratings (FBGs), the broadly chirped Bragg grating concatenation method [1] and UV post-fabrication exposure technique [2] were adapted to provide a gap-type BPF, which had an unique transmission spectra of a narrow passband within a wide stopband. In the case of fiber long-period gratings (LPGs), BPFs have been demonstrated in various configurations such as two identical LPGs cascaded with a core-mode blocker [3], a pair of LPGs (broadband and narrowband) in few-mode fiber [4], and π-phase shift method in the middle of the LPG [5]. Although these prior technologies have been successfully demonstrated with distinctive spectral characteristics, their spectral tunability was very limited and most of them were, in deed, spectrally fixed passive filters. With the progress of WDM technology and the prospect for dynamic switching of wavelengths in optical networks, there are growing needs for dynamic wavelength selective components and persistent efforts have been focused to achieve tunable filtering function with thermo optic, electro optic, or mechanical perturbations [6]. Fiber acoustooptic tunable filter (AOTF) is one of promising devices which offer the advantage of electronic tunability, fast response time, fiber compatibility, and low insertion loss.

In order to cope with these all-fiber tunable bandpass device demands, there has been a recent attempt in AOTF based on conventional single-mode fiber (SMF), where a core-mode blocker at the midpoint of the acoustic interaction length was introduced [7]. This filter accomplished exactly the same functions with the previous one composed of two identical fixed LPGs and a core-mode blocker [3], yet further tunability was achieved owing to the microbending generated by flexural acoustic wave. However, the core-mode blocker, which was based on local damage in the core region of a fiber, could induce a significant scattering loss and weaken the reproducibility in mass production.

Recently, acoustooptic coupling in two-mode hollow optical fiber (HOF) has been reported by the authors [8], where the spectral bandwidth of coupling was tunable in broad range near 1.5 μm. The three layered structure of HOF, the central air hole, germanosilicate ring core, and silica cladding, has provide unique beat length dispersion between the LP01 and LP11 modes of HOF to result in broadband coupling. Generally, conventional SMF-based AOTFs operate in the megahertz frequency range with a narrow bandwidth of several nanometers. Meanwhile, in the HOF segment, the central air hole and ring core result in a significantly different phase-matching condition, so that HOF-AOTF can be activated at the kilohertz frequency range with a much broader band of rejection.

In this letter, we report a novel device configuration that consists of concatenated two AOTFs, a broadband HOF-AOTF followed by a narrowband SMF-AOTF. Due to unique mode coupling and adiabatic mode transformation along the concatenated AOTFs, the device showed novel transmission spectrum that had a narrow passband channel within a wide stopband platform, similar to that of gap-type BPFs in FBGs [2]. In contrast to FBG gap-type BPF, the proposed scheme can provide flexible tunability in the location of the center wavelength and rejection efficiency of both passband and stopband by adjusting the frequency and the voltage of radio-frequency (RF) signals applied to each acoustic transducer, for the first time to the knowledge of the authors.

II. EXPERIMENTAL RESULTS AND DISCUSSION

The schematic diagram of the proposed BPF is shown in Fig. 1. The setup is similar to those of prior all-fiber AOTFs [9], but the device consists of serially connected two AOTFs with 6-cm-long HOF and 12-cm-long SMF (Corning SMF-28). The SMF and HOF are spliced adiabatically for both optical and acoustic guidance, to result in total insertion loss less than 1 dB. Each AOTF is separately driven by their own RF signals.
with different frequencies. The HOF was designed to guide only two core modes (LP\(_{01}\), LP\(_{11}\)) and fabricated by modified chemical vapor deposition process with a three-layer structure: a central air hole, a GeO\(_2\)-doped silica ring core, and a pure silica cladding [10]. In our experiment, the HOF having an air-hole diameter of 4.5 \(\mu\)m and a germanium-doped ring core diameter of 12.5 \(\mu\)m was used. The ring core had a higher refractive index than the silica outer cladding by 0.005, which was similar to conventional SMFs. In this configuration, when the central hole of the HOF is collapsed by some means, the HOF would have the same refractive index profile as the one of conventional SMF.

In AOTF, the mode coupling between optical modes occurs due to the microbending induced by the flexural acoustic wave traveling along the optical fiber. When the wavelength of the acoustic wave matches the beat length between two modes, the resonant mode coupling takes place. Fig. 2 represents an optical wave that is propagating along the concatenated two different optical fibers (HOF and SMF) under two different acoustic modulations. When AOTF1 is activated in a kilohertz frequency range, the symmetric LP\(_{01}\) core mode of the HOF is coupled to the asymmetric LP\(_{11}\) mode over a broad wavelength range as reported earlier [8]. The LP\(_{11}\) mode further propagates along the adiabatic splicing region between HOF and SMF (see Fig. 2). Note that mode conversion from the asymmetric LP\(_{11}\) core mode of HOF to the symmetric LP\(_{01}\) core mode of SMF is not allowed due to the mode orthogonality [11]. However, at the adiabatic taper region, the mode transform from the LP\(_{11}\) core mode of the HOF to the asymmetric higher order cladding modes (LP\(_{1m}\)) of SMF adiabatically. The coupled LP\(_{1m}\) mode in the cladding further propagates along a bare section of a conventional SMF, where AOTF2 selects a specific narrow portion of the spectrum back into the LP\(_{01}\) core mode of SMF.

The transmission spectra of the proposed device were measured with an unpolarized broadband light source (Agilent 83437A) and the results are shown in Fig. 3. When the acoustic frequency of AOTF1 is around kilohertz range, the acoustic wave interacts with the HOF to result in broadband two stop notches due to the unique parabolic beat-length dispersion of HOF, which was previously investigated in [8]. As we further tune the frequency around 84.935 kHz to reach the minimum beat length, an almost flat stopband with a 3-dB bandwidth of more than 97.1 nm was achieved, as shown in Fig. 3(a). The notch-depth of the filter was 8 dB with a peak-to-peak voltage of 10 V, which can be changed continuously by adjusting the applied voltage applied to AOTF1.

As previously mentioned, there are three distinctive mode transformations: 1) LP\(_{01}\) core mode to LP\(_{11}\) core mode in HOF at AOTF1; 2) LP\(_{11}\) core mode of HOF to LP\(_{1m}\) mode of SMF at the HOF-SMF adiabatic splice; and 3) LP\(_{1m}\) mode to LP\(_{01}\) mode in SMF at AOTF2. These successive mode transformations result in a BPF whose typical transmission spectrum is shown in Fig. 3(b). The broad stopband resulted from the mode Conversion 1 while the narrow passband resulted from 2 and 3. The stopband showed 3-dB bandwidth of over 90 nm, 1520–1610 nm, and the maximum rejection efficiency of 9.1 dB (87.7%). In terms of recoupled power, the device showed overall insertion loss of 1.7 dB. Due to the limited finite coupling efficiency of AOTF1, some of the optical power (about 12.3%) that is not coupled in the AOTF1 propagates along the SMF. This remnant optical power, then, can be coupled in the AOTF2, which limits the passband performance of the present device structure. The improvement in the coupling efficiency is being further investigated by the authors by appropriate design of HOF and acoustooptic coupling horn design.
The sharp transmission peak in the broad stopband has a 3-dB bandwidth of 4 nm. Here, the AOTF2 was operated at a frequency of around 2.762 MHz. As in Fig. 3(b), we could achieve the gap-type bandpass peak near 1570 nm within a wide stopband with negligible sidelobes. HOF-AOTF1 provided a broad, flat stopband platform while the SMF-AOTF2 defined the spectral characteristics of the passband. Another important characteristic is that the proposed device has only one passband channel in the stopband window. In general, AOTF based on SMF shows multiple notches corresponding to coupling to the high orders of cladding modes, for example, from the shorter wavelength side, LP11, LP12, and LP13 modes in the spectral range of 1450 \(\sim\) 1650 nm [9]. However, the proposed scheme utilize the adiabatic mode transformation between the HOF and the SMF, which was found to permit the LP_{11} core-mode transform to only one of the higher order LP_{m}cladding modes. Detailed calculation of mode overlap in the electric field distribution of the corresponding guided modes and their coupling strengths are being theoretically investigated by the authors.

The center wavelength of the passband was continuously tunable within the 97.1-nm flat spectral range by changing the RF frequency of AOTF2, as shown in Fig. 4(a). The transmission peak moved to a shorter wavelength with a linear slope coefficient of \(-0.206 \text{ nm/kHz}\), as shown in Fig. 4(b).

Note that two AOTFs do not affect each other because they do not share the resonance RF frequency in coupling; few kilohertz for AOTF1 and few megahertz for AOTF2. AOTF1 make out the spectral characteristics of the broad stopband, such as the central position and filter efficiency, and AOTF2 independently define that of the narrow passband by control the amplitude and frequency of transducer. The filter bandwidth was not adjustable due to their intrinsic dispersion features of SMF and HOF.

### III. CONCLUSION

We have demonstrated a tunable all-fiber gap-type BPF, which was based on the acoustooptic mode coupling in the concatenated broadband HOF-AOTF and narrowband SMF-AOTF composite structure. A broadband input light is first coupled from the fundamental core mode to its second mode of the HOF by the HOF-AOTF. Through the adiabatic mode conversion at the taper region, the second mode of the HOF is coupled to a specific asymmetric cladding mode of the SMF. This cladding mode then recoupled back into a narrowband core mode of SMF by the SMF-AOTF. Disparity in the operating frequencies of HOF- and SMF-AOTFs, in the few kilohertz and few megahertz regions, respectively, enabled independent and flexible tunability of the device to tailor simultaneously not only the passband channel but also the stopband. The center wavelength and rejection efficiency of the passband, of full-width at half-maximum (FWHM) \(~4\text{ nm}\), were continuously tunable within the 90-nm flat spectral range, from 1520 to 1610 nm, cover both C- and \(L\)-band, with an insertion loss less than 1.7 dB. We expect that the proposed device will endow a new degree of freedom in design of dynamic acoustooptic filters for future fiber laser and dense WDM optical communication systems.

### REFERENCES