# All-Fiber Tunable Comb Filter with Nonreciprocal Transmission

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*Abstract*— **We demonstrate an all-fiber nonreciprocal comb filter by using two acoustooptic frequency shifters and a two-mode fiber interferometer. The transmission spectra for two opposite optical propagation directions are both periodic functions of optical wavelength, but different in transmission peak wavelengths. Methods for controlling the spacing and position of the transmission peak wavelengths are demonstrated.**

*Index Terms*— **Acoustooptic devices, optical fiber communication, optical fiber filters, tunable filters, wavelength-division multiplexing.**

MOST OF THE nonreciprocal devices widely used in present optical systems are based on the magnetooptic Faraday rotation. Optical isolators and circulators are two representative nonreciprocal devices where transmission losses are different for two opposite propagation directions [1], [2]. The optical transmission directions in such devices are fixed by the direction of applied magnetic field for a range of operating wavelengths offered by Faraday materials.

Recently, we have proposed and demonstrated an active nonreciprocal device based on an all-fiber interferometer employing two acoustooptic frequency shifters [3]. Unlike the conventional magnetooptic devices, the nonreciprocity in the new device is provided by the energy transfer between the acoustic and optical waves in the frequency shifters. The device has a unique capability of tuning or modulating the magnitude and transmission direction of the nonreciprocity using a simple electronic control. In this letter, we describe the spectral characteristics of such an all-fiber nonreciprocal device and demonstrate its novel function as a tunable nonreciprocal comb filter having periodic wavelength-dependent transmission directions. The device may open up new possibilities in wavelength-division-multiplexed (WDM) communication technologies.

Fig. 1(a) shows the schematic of the basic device which consists of two frequency shifters, FS1 and FS2, and a two-mode fiber (TMF) interferometer. The two FS's are positioned along a strand of the TMF, separated from each other by a length $L$. The FS's produce mode coupling (with an efficiency of 50%) between two propagation modes of the TMF, the $LP_{01}$ and the $LP_{11}$ modes, via a flexural acoustic wave with frequency $f_a$ [4], [5]. Let us consider an optical wave of

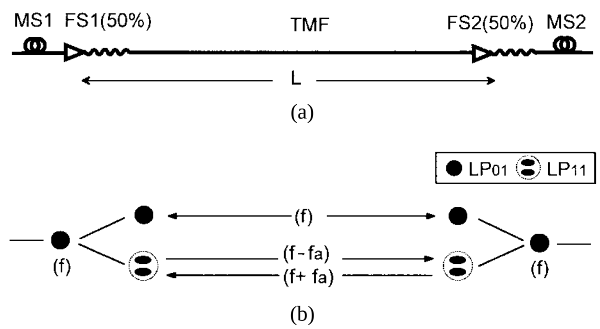


Fig. 1. (a) Schematic of the nonreciprocal device. (b) Illustration of the mode and frequency transitions in the device. TMF: Two-mode fiber. FS: Frequency shifter. MS: $LP_{11}$ mode stripper.

frequency $f$ propagating from left to right (forward propagation) [Fig. 1(b)]. A mode stripper, MS1, eliminates the $LP_{11}$ mode and ensures the light entering FS1 is in the $LP_{01}$ mode. FS1 couples half the input energy to the $LP_{11}$ mode with an associated acoustooptic frequency downshift. Optical signals in the two modes propagate along the length $L$ and interfere with each other at FS2 that couples the signals in the two modes with 50% efficiency. Since FS2 produces frequency upshift when the $LP_{11}$ mode is coupled to the $LP_{01}$ mode, the optical frequency is $f$ for the resulting $LP_{01}$ mode and $f - f_a$ for the $LP_{11}$ mode. MS2 removes the $LP_{11}$ mode component with frequency $f - f_a$ and transmits only the $LP_{01}$ mode. Therefore, the transmission coefficient of the overall device is determined by the phase difference between the $LP_{01}$ and $LP_{11}$ modes at the position of FS2. For the light coming from right to left (backward direction), the same mode transition takes place, but the frequency of the $LP_{11}$ mode becomes $f + f_a$ in the TMF between the two FS's.

The frequency difference of $2f_a$ between forward and backward directions in the TMF results in the nonreciprocal phase shift for the $LP_{11}$ mode by [3]

$$\phi_{nr} \cong \frac{4\pi n_{11g} f_a}{c} L \tag{1}$$

where $n_{11g}$ is the effective group refractive index of the $LP_{11}$ mode. Therefore, the transmittance of the TMF interferometer for the forward and backward propagation directions, $T_{\rm fwd}$ and $T_{\rm bwd}$, is expressed as

$$T_{\rm fwd}(\lambda) \cong \frac{1}{2}\left[1 + \cos\left(\frac{2\pi}{\lambda} \cdot \delta n L + \frac{\phi_{nr}}{2} + \delta_a\right)\right] \tag{2}$$

$$T_{\rm bwd}(\lambda) \cong \frac{1}{2}\left[1 + \cos\left(\frac{2\pi}{\lambda} \cdot \delta n L - \frac{\phi_{nr}}{2} + \delta_a\right)\right]. \tag{3}$$

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Here, the first and second terms in the argument of cosine function represent the phase difference of the two interfering modes, where $\delta n = n_{01}(\lambda) - n_{11}(\lambda)$ is the phase index difference of $LP_{01}$ and $LP_{11}$ modes, $\lambda = c/f$ is the optical wavelength, and $\delta_a$ is the phase difference between acoustic waves in FS1 and FS2, respectively. When $L$ is chosen to satisfy $\phi_{nr} = \pi$ for a given $f_a$, the device exhibits a complementary nonreciprocal transmission in that the sum of $T_{\mathrm{fwd}}$ and $T_{\mathrm{bwd}}$ is always 1. For a given optical wavelength, the nonreciprocal transmission can be controlled by the modulation of $\delta_a$ as demonstrated in [3].

It can be directly seen from (2) and (3) that the transmittance of the device has a strong wavelength dependence owing to the term $(2\pi/\lambda)\delta nL$. As in usual unbalanced interferometers, this phase term causes the transmission to be a periodic function of $\lambda$. The spacing of the adjacent transmission peak wavelengths, or the comb spacing $\Delta\lambda$ ($\ll\lambda$), can be expressed as

$$\Delta\lambda = \frac{\lambda^2}{L} \cdot \frac{1}{\delta n - (d\delta n/d\lambda)\lambda} \tag{4}$$

where the denominator $\delta n - (d\delta n/d\lambda)\lambda$ is equivalent to the group index difference of the two modes. The positions of transmission peaks can be tuned by controlling $\delta_a$, although it is not possible to electrically change the comb spacing. This nonreciprocal wavelength comb filter represents a new function that may be very useful for WDM systems.

Fig. 2(a) shows the experimental setup used to demonstrate the comb filter. The fiber used was an elliptical-core TMF at 1550 nm with cladding diameter of 95 $\mu$m and core size of 13 $\mu$m $\times$ 9 $\mu$m. Two FS's were fabricated on a single strand of the TMF by using coaxial acoustic transducers [5]. The acoustooptic interaction length was 4.5 cm for each device. The plane of the acoustic vibration was matched to the minor axis of the core to produce coupling between the $LP_{01}$ and $LP_{11}^{\mathrm{odd}}$ modes. The phase-matching acoustic frequency was 2.51 MHz for resonant mode coupling at 1550 nm. The length of the TMF between the FS's was 20 m as required to provide the nonreciprocity of $\phi_{nr} = \pi$ from (1). From $f_a =$ 2.51 MHz, the estimated value for the modal beatlength and index difference were $L_B = 550$ $\mu$m and $\delta n = 2.8 \times 10^{-3}$, respectively. The coupling efficiency was adjusted to be 50 $\pm$ 5% at a wide range of wavelengths from 1530 to 1580 nm. The transmission spectra for both directions were measured by using a broadband Er-doped fiber source and an optical spectrum analyzer. All ends of the fibers were cleaved at an angle to prevent optical back reflection.

The device demonstrated a relatively strong polarization sensitivity due to the polarization dependent $\delta n$ of the TMF used for the experiment. The polarization dependence can be eliminated by using a proper TMF [6]. In the experiment, we used fiber polarizers to selectively use only one linear eigen polarization state of the TMF. An elliptical core fiber is preferred to a circular core fiber because it can maintain the polarization states and the lobe orientation of the $LP_{11}$ mode, which is important to get maximum visibility in a TMF interferometer [7]. However, the particular TMF we used did not provide polarization maintenance, and we had to employ polarization controllers (PC's) to compensate for the change

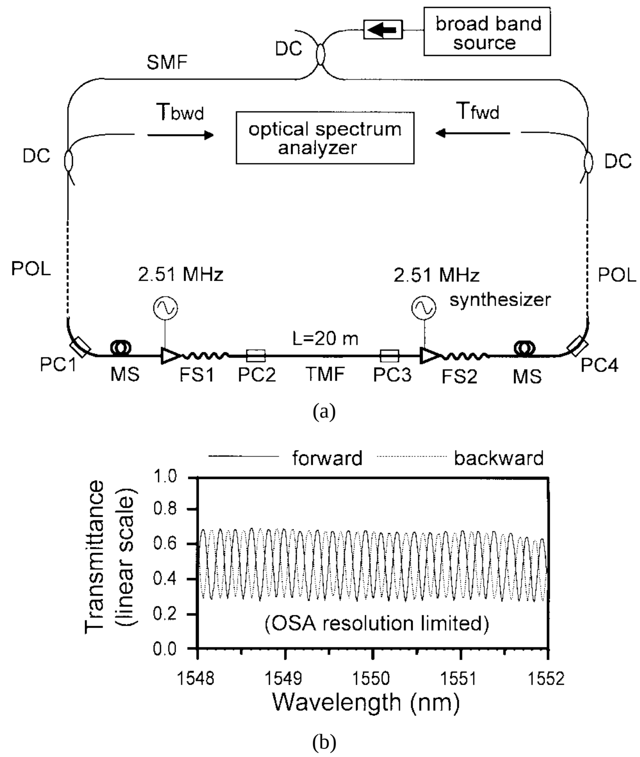


Fig. 2. (a) Experimental setup. DC: directional coupler. SMF: Single-mode fiber. TMF: Two-mode fiber. POL: Polarizing fiber. FS: Frequency shifter. MS: $LP_{11}$ mode stripper. PC: Polarization controller. (b) Measured transmission spectra of the comb filter.

of polarization state in the TMF. PC1 and PC4 were tuned so that the light entering each FS is in the eigen state of the TMF, and then PC2 and PC3 were adjusted to maximize the visibility of the interference signal.

Fig. 2(b) shows the measured transmission spectra for the forward and backward directions, that are indeed nonreciprocal and complementary to each other. For this particular measurement, the absolute values of the maximum and minimum transmissions could not be determined because of the limited resolution (0.1 nm) of the spectrum analyzer. In a separate experiment using a narrowband distributed-feedback (DFB) laser, the background loss of the device was found to be $\sim$1 dB, which was due to the imperfect polarization control, and the extinction was $-24$ dB. The comb spacing was measured to be 0.18 nm. Note that the comb spacing given by (4) is determined by the group index difference which may differ from the phase index difference significantly depending on the operating V-value as well as the refractive index profile of the TMF [8]. For the elliptical core TMF used in the experiment, the modal group index difference can be estimated from (4) using the measured comb spacing resulting in 6.7 $\times$ $10^{-4}$ at 1550 nm, much smaller than the phase index difference $\delta n$ of 2.8 $\times$ $10^{-3}$.

In the following, we further demonstrate methods for controlling the comb spacing and tuning the transmission wavelengths. The comb spacing control was realized by employing mode converters (MC's) in the TMF interferometer, as shown in Fig. 3(a). Two MC's were prepared by squeezing the TMF along the minor axis of the core between a set of corrugated

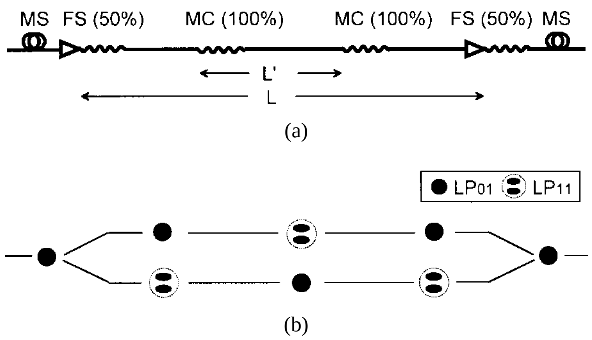


Fig. 3. (a) Schematic of the nonreciprocal comb filter with a variable comb spacing. FS: Frequency shifter. MS: $LP_{11}$ mode stripper. MC: Mode converter. (b) Illustration of the mode transition in the device.

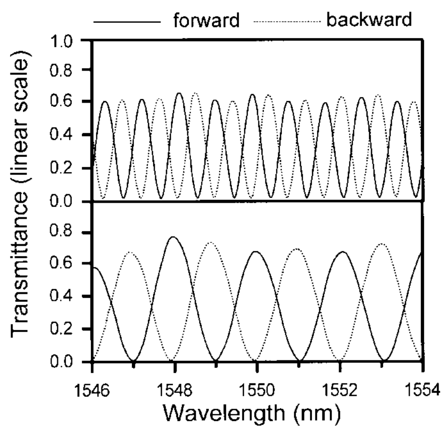


Fig. 4. Forward and backward transmission spectra of the comb filter with comb spacing adjusted to (a) 1 nm and (b) 2 nm.

plates of 2 cm in length [8]. The squeezing pressure was controlled to produce a complete mode exchange between the two modes [Fig. 3(b)]. As a result, the optical pathlength difference of the TMF interferometer was reduced from the original value of $\delta nL$ to $\delta n(L-2L')$ with the MC's where $L'$ is the length between the two MC's. The comb spacing is then given by

$$\Delta\lambda = \frac{\lambda^2}{|L-2L'|} \cdot \frac{1}{\delta n - (d\delta n/d\lambda)\lambda}. \tag{5}$$

Therefore, $\Delta\lambda$ can be adjusted by changing $L'$. When $L' = L/2$, the device would be wavelength independent over a wide spectral range.

Fig. 4(a) and (b) shows the transmission spectra with the comb spacing of 1 and 2 nm, respectively, which were obtained by properly adjusting the positions of the MC's. The transmission is still nonreciprocal and complementary. From the maximum and minimum values of the transmission, the insertion loss and the extinction of the comb filter were measured to be $\sim$2 and $-24$ dB, respectively. The insertion loss was due to the loss in the MC's (0.5 dB each) and the difficulty in the polarization control of the TMF interferometer, that are not fundamental problems.

As mentioned earlier, the acoustic phase difference $\delta_a$ can be controlled to tune the transmission peak wavelengths [3].

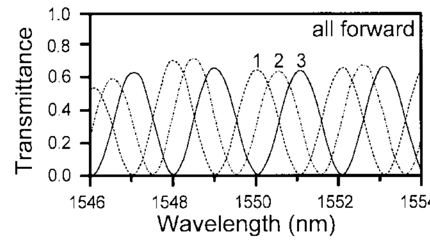


Fig. 5. Tuning of the forward transmission spectra by controlling $\delta_a$. Spectra 1, 2, and 3 correspond to $\delta_a = 0$, $\pi/2$, and $\pi$, respectively.

Fig. 5 shows the forward transmission spectra of the device with 2-nm comb spacing, for three different values of $\delta_a$ of 0, $\pi/2$, and $\pi$. The maximum switching speed of the comb position is about 33 $\mu$s, which is limited by the finite speed of the acoustic wave in the FS. It clearly shows the flexibility of the nonreciprocal device with an electronic control mechanism.

It should be noted that our present device exhibited a relatively large temperature sensitivity due to the lengthy TMF (20 m). An electronic feedback circuit to control the phase $\delta_a$ can be used for the stabilization against the temperature drift [3]. Another way to reduce the temperature sensitivity is to shorten the length of the interferometer by using FS's with higher acoustic frequencies [9], [10].

In conclusion, we have demonstrated an all-fiber nonreciprocal comb filter. The wavelength spacing of the peak transmission could be adjusted between a fraction of a nanometer and a few nanometers by employing two mode converters. The transmission peak wavelengths could be tuned or modulated by a simple electronic means. The insertion loss was 1–2 dB with an extinction ratio of $-24$ dB. Significant improvement in overall performance of the device is expected if a proper two-mode fiber is used. The unique nonreciprocal comb filter may find applications in WDM optical communication and sensor systems such as bidirectional traffic control of WDM channels.

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