

# All-fiber-optic nonreciprocal modulator

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A new all-fiber-optic nonreciprocal device using two acousto-optic frequency shifters is proposed and demonstrated. When the device was operated as an optical isolator, an extinction ratio of 22 dB was obtained. The device's unique modulation capability is also described. © 1997 Optical Society of America

Nonreciprocal optical devices, represented by Faraday rotators based on the magneto-optic effect, have been widely used in various optical systems for nonreciprocal phase, polarization, and transmission properties. Recently, optical isolators,<sup>1,2</sup> circulators,<sup>3,4</sup> and Faraday rotating mirrors<sup>5</sup> have been used extensively in optical communication systems and sensors. Most of the devices use strong magneto-optic material and are pigtailed with single-mode optical fibers. Efforts to develop all-fiber nonreciprocal devices based on the Faraday effect<sup>6-8</sup> have not been very successful because the magneto-optic coefficient of the silica glass is extremely small. In this Letter we propose and demonstrate a new nonreciprocal device in an all-fiber form without the use of the Faraday effect. The nonreciprocity is provided by acousto-optic frequency shifters.<sup>9</sup> The electronic control parameters of the frequency shifters allow the nonreciprocity to be tuned or modulated, which cannot be done with conventional devices.

Figure 1(a) shows the basic idea of the new nonreciprocal device that consists of two frequency shifters separated by a distance  $L$ . The frequency shifter A (B) downshifts (upshifts) the optical frequency by  $f_a$ . Note that the individual frequency shifters are reciprocal by themselves. Light traveling from left to right passes through the section between A and B with its frequency downshifted, while light traveling from right to left passes through it with its frequency upshifted. Therefore this section of fiber operates in a nonreciprocal manner in that the light traveling in opposite directions will accumulate a differential phase shift of

$$\Delta\phi_{nr} = 4\pi f_a n L / c, \quad (1)$$

where  $c$  is the speed of light in vacuum and  $n$  is the refractive index. The dispersion of  $n$  is neglected. It should be noted that the output signals in both directions will have the same frequency as the input. This nonreciprocal phase shifter can be used in many different ways. One example is a Mach-Zehnder interferometer, as shown in Fig. 1(b), that operates as a device with a nonreciprocal transmission. Between ports 1 and 2, the phase difference of the interfering waves is different for the two propagating directions, resulting in different transmittance. If  $L$  is chosen such that light traveling to the left interferes constructively and light traveling to the right interferes destructively, the nonreciprocal interferometer behaves as an isolator.

The device shown in Fig. 1(b) can be readily realized by using a two-mode fiber, mode strippers (MS's), and fiber-optic frequency shifters (FS's), as shown in Fig. 2. The two-mode fiber supports the two lowest-order spatial modes,  $LP_{01}$  and  $LP_{11}$ , and the two modes serve as the two arms of a Mach-Zehnder interferometer.<sup>10</sup> MS's are formed with several turns of fiber loops with small radii, which removes the  $LP_{11}$  mode.<sup>11</sup> The all-fiber frequency shifters<sup>9</sup> use a flexural acoustic wave that produces coupling between the  $LP_{01}$  and the  $LP_{11}$  modes. The coupled optical signal experiences a frequency shift of applied acoustic frequency  $f_a$  [see Fig. 2(b)]. One can tune the coupling coefficient by changing the acoustic energy that is applied to the FS. Therefore a two-mode fiber with 50% coupling efficiency serves the dual role of a frequency shifter and a 50/50 beam splitter for a two-mode fiber interferometer.

Let us first consider the light of frequency  $f_0$  that is shown propagating from left to right in Fig. 2(a). After MS1, only the  $LP_{01}$  mode with a propagation constant  $\beta_{01}$  enters the frequency shifter (FS1) that couples 50% of the light to the  $LP_{11}$  mode. The coupled light has a frequency  $f_0 - f_a$  and a propagation constant  $\beta_{11-}$ . After propagating in a two-mode fiber of length  $L$ , 50% of the light in each mode couples to the other mode by FS2 and produces interference signals. Since the frequency of light coupled from the  $LP_{11}$  to the  $LP_{01}$  mode is upshifted by  $f_a$ , the resulting frequencies are  $f_0$  for the  $LP_{01}$  mode and  $f_0 - f_a$  for the  $LP_{11}$  modes. After the light passes the mode stripper MS2, only the  $LP_{01}$  mode remains; its intensity is determined by the phase difference

$$\Delta\phi_r = (\beta_{11-} - \beta_{01})L + \delta_a. \quad (2)$$

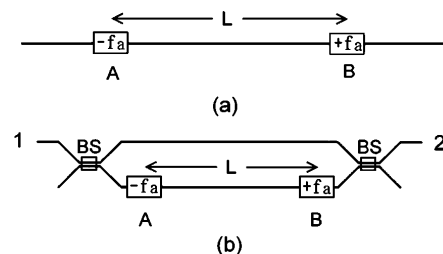


Fig. 1. (a) Nonreciprocal phase shifter and (b) a nonreciprocal interferometer based on a nonreciprocal phase shifter. BS's, 50/50 beam splitters.

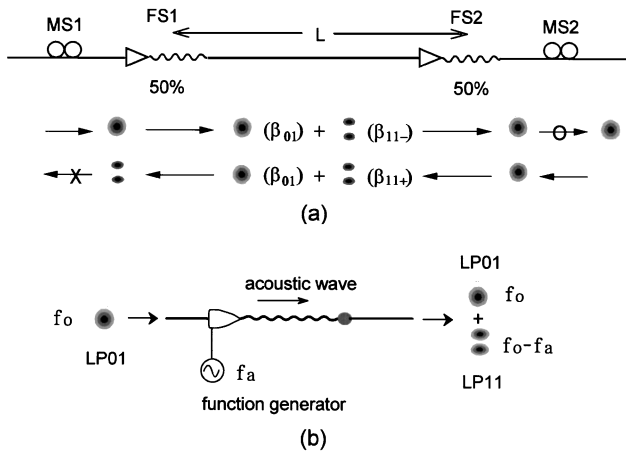


Fig. 2. Schematic diagram of (a) a two-mode nonreciprocal interferometer and (b) an acousto-optic frequency shifter. MS, LP<sub>11</sub> mode stripper; FS, frequency shifter;  $\beta_{01}$ ,  $\beta_{11}$ , propagation constants of the LP<sub>01</sub> and the LP<sub>11</sub> modes.

Here  $\delta_a$  is the relative phase of the sinusoidal acoustic waves in FS1 and FS2, which plays an important role in the tuning of the nonreciprocal device.

For the light traveling from right to left, a similar process takes place, except that the light coupled from the LP<sub>01</sub> mode to the LP<sub>11</sub> mode by FS2 gets upshifted in frequency with a propagation constant  $\beta_{11+}$ . Therefore the phase difference between the interfering waves that remain in the LP<sub>01</sub> mode after the MS1,  $\Delta\phi_l$ , becomes

$$\Delta\phi_l = (\beta_{11+} - \beta_{01})L + \delta_a. \quad (3)$$

From Eqs. (2) and (3), the phase nonreciprocity  $\Delta\phi_{nr}$  becomes

$$\Delta\phi_{nr} = \Delta\phi_l - \Delta\phi_r = (\beta_{11+} - \beta_{11-})L. \quad (4)$$

To operate the device as an optical isolator, one can set, for example,

$$\Delta\phi_r = 2N\pi, \quad \Delta\phi_l = (2N + 1)\pi, \quad (5)$$

and therefore  $\Delta\phi_{nr} = \pi$ . This operation requires that particular values of  $L$  and  $\delta_a$  be used to satisfy the above conditions. In this case, light goes through the device from left to right but cannot be transmitted in the opposite direction. It is important to note that one can easily tune  $\Delta\phi_r$  and  $\Delta\phi_l$  by controlling the relative phase of acoustic waves  $\delta_a$ , although  $\Delta\phi_{nr}$  is determined by the length  $L$  of the two-mode fiber. Unlike conventional optical isolators, this device shown in Fig. 2(a) can control the nonreciprocal transmissions and even switch the direction of transmission. It should be noted that one can operate the device as a pure-phase nonreciprocal device of Fig. 1(a) by simply changing the coupling efficiencies of FS1 and FS2 to 100%. The value of  $\Delta\phi_{nr}$  in Eq. (4) can be expressed in a different form:

$$\begin{aligned} \Delta\phi_{nr} &= (\beta_{11+} - \beta_{11-})L \\ &\cong \left. \frac{\partial\beta_{11}}{\partial f} \right|_{f_0} (2f_a)L = 4\pi \frac{n_{\text{eff}}L}{c} f_a. \end{aligned} \quad (6)$$

Here  $n_{\text{eff}}$  is the effective group refractive index for the LP<sub>11</sub> mode at  $f_0$ , and Eq. (6) is identical to Eq. (1), as expected.

The experimental setup shown in Fig. 3 was used to demonstrate the nonreciprocal device. A polarization-maintaining fiber with bow-tie stress members was used, and its LP<sub>11</sub> mode cutoff wavelength was 1.17  $\mu\text{m}$ . The fiber supported more than two spatial modes at the experimental wavelength of 633 nm, but only the two lowest-order modes were used. Both ends of the fiber were spliced to single-mode fibers, and two polarization controllers were placed in the single-mode fiber sections to control the input polarization states. Light from the He-Ne laser ( $\lambda = 633 \text{ nm}$ ) was divided into two beams by a beam splitter and launched into the opposite ends of the fiber device. The outputs were detected by two photodetectors. To demonstrate the device as an optical isolator, we used an 11-m-long fiber between FS1 and FS2 for  $f_a = 4.31 \text{ MHz}$  to satisfy the condition of  $\Delta\phi_{nr} = \pi$ . Under the conditions of Eqs. (5), an optical isolation of 22 dB and an insertion loss of 2.0 dB were obtained. The loss was mainly from the splice points between the single-mode and the two-mode fibers and also from the lossy MS's. The isolation was determined by the limited extinction ratio of the imperfect MS's, which could be improved further by using a fiber with proper design parameters.

Even in a laboratory, we found that the requirements in Eqs. (5) that were needed to operate the device as an isolator could not be maintained to a desired accuracy because of environmental perturbations. We solved this problem of instability by controlling the phase of the acoustic wave  $\delta_a$  in Eqs. (2) and (3) so that  $\Delta\phi_r$  and  $\Delta\phi_l$  always satisfy Eqs. (5). In the experiment the phase of the electric signal applied to the FS1 was controlled by an electronic feedback circuit. We switched the phase of the electric signal between the two values of  $\delta_a \pm 5^\circ$  at the frequency of 9 Hz, and the corresponding optical power outputs  $I_{\pm}$  at detector 2 were measured. When  $\Delta\phi_l = (2N + 1)\pi$ , the output power is minimum, since it is proportional to  $(1 + \cos \Delta\phi_l)$ , and  $I_+ = I_-$  is satisfied. An electronic feedback circuit controlled the value of  $\delta_a$  to maintain the condition  $I_+ = I_-$ .

Once we have the ability to control the relative phase of the acoustic waves, and therefore  $\Delta\phi_r$  and  $\Delta\phi_l$ , we can introduce a variety of modulation to the nonreciprocal transmission properties. Note that  $\Delta\phi_{nr}$  is

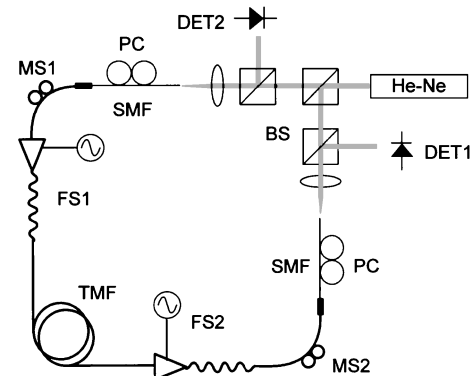


Fig. 3. Experimental setup: SMF's, single-mode fibers; TMF, two-mode fiber; PC, polarization controller; DET1, DET2, detectors.

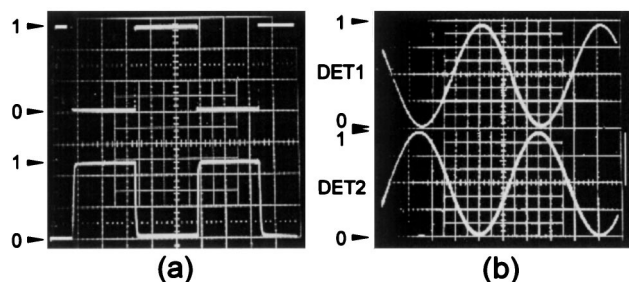


Fig. 4. Nonreciprocal optical transmissions in the opposite directions modulated in (a) square and (b) sine shapes. 0, electrical ground; 1, maximum transmission intensity.

determined by Eq. (4) and cannot easily be modulated. One example is shown in Fig. 4(a), in which  $\delta_a$  is modulated at 40 Hz with a square waveform that has an amplitude of  $\pi$ . The direction of optical transmission is switched with its switching speed of  $\sim 50 \mu\text{s}$ , which is limited by the acoustic-wave velocity in FS. Another example is shown in Fig. 4(b), in which we apply a phase ramp in time  $t$  of  $\delta_a = 2\pi(40)t(\text{rad})$  by making the acoustic frequencies of FS1 and FS2 different by 40 Hz. In this case, the optical transmission in each direction is sinusoidally modulated so that it is out of phase with that in the other direction. The modulation capability of this nonreciprocal device could not be easily obtained by conventional means demonstrated so far. The maximum frequency of square-wave modulation was tens of kilohertz, which was limited by the switching time of the FS. The maximum frequency for the sinusoidal nonreciprocal modulation as shown in Fig. 4(b) can be much higher (hundreds to thousands of kilohertz). The maximum frequency is determined by the maximum difference in the operating acoustic frequencies for FS1 and FS2 for a given optical wavelength. The frequency difference can be made large by using fibers with different parameters for the two FS's.<sup>12</sup>

The device demonstrated here used a highly birefringent fiber for the frequency shifters that resulted in relatively strong polarization dependence.<sup>13</sup> The experiments were carried out only for one eigenpolarization along the fast axis of the birefringent fiber. If the input polarization contains the orthogonal polarization

component, it will not experience mode coupling, and it passes through the device without loss. Although the strong polarization dependence is not desirable for most applications, it may have unique applications. The polarization dependence can be substantially suppressed by using a proper two-mode fiber for the FS's.<sup>14</sup>

In conclusion, we have proposed and demonstrated a new all-fiber nonreciprocal modulator based on acousto-optic frequency shifters. As an example, a device with nonreciprocal intensity transmission with 22-dB isolation is described in detail. This device can be operated for a broad range of wavelengths as long as the fiber guides two spatial modes at the operating wavelengths, while the conventional Faraday devices work for a limited range of wavelengths. The isolation and the loss of the device are determined mainly by the extinction ratio and the loss of the mode strippers, which can be improved further by using a fiber with proper design parameters.

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