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All-optical switch and limiter based on nonlinear polarization in Mach–Zehnder interferometer coupled with a polarization-maintaining fiber-ring resonator

Junqing Li *, Li Li, Lei Jin, Chunfei Li

Department of Physics, Harbin Institute of Technology, 92 Xidazhi Street, Nangang District, Harbin 150001, China

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Abstract

A novel all-optical switch based on nonlinear polarization mechanism using polarization-maintaining fiber ring with a polarization rotator is proposed. Optical switching with low threshold of mW order and optical limiting with broader limiting range, less fluctuation, higher damage threshold and response speed are demonstrated numerically. The deterioration of switching and the improvement of limiting originating from losses are also studied. Considering the tradeoff between switching power and bandwidth, the way to increase bandwidth is discussed.

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1. Introduction

The potential applications of all-optical switches (AOSs) in future optical network attract a great deal of research interest, since AOSs meet the requirements in operation, namely low threshold, high compactness, and fast response. Some kinds of AOSs have been proposed, which are based on nonlinear directional couplers [1] and nonlinear interferometers, such as Mach–Zehnder interferometer (MZI) [2] and Sagnac loop mirror [3]. However, these AOSs usually require higher switching power than Watts at least. Recently, for achieving low power switching, Heebner et al. [4] have proposed an AOS in MZI by introducing a ring resonator (RR) in one arm to enhance nonlinear contribution. The switching threshold is reduced by orders of finesse square due to the enhancement of phase sensitivity to intensity near resonance of RR.

Almost all kinds of AOSs mentioned above are under the assumption of polarization consistency, in other words, the polarization remains unchanged during transmission and interaction of lights in fibers (waveguides). Some researchers even think the change in polarization is not beneficial to construct an AOS. In fact, as a mechanism, the polarization change in fibers (waveguides), such as the change in polarization states or polarization rotation, is quite useful to realize optical switch. It can be of low energy consumption and fast operation, because the physical process does not originate from nonlinear absorption but from nonlinear refraction. Combining some fiber (or waveguide)-based interferometric configurations, one may predict kinds of novel polarization-dependent AOS. Although some parts of the interferometric optical switch may be constructed with traditional bulk polarization components, such as polarization beam splitters and waveplates, such an AOS is not promising in practice because

* Corresponding author. Tel.: +86 45 186414127; fax: +86 45 186221048.
E-mail address: jqli@hit.edu.cn (J. Li).

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of the incompactness in structure, the strong instability caused by environment, the great insertion losses, and so on. Therefore, research on the polarization-dependent AOS in all-fiber (or waveguide) structure is quite significative. Our work is dedicated to this issue. To the best of our knowledge, the AOSs based on nonlinear polarization effects have not been intensively reported yet.

In this paper, we propose a novel AOS in MZI based on nonlinear polarization mechanism, in which the enhancement of nonlinear birefringence and polarization rotation are incorporated. By considering SPM and XPM, optical switching performance is investigated, and the simulation shows the low switching power of mW order. We find that by properly choosing parameters, this configuration can be also used as an optical limiter. The effects of loss on optical switching and limiting are also discussed.

2. The principle of AOS

Fig. 1 shows the configuration of AOS in MZI constructed by two 3 dB polarization maintaining (PM) couplers (C_1 and C_2), two segments of linear PM fibers (PM_1 and PM_2) and a RR coupled to one arm through a 2×2 PM coupler (reflectance coefficient r). The RR consists of a segment of nonlinear PM fiber and a polarization rotator (PR) which rotates the light polarization to a certain angle. For the simplicity of further discussion, the lengths of PM_1 and PM_2 are considered to be balanced and equal to multiples of the beat length, which guarantee the accordance in the polarization of transmitted lights with that of incident into PM_1 and PM_2. The polarized light launched into input port of MZI splits into two parts with same intensity and polarization after the first coupler C_1. One of the two beams transmits through the RR which can enhance the nonlinear birefringence dramatically due to the accumulated phase shift and the amplified intensity near resonance, and then passes through the PM_1 to coupler C_2. The other beam travels along the PM_2 to C_2 directly. At the second coupler C_2, the beams from two arms coherently combine and transmit from output ports 1 and 2, respectively.

A useful method to describe the relation between input and output fields is Jones matrix [5]. The function of PM fiber can be expressed by 2×2 matrices,

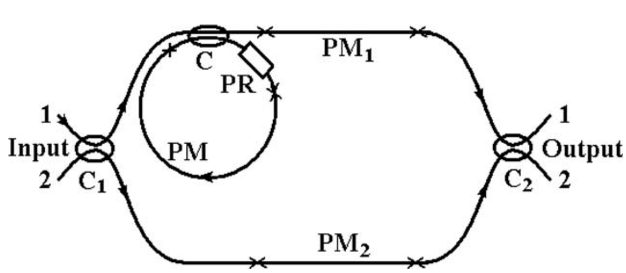

Fig. 1. Configuration of the AOS with a PM fiber ring.

$$[PM] = \begin{bmatrix} e^{-\alpha L/2} & 0 \\ 0 & e^{-\alpha L/2} \end{bmatrix} \begin{bmatrix} \cos(-\phi) & -\sin(-\phi) \\ \sin(-\phi) & \cos(-\phi) \end{bmatrix} \times \begin{bmatrix} e^{-jk\int_0^L \Delta n_x(z)\,dz} & 0 \\ 0 & e^{jk\int_0^L \Delta n_y(z)\,dz} \end{bmatrix} \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}, \tag{1}$$

where α and L are the intensity loss coefficient and the length of PM fiber, respectively. ϕ is the orientation angle of the x-axis (determined by the transmission direction z and the outward direction y orthogonal to paper plane) in respect to the fast optical axis of PM fiber. k is the wavenumber in vacuum. Considering the Kerr nonlinearity of PM fiber, we have

$$\Delta n_x(z) = \frac{\Delta n}{2} - n_2\left(I_x(z) + \frac{2}{3}I_y(z)\right), \tag{2a}$$

$$\Delta n_y(z) = \frac{\Delta n}{2} + n_2\left(I_y(z) + \frac{2}{3}I_x(z)\right), \tag{2b}$$

where Δn represents the birefringence of PM fiber defined as $n_s - n_f$, where n_s and n_f are refractive indices along the slow and fast axis of fiber. n_2 is the nonlinear-index coefficient related to $\chi^{(3)}$. $I_x(z)$ and $I_y(z)$ are the instantaneous intensity along x and y axis of the fiber, which are considered constants in the lossless case. In each of these two expressions, the first intensity-dependent term corresponds to SPM, whereas the second one to XPM. Here the two-photon absorption (TPA) effect, which may result in higher-order intensity-dependent nonlinear refractive index, is ignored for the typical power used in operation since the TPA coefficient in silicon fiber is smaller than 10^{-10} cm/W as measured by Mizunami et al. [6]. A PR and a coupler can be also described by 2×2 matrices,

$$[R] = (1-\eta)\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix},$$
$$[K] = (1-\gamma)\begin{bmatrix} r[I] & j\sqrt{1-r^2}[I] \\ j\sqrt{1-r^2}[I] & r[I] \end{bmatrix}, \tag{3}$$

where η and γ are the insertion loss of PR and coupler, respectively. θ is the rotation angle. $[I]$ is the identity matrix. For a 3 dB coupler, reflectance coefficient r is $\sqrt{2}/2$. The lossless transfer matrix $[T]$ of RR can be calculated as

$$[T] = \frac{1}{M}\begin{pmatrix} 2jr\sin\delta + m_1e^{-j\sigma} + m_2e^{j\sigma} & m_3e^{-j\sigma} + m_4e^{j\sigma} \\ m_4e^{-j\sigma} + m_3e^{j\sigma} & 2jr\sin\delta - m_2e^{-j\sigma} - m_1e^{j\sigma} \end{pmatrix}, \tag{4}$$

where $\sigma = k(\Delta n_x + \Delta n_y)L/2$ and $\delta = k(\Delta n_y - \Delta n_x)L/2$ denote the average phase shift and the phase difference between the x and y components induced by nonlinear birefringence, respectively. The coefficients in the matrix elements above are written as