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Abstract
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Keywords
1550 nm, analytical models, device performance, extinction ratios, Faraday rotations, interferometric switches, magneto-optic switches, multi-mode fibers, Sagnac interferometers

Disciplines
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Comments

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Sagnac interferometric switch utilizing Faraday rotation

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In this paper, a novel fiber-based, magneto-optic switch based on a Sagnac interferometer is presented. Experimental results at 1550 nm are reported and device performance such as extinction ratio for both single-mode and multi-mode fiber is presented. The performance is modeled using an analytical model which includes reflections at magneto-optic interfaces. The paper examines ways to improve the extinction ratio and the performance of the Sagnac configuration.

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INTRODUCTION

As demand for optical data and communication networks grow, there is an increasing need for high speed, high bandwidth, all-optical switching technologies. Magneto-optic based switches have been proposed and studied due to their low insertion loss and possibilities to be integrated into optical systems.1,2 Magneto-optic based switches offer a promising way to create high speed switching in fiber systems. Other fiber, non-magneto-optic switches have also been proposed using Sagnac and Mach-Zehnder interferometers.3–5 In this paper, we propose magneto-optic switching utilizing a Sagnac interferometer. This switch uses a magneto-optic Faraday rotator (MOFR) to create different states of polarization in counterpropagating waves, which result in interference at the output port. A magnetic field is used to control the amount of rotation in the state of polarization (SOP), and therefore, the on-off extinction ratio. The output of interferometers is significantly affected by all of the losses and reflections in the system. Consequently, understanding and controlling various mismatches play a significant role in the device performance. In this paper, the system is studied using an analytical model that includes the reflections at the magnetic-optical interfaces and predicts the phase shift and extinction ratio of the system.

SWITCH CONCEPT

The proposed switch consists of a Sagnac interferometer with a MOFR in the loop as shown in Fig. 1. Port 1 is treated as the input port and port 2 as the output port. In this switch, a 3 dB coupler is used to split the input signal into two counterpropagating waves that travel in opposite directions around the Sagnac loop. These waves are linearly polarized and approximately equal in amplitude. A π/2 phase shift is induced by the coupler in the beam which passes from port 1 to port 4 relative to the beam which passes from port 1 to port 3. In the absence of any difference introduced between the two propagating beams, complete destructive interference will occur at the output port and the input power will be returned to the input port.

In this switch, a bismuth substituted iron garnet Faraday rotator [(Bi1.1Tb1.9)(Fe4.25Ga0.75)O12] (Refs. 6 and 7) is placed in the loop and the bias magnetic field through it is controlled by an external circuit. Due to the nonreciprocal nature of Faraday rotation, the polarization of the light traveling in opposite directions will undergo rotation approximately equal in amplitude but opposite in sign. The degree of rotation determines the amount of interference at the output, and thus, an on and off state can be achieved.

This switch is also capable of fast switching speeds. Traditionally, switching time of magneto-optic switches have been slow (hundreds of microseconds) as compared to electro-optic switching speeds (subnanosecond). However, with the availability of optics-grade orthoferrites, the switching time of this configuration, along with other magneto-optic switches, can be greatly reduced and approach electro-optic switching speeds.6

Basic setup

The behavior of a single mode fiber (SMF) Sagnac interferometer can be modeled well using Jones calculus.9 Assuming polarization independence of the coupler, the output of the 3 dB coupler can be written as

\[
\begin{pmatrix}
E_{3-} \\
E_{4-}
\end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix}
1 & j \\
j & 1
\end{pmatrix} \begin{pmatrix}
E_{1+} \\
E_{2+}
\end{pmatrix},
\]

where \(E_{1+}\) and \(E_{2+}\) are the signals entering ports 1 and 2, respectively, and \(E_{3-}\) and \(E_{4-}\) are the signals exiting ports 3 and 4. In this paper, a wave entering a port will be denoted with “+” and a wave leaving a port will be denoted with “−”.

FIG. 1. (Color online) Sagnac switch with Faraday rotator.
The rotation of the beam traveling from ports 3 to port 4 and passing through a MOFR can be described using Jones calculus as
\[ \begin{align*}
  \begin{bmatrix} E_{3+} \\ E_{4+} \end{bmatrix} &= T e^{-j\phi} \begin{bmatrix} \cos \theta - j \sin \theta \\ j \sin \theta \cos \theta \end{bmatrix} \begin{bmatrix} E_{3-} \\ E_{4-} \end{bmatrix},
\end{align*} \]
where \( T \) is the transmission coefficient, \( \theta \) is the angle of rotation of the SOP, and \( E_x \) and \( E_y \) represent the \( x \) and \( y \) components of an incident beam, respectively. \( \phi \) is the phase change between \( E_{3-} \) at port 3 and \( E_{4+} \) at port 4 described by \( \phi = \beta_l (d - t) \), where \( d \) is the distance from port 3 to port 4, \( t \) is the thickness of the Faraday rotator, and \( \beta_l \) is the phase constant in the fiber. The phase shift incurred from the thickness of the MO is included in \( T \) and will be discussed in the next section. Because the rotation of a MOFR is nonreciprocal, \( \theta \) will not have the same sign for waves traveling through it in opposite directions relative to their reference frames. Equation (2) should be modified appropriately. The power returned to each port is determined by superimposing the exiting waves,
\[ \begin{align*}
  \begin{bmatrix} E_{1-} \\ E_{2-} \end{bmatrix} &= T e^{-j\phi} \begin{bmatrix} (jE_{1x} \cos \theta)\hat{x} + (jE_{1y} \cos \theta)\hat{y} \\ -(E_{1x} \sin \theta)\hat{x} + (E_{1y} \sin \theta)\hat{y} \end{bmatrix},
\end{align*} \]
As expected, when the wave experiences no rotation (\( \theta = 0 \)), the transmitted power is returned to the input port with a \( \pi/2 \) phase shift. If there is a \( 90^\circ \) rotation through the Faraday rotator (\( \theta = 90^\circ \)) then the power is delivered to the output port, port 2.

**Effects of reflections at interfaces**

Since interferometry is based on interference, the operation of a Sagnac interferometer, as well as the proposed Sagnac switch, is greatly affected by reflections at the interfaces. In order to more appropriately model the switch’s behavior, the reflection and transmission characteristics of the MOFR should be considered. Assuming the reflection is polarization independent at the fiber-MO-fiber interface, the reflected portion of the wave at ports 3 and 4 is
\[ \begin{align*}
  \begin{bmatrix} E_{R3+} \\ E_{R4+} \end{bmatrix} &= \frac{1}{\sqrt{2}} \Gamma \begin{bmatrix} E_{1x} e^{-j2\phi_1} \\ jE_{2x} e^{-j2\phi_2} \end{bmatrix},
\end{align*} \]
where \( \Gamma \) is the reflection coefficient and \( \phi_1 \) and \( \phi_2 \) are the relative phases of the reflected wave at ports 3 and 4, respectively, and are described by \( \phi_1 = \beta_l d_1 \) and \( \phi_2 = \beta_l d_2 \), where \( d_1 \) is the distance from port 3 to the MOFR and \( d_2 \) is the distance from port 4 to the MOFR. Including multiple reflections from the fiber-MO-fiber interface, the reflection coefficient can be written as described in Ref. 10 with some slight modifications as
\[ \Gamma = \frac{\Gamma_1 - \Gamma e^{-j2\beta_l}}{1 - \Gamma^2 e^{-j2\beta_l}} = \left( \frac{\eta_2 + \eta_1}{\eta_2 - \eta_1} \right) \left( 1 - e^{-j2\beta_l} \right), \]
where \( \Gamma_1 \) is the reflection coefficient at the fiber-MO interface, \( \eta_1 \) is the intrinsic impedance of the fiber, and \( \eta_2 \) is the intrinsic impedance of the MOFR, and the transmission coefficient as
\[ T = \frac{4 \eta_1 \eta_2 e^{-j2\beta_l}}{(\eta_2 + \eta_1)^2 - (\eta_2 - \eta_1)^2 e^{-j2\beta_l}}, \]
where \( \beta_l \) is the phase constant in the MO. The total output at port 2, including reflections at the interfaces, can be written as
\[ \begin{align*}
  \begin{bmatrix} E_{2x-} \\ E_{2y-} \end{bmatrix} &= T e^{-j\phi} \begin{bmatrix} E_{1x} \sin \theta + \frac{j}{2} \Gamma E_{1x} e^{-j2\phi_1} + \frac{j}{2} \Gamma E_{1x} e^{-j2\phi_2} \\ E_{1y} \sin \theta + \frac{j}{2} \Gamma E_{1y} e^{-j2\phi_2} + \frac{j}{2} \Gamma E_{1y} e^{-j2\phi_1} \end{bmatrix},
\end{align*} \]
The refractive index of the MO at 1550 nm is 2.344 and approximately 1.5 for the fiber. The thickness of Faraday rotator is 330 \( \mu \)m. Figure 2 shows the output \( E_{2x-} \) for different values of \( d_1 \) plus an integer number of effective-wavelength segments (\( L_{eff} \)). The total length of the loop is constant. It can be seen that the on-off extinction ratio is affected by the fiber length. Specifically, when no field is applied through the MOFR in order to achieve an off state, the reflections play a greater role in deteriorating the on-off extinction ratio. Therefore, in order to experimentally improve the extinction ratio, the output at port 2 should be minimized with no field applied. The on-off extinction ratio will be maximized with the MO in this position.

**EXPERIMENT SETUP AND RESULTS**

The experimental setup is shown in Fig. 3. A 1550 nm laser source provides a linearly polarized input to the optical

![FIG. 2. (Color online) Switch output for different values of \( d_1 \), the distance from port 3 to the MOFR, with a fixed loop length; the output would be the same for \( d_1 \) equal to the given numerical value plus an integer number of effective-wavelength segments (\( L_{eff} \)).](Image 334x601 to 538x742)

![FIG. 3. (Color online) Schematic of experimental setup.](Image 316x54 to 556x118)
circuit. An optical isolator is placed after the source in order to prevent reflections back into the laser. In order to measure the power reflected to the input port, an optical circulator is used. A mode stripper is placed in each fiber length to eliminate high order modes. For proof of concept, the magnetic field through the MOFR, controlled by an external circuit, is driven from 0 to 45 Oe at 150 Hz. In order to achieve the 90° rotation required two MOFR samples are used. The output power was detected with a photodetector connected to an oscilloscope.

The experiment was carried out with both SMF and multimode fiber (MMF). In the case of the MMF, only the Sagnac loop was MMF. The output of the photodetector is shown in Fig. 4 for different fields applied to the MOFR.

As expected, when a magnetic field is applied, the power is increased at the output port. For SMF, there is a 15 dB on-off extinction ratio with a 45 Oe field. The rotation $\theta_{FR}$ experienced by the beam is described by $\theta_{FR} = \left( \frac{H_{app}}{H_{sat}} \right) \theta_{sat}$, where $H_{app}$ is the applied field, $H_{sat}$ is the saturation field, and $\theta_{sat}$ is the rotation at the saturation field. Therefore, as the magnetic field increases, the rotation increases and the extinction ratio improves. With MMF, the extinction ratio is 16 dB with an applied field of approximately 50 Oe.

CONCLUSION

A fiber-based magneto-optic Sagnac switch was proposed, implemented, and tested. Switch operation for SMF and MMF was reported with promising performance. An analytical model for switch performance which includes reflection at magneto-optic interfaces was presented. The effect of the magnetic field strength on the extinction ratio was shown. Methods for improving the results were discussed.

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FIG. 4. (Color online) Experimental results: output at port 2 of SMF Sagnac switch for different applied fields.