Magneto-Optic-Based Fiber Switch for Optical Communications

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Magneto-optical switching using Faraday rotation is investigated for optical fiber networks. Nonlinearity of the Faraday rotation was measured, and the optical switch was designed accordingly. The device was implemented experimentally with promising results.

***Index Terms*—All-fiber switch, Faraday effect, magneto-optic switching.**

I. Introduction

ALL OPTICAL switches have generated considerable interest for research as well as industry, and many technologies are currently available [1]. Though the use of magneto-optic (MO) effects for optical switching is well known, it has still not gained wide-spread usage in fiber networks. It was noticed that a very small amount of work had been done in the application of magneto-optics for all optical switching. This was due to a lack of magneto-optic materials with ultrafast response times and high Faraday rotation. Current advancements in bismuth substituted rare earth iron garnets have resulted in materials with ultrahigh bandwidth capabilities and high Faraday rotation. In a recent work on magneto-optical switching by Didosyan *et al.* [2], yttrium orthoferrite was used, and the switch construction was free space in nature. Free-space switches suffer from large insertion loss compared to all-fiber switches, as they need proper beam collimation and alignment of the free-space components. This also affects their compatibility with fiber networks. Consequently we investigate the use of the Faraday effect in an optical on–off switch and propose the design and implementation of an all-fiber switch which can be used as an all optical switch for fiber networks in general. In the all-fiber construction of the switch, light does not exit from the fiber except when propagating through the MO rotator. Also, as the thickness of the Faraday rotator is 330 μm, i.e., about 213 wavelengths long at 1550 nm, the fiber modes are expected to be maintained in the rotator. To our knowledge this is the first reported magneto-optic switch for optical fiber networks. Optical switches based on magneto-optic materials have been reported [3]. However, our switch does not require collimating free-space optical components that have generally been used in previously reported switches.

The performance of magneto-optic devices depends on (and therefore limited by) the properties of the material, i.e., the Faraday rotator (FR) in our case. Rare earth garnets exhibit desirable properties such as high values of magneto-optical figure of merit (MOFM) in the 1000 nm $< \lambda <$ 5500 nm wavelength range, i.e., low absorption of the optical signal and large Faraday rotation. Bismuth substituted iron garnets (BIGs) have advantages that include negligible birefringence, higher MOFM, and adaptability to the use of advanced epitaxial growth techniques [4], with improvement in the temperature dependence and the required bias field [5]. A composition of $(Bi_{1.1}\ Tb_{1.9})(Fe_{4.25}\ Ga_{0.75})O_{12}$ shows good performance in terms of high faraday rotation, low insertion loss, and low temperature dependence. For a wavelength of 1.3 μm, a 330-μm thickness of the material rotated the state of polarization (SOP) by 45°. The samples were grown by liquid phase epitaxy techniques and exhibited low intrinsic losses.

II. Faraday Rotation

The specified Faraday rotation of the samples of BIG is 45° at saturation magnetic field of 350 Oe. Typically Faraday rotation θ for ferrimagnetic materials can be treated as linear with applied field ($H_{\rm app}$) up to its saturation field ($H_{\rm sat}$). In the linear region the Faraday rotation is $\theta = \theta_{\rm sat}$ ($H_{\rm app}/H_{\rm sat}$) where $\theta_{\rm sat}$ is the rotation at saturation. This relationship is true when the diameter of the optical beam incident on the surface of the material is large enough to sample a large number of domains in order to average out the effects of the contributions by individual domains. For smaller beam sizes this relationship does not hold, and individual contributions play an important role in the determination of the Faraday rotation. In the proposed switch, the diameter of the light beam propagating through the FR was about 62.5 μm, comparable to the measured domain size of about 20 μm, as shown in Fig. 1, of the rotator. For measuring Faraday rotation, a polarizer crossed with respect to the linearly polarized input light is placed at the output. The polarizer converts the rotation of the SOP of the incoming light into intensity modulation as

$$P_{\rm out} = P_{\rm in} \cos^2 \alpha \tag{1}$$

where α is the angle between the optical axis of the polarizer and the polarization axis of the incoming signal.

The measured Faraday rotation with applied field can be clearly seen in Fig. 2, which shows that a Faraday rotation of 90° is obtained at a field of about 160 Oe.

In simple terms it can be said that the domains in the direction of the external field begin to expand as the magnetic field is increased, resulting in an increase in Faraday rotation. The downward trend of the Faraday rotation can be explained by the square of the cosine term of the polarizer output. Thus, due to the small size of the beam, a large Faraday rotation could be

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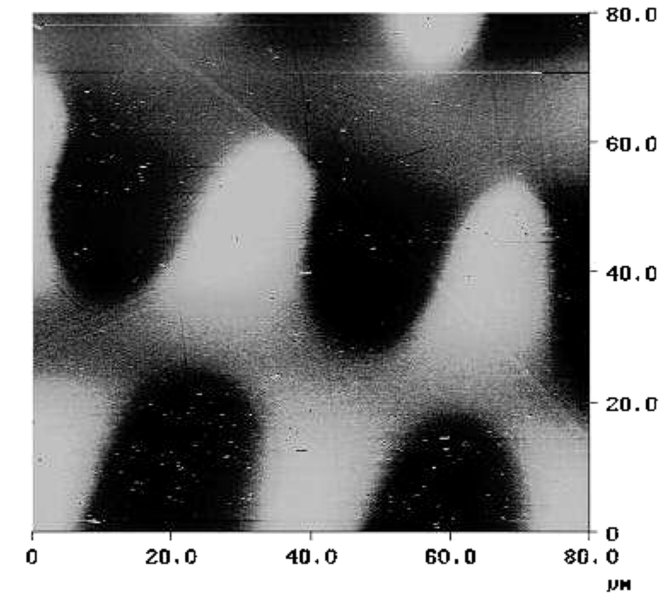

Fig. 1. Magnetic force microscope image of the domains that measure about 20 μm.

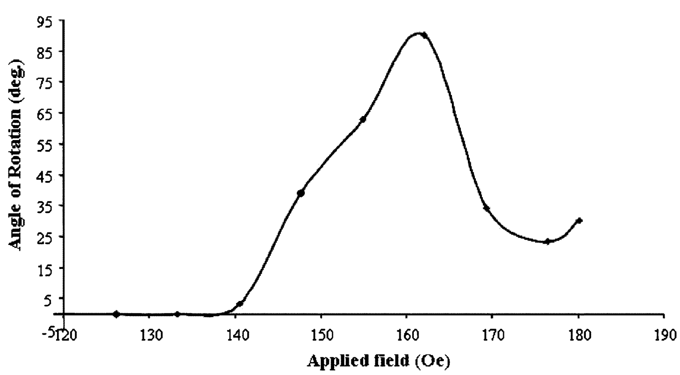

Fig. 2. Measured Faraday rotation for the MO rotator clearly shows nonlinear behavior.

obtained at low fields. However, it is important to note that the positioning of the beam on the surface of the MO sample becomes important in such a case.

III. Switch Performance

Fig. 3 shows the schematic of the proposed all-fiber switch. The switch operation is as follows. A polarization beam splitter (PBS) splits the incoming 1.3-μm optical signal into orthogonal polarizations, which travel two equal length paths. The polarizers in the paths are aligned with the incoming light signals. In order to block the signal from the output port, a 5-A current is supplied by the solenoid driver circuit to produce a field of 160 Oe. This rotates the SOP of the optical signals in the two paths 90° away from the optical axis of the polarizers thus not allowing light to pass to the output. In the light transmission state, no field is applied to the MO rotators, enabling the polarizers to pass the incoming light beams that are then coupled by the polarization beam coupler (PBC) at the output port.

The insertion loss of the switch was measured to be 4.8 dB, and the extinction ratio was measured to be 20 dB. The insertion loss of the device can be lowered by index matching at the

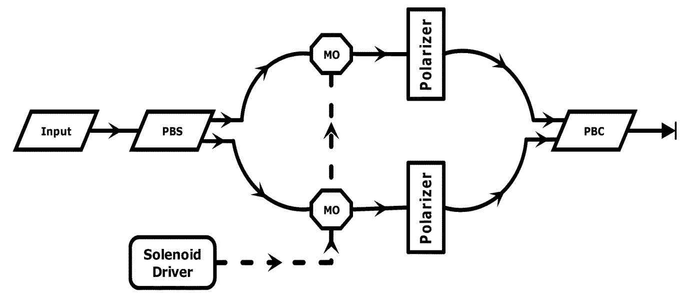

Fig. 3. Schematic of the proposed switch with polarizers in both paths.

interfaces of the fiber and the Faraday rotator. Another factor that contributes to the loss in the system is that the fibers that are coupled with the MO rotators are multimode fibers and the remaining fibers are single mode fibers. The loss is significant when light travels from the MMF to the SMF as the mode field diameter of SMF $(\mathrm{MFD_{SMF}}) < \mathrm{MFD_{MMF}}$. This loss can be reduced by using a tapered fiber section [6].

In our implementation of the magneto-optical switch, obtaining a rotation of more than 90° led to simplification of the switch design, low insertion loss, and reduction in the material cost of the switch, due to the following reasons. The required external magnetic field was low; hence, a simple and fast solenoid for the drive circuit could be constructed with relative ease, and just one MO block can be used for rotating the SOP by 90°. Also the thickness (330 μm) of the FR was much less than that for the orthoferrite FR (1.2 mm) employed in [4], leading to less insertion loss in our case for obvious reasons.

IV. Switching-Time Considerations

The switching time of the device depends on the switching of the magnetic domains in the magnetic material. In an external magnetic field, the magnetic domains in the direction of the field increase in size by two main mechanisms: rotation of individual magnetic moments and motion of domain walls. Due to the finite velocity of domain walls, domain wall motion occurs on a much larger time scale as compared to individual magnetic moment rotation. Consequently the switching time obtained is much larger. Also the displacement of domain walls is not reversible due to surface defects, impurities, lattice defects, and other phenomena which minimize the associated magentostatic energy, thus pinning them to the defect sites. This leads to a fluctuating output power level for different switching cycles, i.e., the extinction ratio is not stable. However, if the domain walls are tightly pinned in their respective positions the problems can be solved. Cutting grooves in planes parallel to the domain walls is an example of pinning domain walls at surface defects [4]. Introducing impurities in the material also helps to pin domain walls [7]; however, this method, due to its intrusive nature, may affect the properties of the material, which is not desirable for device performance. Currently efforts are ongoing for pinning the domain walls at all times, by introducing surface defects.

Another important factor determining the switching time is the external circuit that provided the bias magnetic field. There is a time constant associated with the inductance of the current coil which it is safe to say is generally greater than the switching time limit determined by the domain dynamics. How fast the

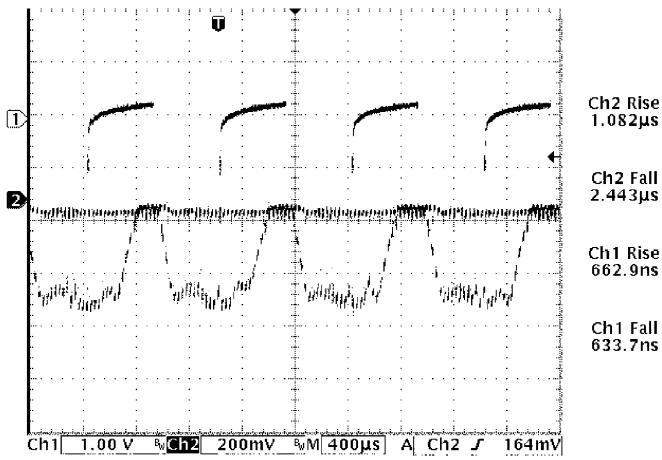

Fig. 4. Measured external applied voltage (channel 1) and the switching of the optical signal (channel 2) waveforms.

current reverses in the current coil determines the switching time. Back emf is proportional to di/dt; therefore, a large voltage capacity is needed for rapid change in the current. This was achieved by connecting four individual H-bridge ICs capable of controlling DC currents up to 5 A that can be pulse width modulated up to 10 kHz. Fig. 4 shows the switching of the optical power at the output with the measured switching time of about 2 μs.

V. Conclusion

An all-fiber magneto-optical switch was proposed and demonstrated with promising performance and compatibility with fiber networks. Enhanced Faraday rotation obtained due to the small beam size of the incident signal decreased the power and material requirement for the switch. The switching time of the device can be potentially much less, on the order of a few nanoseconds, which is desirable for bit-level switching in fiber communications networks. Currently, work on restriction of the domain wall motion and a faster external circuit is ongoing for improvement of the device performance.

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