Low power field generation for magneto-optic fiber-based interferometric switches

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A new fiber-based, magneto-optic switch is proposed with a novel approach for low power and efficient operation. The switch, with reasonable switching speed compared to competitive designs, operates at considerably reduced power levels, which makes it a practical deployable solution. The basic switch setup consists of a Faraday rotator in a Sagnac fiber-optic interferometer in which optical switching is controlled by an electronic driving circuit. The electronic system generates a magnetic field through the Faraday rotator by driving current through a specially designed two-coil system. The new coil system allows for sufficient field generation at low quiescent power levels while maintaining very short optical rise and fall times. The design and considerations as well as the effect of mutual inductance between the two coils and its influence on switching times are investigated. The optical system consists of a Sagnac interferometer with a Faraday rotator within the Sagnac loop. Appropriate phase shift for interference is achieved by the proposed field generating system designed for the magneto-optical element. The theory of operation, design, experimental results, and optical and electronic setup are presented and analyzed. © 2012 American Institute of Physics. [doi:10.1063/1.3679391]

INTRODUCTION

Optical networks are the predominant high speed and long-distance data communications technology.1 Advantages in bandwidth and speed, in addition to the ability to produce high-quality optical devices at a low cost,2 make these technologies more favorable over alternatives. Bottlenecks in optical networks such as the optical-electrical (OE) and electrical-optical (EO) conversions limit the system’s capabilities. At these points, bandwidth becomes limited to the electrical system, and loss and delays can occur. Small, all-optical solutions are needed with low power operation at a low cost. Technologies have been suggested and used in previous works with reasonable power operation.3 Magneto-optic (MO) switching technologies have shown promise in the realization of all-optical routing devices that reduce the effect of these bottlenecks enabling fast, dynamic route setting with low power operation4–6 and the potential for integration.7 In this paper, we introduce a new method for designing the field generation system used to magnetize the MO material with low power operation and improved scalability.

EXPERIMENTAL SETUP

The experimental setup includes the optical system and the field generation system (Fig. 1). The MO material used is a bismuth-doped iron garnet (BIG) [(Bi1.1Tb1.9)(Fe4.25Ga0.75)O12] (Ref. 8) and is placed in the Sagnac loop, ideally such that the optical paths on either side of the material are equidistant.

The high speed field generation system controls and enables the magnetized state of the MO material and is placed appropriately. This is the driving force that constitutes the switching capability of the system. The proposed circuit is composed of two separate circuits that drive current through coil1 and coil2 of the two-coil system, which is shown in Fig. 2. The circuit that drives the current through coil1 provides a very rapid, high current pulse to quickly magnetize the MO material. The mutual inductance does not affect the total field in the MO material, but it does affect how the input signals are shaped to achieve the total field. For example, Vp1 and Vp2 have identical voltage profiles, but the voltage seen at the gate of MOSFET M1 decreases rapidly as a result of the charging series capacitor. The purpose of this is to control the initial magnetization of the material while minimizing total current drawn. Coi1 should energize for only a brief moment to quickly magnetize the MO material. The circuit driving the current through coil2 provides a longer pulse of less amperage to sustain the material’s magnetization. The distinction between both control circuits is advantageous.

FIG. 1. Fiber-based Sagnac interferometer.
because effects of mutual inductance can be compensated by adjusting the input voltage profiles. Bypass capacitors, current sense resistors, protection diodes, and other passives were placed appropriately.

**PROPOSED SYSTEM**

To achieve all-optical switching, fiber-based interferometers have been shown to be reasonable and practical solutions. While different interferometer topologies could be used, the fiber-based Sagnac has been proposed and successfully demonstrated for this application. This design is also advantageous because the number of components required to achieve optical switching is minimal, allowing for greater scalability and deployment. Switching occurs by magnetizing the MO material using the suitably designed coils and field generation system, achieving appropriate rotation of polarization for interference.

Traditionally, the MO material is placed at the center of a coil and is magnetized by passing current through this coil. To have fast switching capabilities, a coil of few turns is needed to minimize inductance. Although, this means that high current is required to generate a strong enough magnetization field. In this work, a novel two-coil system is proposed that reduces the amount of current required for the magnetization field while still maintaining short optical rise times.

The two coil system consists of coil1 with N1 turns and coil2 with N2 turns where N2 ≫ N1, as shown in Fig. 3. Coil1 is wrapped around coil2 coaxially and centered about its length. In this design, coil1 has a low inductance that allows for fast initial magnetization of the MO material. Coil2 uses much less current to maintain the same field strength for longer periods of time. Using both coils, optical signal routing is achieved with lower power dissipation than competitive designs.

**RESULTS**

Given a turns ratio of 7:1 with 28 gauge wire for the two-coil system, a current of 1 A through coil2 of 21 turns and length 6.5 mm, and a maximum current of 4 A through coil1 of 3 turns and length 1 mm, a total field of approximately 191 G through the MO material can be generated. This was calculated using the following equation:

\[
B = \frac{\mu_0 N_1 I_1}{L_1} + \frac{\mu_0 N_2 I_2}{L_2},
\]

where \( N \) is the number of turns, \( I \) is the current through each coil, and \( L \) is the length of each coil. An optical rise time of 267 ns was achieved with both coils energized, which is competitive with contemporary switches. The total current required for this was significantly reduced in comparison to single coil configurations.

In the results shown in Fig. 4, the optical signal sustains after the electrical pulses have turned off. This elongated fall time is a function of the MO material’s position between fiber ends in addition to the ringing seen in coil2. Also, given the current through coil1, if the current through coil2, I2, is increased too high, a secondary peak in the optical output begins to emerge near 2.5 \( \mu \)s. This peak becomes more prominent the higher I2 is increased. The peak occurs due to coupling on coil1 when coil1 turns off if I2 is high enough. Therefore a practical I2 was chosen such that the optical
response did not overly deteriorate and yet sufficient magnetization of the MO material could be achieved.

The measured coupling coefficient of the system was found to be approximately 0.8 for a turns ratio of 7:1. The turns ratio was chosen based on optimization of optical rise time (due to large inductance) and size requirements given a specific wire gauge. In Fig. 5, the effect of mutual inductance is shown. Here the voltage across coil 2 is measured while coil 1 is energized, and also the voltage across coil 1 is measured while coil 2 is energized. From these figures it can be seen that coupling is most prominent in the former case. The coupling coefficient is found by dividing the peak coupled voltage by the source voltage, resulting in a coefficient of approximately 0.8 in this case. In addition, the ringing in coil 2 is a result of an RLC circuit consisting of the transistor capacitance, the inductance of the coil, and parasitic resistance. This ringing may be dampened by replacing D5 in the schematic with a resistor of value $V/I_2$ where $V$ is approximately 40 V and $I_2$ is the current through coil 2.

CONCLUSION

A device that implements a new method of fiber-based magneto-optic switching has been realized that operates at powers lower than previous work. The two-coil system can provide sufficient magnetization for Faraday rotators made of bismuth-doped iron garnet for optimal switching speeds. This proposed switching concept introduces new ideas and challenges that can be utilized for novel classes of deployable fiber-based magneto-optical switches.

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