Magneto-optic fiber Sagnac modulator based on magnetic fluids

Peng Zu,[1] Chi Chiu Chan,[1,*] Lew Wen Siang,[2] Yongxing Jin,[3] Yifan Zhang,[1] Liew Hwi Fen,[2] Lihan Chen,[1] and Xinyong Dong[3]

[1]*School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore, 637459*

[2]*School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore, 637371*

[3]*Institute of Optoelectronic Technology, China Jiliang University, Hangzhou, China 310018*

**Corresponding author: eccchan@ntu.edu.sg*

Received January 21, 2011; revised March 13, 2011; accepted March 14, 2011; posted March 17, 2011 (Doc. ID 141384); published April 13, 2011

A magneto-optic modulator with a magnetic fluid film inserted into an optical fiber Sagnac interferometer is proposed. The magnetic fluid exhibits variable birefringence and Faraday effect under external magnetic field that will lead to a phase difference and polarization state rotation in the Sagnac interferometer. As a result, the intensity of the output light is modulated under the external magnetic field. Moreover, the modulator has a high extinction ratio and can easily be integrated in a single-mode fiber system. The performance of the modulator is not affected by ambient temperature variation from room temperature to 40 °C.

OCIS codes: 060.2340, 060.2630, 230.3810, 230.4110.

The optical fiber modulator is a crucial device in optical fiber communication systems. Electro-optic (EOM) and acousto-optic modulators (AOM) are the most commonly used modulators in optical fiber communication and sensing systems. Recently, magneto-optic modulators employing magnetic fluid (MF) have also been intensively investigated.

MF is a highly stable colloidal suspension of single-domain ferromagnetic nanoparticles in a suitable carrier liquid. It has attracted a great deal of interest from researchers due to its remarkable and versatile magneto-optic properties such as tunable refractive index [1,2], birefringence [3,4], Faraday effect [5], magnetochromatics [6,7], and field-dependent transmission [5,8,9]. Additionally, it is a superparamagnetic function material that exhibits no hysteresis effect in photonics devices and sensing applications. Many MF-based photonics devices for characterization of magnetic modulation, especially optical fiber devices, have been developed. H. E. Hrong demonstrated a magneto-optic modulator by employing MF as a cladding layer with tunable refractive index [2,10]. The extinction ratio achieved was 4%, which is quite small. The multimode fiber (MMF) employed limited the applications in single-mode fiber (SMF) systems. Configuration of a free-space Mach–Zehnder interferometer (MZI), which made use of the tunable refractive index property of MF films, was proposed to realize modulation and improve the extinction ratio slightly [11]. Optical fiber-based MZI and cascaded modulators utilizing MF were also demonstrated to realize optical logical operations with a further improved extinction ratio of 20% [12]. Additionally, a magneto-optic modulator, which acted as an optical switch, was implemented by means of the field-dependent transmission property of MFs [13].

In this Letter, a novel magneto-optic modulator based on an optical fiber Sagnac interferometer (OFSI) is proposed. In contrast to others in the literature, the proposed modulator relies on the magnetically controlled birefringence property of the MF. One of the distinguishing features is the high extinction ratio. The detailed principle, experimental demonstration, and performance are presented as follows.

The structure of the optical fiber modulator based on MF film is shown schematically in Fig. 1. The two counterpropagating beams, which are split by a 3 dB SMF coupler, pass through a section of polarization maintain fiber (PMF) as well as the MF film, recombine, and interfere at the coupler.

Ignoring the loss in OFSI, the transmission spectrum can be given approximately as a periodic function of wavelength [14]:

$$T = [\sin(BL/\lambda)\cos(\theta_1 + \theta_2)]^2. \tag{1}$$

The combination of the PMF with the MF film is considered as a whole polarization component for simplifying the analysis, which is similar to an optical wave plate. θ_1 and θ_2 are the angles between the beam and the equivalent fast axis or slow axis of the polarization component. B is the birefringence in the Sagnac loop, L is the length of birefringent material, and λ is the operating wavelength. In the absence of birefringence in the Sagnac loop, all of the input light, at all wavelengths, will reflect back to the input port and none will appear at the output port for a perfect 3 dB coupler. The introduction of birefringence will lead to a wavelength-dependent output. $BL = B_0L_0 + B_mL_m$, where B_0 and L_0 are the birefringence and length of the PMF, while B_m and L_m are the birefringence and the thickness of the MF film, respectively. The wavelength difference between the adjacent minima is given by [14]:

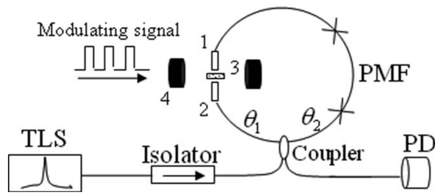

Fig. 1. Scheme of optical fiber modulator based on OFSI. (1), (2) collimator; (3) magnetic fluid film; (4) electromagnet.

0146-9592/11/081425-03$15.00/0

$$S = \lambda^2/BL. \tag{2}$$

Equation (2) shows that S is inversely proportional to BL. Since the thickness of the MF film is so small that MF film alone cannot generate the appropriate range of S, thus, the section of PMF is needed for introducing the initial adequate constant birefringence for offset purpose. The MF film then introduces additional relatively small birefringence variation for spectrum shift under the external magnetic field. In addition, the MF film causes the polarization state rotation due to Faraday effect which affects the amplitude of the interference spectrum. Hence, the intensity modulation can be monitored by measuring the transmission power of a single wavelength light.

A water-based MF (EMG605, Ferrotec) that contained ferrite nanoparticles, Fe_3O_4, with a nominal particle diameter of 10 nm and particle concentration of 3.9%, was injected in a 22 mm × 22 mm glass cell with a thickness of 50 μm and sealed with UV glue to form a MF film. Under an external magnetic field, the MF film exhibited the properties of magnetically controlled birefringence and Faraday effect [3,5]. The MF film was placed between a pair of optical fiber collimators with its plane normal to the light direction and parallel to the magnetic field direction (Fig. 1). The magnetic field was supplied by an electromagnet (EM4-HVA, LakeShore) and measured with a gaussmeter (model 425, LakeShore). The section of a 50 cm length PMF with birefringence of 3.3×10^{-4} (PMF, PM-1550-HP, Thorlabs) was used in the OFSI. The coupler, isolator, and collimators were all operated at 1550 nm. First, a C + L band amplified spontaneous emission (ASE, 1520–1610 nm) light source and optical spectrum analyzer (OSA, AQ6370) were employed to measure the sinusoidal interference transmission spectra under variable external magnetic fields at 23.7 °C (Fig. 2). The curve labeled as 0 Oe is the transmission spectrum under zero magnetic field, whose period is 11.2 nm. With the magnetic field strength increasing from 0 Oe to 2000 Oe, the transmission dip around 1550 nm, which was taken as an example, shifted to the longer wavelength side from 1551.7 nm to 1553.3 nm, and the fringe contrast (visibility) decreased from 34 dB to 14 dB. The spectrum shifted quickly when the magnetic field strength was smaller than 180 Oe. With the magnetic field strength increasing further, the spectrum shift tended to be saturate gradually. This means that a small magnetic field strength is sufficient for modulation, for example, 50 Oe, which makes high-speed modulation feasible.

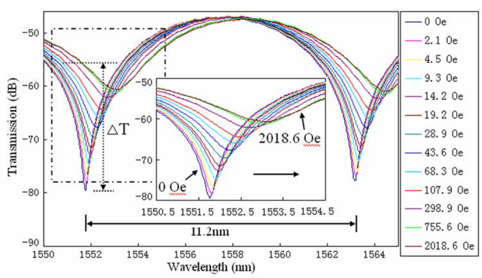

Fig. 2. (Color online) Measured transmission spectra of the magneto-optic modulator under different magnetic field strengths.

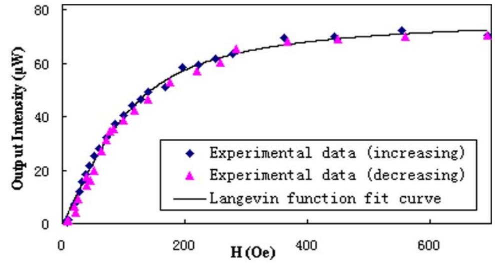

Fig. 3. (Color online) Output intensity of the modulator versus the external magnetic field.

A tunable laser source (TLS, AQ8203) and a photodiode (HRPD-2841A) were then employed to realize an intensity modulator. The extinction ratio is dependent on the transmission intensity variation with magnetic field at a certain wavelength of the TLS. In order to obtain the best extinction ratio, which is denoted by ΔT as shown in Fig. 2, the wavelength of the TLS was set to be equal to the transmission dip wavelength under zero magnetic field, 1551.7 nm. The input intensity was 10 mW. The output intensity changed with the rapid variation of external magnetic field, which also tended to be saturated at larger magnetic field strength (Fig. 3). The intensity was measured while the magnetic field strength was rapidly increased and decreased. The results show good repeatability, which indicates that, as is well known, there is no hysteresis effect in MF. Langevin function was used to fit the data with a high R^2 value of 0.995 [15].

To demonstrate the feasibility of this magneto-optic modulator, square-wave and sinusoidal-wave modulations of the magnetic field strength were applied on the MF film and the corresponding optical outputs were recorded, and are shown in Fig. 4. The amplitudes of magnetic field strength for the square-wave and sinusoidal-wave modulations were set at 180 Oe and 100 Oe, respectively, while the corresponding extinction ratios were 19.5 dB and 18.3 dB, respectively. These ratios can be further improved to about 25 dB by applying a stronger magnetic field, according to the results in Fig. 2, at the cost of reducing the modulation frequency. The frequency response of the proposed modulator is dominated by the response time of the ferromagnetic nanoparticles in MF, which depends on the concentration of the MF and external magnetic field strength. The response times measured in several previous

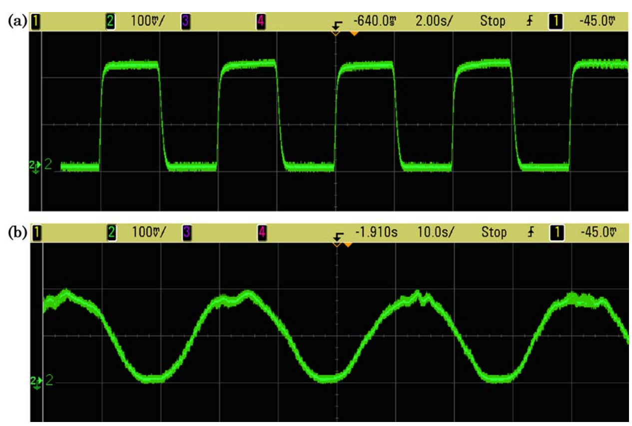

Fig. 4. (Color online) Results of light intensity modulation by (a) square wave and (b) sinusoidal wave.

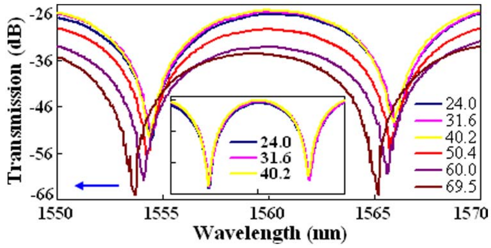

Fig. 5. (Color online) Measured transmission spectra under different temperatures. Inset: Transmission spectra remain unchanged from 24 °C to 40 °C.

investigations had values ranging from 10–30 ms [2,4,12], so the highest modulation frequency was around 100 Hz. The proposed modulator may not work in high-modulation frequency applications in optical communication systems, but it is good enough for applications such as switches, routers, and displays [2].

The temperature-dependence experiment was performed from room temperature (24 °C) to 70 °C under zero magnetic field and the transmission spectra are recorded in Fig. 5. From room temperature to 40 °C, the transmission spectrum remained almost unchanged (inset in Fig. 5). When the temperature was increased to 70 °C, the transmission spectrum shifted to the shorter wavelength side and the level decreased by 10 dB, but the fringe contrast (visibility) remained at 30 dB without any decrease. The decrease in the level is due to the temperature-dependent transmission property of the MF [16], which affects the absolute output intensity but does not affect the extinction ratio of the modulator. Therefore, the performance of the modulator will not be affected by temperature variation from room temperature to 40 °C. At a higher temperature (e.g., 70 °C), the modulator can also work in a small ambient temperature variation range.

The configuration of the magneto-optical modulator is based on OFSI, which has significant advantages over other optical fiber interferometers such as MZI. Because the two beams for interference counterpropagate in the completely same path and experience the same loss, the OFSI does not require complicated matching of the fiber length or equalization of the optical intensity, as in a MZI. The proposed modulator is easily integrated into the fiber communication system because all of the fibers used are SMF, which has potential to be manufactured as an integrated component similar to commercially available fiber isolators.

In conclusion, the magneto-optical modulator based on a SMF Sagnac interferometer is feasible, in which MF acting as a magnetic field sensitive material offers magnetically controlled birefringence and Faraday rotation. The experimental data on the transmission intensity of the modulator were well fit by Langevin function and showed good repeatability. Magnetic fields, which were modulated as square and sinusoidal forms, were applied on the modulator with high extinction ratios of 19.5 dB and 18.3 dB, respectively, that can be further improved by increasing the strength of the magnetic field at the cost of reducing the modulation frequency. The performance of the modulator is not affected by the ambient temperature variation from room temperature to 40 °C. Finally, the proposed setup is very simple, and the modulator has the potential to be developed into an integrated optical fiber device.

References

1. H. E. Horng, C. Y. Hong, S. Y. Yang, and H. C. Yang, Appl. Phys. Lett. **82**, 2434 (2003).
2. H. E. Horng, J. J. Chieh, Y. H. Chao, S. Y. Yang, C. Y. Hong, and H. C. Yang, Opt. Lett. **30**, 543 (2005).
3. Z. Y. Di, X. F. Chen, S. L. Pu, X. Hu, and Y. X. Xia, Appl. Phys. Lett. **89**, 211106 (2006).
4. P. C. Scholten, IEEE Trans. Magn. **16**, 221 (1980).
5. L. Martinez, F. Cecelja, and R. Rakowski, Sens. Actuators. A Phys. **123**, 438 (2005).
6. H. Horng, C. Hong, W. Yeung, and H. Yang, Appl. Opt. **37**, 2674 (1998).
7. H. Horng, S. Yang, S. Lee, C. Hong, and H. Yang, Appl. Phys. Lett. **79**, 350 (2001).
8. H. Horng, C. Chen, K. Fang, S. Yang, J. Chieh, C. Hong, and H. Yang, Appl. Phys. Lett. **85**, 5592 (2004).
9. H. Horng, S. Yang, W. Tse, H. Yang, W. Luo, and C. Hong, J. Magn. Magn. Mater. **252**, 104 (2002).
10. J. J. Chieh, S. Y. Yang, H. E. Horng, C. Y. Hong, and H. C. Yang, Appl. Phys. Lett. **90**, 133505 (2007).
11. C. Y. Hong, S. Y. Yang, K. L. Fang, H. E. Horng, and H. C. Yang, J. Magn. Magn. Mater. **297**, 71 (2006).
12. J. Chieh, C. Hong, S. Yang, H. Horng, and H. Yang, J. Nanopart. Res. **12**, 293 (2009).
13. H. E. Horng, C. S. Chen, K. L. Fang, S. Y. Yang, J. J. Chieh, C. Y. Hong, and H. C. Yang, Appl. Phys. Lett. **85**, 5592 (2004).
14. O. Fraza˜o, J. Baptista, and J. Santos, Sensors **7**, 2970 (2007).
15. R. Rosenweig and R. Rosensweig, *Ferrohydrodynamics* (Dover, 1998).
16. N. A. Yusuf, H. Abusafia, I. Abualjarayesh, and S. Mahmood, J. Magn. Magn. Mater. **85**, 85 (1990).