Volume 1, No.1, March – April 2012
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at www.warse.ijatcse.current

Recent Advances of Wide Band Magneto-Optical Modulators In Advanced High Speed Optical Communication Systems

Ahmed Nabih Zaki Rashed
Electronics and Electrical Communications Engineering Department
Faculty of Electronic Engineering, Menouf 32951, Menoufia University, EGYPT
ahmed_733@yahoo.com

ABSTRACT

The technology involves a new type of compact device based on magneto-optics in a fiber micro modulator. This type of modulator allows the user to inter manipulate and control the propagation of the incoming light. The operation mechanism uses external magnetic field to manipulate Fe micro particle in order to cause modulation of an optical signal that propagates along an optical waveguide. This paper has presented Yttrium Iron Garnet (YIG) and lithium niobate ($LiNbO_3$) which are examined for use as a wideband magneto-optic modulator. A wideband YIG modulator has recently been developed which represents a great improvement over other magneto -optic modulators.

Keywords: Magneto-optic Modulation**,** Faraday Rotation Effect, $LiNbO_3$, YIG, Ultra Fast Magnetic Field.

1. INTRODUCTION

Over the last several years, the demand for high bandwidth networking has dramatically increased, encouraging the continued development of high-speed electrical and optical devices. In particular, the realization of high bandwidth, low power, efficient modulators plays a fundamental role in the improvement of integrated optical systems and networks. Contemporary optical modulation devices rely primarily on Electro-Optic (EO) interaction in nonlinear materials. By exploiting the Pockels effect, the electric field associated with a high-speed electrical signal is employed to modulate an optical beam. However, in recent years, there has been an emergence of a new class of photonic devices based on the magneto-optic (MO) effect [1][2]. These devices utilize the Faraday effect, in which the magnetic field associated with an electrical signal modulates an optical beam. Such magneto-photonic devices offer high bandwidth modulation and switching capabilities comparable to those based on the EO effect. The recent interest in such technology is stimulated by current advances in the growth of a variety of MO materials, namely rare-earth iron garnets [3]. High-quality magnetic garnet films are readily available in a variety of forms and can be grown by epitaxial or sputter methods for particular applications. Such films have a large Faraday rotation, low absorption in the near infrared, and a low saturation magnetization. Furthermore, their optical properties can be easily manipulated by doping, such as the substitution of bismuth in yttrium iron garnets [4]. Research into the application of rare-earth iron garnets has resulted in the development of a variety of unique MO photonic devices, such as resonant/non resonant modulators, polarization sensitive beam deflectors, switches, and isolators. In spite of these benefits, MO device technology is still in its infancy and has not yet been fully explored for integrated high-speed optical technology. Magneto photonic devices to date have relied on the propagation of light waves through the MO material. As the light beam travels through the MO medium, its plane of polarization is rotated according to the Faraday effect [5], resulting in a polarization modulation. However, the transmission arrangement presents difficulties associated with the MO material such as optical absorption of the light beam as it propagates through the interaction region, as well as inherent birefringence. To observe a maximum MO effect, it is desirable to have a MO material with large Faraday rotation, negligible birefringence, and very little absorption. Of the various MO materials available, bismuth-substituted yttrium iron garnet (Bi-YIG) is often chosen for the backbone of a variety of MO devices as it has a very large MO interaction [6].

Optical modulators have become indispensible in many applications or optical instruments. Light interacts with matters in various macroscopic ways. The most commonly known phenomenon include Electro-Optical (EO) effect, Acousto-Optical (AO) effect, and Magneto-Optical (MO) effect. AO modulators and EO modulators have already found many applications, and state-of-the-art modulators are already commercially available. However, AO modulator inherently suffers from slow modulation speed. Although EO modulator is capable of fast modulation [7], it requires a relatively high accuracy on the alignment in free-space applications. MO effect, on the other hand, finds its application only as an optical isolator so far. Although there have been many researches on MO modulators in integrated optics [8], the possibility of a free-space MO modulator has not been widely investigated. The MO modulator can not only work as an intensity modulator when combined with two linear polarizer, but can also work as a polarization rotator alone.

In the present study, magneto-optic materials have unique physical properties that offer the opportunity of constructing devices with many special functions not possible from other photonic devices. The most significant of these properties are that the linear magneto-optic effect can produce circular birefringence and that, unlike other optical effects in dielectric media, it is nonreciprocal. All practical magneto-optic devices exploit one or both of these two properties. Important applications of these devices include polarization control, optical isolation, optical modulation, and magneto-optic recording. The basic principles of magneto-optic modulator effects are considered in this study.

2.MAGNETO-OPTICAL MODULATOR SCHEMATIC VIEW

As the internet and modern communications becomes increasingly prevalent across the globe, all-optic networks. In recent years, for the sake of satisfying high speed transmission and exchange of optical-message through fiber-optic networks, optical switch has been significantly improved as an important element for optical communication by continuous widely research [9].

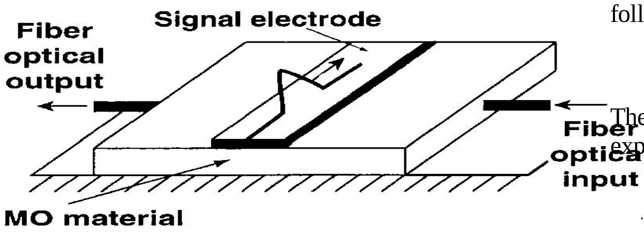

Figure. 1: Basic Construction of MO Modulator under study

As shown in Figure 1, the proposed structure of MO modulator based on a microwave micro strip line with a polarization sensitive MO active medium and fiber optic continuous wave (CW) light delivery. As the requirement from the optical communication technique, it should be characterized as low crosstalk, low insert loss, short switching time and low polarization sensitivity together with special requirement on extinction ratio, switch scale and dimension. As the factors that will affect the optical switch parameters, it consists of the quality of separate units technical index (transmissivity, rotation angle etc.) and also the quality of units final assembly and adjusting1. So far, a variety of optical switches have been developed. In comparison to the various other optical switches, the magneto-optic switch based on Faraday rotation effect for light consists of special optical route including a type of high-quality magneto-optic material YIG crystal, a novel switch of generating pico second-order electrical pulses and Faraday rotator configuration with ultrafast magnetic field. It is featured as low insertion loss, low crosstalk, high switching speed and small bulky size. Using the polarization and Faraday Effect of magneto-optic crystal, the magneto-optic switch can hold the function of all-optical switching, which is needed in all-optical communication networks [10].

3. THEORETICAL MODEL ANALYSIS

When a transparent material is placed in a magnetic field and linearly polarized light is passed through it along the direction of the magnetic field, the emerging light is found to remain linearly polarized, but with a net rotation θ in degree, of the plane of polarization that is proportional to both the thickness d in mm, of the sample and the strength of the magnetic field B in Tesla, along traveling direction, according to the empirical relation [11]:

$$\theta = \frac{180\ B\ V\ d}{\pi}\ ,\ \text{Degree} \qquad (1)$$

Where V is the Verdet constant for the material. The Verdet constant is both temperature and wavelength dependent. The Faraday Effect is similar to optical activity. The difference is that optical activity doesn't require an externally applied magnetic field to rotate the light polarization and it only depends on the traveling length and material concentration. The modulation depth, M_p can be expressed in terms of pulse duration τ in psec, and angle of rotation θ in degree, by using MATLAB curve fitting program as the following formula [12]:

$$M_p = 0.1021 + 0.0765x10^{-5}(\theta\tau) + 0.0032x10^{-8}(\theta\tau)^2 \qquad (2)$$

The transmittance of MO modulator T_m, can be expressed as follows:

$$T_m = \cos^2\left[0.5\left(\pi+\theta\right)\right] \qquad (3)$$

The signal to noise ratio (SNR) of MO modulator can be expressed as the following formula [13]:

$$SNR = 10\log\frac{2\Re P_0\, r\, \theta}{q\, BW_e}\ , \qquad (4)$$

Where r is the reflection coefficient, BW_e is the electrical bandwidth, P_0 is the laser power, q is the electron charge, and $\Re$ is the its modulator responsivity. The bit error rate (BER) essentially specifies the average probability of incorrect bit identification. In general. The higher the received SNR, the lower the BER probability will be. The bit error rate (BER) is related to the signal to noise ratio (SNR) as follows [12] [13]:

$$BER = 0.5\left[1 - erf\left(\frac{\sqrt{SNR}}{2\sqrt{2}}\right)\right]\ , \qquad (5)$$

Moreover the refractive index of the $LiNbO_3$, and YIG are cast under the Sellemier equation as the following [14] [15]:

$$n^2 = B_1 + B_2M + \frac{B_3 + B_4M}{\lambda^2 - (B_5 + B_6M)^2} + \frac{B_7 + B_8M}{\lambda^2 - B_9^2} - B_{10}\lambda^2 \qquad (6)$$

The set of parameters is dimensionally adjusted for $LiNbO_3$ as: B_{1Li}=5.35583, B_{2Li}=4.629x10^{-7}, B_{3Li}=0.100473, B_{4Li}=3.862x10^{-8}, B_{5Li}=0.20692, B_{6Li}=-0.89x10^{-8}, B_{7Li}=100, B_{8Li}=2.657x10^{-5}, B_{9Li}=11.34927, B_{10Li}=0.015334, and M=(T-T_0)(T+570.82). While the set of parameters is dimensionally adjusted for YIG as: B_{1YIG}=0.00987, B_{2YIG}=1.43567x10^{-11}, B_{3YIG}=0.10765x10^{-3}, B_{4YIG}=0.00532x10^{-8}, B_{5YIG}=0.0541, B_{6YIG}=10.4329x10^{-9}, B_{7YIG}=1234, B_{8YIG}=0.05437x10^{-7}, B_{9YIG}=14927, B_{10YIG}=0.00384, and M=(T-T_0)(T+590.54). Thus the previous equation can be simplified as the following formula:

$$n^2 = B_{12} + \frac{B_{34}}{\lambda^2 - B_{56}^2} + \frac{B_{78}}{\lambda^2 - B_9^2} - B_{10}\lambda^2 \qquad (7)$$

Where $B_{12}=B_1+(B_2M)$, $B_{34}=B_3+(B_4M)$; $B_{56}=B_5+(B_6M)$, and $B_{78}=B_7+(B_8M)$. In the general case, if the device operation efficiency, $\eta \neq 1$, the inductance L and internal electrical resistance R_e of MO modulator, we have [16]:

$$L = \frac{\eta\, \lambda^2}{c^2\, L_m\, \mu_0\, n^6} \qquad (8)$$

$$R_e = \frac{\eta\, \Delta\lambda}{c\, L_m\, \mu_0\, n^6} \qquad (9)$$

Where L_m is the modulator length, c is speed of light, μ_0 is the free space permeability, $\Delta\lambda$ is the spectral linewidth of the laser diode, and n is the refractive index of the selected material based MO modulator.

4. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

We have deeply investigated the recent advances of wide band magneto optical modulators in advanced high speed optical communication systems over wide range of the affecting operating parameters as shown in Table 1.

Based on the model equations analysis of MO modulator, assumed set of the operating parameters, and the set of the series of the Figs. (2-12), the following facts are assured:

i) Figs. (2-4) have assured that angle of rotation increases with increasing MO modulator thickness and applied magnetic field intensity for both materials based MO modulator devices. We have indicated that YIG MO modulator has presented higher angle of rotation than $LiNbO_3$ MO modulator at the same operating conditions.

ii) Figs. (5-7) have demonstrated that modulation depth increases with increasing MO modulator thickness and applied magnetic field intensity for both materials based MO modulator devices. As well as we have observed that YIG MO modulator has presented higher modulation depth compared to $LiNbO_3$ MO modulator at the same operating conditions.

iii) As shown in Fig. 8 has indicated that modulator transmittance increases with increasing MO modulator thickness and applied magnetic field intensity for both materials based MO modulator devices. We have indicated that YIG MO modulator has presented higher transmittance than $LiNbO_3$ MO modulator under the same considerations.

iv) Figs. (9, 10) have demonstrated that SNR increases and BER decreases with increasing MO modulator thickness and applied magnetic field intensity for both materials based MO modulator devices. As well as we have observed that YIG MO modulator has presented higher SNR and lower BER compared to $LiNbO_3$ MO modulator at the same operating conditions.

v) As shown in Figs. (11, 12) have assured that modulator inductance and resistance decrease with increasing MO modulator length for both materials based MO modulator devices. As well as we have observed that YIG MO modulator has presented lower resistance and inductance compared to $LiNbO_3$ MO modulator at the same operating conditions.

Table 1: Proposed operating parameters for magneto-optical modulators

Parameter	Definition	Value and unit
$T=T_0$	Ambient temperature=room temperature	300 K
τ	Pulse duration	100 psec
d	Modulator thickness	5 mm —25 mm
B	Magnetic field intensity	0.1 web/mm^2—1 web/mm^2
λ	Operating signal wavelength	1.3 μm
V	Verdet constant for $LiNbO_3$	4.54x10^{-6} rad/A
	Verdet constant for YIG	5.65x10^{-6} rad/A
q	Electron charge	1.6x10^{-19}C
BW_e	Electrical bandwidth	1 MHz
P_0	Laser power	1 mWatt
$\Re$	Modulator responsivity	0.4 A/Watt
r	Reflection coefficient	0.55 at λ=1.3 μm
$\Delta\lambda$	Spectral linewidth of optical source	0.1 nm
c	Speed of light	3x10^8 m/sec
L_m	Modulator length	50 mm —100 mm
μ_0	Free space permeability	4πx10^{-7} H/m
η	Device operation efficiency	0.9

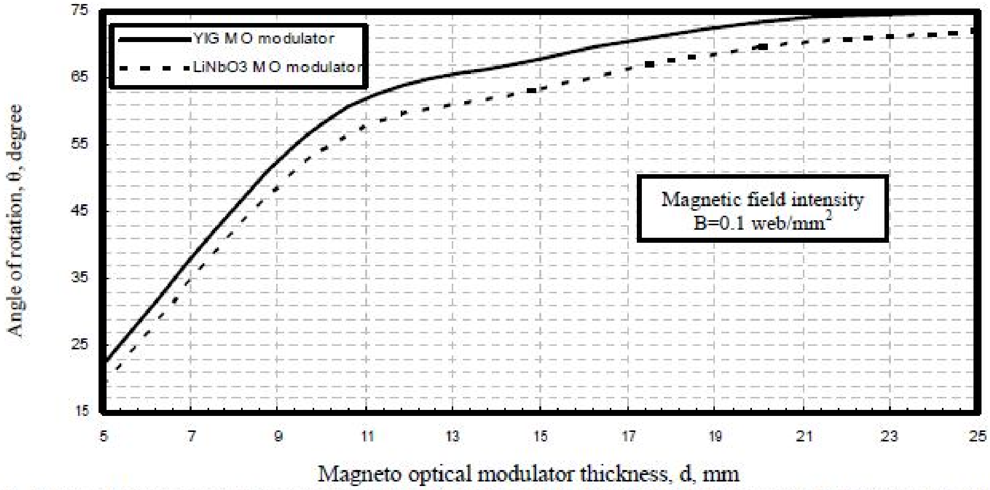

Fig. 2. Angle of rotation in relation to magneto optical modulator thickness and magnetic field intensity at the assumed set of the operating parameters.

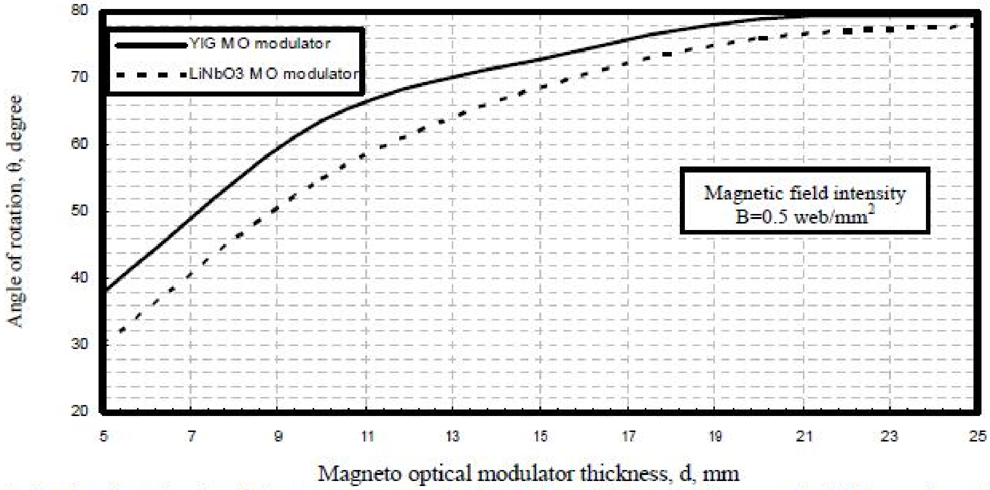

Fig. 3. Angle of rotation in relation to magneto optical modulator thickness and magnetic field intensity at the assumed set of the operating parameters.

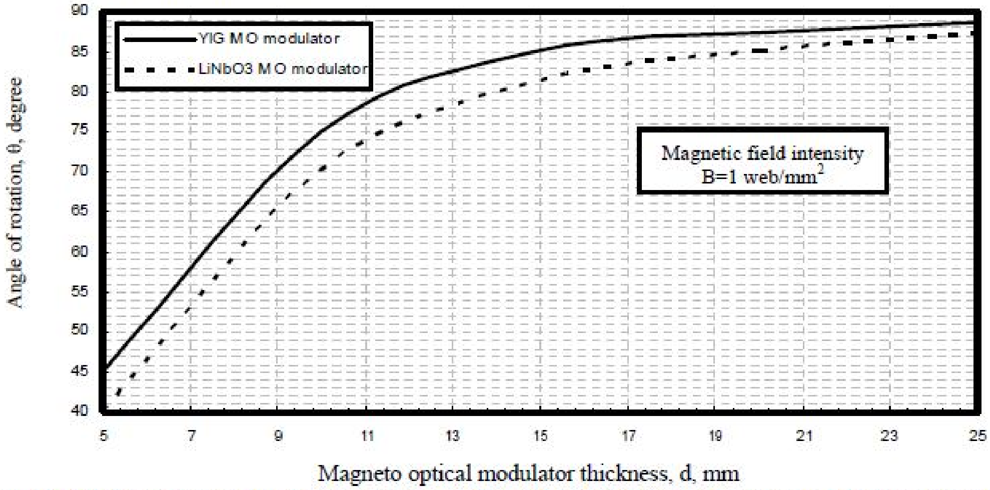

Fig. 4. Angle of rotation in relation to magneto optical modulator thickness and magnetic field intensity at the assumed set of the operating parameters.

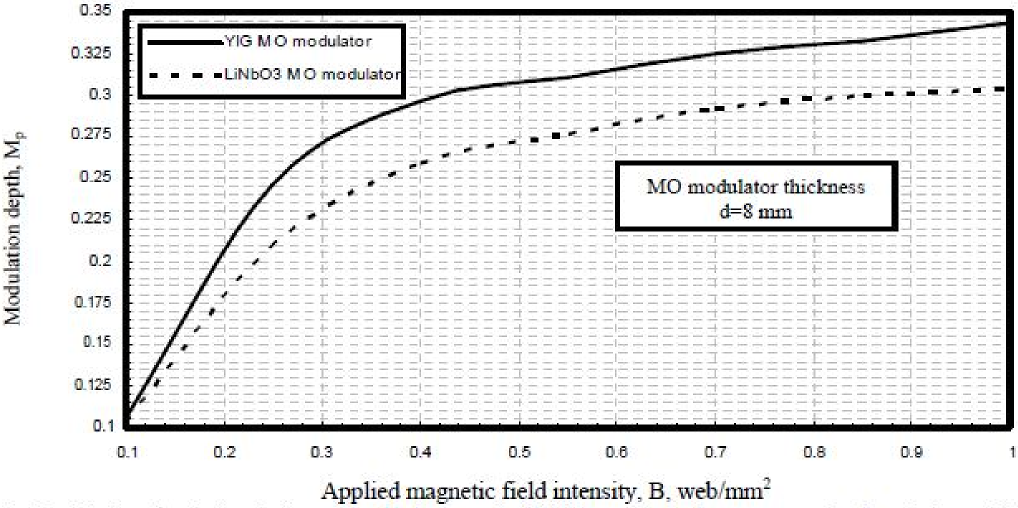

Fig. 5. Modulation depth in relation to applied magnetic field intensity and magneto optical modulator thickness at the assumed set of the operating parameters.

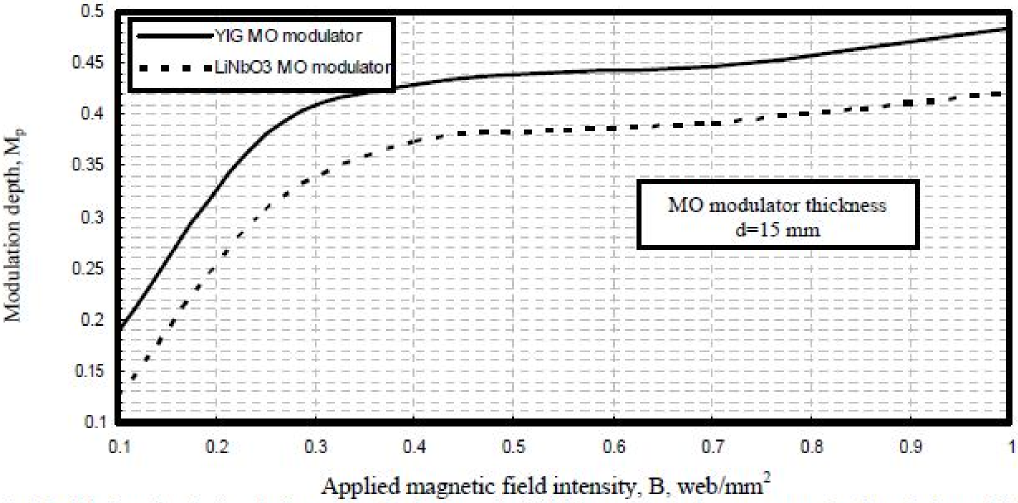

Fig. 6. Modulation depth in relation to applied magnetic field intensity and magneto optical modulator thickness at the assumed set of the operating parameters.

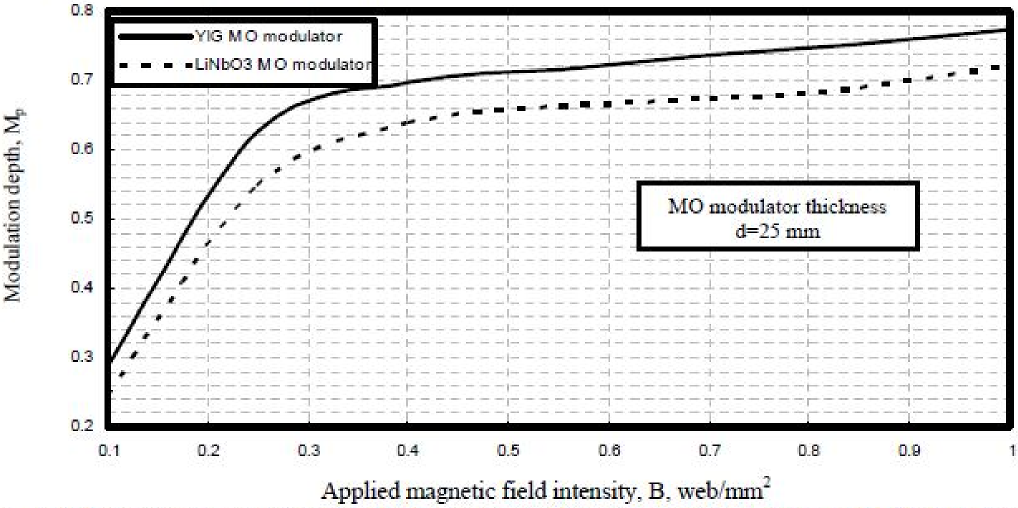

Fig. 7. Modulation depth in relation to applied magnetic field intensity and magneto optical modulator thickness at the assumed set of the operating parameters.

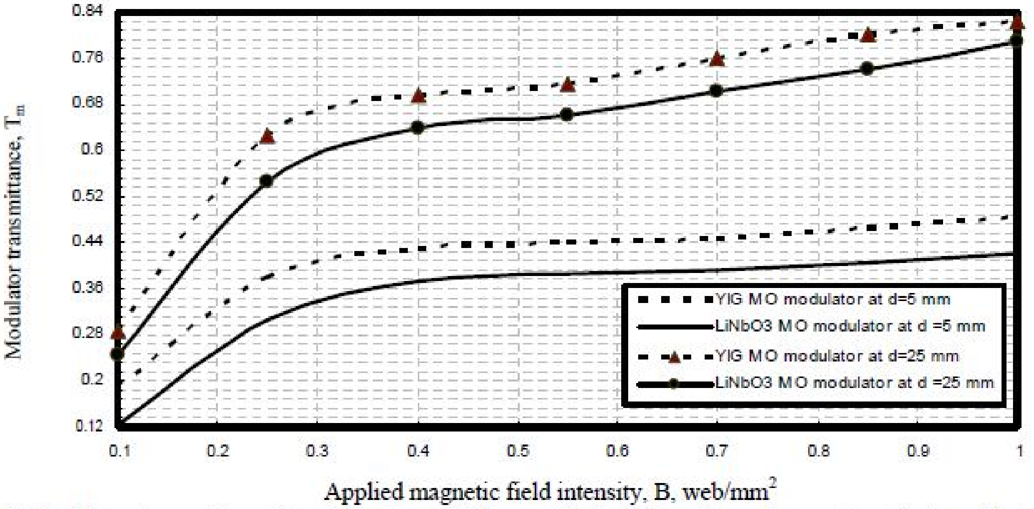

Fig. 8. Modulator transmittance in relation to applied magnetic field intensity and magneto optical modulator thickness at the assumed set of the operating parameters.

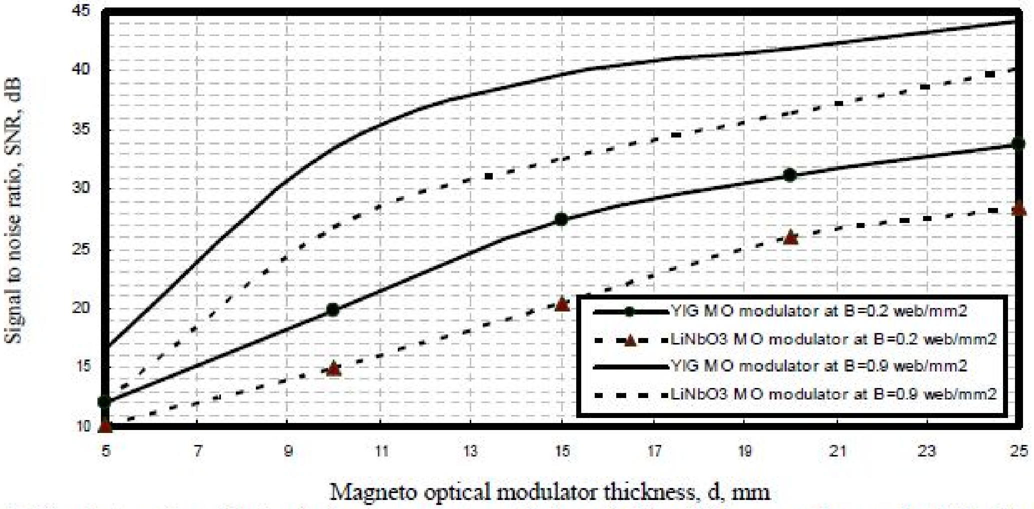

Fig. 9. Signal to noise ratio in relation to magneto optical modulator thickness and magnetic field intensity at the assumed set of the operating parameters.

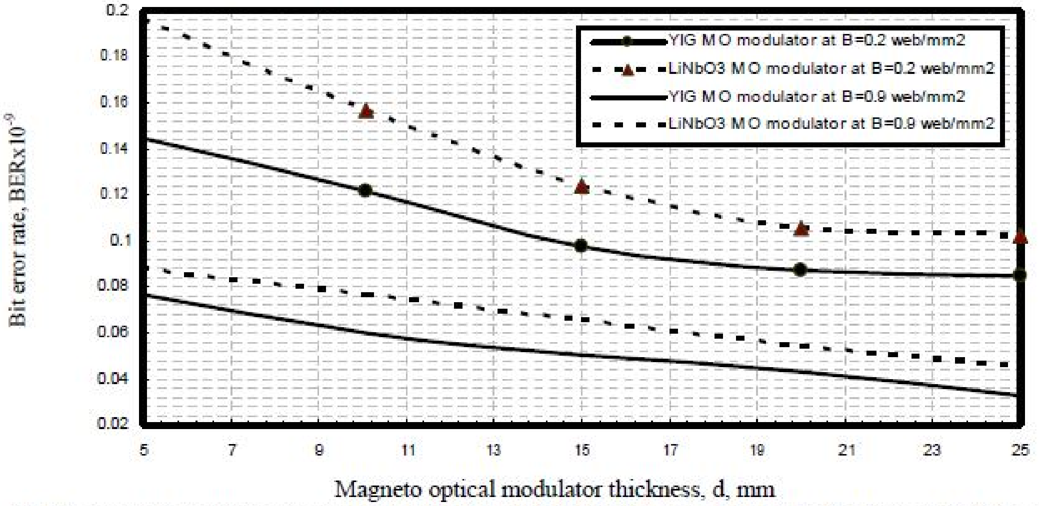

Fig. 10. Bit error rate in relation to magneto optical modulator thickness and magnetic field intensity at the assumed set of the operating parameters.

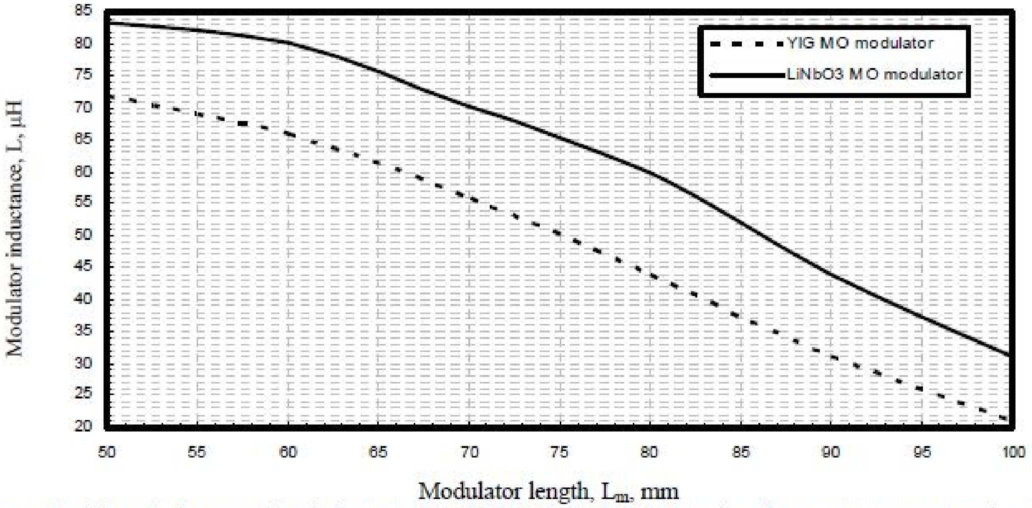

Fig. 11. Modulator inductance in relation to magneto optical modulator length and room temperature at the assumed set of the operating parameters.

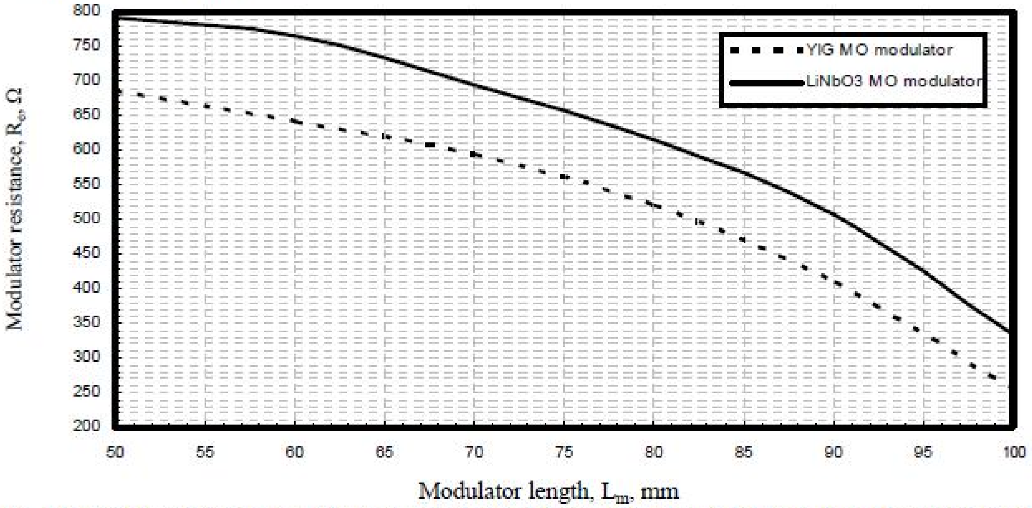

Fig. 12. Modulator resistance in relation to magneto optical modulator length and room temperature at the assumed set of the operating parameters.

5. CONCLUSION

The Faraday effect or Faraday rotation is a magneto-optical phenomenon, or an interaction between light and a magnetic field. The rotation of the plane of polarization is proportional to the intensity of the component of the magnetic field in the direction of the beam of light. It is observed that the increased applied magnetic field intensity and MO thickness, resulting in the increased angle of rotation, modulation depth, transmittance, signal to noise ratio, and the decreased bit error rate for both materials based MO modulators under the same considerations. It is theoretically found that YIG based MO modulator has presented the highest angle of rotation, modulation depth, transmittance, and signal to noise ratio, and the lowest bit error rate, inductance and resistance circuit values under the same operating conditions. Therefore this made YIG based MO modulator is the best candidates selected materials for wide bandwidth and high speed applications in advanced optical communication systems.

REFERENCES

1. Abd El-Naser A. Mohammed, Ahmed Nabih Zaki Rashed, and Mohamoud M. A. Eid. **Rapid Progress of A Thermal Arrayed Waveguide Grating Module for Dense Wavelength Division Multiplexing Applications**, Advanced Science Letters, Vol. 5, No. 1, pp. 56-63, Jan. 2012.
2. S. E. Irvine and A. Y. Elezzabi. **Modeling of High Speed MO Beam Deflection**, IEEE J. Quantum Electron., Vol. 38, No. 2, pp. 1428–1435, Oct. 2002.
3. D. Young and C. S. Tsai, “GHz Bandwidth Magneto Optic Interaction in Yttrium Iron Garnet Gadolinium Gallium Garnet Waveguide Using Magnetostatic Forward Volume Waves,” Appl. Phys. Lett., Vol. 53, No. 3, pp. 1696–1698, 1988.
4. Abd El-Naser A. Mohammed, Gaber E. S. M. El-Abyad, Abd El-Fattah A. Saad, and Ahmed Nabih Zaki Rashed. **High Transmission Bit Rate of A thermal Arrayed Waveguide Grating (AWG) Module in Passive Optical Networks**, IJCSIS International Journal of Computer Science and Information Security, Vol. 1, No. 1, pp. 13-22, May 2009.

5. H. Dötsch, P. Hertel, B. Lührmann, S. Sure, H. P. Winkler, and M. Ye. **Applications of Magnetic Garnet Films in Integrated Optics**, IEEE Trans. Magn., Vol. 28, No. 3, pp. 2979–2984, Sept. 1992.
6. S. E. Irvine and A. Y. Elezzabi. **A miniature Broadband Bismuth Substituted Yttrium Iron arnet Magneto Optic Modulator**, J. Phys. D, Vol. 36, No. 3, pp. 2218–2221, 2003.
7. Prabhakar and D. D. Stancil. **Wideband Optical Modulation Via the Magneto Optic Interaction in A bismuth-Luetriu Iron Garnet Film**, Appl. Phys. Lett., Vol. 71, No. 2, pp. 151–153, 1997.
8. S. Tsai. **Integrated Acousto Optic and Magneto Optic Devices for Optical Information Processing**, Proceedings of IEEE, Vol. 84, No. 3, pp. 853–869, June 1996.
9. F. Zhou, H. Lu, Z. Cao, and Q. **Shen. Electro Optic Polymer Light Modulator Based on Attenuated Total Reflection**, Proceedings of SPIE, Vol. 49, No. 5, pp. 395–398, 2002.
10. J. Bremer, V. Vaicikauskas, F. Hansteen, and O. Hundrei. **Influence of Surface Plasmons on the Faraday Effect in Bismuth Ssubstituted Yttrium Iron Garnet Films**, J. Appl. Phys., Vol. 89, No. 1, pp. 6177–6182, 2001.
11. Abd El-Naser A. Mohammed, Abd El-Fattah A. Saad, and Ahmed Nabih Zaki Rashed. **Matrices of the Thermal and Spectral Variations for the fabrication Materials Based Arrayed Waveguide Grating Devices**, International Journal of Physical Sciences, Vol. 4, No. 4, pp. 205-211, April 2009.
12. Abd El-Naser A. Mohammed, Mohamed A. metawe'e, Ahmed Nabih Zaki Rashed, and Amina E. M. El-Nabawy. **Unguided Nonlinear Optical Laser Pulses Propagate in Waters With Soliton Transmission Technique**, International Journal of Multidisciplinary Sciences and Engineering (IJMSE), Vol. 2, No. 1, pp. 1-10, March 2011.
13. Abd El-Naser A. Mohammed, Ahmed Nabih Zaki Rashed, and Mohammed S. F. Tabour. **Transmission Characteristics of Radio over Fiber (ROF) MillimeterWave Systems in Local Area Optical Communication Networks**, International Journal of Advanced Networks and Applications, Vol. 2, No. 6, pp. 876-886, May/June 2011.
14. M. Caldwell and E. Yeatman. **Surface Plasmon Spatial Light Modulators Based On Liquid Crystal**, Appl. Opt., vol. 31, pp. 3880–3891, 1992.
15. Abd El-Naser A. Mohammed, Abd El-Fattah A. Saad, and Ahmed Nabih Zaki Rashed. **Estimated Optimization Parameters of Arrayed Waveguide Grating (AWG) for C-Band Applications**, International Journal of Physical Sciences, Vol. 4, No. 4, pp. 149-155, April 2009.
16. Abd El-Naser A. Mohammed, Abd El-Fattah A. Saad, and Ahmed Nabih Zaki Rashed. **Thermal Sensitivity Coefficients of the Fabrication Materials Based A thermal Arrayed Waveguide Grating (AWG) in Wide Area Dense Wavelength Division Multiplexing Optical Networks**, International Journal of Engineering and Technology (IJET), Vol. 1, No. 2, pp. 131-139, June 2009.
17. Ahmed Nabih Zaki Rashed. **Ultra High Speed $LiNbO_3$ and Polymer Electrooptic Modulators in Lightwave Optical Access Communication Networks**, International Journal of Advanced Science and Technology, Vol. 35, pp. 41-60, Oct. 2011.