

# The magneto-optical Co-based amorphous thin film as a magnetic field sensor

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The aim of the present paper is to report the results of a research conducted to investigate the possibility of application of magneto-optical cobalt based amorphous thin films as a magnetic field sensor. The sensing element is prepared by pulsed laser deposition technique in one-dimensional magneto-phonic crystals with  $(\text{TiO}_2/\text{SiO}_2)^6/\text{Co}_{67}\text{Fe}_4\text{B}_{14.5}\text{Si}_{14.5}/(\text{SiO}_2/\text{TiO}_2)^6$  structure. The optical and magneto-optical properties of the sample were studied in detail so as to use the hypotheses formulated to achieve good Faraday rotation of the media originating in the weak localization of light. Results indicate that Co-based amorphous thin films can be considered a candidate for use as a magnetic field sensor due to their efficient linearity behaviour with respect to the applied current.

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**Keywords:** Co-based amorphous thin film, magnetic field sensor, magneto-phonic crystal, magneto-optical Faraday rotation

## 1. Introduction

Amorphous magnetic thin films have are of great significance due to their unique magneto-transport and magneto-optical properties [1]. The magneto-optical Co-based amorphous thin film produced by pulsed laser deposition technique [2], which has proven to be the best method available so far for the preservation of stoichiometry and soft magnetic properties, has become an attractive solution in designing magneto-optical sensors. In the magneto-optical sensors, it is generally demanded that the sensing materials have good magneto-optical properties of large Faraday rotation, high magneto-optical figures of merit and suitable saturation magnetic field [3, 4]. While amorphous thin films owing to their nanometric size, offer a low magneto-optical Faraday rotation despite their good magnetic properties [5]. One of the best candidates to solve this problem is the application of magneto-phonic crystals (MPC). However, these structures suffer from an important drawback- a higher Faraday rotation is associated with reduced transmission.

In order to enhance Faraday rotation, we propose the use of amorphous magnetic materials in magneto-phonic crystals. Actually MPCs are promising structures that can deliver an enormous magneto-optical Faraday rotation (FR) in optical signal by trapping light around carefully engineered defects in the band gap [6, 7]. Thus enhanced Faraday rotation and then sensitivity of these structures as sensors can be achieved by using magnetic thin films as a defect in one-dimensional magneto-phonic crystals (1D-MPC).

## 2. Film structure and numerical calculations

A typical example of a 1D-MPC film structure is expressed as  $(N_1N_2)^n/M/(N_2N_1)^n$ . In this structure, n is the

periods of the dielectric layers and M,  $N_1$  and  $N_2$  are Co-based amorphous magnetic thin films,  $\text{SiO}_2$  and  $\text{TiO}_2$  respectively. The properties of multilayer films are clarified by solving Maxwell's equations with the bigyrotropic dielectric tensor for the magnetic layer under the electromagnetic boundary conditions imposed at all discontinuous planes.

The optical field inside each layer is given as a sum of four normal modes: right and left circular polarized waves propagating in both directions along the MPC normal direction. Then a set of  $4 \times 4$  matrices is calculated that each of them corresponds to each layer of the structure and determines the values of optical field on the boundaries. By multiplying all the matrices one can obtain the matrix that characterizing transmittance and Faraday rotation angle of light [8].

Also, the numerical calculation was performed using the values of diagonal and off-diagonal element of permittivity tensor for magnetic layer (Fig. 1) that calculated by means of refractive indices and magneto-optic Voigt constant for magnetic defect layer as  $Q_{\text{CoFeSiB}} = 0.043 + i6.94 \times 10^3$  where we used the Voigt constants of pure Co and Fe [9].

In addition, the refractive indices of  $\text{SiO}_2$  and  $\text{TiO}_2$  layers measured by transmission and absorption spectrum and Kramers-Kroning relations are  $n_{\text{SiO}_2} = 1.52$  and  $k_{\text{SiO}_2} = 0$  and  $n_{\text{TiO}_2} = 2.01$  and  $k_{\text{TiO}_2} = 0$ .

## 3. Experimental procedure

We fabricated one-dimensional magneto-phonic crystal film of  $(\text{TiO}_2/\text{SiO}_2)^6/\text{Co}_{67}\text{Fe}_4\text{B}_{14.5}\text{Si}_{14.5}/(\text{SiO}_2/\text{TiO}_2)^6$  /glass structure. The

magnetic layer ( $\text{Co}_{67}\text{Fe}_4\text{B}_{14.5}\text{Si}_{14.5}$  film) of the 1D-MPC was formed using pulsed laser deposition technique, using a 355 nm wavelength pulsed laser beam produced from a Nd:YAG laser. The laser beam was focused onto an amorphous ribbon target  $\text{Co}_{67}\text{Fe}_4\text{B}_{14.5}\text{Si}_{14.5}$  that rotating 180 rpm via a 50 cm focal length lens. Typical deposition parameters consisted of laser pulse energy of 100 mJ, a pulse frequency 10 Hz and a total number of pulses for one deposition of around 6000. The depositions were carried out in a vacuum chamber evacuated to a pressure of  $5 \times 10^{-5}$  mbar and the central magnetic layer has thickness of 15 nm, and all other layers have quarter-wavelength thickness in the respective material with regard to  $\lambda_0$  ( $\lambda_0 = 520$  nm).

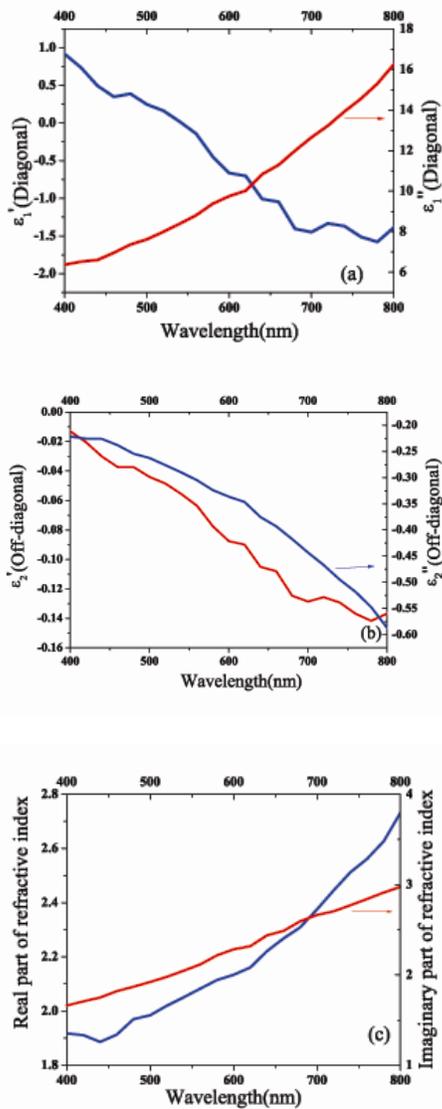


Fig. 1. spectrum of (a) diagonal and (b) off-diagonal element of permittivity and (c) the refractive index of  $\text{Co}_{67}\text{Fe}_4\text{Si}_{14.5}\text{B}_{14.5}$  magnetic thin film used in calculation.

The optical properties of our 1D-MPC structure were investigated by using a UV-Visible spectrometer. Wavelength dependent Faraday rotation was measured by means of a Chromex spectrometer. The measurement setup comprised of an optical path where the light from halogen lamp passed through the collimator, polarizer, sample and analyzer before it was analyzed in the spectrometer. In this method, the sample was magnetized to saturation parallel and antiparallel to incident light by the aid of applied magnetic field. The Faraday rotation angle at each wavelength corresponded to the relative shift of the intensity curve,  $I_\lambda(\alpha)$ , once measured in a sample magnetized to saturation and once in a sample unmagnetized[10].

Finally, to test 1D-MPC as a sensor, the sample was placed in a DC magnetic field and the result in the form of Faraday rotation was then tested. In this method, the laser light (635 nm) is modulated by an electrical modulator and the intensity of light was analyzed by a silicon PIN photodiode that connected to the lock-in amplifier, which was programmed to a reference voltage of the same frequency of laser's light and a fixed phase relationship to that of the signal.

#### 4. Results and discussion

The optical and magneto-optical properties of the sample with  $(\text{TiO}_2/\text{SiO}_2)^6/\text{Co}_{67}\text{Fe}_4\text{B}_{14.5}\text{Si}_{14.5}/(\text{SiO}_2/\text{TiO}_2)^6$  /glass structure are shown in Fig.2.

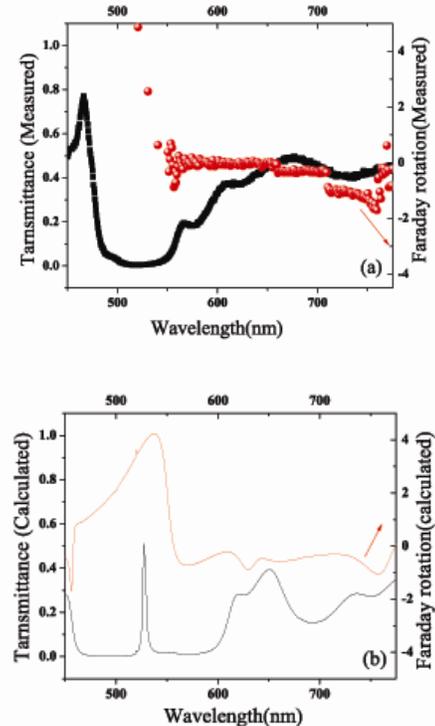


Fig. 2. (a) measured and (b) calculated optical properties and magneto-optical Faraday rotation angle

(Degree) of 1D-MPC with  $Co_{67}Fe_4Si_{14.5}B_{14.5}$  defect layer.

As demonstrated in this figure, in the Co-based 1D-MPC the weak light localization can be observed around 566 nm (Fig.2 (a)) similar to the designed result and the forbidden band is lower in the measured data with respect of calculated one. The weak intensity (20%) of the localized peak is attributed to a decrease in transmittance of magnetic defect layer around this wavelength. Also, the calculated transmittance (Fig.2 (b)), when the thickness of magnetic defect layer is set to 15 nm is compared to the measured value. In the fabrication process, the layers roughness, which might occur during deposition, must be taken into account. The shift in the calculation spectra with respect to the measured one, to the lower wavelengths, can be explained by ignoring the films roughness [11, 12]. Also, it can be accounted for due to the fact that roughness increases the optical thickness of periods, and subsequently, enhances the absorption and yields to decrease the transmission at localized mode.

In fact, the magnetic defect layer has a rough surface, this smear out the localized level, makes the peak of FR broad and reduces transmission in photonic band gap. Also the magnetic defect layer may have a thickness larger than the target thickness, in which the wavelength at which FR reaches a maximum is shifted to the longer wavelength.

As mentioned above, Fig.2 shows the measured and calculated wavelength dependent magneto-optical Faraday rotation. The measured Faraday rotation spectrum of 1D-MPC, at saturation magnetic field, 60 Oe, has a peak with  $-0.8^\circ$  which is close to the localized peak in transmittance spectra at 556nm and a broad peak near the localized wavelength. Another broad peak of Faraday rotation spectrum with  $-1.7^\circ$  at about 759 nm is observed. Regarding the calculated spectrum, at vicinity of localized mode, resonance occurs and Faraday rotation increase to  $-0.73^\circ$  whose value is close to the measured amount. Moreover, the broad peak of Faraday rotation at localized wavelength confirmed by measured one. This result shows that while an enhancement of rotation is produced it is accompanied by a significant decrease in transmission, which is a typical feature of 1D-MPC.

Besides, the sample was placed in a DC magnetic field and the sample's answer was tested. The intensity of modulated light at the detector's input is given by Malus' law as:

$$I = I_0 \sin(\omega t + \varphi) \cos^2(\theta_a - \theta_F) \quad (1)$$

Where,  $\theta_a$  is the angle between analyzer and polarizer,  $\theta_F$  is the Faraday rotation and  $\omega$  is the modulated frequency of light. By using the equation

$$v = \alpha I + v_{off} \quad (2)$$

We can change the intensity of light to the voltage that can be recorded by lock-in amplifier. Then the

relation between this amplitude and Faraday rotation is given by:

$$\frac{R - \frac{1}{2}R_{B=0}}{\frac{1}{2}R_{B=0}} = \sin(2\theta_F) \quad (3)$$

In which  $R_{B=0}$  and  $R_{B=0}$  are the amplitudes of signal that measured without and with magnetic field.

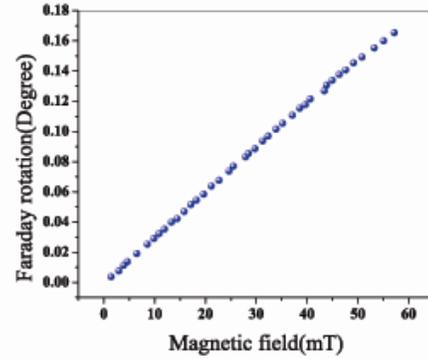


Fig. 3. measured Faraday rotation as a function of applied magnetic field.

Fig. 3 demonstrates the relation between output Faraday rotation and the applied magnetic field that measured in saturation magnetic field.

As shown in this figure, the output signal and the amount of applied magnetic field had good linearity that makes our device suitable for magnetic field sensors.

Furthermore, the sensitivity of a magneto-optical sensor has a direct relationship to Faraday rotation and reverse connection to the saturation magnetic field [13]. According to this relation, larger amount of Faraday rotation and lower value of saturation magnetic field result in obtaining higher sensitivity. Here, the adopted approach of using amorphous magnetic materials as a defect layer in 1D-MPC provides an opportunity to increase Faraday rotation in front low amount of saturation magnetic field and consequently to increase the amount of sensitivity of magneto-optical field sensor. Therefore, the sensitivity of these sensors increases at a localized wavelength as a result of enhanced Faraday rotation.

## 5. Conclusions

We used amorphous magnetic materials in the form of thin films surrounded into 1D-MPC with  $(TiO_2/SiO_2)^6/Co_{67}Fe_4B_{14.5}Si_{14.5}/(SiO_2/TiO_2)^6/glass$  structure. Optical, magneto-optical and magnetic properties of 1D-MPC were investigated in the visible range. Amorphous 1D-MPC was shown to be responsible for the creation of

localized state in the optical spectrum of the designed structure. The Faraday rotation, due to localized mode, was enhanced and as a result, the sensitivity of magnetic field sensors based on these thin films increased at localized wavelength.

Finally, the good linearity of 1D-MPC with respect to the applied current, to a large extent simulated the development of a number of novel types of magnetic field sensors for science and engineering, which allows high speed and remote probing of magnetic field.

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