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# Magnetic field sensors and visualizers using magnetic photonic crystals

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## ABSTRACT

Magneto-optical imaging is widely used to observe the domain patterns in magnetic materials, visualize defects in ferromagnetic objects, and measure the spatial distribution of stray magnetic fields. Optimized 1D magneto-photonic crystals enable a significant increase in the sensitivity of magneto-optical sensors. The properties of such devices based on the optimized reflection (doubled Faraday rotation) mode and the use of 1D magnetic photonic crystals as sensors are discussed. Experimental results of the fabrication and characterization of ferrite-garnet layers possessing uniaxial magnetic anisotropy are shown, and an optimized film structure suitable for magneto-optical imaging is proposed.

**Keywords:** Magnetic photonic crystals, magnetic domains, magneto-optical magnetic field sensors.

## 1. INTRODUCTION

Magneto-optical (MO) imaging and sensing devices utilizing Bi-substituted iron garnet films are widely used to examine the spatial distribution of magnetic fields produced by magnetized objects [1-5], to study the vortex matter in high-temperature superconductors [6], and as current sensors [7]. Depending on the properties of the objects under study, the sensing films with in-plane, inclined, and perpendicular orientation of the magnetization vector with respect to the film plane are used [1]. The in-plane magnetized films usually provide good flexibility for the characterization of objects under study. At the same time, films possessing the maze-like domain structure and small saturating magnetic fields are more suitable for detecting localized magnetic defects in ferromagnetic samples [3].

A typical configuration of a MO sensor is shown in Fig. 1. Usually, a Bi-substituted iron garnet film with a thickness of 2 to 5 μm coated with a thin aluminium reflecting layer is placed on top of the sample. A polarized light beam passes through the sensing film, is reflected, and rotates the polarization vector in proportion to the vertical component of the magnetic moment of the sensing film. In films with in-plane and inclined direction of magnetization, the magnetic stray field produced by the sample rotates the local magnetic moment of the sensing film in either the "up" or "down" direction. If a sensor is based on a film with the perpendicular direction of the magnetization with respect to the film plane, such a film possesses a maze-like or stripe domain structure. To characterize the performance of MO sensors with in-plane magnetization, the photo-response (P/R) characteristic reported by Klank et al. is adopted [4]:

$$P/R = \frac{I_{out}}{I_{inc}} = \frac{1}{2}\left[1+\sin\left(2\Phi_F h\cos\theta\right)\right]\exp\left(-2\alpha h\right) \tag{1}$$

where $I_{out}$ and $I_{inc}$ are the incident and output intensities of the light, respectively, $\Phi_F$ and $h$ are the specific Faraday rotation of the sensing film and the film thickness, and $\alpha$ is the absorption coefficient of the film material. The term $cos(\theta)$ is equal to $B_n/B_s$, where $B_n$ is the component of magnetic induction applied in the direction perpendicular to the film plane, and $B_s$ is the magnetic induction necessary to saturate the magnetization in the film along the film normal; $\theta$ is the angle between the film normal and the magnetization vector **M**. The dynamic range of an MO sensor is determined by $B_s$, which depends on the film composition and can vary from 10 to 2000 Oe. The sensitivity $S$ is given by [4]:

$$S = \frac{d\left(P/R\right)}{dB_n}\Big|_{B_n=0} = \frac{\Phi_F h}{B_s} \tag{2}$$

Thus, the higher the sensitivity, the lower the dynamic range is, and vice versa.

Another important parameter is the spatial resolution of the film determined by its magnetic properties, thickness, and also the distance between the reflecting mirror and the sample surface.

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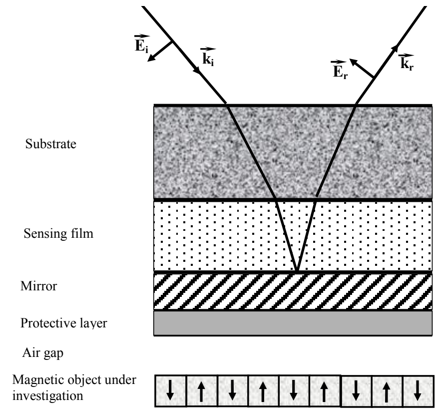



Fig.1. Operation of MO thin film sensors in reflection mode.

The approach of using magnetic photonic crystals (MPC) provides an opportunity to increase the Faraday rotation angle of the MPC by about an order of magnitude in the visible spectral region, compared with thick non-structured films, even with rather high absorption levels of over $10^3$ $cm^{-1}$ of iron garnet films in this spectral region. In the infrared, where the absorption coefficient drops to about $10^{-3}$ $cm^{-1}$, the growth of the sensitivity will be much higher, but the spatial resolution is worse, since the optimal thickness of the sensing film is increased substantially in this case. The reflection-mode operation of 1D MPC for use in film-based MO isolator devices was considered in [8-9]. The authors discussed the case of non-absorbing MO materials and described an MPC structure of the type $(SiO_2/Ta_2O_5)k$/Bi:YIG/$(Ta_2O_5/SiO_2)k$/R with a reflecting layer *R* [9]. Here, we extend the analysis of the reflection-mode MPC operation by considering the case of using MPC structures optimized for sensors working in the visible spectral region, where it is necessary to account for significant material absorption. We also propose an optimized MPC sensor structure and report experimental results of the fabrication of MO garnet layers using RF magnetron sputtering, and the garnet properties achieved.

## 2. SENSITIVITY OF MPC SENSORS

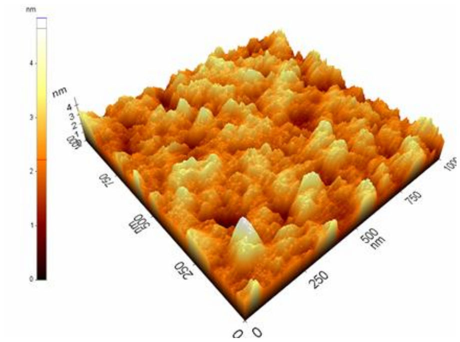
In many practical situations, sensing films with maze-type domain structure are desired. This is due to their suitability for the detection of small localized magnetic defects (for example, cavities inside ferromagnetic objects). An MPC sensor possessing the domain structure can significantly increase the sensitivity of MO sensors (by up to two orders of magnitude), depending on the absorption coefficient of the MO and dielectric media in the desired spectral region and the magnetic and MO properties of the materials used. From (2), the sensitivity of a single-layer film is determined by its Faraday rotation and $B_s$. The Faraday rotation can be increased by optimizing the MPC structure and its composition. $B_s$ can be reduced substantially by optimizing the thicknesses of individual MO layers. For a single-layer sensor, the attainable values of $\Phi_F$ and $B_s$ are interrelated via the composition and MO properties of the material. Dy, Sm and Lu ions are often introduced into the garnet composition to provide the necessary value of uniaxial magnetic anisotropy and to achieve the stripe- or maze-like domain structure, as well as the “squareness” of the hysteresis loop.

In the usual case of a single-layer sensor, for an optimum thickness of the sensor film, $B_s$ is in the range of 500-1000 Oe, depending on the film thickness and composition. As a result, attaining the ultimate MO properties leads to a significant drop in the magnetic sensitivity.

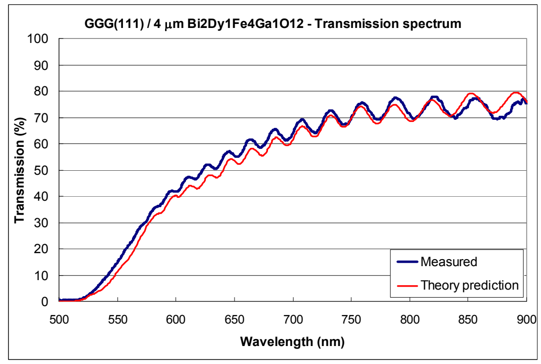
For the MPC structure proposed in this paper, the thickness of individual MO layers is near 50 nm, and there is a possibility to optimize the saturation field and the domain size in the individual layers of the structure.

## 3. RESULTS: MO FILMS FABRICATION, CHARACTERISATION AND OPTIMIZATION OF MPC STRUCTURE FOR SENSOR DEVELOPMENT

We have manufactured a number of batches of MO garnet films with different compositions and thicknesses using RF magnetron sputtering technique. The results of optical, magneto-optical and magnetic characterisation (shown in Fig. 2) show that layers of $Bi_2Dy_1Fe_4Ga_1O_{12}$ deposited onto garnet (GGG) substrates (crystallised into garnet phase by high-temperature oven annealing) are very suitable for the described application, and are good candidates for incorporation into our optimized MPC structures (the experiments in this area will be reported elsewhere).



**(a)**

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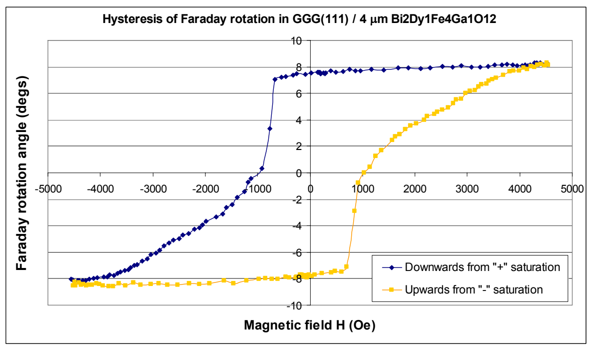


**(c)**

Fig.2. Experimental results on surface quality inspection (AFM), and the optical and MO characterisation of a 4 μm thick garnet-phase layer of $Bi_2Dy_1Fe_4Ga_1O_{12}$ showing a measured hysteresis loop of Faraday rotation at 633 nm and good magnetic memory properties achieved through selecting the garnet composition that provides a sufficient level of uniaxial magnetic anisotropy. The latter keeps the magnetic moment of film in the direction normal to the film plane. RMS surface roughness of garnet layers is typically about 2 nm across a randomly-selected film area of $1\mu m^2$.

We computationally evaluated a number of MPC structural types for their suitability for the proposed application. The absorption of sputtered layers of $Bi_2Dy_1Fe_4Ga_1O_{12}$ is in the range of $10^3$ – $2x10^3$ $cm^{-1}$ near 560 nm. We found that MPC structures of type GGG/(M)a(LM)b(M)c(ML)d/Ag, where the material of dielectric layers L is GGG, were particularly promising, since these showed a good enhancement in the Faraday rotation compared to single-layer films of the same thickness (a large MPC gain factor). Our optimization algorithm [10] found global optima with the maximized Faraday rotation per thickness of either the entire structure, or only its magnetic layers, by calculating the responses of all structures of this type for a range of repetition indices (a...d) of (1...15), for the absorption ranging from 800 to 4500 $cm^{-1}$. The saturated gyration of garnet at 560 nm used in calculations was g = -0.04, corresponding to $\Phi_F$ = -5º/μm, which is even below a typical value of -7º/μm we measure in our films in the green spectral region. The thickness of the reflecting layer of silver ($n_{Ag}$ = 0.12 + i3.44 at 560 nm) was kept constant at 100 nm during the optimization. All optical thicknesses for layers (L, M) of the structure were kept equal to the quarter of the design wavelength (560 nm). The algorithm grouped all MPC designs from the computational domain which had reflectivity of greater than 40% at the design wavelength, Faraday rotation angles of > 10º, having $\Phi_F$ peaks within ±5 nm from 560 nm, and limited in thickness by 3μm. The designs with either the largest MPC gain factor, or the largest $\Phi_F$ were obtained by filtering this pre-selected group. Figs 3(a) and (b) show the reflection and Faraday rotation spectra for the design optimized by maximizing the Faraday angle per unit combined MPC thickness obtained with the absorption in garnet layers of 1200 $cm^{-1}$. This structure is described by the formula GGG/(M)1(LM)4(M)2(ML)6/Ag composed of 20 layers with a thickness of only 1.51 μm. This MPC design was selected as a candidate for the experimental implementation of our sensors due to having a small thickness (only 215 nm) in its thickest magnetic layer, which will lead to achieving the saturation of magnetization in small fields. The variation in the maximum MPC gain factor, achievable by optimizing the design domain for the described structural type, with absorption is shown in Fig. 3(c).

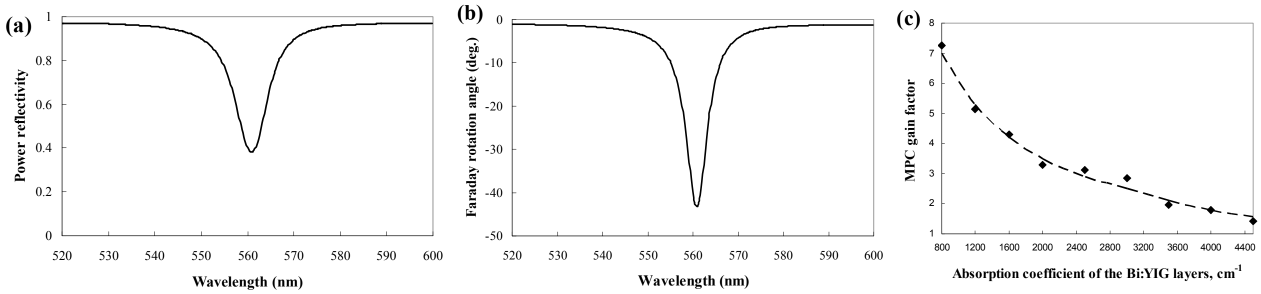


Fig.3. Spectrum of reflectivity (a) and Faraday rotation in reflection mode (b) of an optimized sensor structure GGG/(M)1(LM)4(M)2(ML)6/Ag designed for operation around 560nm. (c) Variation in optimum MPC gain factor with the absorption coefficient of magnetic layers for optimized structures of type GGG/(M)a(LM)b(M)c(ML)d/Ag.

# 4. CONCLUSION

In this paper, we have proposed the use of 1D Magneto-Photonic Crystal (MPC) structures in Magneto Optic (MO) vizualisers and sensors. A significant increase in the device sensitivity has been predicted compared with the case of single-layer sensing films. The analysis taking into account the real absorbance characteristics of existing sensing films has been included, and the results of characterisation of the optical, magnetic, and MO properties of (Dy,Ga)-doped iron garnet thick film layers made by RF sputtering have been shown. An emphasis has been placed on the optimization of MPC aimed at the possibility of the practical implementation of nano-structured sensors and on enhancing the magnetic and MO sensitivity in sensor-type applications. Experimental results on fabricated single garnet layers have demonstrated excellent surface quality and good magnetic and MO properties achieved through selecting the garnet composition that provides a sufficient level of uniaxial magnetic anisotropy. The experimental results in conjunction with our theoretical approach for MPC design will open the way towards practical implementations of high-sensitivity magnetic field sensors and visualizers.

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