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Nanostructured Engineered Materials With High Magneto-Optic Performance for Integrated Photonics Applications

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Abstract- **In this paper, we experimentally investigate the performance of a set of technologies used for the deposition, annealing and characterization of high-performance magneto-optic rare-earth-doped garnet materials and all-garnet heterostructures for use in photonic crystals and novel integrated-optics devices.**

I. INTRODUCTION

Magnetic photonic crystals (MPC) provide novel functionalities (such as fast tunability) in optical integrated circuits for optical communication networks and sensors [1]. Until now, since the first report about the superior magnetooptical properties of bismuth-substituted iron garnets [2], this class of materials remains being considered the best magnetooptical media for use in MPC structures. This is because bismuth-substituted iron garnets demonstrate the highest Faraday rotation in the visible and near infrared spectral regions and excellent optical transmittance in the infrared region. The optical transmittance band of iron garnet materials is typically from 500 nm to greater than 5000 nm, where optical absorption coefficients as low as 10^{-1} cm^{-1} have been reported for pure $Y_3Fe_5O_{12}$ at 1300 nm, and the absorption coefficients smaller then 80 cm^{-1} near 800 nm and near 1000 cm^{-1} in the red spectral region (630-650 nm) have also been reported [3]. Cerium-substituted iron garnet possesses even higher specific Faraday rotation near 700 nm compared with bismuth-substituted iron garnets, but unfortunately has a higher optical absorption level then bismuth-containing compositions [3].

The practical use of MPC and magneto-optic garnet materials in real photonic devices is seriously limited at present due to high excess optical absorption levels observed in sputtered magnetooptical films (compared to epitaxial monocrystalline films), especially in the visible spectral region. As a result, until now the Faraday rotation angles of only up to 7.5° (observed only at the saturated magnetisation, in a material without remnant magnetisation) were demonstrated experimentally in MPC structures with a "defect mode" in the MPC's photonic bandgap engineered for the near-infrared spectral region [4]. Based on existing literature, extensive research is still needed in the area of magnetooptical materials to fabricate high-performance MPC structures, and the main issue that needs special attention is the ability to recognize the source of the additional optical absorption in the RF-sputtered films in comparison with monocrystalline epitaxial films fabricated using liquid-phase epitaxy (LPE) processes. Another important question needs to be addressed is: what is the optimal composition of the garnet film for creating the layers within MPC structures suitable for practical development of photonic devices? To successfully fabricate MPC structures, a number of material properties must be optimized simultaneously, including the optical absorption, specific Faraday rotation, surface quality, microstructure quality, and either the presence or absence of domain structure and magnetic memory properties (remnant magnetisation).

II. FABRICATED GARNET FILMS

Several batches of high-quality ferrimagnetic-phase garnet films were manufactured and characterized. Different material compositions doped with Bi, Dy and Ga ions were used with thicknesses ranging between 50 and 5000 nm. All of these films possessed a sufficient level of uniaxial magnetic anisotropy for orienting the film's magnetic moment in a direction perpendicular to the film plane. The investigated film compositions differed primarily in their bismuth content (number of Bi atoms per formula unit), which was varied between 2 and about 2.6 by means of using a co-sputtering process which introduced the stoichiometric excess of bismuth oxide into our garnet films. The doping of garnets with Dy and Ga atoms ensured a nearly-square magnetic hysteresis loop of our films, thus enabling excellent magnetic memory properties. The deposition technology used was RF magnetron sputtering in low-pressure (1 mTorr) Ar plasma using a composite oxide-mix-based target of nominal stoichiometry $Bi_2Dy_1Fe_4Ga_1O_{12}$, as well as an additional Bi_2O_3 target for adjusting the level of Bi doping during the co-sputtering processes, as well as for forming composite garnet-oxide films. In order to crystallise the amorphous sputtered films (deposited at substrate temperatures between 250-500 ^oC) into polycrystalline ferrimagnetic garnet phase whilst preserving the high layer quality, a post-deposition high-temperature oven annealing process had to be developed and optimised for each composition of garnet films obtained. Magnetic photonic crystals using iron garnet layers as magnetic constituents are unique in the sense that not only it is the structural periodicity but also the presence of crystalline-phase garnet layers is what makes these structures belong to the class of photonic crystals.

III. RESULTS AND DISCUSSION

The fabricated garnet films were characterised optically, magnetically and magneto-optically. It was particularly found that the garnet layers possessed a combination of properties that are highly desirable for the design and manufacture of integrated-optics devices based on MPC (the results for $Bi_2Dy_1Fe_4Ga_1O_{12}$ are shown and explained in Fig. 1). In particular, the magneto-optic quality factor, determined by the ratio of the specific Faraday rotation to the material absorption, was in some wavelength regions (Fig. 2) comparable to the best reported garnets with a higher Bi content per formula unit (near 3 atoms), which do not possess magnetic memory properties and uniaxial magnetic anisotropy.

The properties of garnet layers achieved using our deposition and annealing technologies are attractive for several applications [5]. The optical and magneto-optic performance characteristics of some of our high-Bi-content composite garnets obtained using excess Bi_2O_3 during the deposition are extremely promising and will be reported elsewhere, together with analyses explaining the material improvements achieved.

The results of surface quality and microstructural characterisation (AFM/SEM images) of several amorphous and annealed layers of our garnet materials on either glass or GGG(111) substrates are shown and explained in Fig. 3. It is important to note that optimisation of annealing regimes is key to obtaining the high-quality microstructure and surfaces in garnet layers. Uniaxial magnetic anisotropy in our garnet layers (both in $Bi_2Dy_1Fe_4Ga_1O_{12}$ and all Bi_2O_3:$Bi_2Dy_1Fe_4Ga_1O_{12}$ composites tested) was sufficient for orienting the film's magnetic moment in the direction perpendicular to the film's plane, which is confirmed by the nearly-square hysteresis loop (Fig. 1 (c)) and by the presence of domain structure shown in Fig. 4. The optical and MO performance of magnetic multilayers and MPC is critically dependent on obtaining the layer microstructure with minimum grain size. For all-garnet heterostructures composed of alternating layers of ferrimagnetic Bi/Dy-doped iron garnet and paramagnetic GSGG (or GGG), the optimum performance was only achievable when the annealing regime was simultaneously optimised for both garnet types, so that the thicknesses of amorphous interface layers between different garnet types were minimised. For heterostructures having very thin Bi-doped garnet layers (about 50 nm thick), it was difficult to obtain good agreement between predicted and measured MO performances (specific Faraday rotation). The heterostructure of Fig. 5, for example, was found to perform well optically as confirmed by its measured transmission spectrum, yet it showed less than 50% of the expected enhanced Faraday rotation performance at the wavelength of its transmission peak (532 nm), which we attribute to the effect of interface layers not being completely crystallised during annealing.

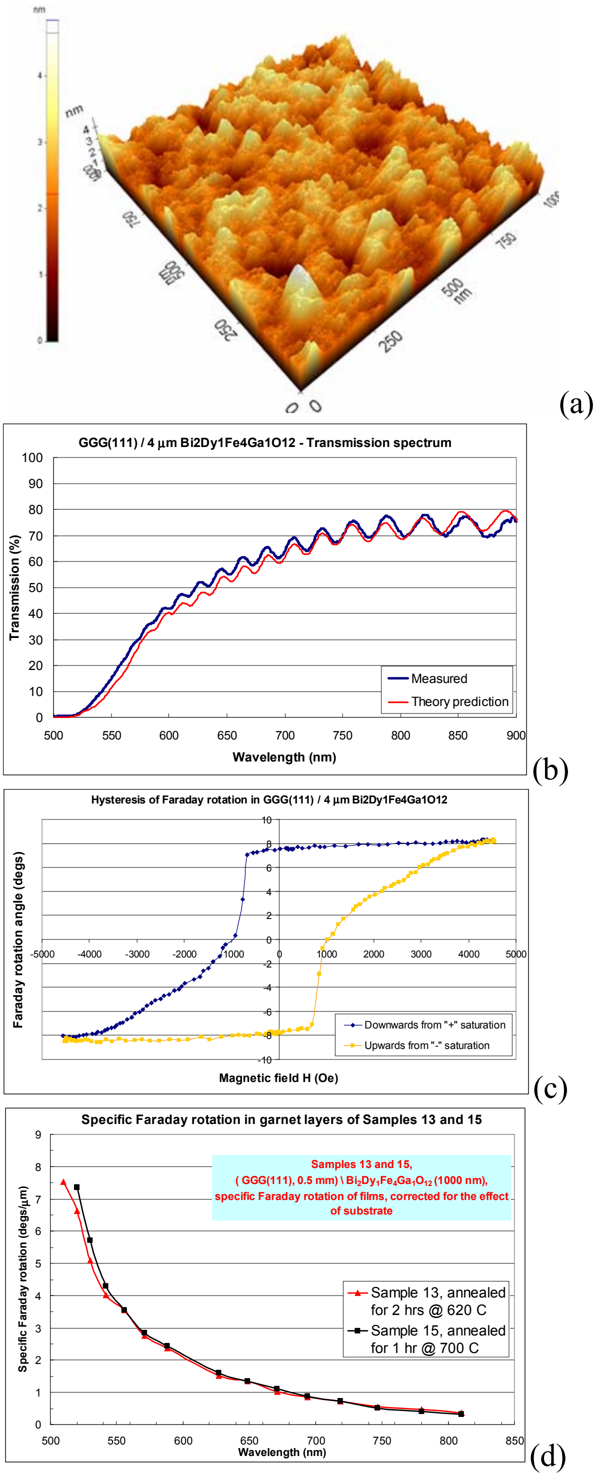
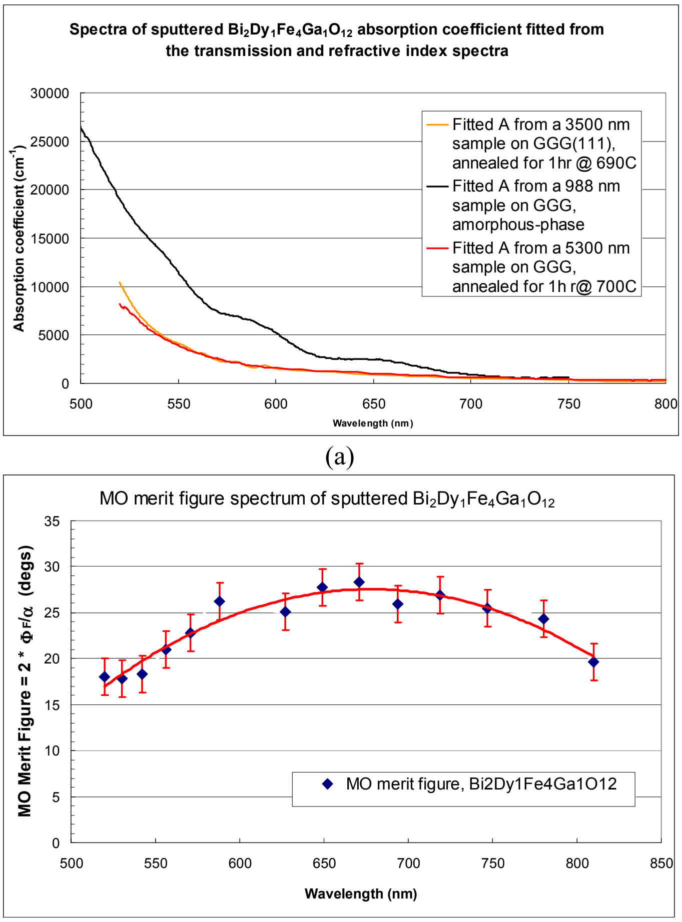


Fig.1. (a) Results of surface quality inspection (AFM), and (b-d) the optical, magnetic and MO characterisation of a 4 µm thick garnet-phase layer of $Bi_2Dy_1Fe_4Ga_1O_{12}$ showing a measured hysteresis loop of Faraday rotation at 633 nm and excellent magnetic memory properties achieved through selecting the garnet composition that provides a sufficient level of uniaxial magnetic anisotropy. RMS surface roughness of our garnet layers is typically about 2 nm across a randomly-selected film area of 1µm^2. The combination of optical, magnetic and MO properties achieved in our garnet layers makes them very attractive for use in nanostructured photonic components, devices and sensors.



(a)

(b)

Fig.2. Experimental results of the optical and MO characterisation of high-quality sputtered $Bi_2Dy_1Fe_4Ga_1O_{12}$ layers: (a) typical absorption coefficient spectra; (b) spectral dependency of MO quality factor ($2\Theta_F/\alpha$) for $Bi_2Dy_1Fe_4Ga_1O_{12}$ layers measured across most of the visible and near-IR regions.

In order to test the performance of our garnet materials and their suitability for use in MPC-based devices, we optimized the MPC for usage as a magnetic field visualizer operating in either transmission or reflection mode with image memory, using the analysis reported in [5] and [6].

The 14-layer heterostructure of Fig. 6 was designed with Bi-doped garnet layers of 200 nm thickness, and that structure performed well in terms of both the transmission spectrum and the expected enhanced Faraday rotation at its transmission peaks around 635 and 670 nm.

At the 635nm transmission peak, the heterostructure shown in Fig.6 exhibited around 2.7° of Faraday rotation per micron of magnetic material thickness. This is a significant enhancement in magneto-optical performance in comparison to a Faraday rotation of around 2.0° per micron attained using single-layer (Bi_2Dy_1)IG films, as evident from the Faraday rotation spectra shown in Fig. 1(d).

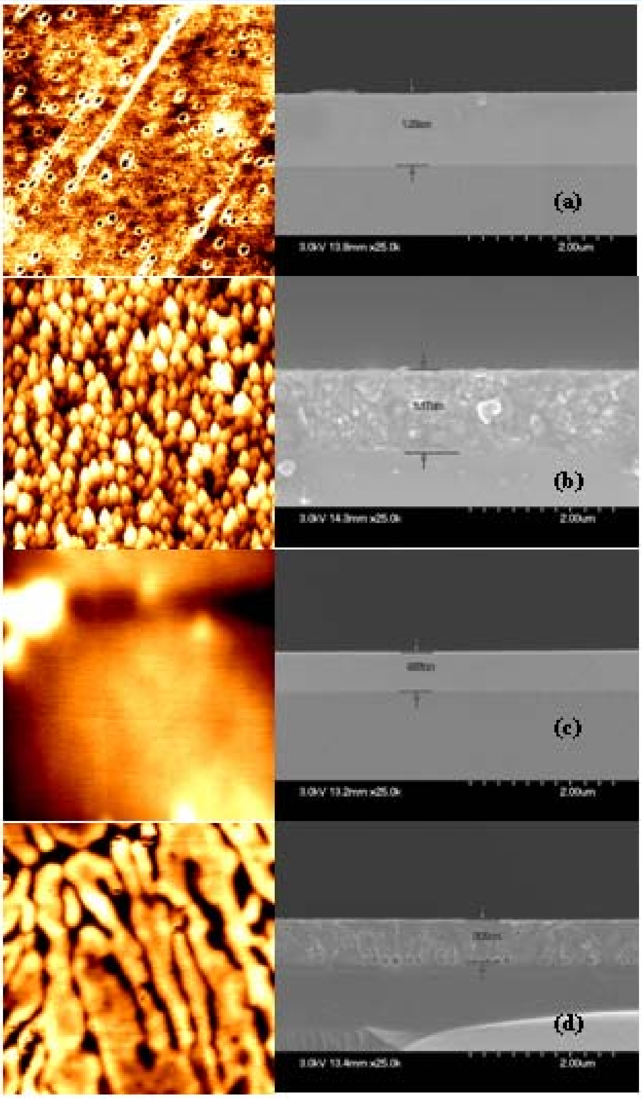


Fig. 3. AFM surface images and SEM microstructure images of MO garnet layers. (a) 1020 nm thick amorphous (as deposited) layer of $Bi_2Dy_1Fe_4Ga_1O_{12}$ on a glass substrate; (b) 1170 nm thick layer of $Bi_2Dy_1Fe_4Ga_1O_{12}$ on a GGG(111) substrate annealed for 1hr @ 700C and having a granular structure of nanocrystallites; (c) 556 nm thick layer of high-MO-quality composite garnet Bi_2O_3 : $Bi_2Dy_1Fe_4Ga_1O_{12}$ on a glass substrate, annealed for 1 hr @ 520C and having an almost perfect microstructure; (d) 603 nm-thick layer of composite Bi_2O_3 : $Bi_2Dy_1Fe_4Ga_1O_{12}$ with high excess Bi_2O_3 content, on a glass substrate, possibly over-annealed (2 hrs @ 580C). The AFM/SEM images are courtesy of Young Min Song, Gwangju Inst. of Science and Technol., South Korea.

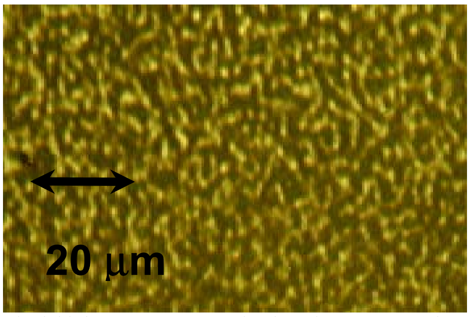


Fig. 4. A typical high-contrast magnetic domains pattern (observed using a transmission-mode polarising microscope) in our all-garnet heterostructures having several in-built MO garnet layers of about 200 nm thickness.

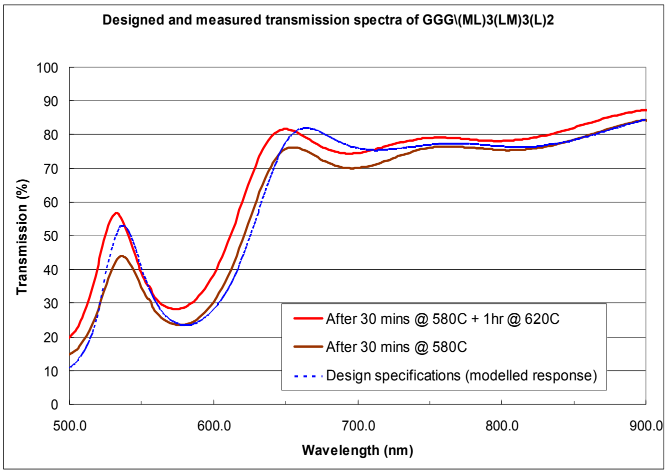


Fig.5. Model comparison and the measured results of optical characterisation of an annealed all-garnet heterostructure GGG/(ML)3(LM)3(L)2 (L = GSGG, M = $Bi_2Dy_1Fe_4Ga_1O_{12}$, quarter-wave layers) having a peak of enhanced optical transmission near 532 nm band. The MO response (Faraday rotation angle) at the peak wavelength was however less than half of expected value, due to the imperfect microstructure obtained in very thin (54 nm) (Bi,Dy):IG layers.

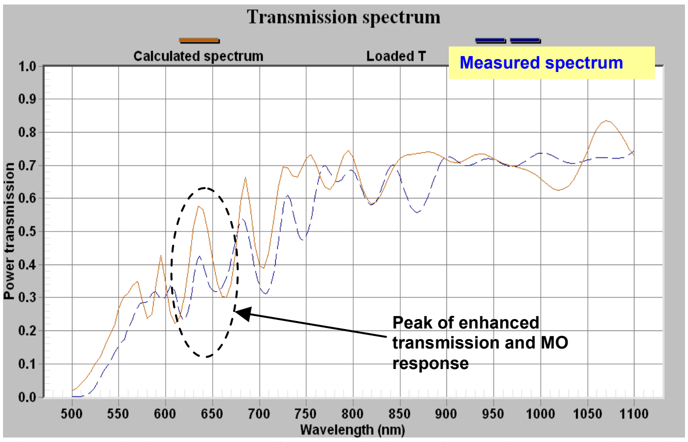


Fig.6. Transmission spectrum of an annealed complex (14 layers) quasiperiodic all-garnet heterostructure GGG\(MM)1(LM)3(MM)2(ML)4 where L = GSGG, quarter-wave layers, M = $Bi_2Dy_1Fe_4Ga_1O_{12}$, $3\lambda/4n$ layers, purpose-designed for testing the MO performance of sputtered MPC structures through the visualization of magnetic fields of magnetised objects in either the transmission or reflection mode, with image memory.

The heterostructure described in Fig. 6 can be viewed as a simple MPC due to its quasi-periodic design. It was used to memorise and visualise the magnetic recording pattern of a credit card's magnetic stripe using a transmission-mode polarising microscope (the measured result is displayed in Fig. 7).

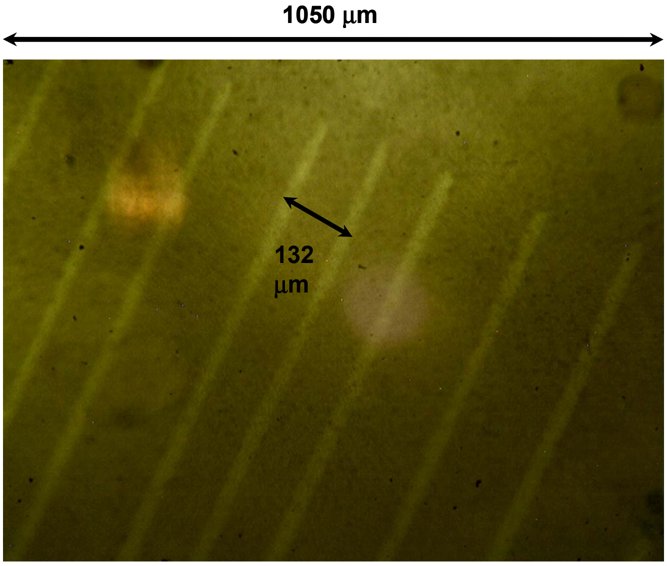


Fig.7 A high-contrast image of a credit card's magnetic recording pattern obtained using the heterostructure of Fig. 6 (after being placed in contact with the card's magnetic stripe) in transmission mode. A single thick layer of (Bi,Dy):IG wouldn't have been able to be used for obtaining this MO image, due to having typically a much larger coercive force (near 1 kOe) compared to the nanostructured material system designed (less than 500 Oe).

IV. CONCLUSION

We have manufactured and characterised layers of doped iron garnet materials as well as quasiperiodic all-garnet heterostructures possessing very high optical and magneto-optical quality, as well as attractive magnetic properties, which are suitable as components of future magnetic photonic crystals capable of demonstrating novel functionalities which are desirable in next-generation integrated-optics devices.

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