Nano-Structured Magnetic Photonic Crystals for Magneto-Optic Polarization Controllers at the Communication-band Wavelengths

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Abstract—**We investigate the properties of optimized magnetic photonic crystal structures for use in integrated-optics polarization controllers. We engineer the enhancement of Faraday rotation near 1550 nm and describe a novel hysteresis-based driving scheme suitable for implementing ultra-fast polarization controllers.**

Index Terms— **Faraday rotation, magnetophotonic crystals, magneto-optic garnet materials.**

I. INTRODUCTION

THE control over the state of polarization of light waves is extremely important in a range of applications, including the development of laser- and fibre-based optical sensors, optical communications hardware, lightwave measurement and characterization systems, as well for the development of optical integrated circuits. Magnetic photonic crystals (MPC) are an emerging new type of nano-structured media which can provide new and unique functionalities for the design of integrated-optics components and systems [1-3].

Bi-doped iron garnet materials are very attractive for the synthesis of MPC due to their excellent magneto-optic (MO) properties. These materials demonstrate the highest Faraday rotation per unit thickness and very low optical losses in the infrared range [4]. Many different types of 1-D MPC structures have been proposed for enhancing the Faraday rotation of polarized light transmitted through micron-scale structures and multilayer films composed of MO and dielectric materials [3]. A structure reported in [1] predicts almost 100% wide-band transmission and near 45^0 Faraday rotation at 1.55 µm using Cerium-substituted yttrium iron garnet (Ce:YIG) and gadolinium gallium garnet (GGG) layers in a complex film of total thickness 35-40 µm, however, the structures of such complexity are very challenging for practical on-chip integration.

The maximum Faraday rotation angles that have been demonstrated experimentally so far with all-garnet heteroepitaxial MPCs are 20.06^0 at the wavelength of 750 nm and 8.4^0 at 980 nm, as reported in [3].

In this paper, we report on several designs of MPC structures capable of demonstrating very large Faraday rotation angles (in excess of 30^0) at 1550 nm which have been generated using materials characterization data obtained using our technologies for the deposition and annealing of MO garnet materials. We also propose the development of MPC-based polarization controllers for various applications in telecommunication and sensing systems. We use bismuth- and gallium-doped dysprosium iron garnet compounds as magnetic constituent and GGG and TiO_2 as non-magnetic materials. High magneto-optic quality factor of these nanostructured materials allows controlling the polarization plane of transmitted light across a wide range, by achieving Faraday angles of up to 45º using optimized 1D MPCs. RF magnetron sputtering followed by oven annealing at temperatures near 700 ºC is the core technology used for the fabrication of custom-designed MPC.

II. OPTIMIZED MPC STRUCTURES FOR POLARIZATION CONTROLLER DEVELOPMENT

A number of MPC structures have been computationally optimized where the layer thicknesses (both magnetic and non-magnetic materials were modeled as quarter-wavelength layers) and all relevant MO parameters (coercive force, saturation magnetization and gyration) have been accounted for. The spectral properties of MPCs have been analyzed theoretically (using 4x4 transfer-matrix method) for a wide range of a multi-defect structural formulae of type $(NM)^a(MN)^b, \ . \ . \ . \ , (MN)^z$ which provided optimized MPC designs within a set of pre-defined criteria. Here *M & N* represent the magnetic and nonmagnetic constituents and the repetition indices [a,........,z] can be varied within the practical range of total thicknesses (up to 15 µm). We have obtained optimized MPC designs with the structural formulae such as
(a) $S(N_1N_2)^8(MN_2)^1(MM)^{15}(MN_2)^1(N_2N_1)^8$,
(b) $S(N_1N_2)^8(MN_2)^1(MM)^{14}(MN_2)^1(N_2N_1)^7$ and
(c) $S(N_1N_2)^{10}(MN_2)^1(MM)^{14}(MN_2)^1(N_2N_1)^{10}$, where N_1&N_2 represent non-magnetic materials (TiO_2 and GGG) and M stands for $Bi_2Dy_1Fe_{4.3}Ga_{0.7}O_{12}$, while S is the GGG substrate of refractive index 1.94. During the modeling process, air was considered as the exit medium (the effect of all substrate backreflections was fully accounted for) and the gyration of only -0.001i at the design wavelength 1550 nm was used, corresponding to a specific Faraday rotation of about -0.1^0 /µm, an expected minimum value for our garnet composition. The Faraday rotation of MPCs varies greatly with gyration, and the ultimately desirable Faraday rotation (45^0) is predicted to be provided by structure (c) with the gyration of -0.0016i.

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This MPC structure is composed of 43 layers and has a total thickness of only 12.72 μm, while the other structures (a) and (b) have the thicknesses of 11.65 μm and 10.95 μm, but they don't show more than 31^0 of Faraday rotation with g = -0.001i. The transmission and Faraday rotation responses of an optimized design (c) at g = -0.001i (a conservative estimate) are shown in Fig. 1. The optical and MO properties of structure (c) can therefore be useful for the development of ultra-high-speed, wide-range polarization controllers.

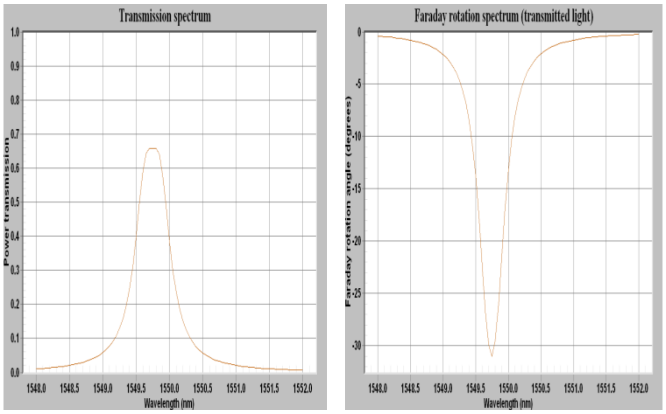
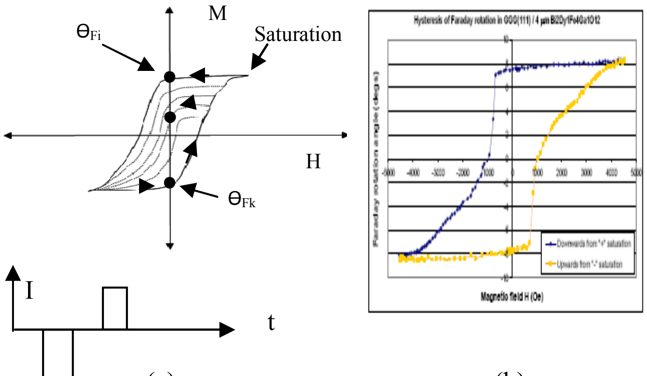


Fig. 1. Transmision and Faraday rotation spectra of the structure $S(N_1N_2)^{10}(MN_2)^1(MM)^{14}(MN_2)^1(N_2N_1)^{10}$ with 43 deposited layers, total thickness of 12.72 µm (the gyration is -0.001i) designed to generate in excess of +/-31^0 of Faraday rotation range for the transmitted light at 1550 nm.

III. FABRICATION AND CHARACTERIZATION OF MPC

Garnet films as well as the magnetic photonic crystals are fabricated using RF magnetron sputtering technology and composite oxide-based targets. A post deposition high temperature annealing process leads to obtaining polycrystalline-phase films. To obtain the optical and magnetic properties of MO films it is necessary to optimize some process parameters such as deposition process, annealing regimes and also the layer microstructure properties as the optical and magneto-optical performance are critically dependent on these parameters [4]. Crystallization of garnet materials and simultaneous crystallization of different garnet layers within the heterostructure provides a significant chance to manufacture MO garnet films and MPCs for the practical applications.

The remnance properties of our uniaxially-anisotropic garnet material will allow control over the states of remnant magnetization. By applying sequentially two very short current pulses, the remnant magnetization state of MPC can be brought to any value in between its two oppositely-magnetized saturation states within a short pulses' duration of 20-50 ns, which can switch the Faraday rotation angle to any angle between the two range-limiting states. Figure 2(a) shows the schematic diagram of utilizing the hysteresis of Faraday rotation and the minor hysteresis loops, while figure 2(b) shows the measured (major) hysteresis loop of Faraday rotation in a film of our garnet material.



(a) (b)

Fig. 2. (a) Schematic diagram of magnetic hysteresis loops including minor loops, where the minor loops show the control over the remnant state of magnetization with the very short current pulses that provides the possibility to control the polarization direction of the light propagated through the photonic crystals. (b) The measured (major) hysteresis loop of $Bi_2Dy_1Fe_4Ge_1O_{12}$ garnet-phase layer at 633 nm, with the remnant magnetization states.

IV. CONCLUSION

We have established the technologies for RF magnetron sputtering and high-temperature annealing of several magneto-optic Bi-doped iron garnet compounds possessing high magneto-optic quality (especially in the infrared spectral range), as well as uniaxial magnetic anisotropy (magnetic memory properties). Using our custom-designed algorithm for the optimization of MPC structures and our materials characterization data, we investigated the predicted performance of MPCs in the infrared range. A new approach has been proposed for achieving precise polarization control of optical waves transmitted through optimized MPCs, which utilizes a family of minor hysteresis loops and multiple levels of remnant magnetization achievable in our garnet layers. Currently, MPCs are being developed, which possess very large Faraday rotations at communication-band wavelengths and are suitable for the realization of ultra-fast, high-resolution and wide-range integrated polarization controllers.

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