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Properties of magnetic photonic crystals in the visible spectral region and their performance limitations

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ABSTRACT

We report on the results of computer modelling and performance analysis of the optical and magneto-optical (MO) characteristics of one-dimensional magnetic photonic crystals (MPC) of several classic design types (having either a single structure defect, or a number of these), designed for applications in the visible spectral region. The calculations are performed accounting for the real levels of optical absorption achievable in existing MO materials which currently demonstrate the best MO quality (bismuth-substituted ferrite garnets). We consider $Bi_2Dy_1Fe_4Ga_1O_{12}$ as the base material for use within quarter-wave thick MO layers of MPC; silica is used for the non-magnetic transparent quarter-wave layers. The achieved results can be used to clarify the nature of the differences that exist between the expected practical potential of MPCs in integrated photonics, and the actual attained experimental results. Our results show that in MPCs optimized for light intensity modulation applications, in the red spectral region (near 650 nm), the achievable levels of optical transmission are limited to about 30%. This coincides spectrally with the peaks of Faraday rotation reaching their maxima at about 25°, with further transmission increases possible in the near-infrared region. Larger Faraday rotation angles are only achievable currently in structures or single film layers with reduced transmission.

1. Introduction

Starting from the early pioneering works [1,2], photonic crystals continue to attract the attention of theoreticians and photonics experimenters, due to the potential of MPC to achieve breakthrough results in applied optics, photonics, and in the development of novel photonic integrated circuits. A summary of the initial stages of the studies conducted in the area of photonics crystals is presented in [3]. The idea of incorporating the MO materials into the structure of photonic crystals dates back to the end of last century [4,5]. Theoretical analyses have predicted that MPCs having a single structural periodicity defect based on multilayers containing bismuth-substituted ferrite garnet separated by non-magnetic dielectric layers (SiO_2 and TiO_2) could achieve a Faraday rotation angle up to 300 times greater at 1.15 μm, compared to that observed using a single magnetic layer of thickness equal to the sum of the thicknesses of the individual magnetic layers in the MPC [4,5].

Unfortunately, high amplification in the Faraday effect magnitude was only reached at optical transmission as low as 2% (in MPCs demonstrating Faraday rotation angles reaching 45°), which is quite impractical from the MPC applications point of view. A specific MPC design type, in which a relatively thick MO material film (compared to a standard quarterwave-thick structural element) has been placed in-between two Bragg mirrors, has also been reported. This MPC geometry has resulted in observing a considerable enlargement in the angle of Faraday rotation for the plane-polarized input light passing through the MPC structure, in both the Faraday geometry and the Kerr-effect (reflection) geometry [6,7].

It has also been possible to observe an increase in the Faraday rotation at the edges of photonic bandgaps in classic-type MPCs composed of quarter-wave layer sequences containing Bi-substituted iron-garnet and SiO_2 layers [8]. In addition, it has been established that with the increasing number of the periodic quarter-wave layers within MPC containing a single structure periodicity defect, at a certain level of Faraday-effect enhance-

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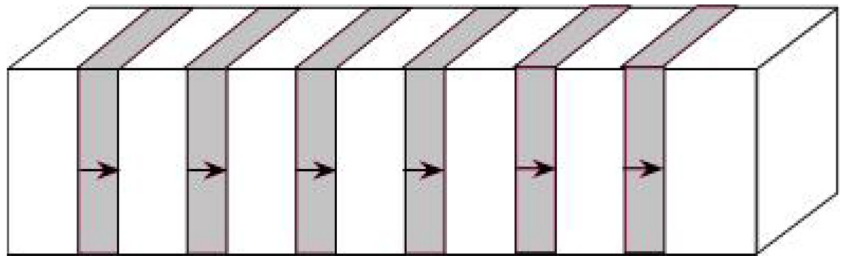

Fig. 1. A schematic diagram of a 'classic' 1D MPC structure type $(HM)^n$, composed of a set of two-material layer sequences having different refractive indices and thicknesses $\lambda/(4n_1)$ and $\lambda/(4n_2)$.

ment within a transmission-line peak located within the photonic bandgap, there appears a transmission-trench of increasing depth with the increasing layer number [9]. This effect will be discussed within the next sections.

As a result, it has so far been impossible to fulfill in practice the main requirement necessary for realizing non-reciprocal MO components, that is, reaching 45° of the polarization-plane rotation for the transmitted linearly-polarized light, at insertion losses not exceeding about 1 dB. At the same time, in the past, the published theoretical works [10,11] on the analysis of the optical transmission and Faraday rotation spectra in MPC overlooked the presence of optical absorption in the MO materials. It is known [12], that high-quality monocrystalline films of Bi-substituted ferrite garnets obtained by the liquid-phase epitaxial method, and containing about 1 formula unit (f.u.) of Bi substitution, e.g. in $Bi_1Y_2Fe_5O_{12}$ films, at the wavelength of 780 nm, the optical absorption coefficient α is near $100\ cm^{-1}$, and the same absorption coefficient is near $1000\ cm^{-1}$ at 650 nm. The values of α are typically derived from the absorption law (using a known formula $I = I_0 \cdot \exp(-\alpha \cdot H)$, where I is the transmitted light intensity, and I_0 is the intensity of incident light, and h is the film thickness in cm). It is also important to note that, in a number of studies, the absorption coefficient values have been computed using another formula (based on logarithmic transmission measurements); in these cases, the calculated absorption coefficient would have been underestimated by a factor of around 2.3.

The optical absorption coefficients of garnet films developed using RF magnetron sputtering, reactive ion-beam sputtering, or pulsed laser deposition, are in most cases higher than the values shown above for the epitaxial garnet layers, and are usually between 2000 and $5000\ cm^{-1}$ at 650 nm [13]. A detailed discussion of the main results achieved so far in the fields of the design and practical implementation of the various MPC types can be found in review literature [14,15]. Relatively recent research directions in the applied magnetophotonics are being explored actively at present [16–19], which include the development of highly sensitive sensor devices employing MPC-enabled magneto-plasmonics. Some alternative and novel approaches to constructing and tuning the properties of photonic crystals using magnetic fluids have also been developed recently [20,21], extending the available range of magnetic materials for MPC beyond solid-state film-based materials.

In this work, we report on the current limitations of MPC employing highly bismuth-substituted iron garnet films within optimized quasi-periodic multilayer structures, in terms of the achievable performance characteristics which underpin their functionality in integrated optics applications. We investigate the role of performance-limiting factors such as optical absorption of high-performance garnet materials and the tendency of spectral transmission peaks of optimized MPCs to split at high magnifications of Faraday rotation. The findings clarify the potential performance parameters achievable with MPC technologies, based on today's MO materials, and highlight the need to continue developing new MO materials for applications in the visible spectral range.

2. Classification of the different main types of MPC structures and analysis of their performance

This section aims to classify the different MPC design types developed to date. Fig. 1 shows a MPC of a classic design type of structure $(HM)^n$ where H denotes a non-magnetic material layer of thickness $\lambda/(4n_H)$, M is a MO material layer of thickness $\lambda/(4n_M)$, and λ is the design wavelength. Parameters n_H and n_M denote the refractive index of the non-magnetic and magnetic materials, respectively. This structural type of MPC designs is characterized by a set of the so-called photonic bandgaps, which are regions of spectrum in which the propagation of light is prohibited, even if both optical materials were ideally transparent (optically lossless) across the same spectral regions.

Since we are considering magnetic photonic crystals, it is supposed that (at least) one of the materials used possesses magnetic properties. Of special interest is another MPC class, which is usually termed "MPC possessing structural defect(s)". Fig. 2 shows MPCs with a singular structure defect, of type $(HM)^n(MH)^m$ (Fig. 2(a)) and $(H_1H_2)^n(M)^6(H_2H_1)^m$ (Fig. 2(b)). For the calculations (presented within the next section), we supposed that all magnetic (M) layers were composed of $Bi_2Dy_1Fe_4Ga_1O_{12}$, having a refractive index of $n_M = 2.4$, with layer thickness being $\lambda/(4n_M) = 67.7$ nm, and the specific Faraday rotation of 2°/μm at the design wavelength of 650 nm. We also presume that both the substrate and H layers are composed of silica (SiO_2) with $n_H = 1.5$, and that the corresponding quarter-wave thickness of H layers was $\lambda/(4n_H) = 108.3$ nm. The layer thicknesses were selected in this way to ensure that the optical transmission line which appears within the photonic bandgap of the MPC, was centered at 650 nm.

2.1. Computational modelling of the optical transmission and Faraday rotation for 1D single-defect MPC of structure $(MH)^5(HM)^5$

To enable computational analysis of MPC performance, a computer program was developed, allowing the modelling (and optimization) of arbitrary MPC design types and visualization of their spectrally-dependent performance parameters. A graphical interface was designed using Microsoft Visual Studio .NET 2003 [9], and an algorithm was implemented using Managed C++, which enabled conveniently setting up and running the arbitrary multi-parameter numerical optimization tasks aimed at identifying the best MPC designs of any selected structural type. All relevant materials-related data, including the spectral dispersion dependencies for both the refractive indices and their specific Faraday rotation, were accounted for in the calculations.

Fig. 3 shows the computed results for the spectral dependencies of the optical transmission and the (one-way) Faraday rotation angle in the spectral region between 640 and 660 nm, within the