2005

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This is an Author's Accepted Manuscript of: Vasiliev, M. , Alameh, K. , Belotelov, V., Kotov, V., & Zvezdin, A. (2005). Optimised nano-engineered 1-D magnetophotonic crystals for integrated-optical modulators. Proceedings of IFIP VLSI-SoC 2005. (pp. 411-415). Perth. IFIP. Available here.

Optimized nano-engineered 1-D magnetophotonic crystals for integrated-optical modulators

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Abstract

The optimization of multilayer 1D magnetophotonic crystals with multiple nano-engineered defects enables novel practical photonics applications. The properties of several optimized structures suitable for infrared intensity modulators are discussed. A novel approach to the design of integrated multi-channel WDM/DWDM transmission loss equalizers is proposed. We also show the effect of material absorption on the spectral properties of magnetic photonic crystals, which is a factor of primary importance for the design of short-wavelength infrared modulators.

1. Introduction

Recently, the use of single-crystal magneto-optic films has opened the way towards the realization of integrated optical isolators [1]. The required thickness of a MO film that can rotate the light polarization by 45° is around 500 microns for the 1550 nm telecommunications window. This high thickness limits the density of components that can be integrated in a single integrated photonic chip. The capability of thin MagnetoPhotonic Crystals (MPC) to realize high polarization rotation has attracted the interests of many researchers [1-11].

Most of the recent research activities on MPC structures have focused on optimizing the thickness of 1-D structures to simultaneously achieve 45 degrees Faraday rotation angle and high transmission within an optical telecommunication window of a few nanometers. MPC's based on quarter-wavelength stacks - sequences of magnetic and nonmagnetic layers with multiple defects, or missing layers, have been shown to possess a significant potential for the practical implementation of integrated optical isolators due to the resonant enhancement of Faraday rotation observed in such structures. 1-D magnetophotonic structure designs featuring "flat-top" response, almost 100 % transmission within a few nm bandwidth and 45 degrees Faraday rotation at 1550 nm can contain in excess of 200 layers [4], limiting their applications to the 1.3 μm and 1.55 μm windows where the magnetic materials possess very low material absorption.

The design of magneto-optic modulators for the light intensity control applications in the short-wavelength infrared region (around 850 nm) requires accurate modeling of the MPC optical properties in the presence of absorption, and necessitates the development of optimization algorithms. Broadband MPCs having high Faraday rotation and low rotation ripple are desirable whenever an optical source suffers spectral instabilities and variable operating temperatures.

In addition, when a modulator requires precise control of the transmitted intensity over the entire spectral width of the source, the spectral flatness of the Faraday rotation becomes a critical issue.

In the short-wavelength infrared range, where the absorption of iron garnets is in the range of several hundred cm^{-1} [8], there is a trade-off between the minimization of thickness and achieving the required spectral response. Moreover, the spectral widths of magneto-optic resonances generating the enhancement of Faraday rotation in MPCs become narrower as the design wavelength decreases, making it necessary to incorporate more phase shifts into the design of broadband MPCs. The stringent and often conflicting restraints on the modulator element's optical properties imposed by the requirements of practical applications lead to the necessity of employing optimization algorithms during the design of MPC structures. The development of suitable optimization algorithms involves certain trade-offs between the maximum size of the processed fraction of the parameter space volume, the closeness of solutions found to the global optimum within the constraints used, and the speed of computation.

In this work, we discuss the approach to optimization undertaken and the design of MPCs with emphasis on the application-specific optimization of multi-defect structures. We also present optimization results for applications requiring either low rotation ripple around 45 degrees rotation within a broad bandwidth, or a narrow-linewidth operation utilizing small controlling magnetic fields. In addition, we discuss a novel approach to the design of WDM/DWDM transmission loss equalizers based on an optimized MPC and the oblique incidence geometry. The material absorption in the magnetic layers was accounted for, and we demonstrate its effect on the modeled transmission and Faraday rotation spectra.

2. Theoretical background

A typical MPC structure is shown in Figure 1. This structure is denoted by $(MN)^a(NM)^b(MN)^c......(NM)^z$, where *M*, and *N* represent magnetic and non-magnetic materials, and the repetition indices *a, b, ...z* are integers. This structure represents a stack of quarter wavelength plates with defects represented by half wave steps.

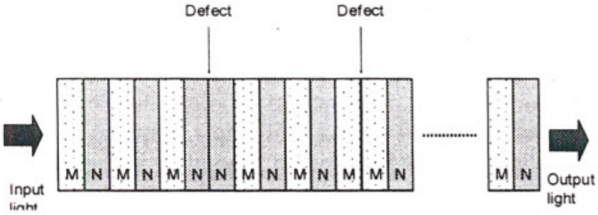

Figure 1. Typical MagnetoPhotonic Crystal (MPC) structure.

Theoretical analysis of the spectral properties of MPCs was performed using the transfer matrix approach [2, 9]. The essence of this method is to find a transfer matrix which relates the electric and magnetic field of the light in front of the MPC and behind it. The transfer matrix for the whole structure is found as the product of the transfer matrices for each layer of MPC. The transfer matrices are determined by the layers thicknesses and their dielectric tensor. While non-magnetic constituents of MPC can be usually regarded as isotropic media having a diagonal dielectric tensor, magnetic layers are described by the magnetization-dependent non-diagonal tensor, which is for the case of the magnetization directed along *Z*-axis given by

$$\hat{\varepsilon}_M = \begin{pmatrix} \varepsilon_1 & -ig & 0 \\ ig & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_2 \end{pmatrix}, \qquad (1)$$

where the gyration, g, and dielectric constant, ε_2, depend on the magnetization, with g and $b = \varepsilon_2 - \varepsilon_1$ vanishing at zero magnetization. This implies that optical anisotropy for such materials is purely magnetic field-induced [12]. The gyration vector g is linear with respect to the media magnetization, while the Cotton-Mouton constant *b* is proportional to the magnetization squared, which classifies them as being first- and second-order magneto-optical constants, respectively. For the conventional magnetooptical materials (e.g., for the yttrium iron garnets) the second-order effects can be neglected, and consequently, we restrict our consideration here to only the first order magneto-optical phenomena by setting the Cotton-Mouton constant, *b*, to zero. For the optical domain the permeability tensor $\hat{\mu}$ is considered to be a unity tensor.

The transfer matrices formalism deals with the proper modes - waves which preserve their polarization state while traveling through the media. For the isotropic dielectric proper modes are usually a set of two orthogonally polarized waves. In the case of normal light incidence, the proper modes in the magnetic media for the electromagnetic radiation propagating parallel to the magnetization are two clockwise and counterclockwise circularly polarized waves of different refractive indices:

$$n_{\pm} = \sqrt{\varepsilon_1 \pm g}\ . \qquad (2)$$

In the case of oblique incidence, the proper modes are two elliptically polarized waves, and the spectral response of the structure depends on both the incidence angle and the state of polarization of incident light [11]. A detailed description of the transfer matrices technique is omitted here but it can be found elsewhere [2,9].

In order to search the parameter space composed of a multitude of possible designs with variable layer sequences, numbers of defects and layer repetition indices, an efficient Windows-based C++ algorithm was developed, allowing the complete target performance-based spectral analysis of about 20000 design variations per minute.

The optimization approach used in our algorithm is based on "exhaustive computation" of either the entire parameter space defined by an arbitrary selected type of a structural formula, or of an arbitrarily sampled fraction of such space. The latter technique, whilst not generally leading to the location of global optima, often allows finding suitable solutions quickly, even within very large multi-defect parameter spaces, by limiting calculations to a selected subset of the design domain. For example, considering only symmetric combinations of sub-stack repetitions reduces the computation time substantially. Even though the processing of complete parameter spaces (within the restraints imposed on the maximum number of sub-layer repetitions and the maximum total thickness) is quite computationally-intensive, we found this approach very useful practically, especially when considering MPC structure types with up to seven phase shifts.

3. Results and discussion

A. MPC Optimization for short-wavelength infrared applications

The search for globally optimized MPC structures (considering the entire parameter space within a chosen type of design formula, including non-symmetric layer sub-sequences) using a set of simultaneous target requirements with respect to bandwidth, transmission, Faraday rotation angle, rotation ripple and thickness was limited to structures with a maximum of 7 defects. The structures under consideration were defined by the formula $(NM)^a(MN)^b....(MN)^z$, where M layers denote the magnetic bismuth substituted YIG, and N layers denote the non-magnetic silica (SiO_2) layers considered non-absorbing. The choice of this type of the structural formula was dictated by the fact that its multi-defect parameter space was found to contain a huge variety of MPC designs with the spectral properties varying from highly resonant, narrow-linewidth to the ultra-broadband, and with a great number of possible spectral shapes of transmission and Faraday rotation responses. We believe it is for this reason a number of MPCs based on this structural formula was previously reported in the literature as being potentially suitable for future integrated-optics applications, with most emphasis previously placed on isolator applications. In this paper, we show results of the application of our optimization algorithm applicable for building practical light intensity modulation devices in both short-wavelength infrared and communications-band ranges, as well as propose a new scheme for building high-resolution magnetic field sensors based on using the tailor-made spectral properties of an optimized MPC.

During the optimization of multi-defect structures containing highly absorptive magnetic layers (850 nm intensity modulator application), the range of repetition indices [a..z] was limited to [1..10] and film thicknesses considered of practical interest were limited by 10 microns. All layer thicknesses were set equal to the quarter of the design wavelength in the corresponding material, and only the case of normal light incidence was considered. The results of our optimization are however, also applicable for the case of oblique incidence at small angles, where the Faraday rotation responses of s- and p-polarized components of incident light are almost identical, with an added advantage of the tunability of the spectral region of MPC operation with the variable angle of incidence [11]. In most optimized MPCs utilizing similar structural formula reported to date, symmetric sequences of repetition indices are used, however, in our modeling all possible combinations of those were considered, in fact, the non-symmetric sub-stack sequences represented the majority of optimized solutions (regardless of the nature of target requirements used) found in our modeling. The limitation on the range of repetition indices was dictated by the necessity to reduce the volume of the parameter space whilst at the same time considering a large number of multidefect designs with moderate thicknesses.

A sample result of optimizing the structures with up to 7 defects with respect to bandwidth and flatness of Faraday rotation (together with other requirements specifying the maximized transmission simultaneous with the rotation angles around the design wavelength being in the vicinity of 45 degrees at saturated gyration) is represented in Figures 2 and 3. The parameters used during the calculations were: design wavelength 850 nm, $\varepsilon(SiO_2) = 2.10$, $\varepsilon(Bi:YIG) = 7.29$, and saturated gyration $g = 0.0256$ was inferred from the material's specific Faraday rotation (at the saturation magnetization) of 2 degrees per micron, which correlates with the experimental data presented in [8].

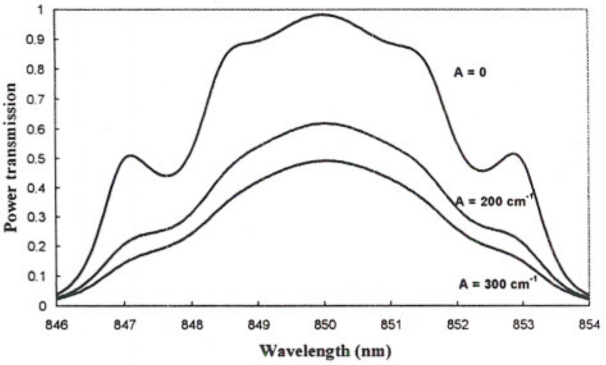

Figure 2. Transmission spectra of the magnetophotonic crystal structure $(NM)^3(MN)^7(NM)^7(MN)^2(NM)^2(MN)^7(NM)^5(MN)^1$ optimized for broad bandwidth, low rotation ripple operation at 850 nm in the presence of saturated magnetization ($g = 0.0256$). The effect of material absorption inside the magnetic layers is shown.

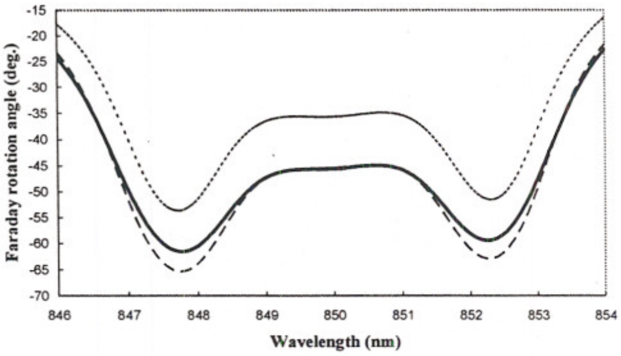

Figure 3. Faraday rotation spectra of the optimized photonic crystal structure $(NM)^3(MN)^7(NM)^7(MN)^2(NM)^2(MN)^7(NM)^5(MN)^1$ for various values of the absorption coefficient and gyration: $A = 200\ cm^{-1}$, $g = 0.02$ (dotted line); $A = 200\ cm^{-1}$, $g = 0.0256$ (dashed line); $A = 300\ cm^{-1}$, $g = 0.0256$ (solid line).

The refractive indices of the optical substrate and the exit medium were assumed to be matched to the mean index (1.88) of the structure. The optimized magnetophotonic crystal structure is represented by the formula: $(NM)^3(MN)^7(NM)^7(MN)^2(NM)^2(MN)^7(NM)^5(MN)^1$ with a total of 68 layers and a thickness of only 7.6 microns.

The effect of absorption on MPC spectral properties, limiting the structure's performance in both transmission and achievable Faraday rotation angles, is shown. The value and flatness of Faraday rotation near the design wavelength were found to vary only very insignificantly in response to changes in the absorption coefficient. The flatness of the Faraday rotation response is also maintained under variable gyration conditions. To the knowledge of the authors, we report here for the first time a design of an MPC structure capable of achieving the 45 degrees of ripple-free Faraday rotation within a bandwidth of about 2 nm and at the same time requiring a moderate number of layers, at this wavelength. This makes our proposed structure suitable for the practical implementation in infrared isolators and intensity modulators.

The optimized MPC provides low-ripple Faraday rotation of 5.97 degrees per micron near the design wavelength, which results from the presence of weakly resonant cavities in the structure that effectively increase the propagation path length. The influence of absorption on the MPC spectral properties is also structure-dependent, which results in a trade-off between the degree of resonant amplification of Faraday rotation and the achievable transmittance.

The angle of Faraday rotation in Figure 3 varies by only ±1 degree around -45.9 degrees within the spectral interval between 849.06 nm and 851.17 nm. Further adjustment for the degree of flatness of the Faraday rotation is possible by varying the refractive indices of the index-matching layers at the edges of film.

B. Optimized MPC for integrated modulators and WDM equalizers

The ability to tune the operational wavelength of the MPC by varying the angle of incidence analyzed in [11] opens up a possibility of designing demultiplexers with magneto-optic equalization of transmission loss. A passive or reconfigurable (based on a spatial light modulator utilizing liquid crystal on silicon (LCOS) technology) diffraction grating can be used to generate an appropriate (peak transmission-tuned) array of incidence angles for the light carrying several WDM signal channels [13]. The light incident on the MPC has to be polarized (in an arbitrary plane for the case of near-normal incidence, since the s- and p-polarization responses in both transmission and Faraday rotation are then nearly identical). Another polarizer (analyzer) can be used in the optical path after the MPC to achieve extinction when the plane of polarization is rotated magnetooptically by 45 degrees in a chosen direction. The transmitted intensity in each channel can then be controlled independently by rotating the required planes of polarization by ±45 degrees with magnetic fields applied locally using an array of integrated current-carrying coils encircling the propagation paths of light. The crosstalk in the output will be very low due to the spatial separation of the channel propagation paths and the spectral sharpness of the MPC transmission resonances which are tuned to their corresponding angles of incidence. Due to the very low absorption of bismuth or cerium-substituted YIG in the 1.55 μm optical telecommunications window, it is possible to design MPC structures possessing very sharp spectral resonances having high transmission coupled with significantly enhanced Faraday rotation. In this case, relatively small magnetic fields can achieve large Faraday rotations within narrow spectral windows, which can be tuned by changing the incidence angle. For example, an MPC structure with a design formula $(NM)^{10}(MN)^{1}(NM)^{1}(MN)^{10}$, in which SiO_2-layers are used for non-magnetic constituent ($\varepsilon = 2.24$), has a very sharp resonant behaviour in both transmission and Faraday rotation near the wavelength of 1.55 μm. This quarter-wave stack structure is composed of 44 layers and has a thickness of 9.55 μm. The spectral response of this structure, its variation with the angle of incidence and its optical response to the gyration are shown in Figure 4. Here, we assumed the surrounding media to be SiO_2 (substrate) and air. The gyration required for achieving the 45 degrees of rotation is $g = 0.0017$, which can be achieved at less than 20% of the saturation magnetization for Ce:YIG.

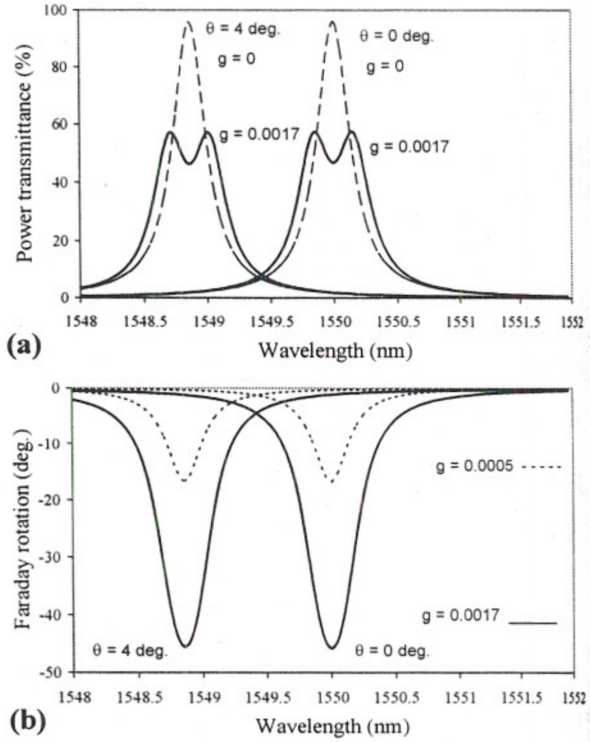

Figure 4. Transmittance and Faraday rotation spectra of the structure $(NM)^{10}(MN)^{1}(NM)^{1}(MN)^{10}$ at normal and 4 degrees incidence with various strengths of the applied magnetic field.
(a) Averaged (unpolarised) transmittance spectra at normal and 4° incidence and their variation with gyration;
(b) Faraday rotation spectra for p-component of incident light at normal and 4° incidence at various gyrations. The spectral responses of s- and p-components of polarization are almost identical at near normal incidence.

The splitting of two transmission resonances and its associated reduction in peak transmission observed at high levels of induced gyration limit the dynamic range of the device and introduce some extra loss, however, in some equalizer applications these drawbacks can be outweighed by the advantages of the high-speed operation characteristic of the magneto-optic devices. The response time required for switching of each channel from a minimum to a maximum of transmitted intensity can be as short as tens of nanoseconds.

The range of incidence angles (and, consequently the number of channels that can be processed by a single device of this type) can in principle be extended to large angles if control of the polarization of incident light is implemented.

The wavelength-tuning curve (the dependency of the MPC operational wavelength on the angle of incidence) of the structure being considered is shown in Figure 5. This dependency is highly nonlinear for very small angles of incidence, but for moderate incidence angles, it can be approximated by a linear function with a slope of about 1 nm/deg for index-unmatched air and glass surrounding media and 6.7 nm/deg for index-matched surrounding media. The structure of the dispersion grating to be used for demultiplexing the multi-channel optical input must be optimized to closely match its angular dispersion function with a selected section of the wavelength-tuning curve of the MPC.

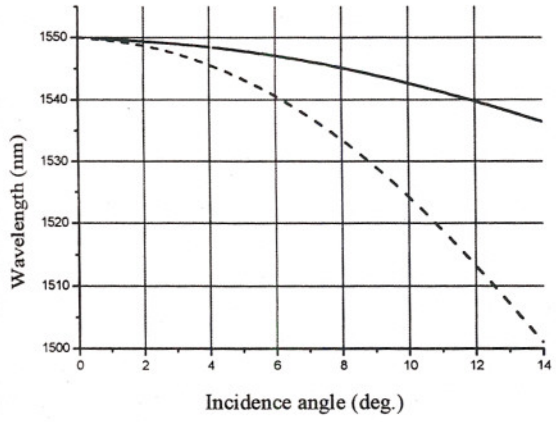

Figure 5. MPC operational wavelength as a function of incidence angle for the structure $(NM)^{12}(MN)^{1}(NM)^{1}(MN)^{12}$ sandwiched between (i) air and glass ($\varepsilon_a = 1, \varepsilon_b = 2.310$) (solid line), or (ii) two identical media index-matched to the mean refractive index of the structure ($\varepsilon_a = \varepsilon_b = 3.168$) (dashed line).

4. Conclusions

The properties and predicted performance of several MPC structures with multiple phase shifts optimized for infrared-range integrated optics applications have been discussed. We placed a particular emphasis on reducing the number of layers required for achieving the desired MPC properties for use in intensity modulators and accounted for the material absorption effects. Several features of the optimized MPCs are reported for the first time, for example, the achieved spectral flatness of Faraday rotation in the short-wavelength infrared range, and the possibility of building communications-band intensity modulators and WDM equalizers requiring a very small controlling magnetic field.

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