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# Magnetic Photonic Crystals: 1-D Optimization and Applications for the Integrated Optics Devices

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# Magnetic Photonic Crystals: 1-D Optimization and Applications for the Integrated Optics Devices

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***Abstract*—The optimization of multilayer one-dimensional (1-D) magnetophotonic crystals (MPCs) with multiple phase shifts, enabling their design to be tailored to practical photonics applications, is reported. The properties of sample optimized structures suitable for application in infrared intensity modulators are discussed. A novel scheme of high-resolution magnetic field sensing using MPCs is proposed. The effect of material absorption on spectral properties is shown.**

***Index Terms*— Faraday rotation, magnetic photonic crystals, optimization, sensors.**

## I. INTRODUCTION

RECENTLY, a considerable amount of research interest was dedicated to the field of magnetooptics; in particular, various approaches to the design of magnetophotonic crystals (MPCs) with properties suitable for the fabrication of integrated optical isolators have been reported [1]–[11].

Most of the recent research activities have focused on optimizing the thickness of one-dimensional (1-D) structures to simultaneously achieve 45° of Faraday rotation angle and high transmission within an optical telecommunication window of a few nanometers. MPCs based on quarter-wavelength stacks, which are sequences of magnetic and nonmagnetic layers with multiple phase shifts (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. One-dimensional magnetophotonic structure designs featuring “flat-top” response, almost 100% transmission within a large bandwidth (several nanometers), and 45° of Faraday rotation at 1550 nm can contain in excess of 200 layers [4], limiting their applications to the 1.3- and 1.55-$\mu$m windows where the magnetic materials (typically iron garnets with dopants) possess very low material absorption.

The design of magnetooptic modulators for 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 in applications involving an optical source with spectral instabilities and variable operating temperatures.

Furthermore, in modulator applications requiring 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 $\mathrm{cm}^{-1}$ [8], the tradeoff between the minimization of thickness and the realization of arbitrary spectral properties is a difficult task. Moreover, the spectral widths of magnetooptic 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 optical properties of the modulator element 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 tradeoffs 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 paper, we discuss the approach to optimization undertaken and the design of MPCs with emphasis on the application-specific optimization of multidefect structures. We also present results on optimized transmitted intensity modulation for applications requiring either low rotation ripple around 45° within a moderately broad bandwidth or a narrow-linewidth operation utilizing small controlling magnetic fields. In addition, we discuss the reconfiguration of the spectral transmission of a particular MPC structure that can be used for high-sensitivity magnetic field sensing. Furthermore, the material absorption in the magnetic layers is quantitatively investigated and its effect on the modeled transmission and Faraday rotation spectra is accurately simulated.

## II. THEORY

The theoretical analysis of the spectral properties of MPCs has been performed using the transfer matrix approach [2], [9]. The essence of this method is to find a transfer matrix that relates the electric and magnetic fields of the light in front

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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 layer thicknesses and their dielectric tensor. While nonmagnetic constituents of MPC can be usually regarded as isotropic media having a diagonal dielectric tensor, magnetic layers are described by the magnetization-dependent nondiagonal tensor, which is for the case of magnetization directed along the $z$-axis given by

$$\hat{\varepsilon}_M = \begin{pmatrix} \varepsilon_1 & -ig & 0 \\ ig & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_2 \end{pmatrix} \tag{1}$$

where the gyration $g$ and the dielectric constant $\varepsilon_2$ depend on the magnetization, with $g$ and $b = \varepsilon_2 - \varepsilon_1$ vanishing at zero magnetization. This implies that the 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 magnetooptical constants, respectively. For conventional magnetooptical materials (e.g., for the yttrium iron garnets), the second-order effects can be neglected, and consequently, it is reasonably accurate to restrict our consideration here to only the first-order magnetooptical phenomena by setting the Cotton–Mouton constant $b$ to zero. For the infrared-visible domain, the permeability tensor $\hat{\mu}$ is considered to be a unity tensor.

The transfer matrices formalism deals with the proper modes—waves that preserve their polarization state while traveling through the media. For the isotropic dielectric, proper modes are usually a set of two orthogonally polarized waves. Proper modes in the magnetic media for the electromagnetic radiation propagating parallel to the magnetization are two clockwise and counterclockwise circular polarized waves of different refractive indices

$$n_{\pm} = \sqrt{\varepsilon_1 \pm g}. \tag{2}$$

Detailed description of the transfer matrices technique is omitted here but can be found elsewhere [2], [9].

An MPC structure is defined by many parameters, such as layer sequences, numbers of defects, and layer repetition indices, and generally, the optimization of MPC structures leads to a multitude of possible designs. We have developed an efficient Windows-based C++ algorithm, which generates a look-up table of all possible design variations (about 20 000 designs/min), from which an optimum MPC structure is obtained by successive tightening of the spectral response specifications.

The optimization approach used in our algorithm is based on the "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, while not generally leading to the location of the global optima, often allows finding suitable solutions quickly, even within very large multidefect parameter spaces, by limiting calculations to a selected subset of the design domain. For example, considering only symmetric combinations of substack repetitions reduces the computation time substantially. Although the processing of complete parameter spaces (within the restraints imposed on the maximum number of sublayer 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.

## III. RESULTS AND DISCUSSION

### *A. Optimization of MPC Properties 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 nonsymmetric layer subsequences) 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 seven defects. The structures under consideration were defined by the formula $(NM)^a(MN)^b, \ldots, (MN)^z$, where $M$ layers denote the magnetic material (bismuth substituted YIG) and $N$ layers denote the nonmagnetic silica ($SiO_2$) layers considered nonabsorbing. The choice of this type of structural formula was dictated by the fact that its multidefect parameter space was found to contain a huge variety of MPC designs with the spectral properties varying from highly resonant narrow linewidth to ultrabroadband, and with a great number of possible spectral shapes of transmission and Faraday rotation responses. We believe it is for this reason that a number of MPCs based on this structural formula were previously reported in the literature as being potentially suitable for future integrated-optics applications, with most emphases previously placed on isolator applications. In this paper, we show results, obtained from 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 multidefect structures containing highly absorptive magnetic layers (850-nm intensity modulator application), the range of repetition indices $[a, \ldots, z]$ was limited to $[1, \ldots, 10]$, and the film thicknesses considered of practical interest were limited by 10 $\mu$m. 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 nonsymmetric substack sequences represented the majority of optimized solutions

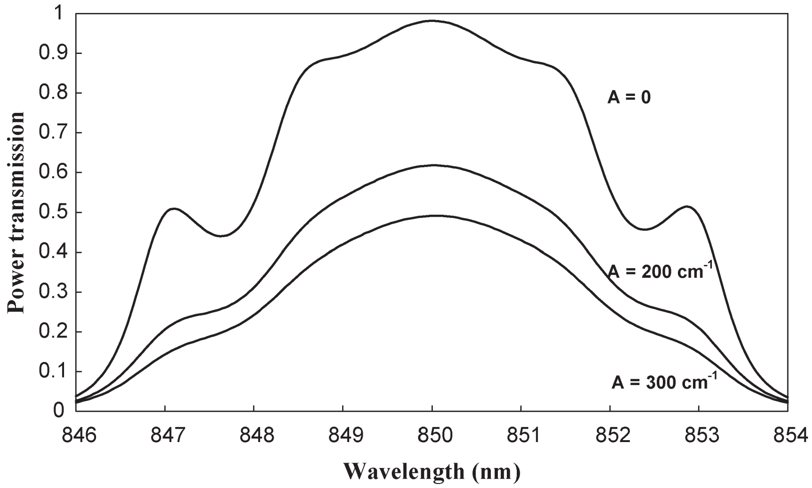

Fig. 1. Transmission spectra of the MPC structure $(NM)^3(MN)^7(NM)^7(MN)^2(NM)^2(MN)^7(NM)^5(MN)^1$ optimized for broad-bandwidth low-rotation-ripple operation at 850 nm in the presence of saturated magnetization ($g = 0.0256$). The effect of material absorption inside the magnetic layers is shown.

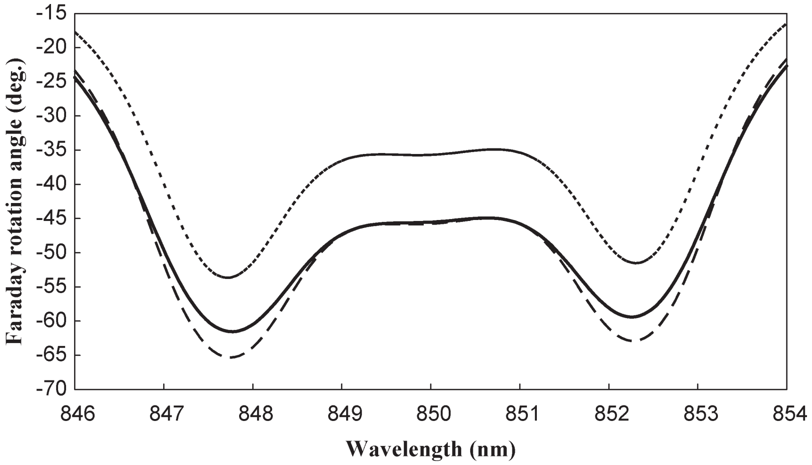

Fig. 2. Faraday rotation spectra of the optimized photonic crystal structure $(NM)^3(MN)^7(NM)^7(MN)^2(NM)^2(MN)^7(NM)^5(MN)^1$ for various values of the absorption coefficient and gyration: $A = 200$ cm$^{-1}$, $g = 0.02$ (dotted line); $A = 200$ cm$^{-1}$, $g = 0.0256$ (dashed line); $A = 300$ cm$^{-1}$,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

(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 while at the same time considering a large number of multidefect designs with moderate thicknesses.

The optimum transmission and the Faraday rotation spectra that maximize the bandwidth and flatness of the Faraday rotation of MPC structures with up to seven defects (together with other requirements specifying the maximized transmission simultaneous with the rotation angles around the design wavelength being in the vicinity of 45° at saturated gyration) are shown in Figs. 1 and 2, respectively. The parameters used during the calculations were design wavelength $= 850$ nm, $\varepsilon(SiO_2) = 2.10$, and $\varepsilon(Bi : YIG) = 7.29$, and the saturated gyration $g = 0.0256$ was inferred from the material's specific Faraday rotation (at the saturation magnetization) of $2°/\mu$m, which correlates with the experimental data presented in [8].

The refractive indices of the optical substrate and the exit medium were assumed to match the mean index (1.88) of the structure. The optimized MPC 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 $\mu$m.

As seen in Figs. 1 and 2, the absorption of the MPC layers limits the structure's performance in both transmission and achievable Faraday rotation angles. The magnitude 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. In our knowledge, we report here for the first time a design of an MPC structure capable of achieving the 45° 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 practical for the implementation of infrared isolators and intensity modulators.

The optimized MPC provides a low-ripple Faraday rotation of $5.97°/\mu$m 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 tradeoff between the degree of resonant amplification of Faraday rotation and the achievable transmittance.

The Faraday rotation in Fig. 2 varies by only ±1° around $-45.9^\circ$ within the spectral interval between 849.06 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 the film.

### *B. Optimization of Narrowband Resonances With Respect to Thickness, Transmittance, and Required Magnetization for Communications-Band Modulator Applications*

Due to the very low absorption (below 1 $\text{cm}^{-1}$) of bismuth or cerium-substituted yttrium–iron garnets in the communications-band wavelength range, it is possible to design MPC structures possessing very sharp spectral resonances having high transmission coupled with a significantly enhanced Faraday rotation. This, in turn, allows using relatively moderate magnetic fields to achieve Faraday rotations of ±45° and therefore enable the control of transmitted intensity within a narrow spectral window corresponding, for example, to a selected wavelength division multiplexing (WDM)/dense WDM (DWDM) transmission channel in an optical network.

The application of our optimization algorithm to three-defect symmetric structures of type $(NM)^a(MN)^b(NM)^c(MN)^d$ using the target criteria allowing the selection of high-transmission designs with maximized rotation angle per unit thickness of 1550 nm has resulted in finding a generalized structural formula $(NM)^x(MN)^1(NM)^1(MN)^x$ defining a class of optimized MPCs based on $\text{SiO}_2/\text{Ce}$: YIG combination fitting into these requirements. Moreover, we found that the sharpness of the spectrally coincident transmission and rotation resonances is increasing monotonically with $x$. Thus, it is easy to balance the requirements related to the transmission bandwidth and the maximum strength of the controlling magnetic field required to operate MPC-based modulators, by selecting an appropriate $x$ value in the above formula, at the stage of device design. The relative simplicity of this structural formula leads to the possibility of fabricating practical devices utilizing the unique magnetooptical response features of these photonic crystals, which we illustrate in the following examples.

For example, an optimized MPC structure with design formula $(NM)^{12}(MN)^1(NM)^1(MN)^{12}$, in which $\varepsilon_M = 4.884$ (Ce:YIG) and $\varepsilon_N = 2.24$ ($\text{SiO}_2$), has a very sharp resonant behavior in both transmission and Faraday rotation near the wavelength of 1550 nm. This quarter-wave stack structure is composed of only 52 layers and has a thickness of 11.29 $\mu$m. The transmittance and Faraday rotation spectra of this structure are shown in Fig. 3. During the modeling process, we assumed that both the substrate and the exit medium were index matched to the mean refractive index (1.78) of the structure; however, the predicted performance of the index-unmatched designs is in this case very similar. The gyration required for achieving the 45° of rotation is $g = 0.00023$, which can be achieved at about 2.5% of the saturation magnetization for Ce:YIG. To the best of our knowledge, this is the smallest predicted gyration required for achieving the 45° of Faraday rotation in any structure of comparable thickness reported in the literature so far.

The magnetic-field-induced splitting of the bandgap defect mode into two transmission resonances and the associated reduction in peak transmission are observed at high levels of induced gyration. This limits the dynamic range of modulators based on such structures and introduces some extra transmission loss. For example, a modulator can be designed to minimize the transmitted intensity when the plane of polarization of incident light is magnetooptically rotated by $-45^\circ$ and to maximize transmittance at 45° of Faraday rotation. When such a system operates at 1550 nm, about 3 dB of loss is generated by the splitting effect at maximized transmittance. The minimum transmitted intensity depends on the induced ellipticity and the spectral overlap between the communications channel and the MPC transmission spectrum. The latter can be adjusted within a small range by controlling the sharpness of MPC resonance through variations in the design formula. However, in a variety of broadband communications applications, these drawbacks can be outweighed by the advantages of the high-speed operation characteristic of the magnetooptic devices. The response time required for switching such a device from a minimum to a maximum of transmitted intensity can be as short as tens of nanoseconds, which we tested experimentally using a single-layer Bi:YIG film during measurements of its Faraday rotation response under pulsed magnetic field excitation conditions. These results will be reported in detail elsewhere.

### *C. Proposed Scheme for the High-Resolution Sensing of Magnetic Fields Using an Optimized Sharply Resonant MPC Structure*

The effect of splitting the MPC transmission resonances caused by the magnetic circular birefringence can be utilized for the sensing of magnetic fields or electric currents. For example, a highly magnetooptically resonant structure defined by the formula $(NM)^{15}(MN)^1(NM)^1(MN)^{15}$, in which Ce:YIG and $\text{SiO}_2$ are respectively chosen (similarly to subsection $B$) for magnetic and nonmagnetic constituents, can be used to generate a magnetic-field-dependent frequency separation between its two narrow-linewidth [full-width at half-maximum (FWHM) of less than 20 pm] transmission resonance peaks. The transmission spectrum of this structure at various levels of induced gyration is shown in Fig. 4. Here, an $\text{SiO}_2/\text{air}$ surrounding is assumed. The frequency separation between the two peaks (and consequently, the strength of the applied magnetic field) can be accurately determined by measuring their differential (beat) frequency in the RF domain if both spectral components are incident on the same photodetector. A bias magnetic field can be used to make the transmission peaks split initially, which will also enable the determination of external magnetic field direction together with its magnitude. About 1.5 GHz/mT of peak frequency separation sensitivity near 1550 nm was predicted from modeling of the gyration dependency of the MPC spectral transmission response and the reported value of the saturation magnetization (1400 Gs) for substituted YIG films [13]. If the frequency resolution in the signal processing

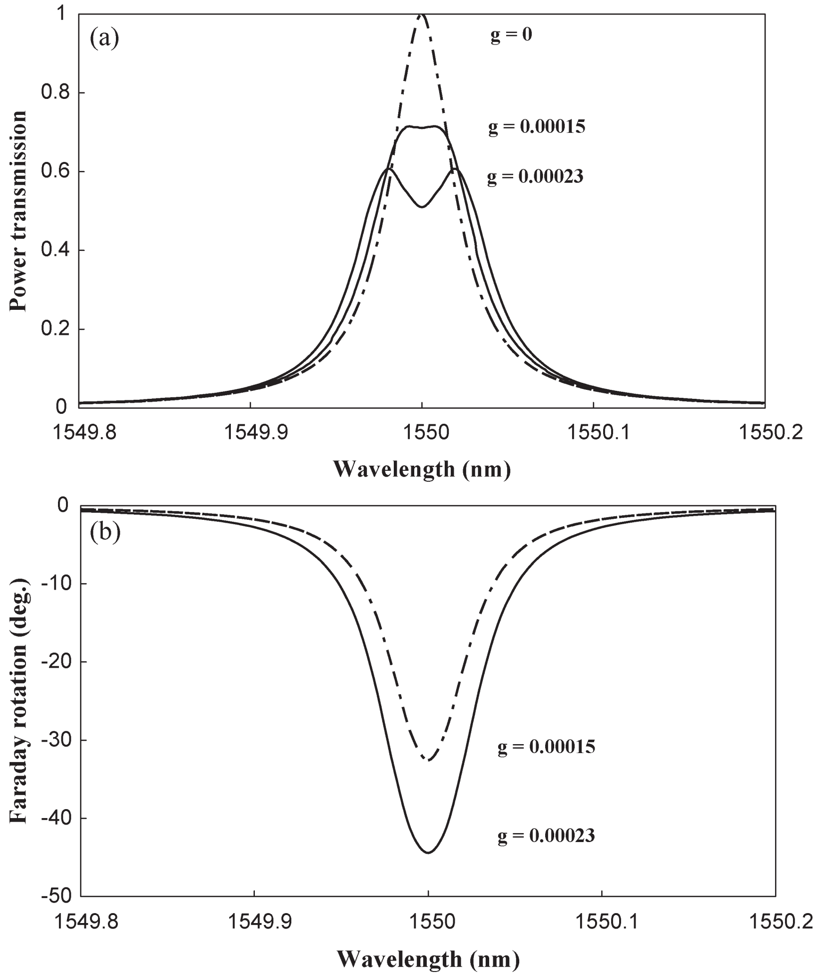

Fig. 3. Spectral and magnetooptic responses of the optimized structure $(NM)^{12}(MN)^1(NM)^1(MN)^{12}$. (a) Transmission spectrum in the absence of magnetic field and its response to magnetization. (b) Faraday rotation spectra at $g = 0.00015$ (dash-dotted line) and $g = 0.00023$ (solid line).

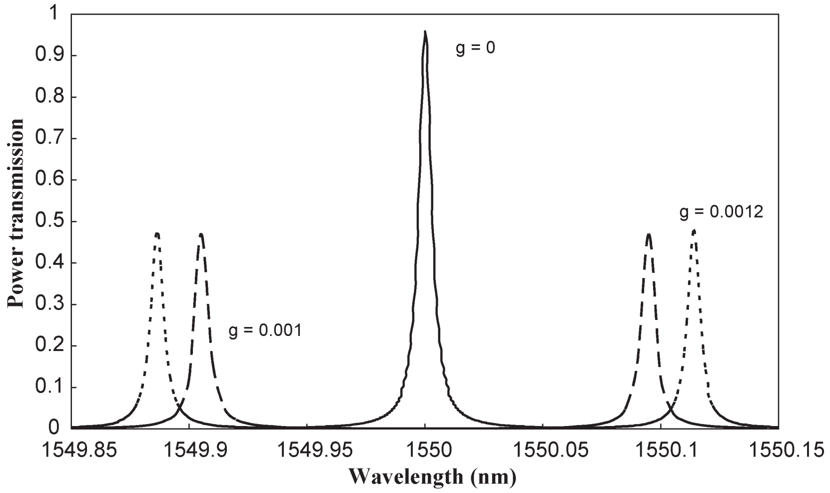

Fig. 4. Spectral transmission responses of the optimized MPC structure $(NM)^{15}(MN)^1(NM)^1(MN)^{15}$ for $SiO_2$/air external media combination at various levels of induced gyration: Transmission in the absence of magnetic field (solid line), at $g = 0.001$ (dashed line), and at $g = 0.0012$ (dotted line).

electronics is about 1 kHz, then the theoretical resolution of magnetic field sensing is in the nanotesla range, with the sensor response (the detected beat frequency) being approximately linear with magnetization and consequently with the applied magnetic field strength.

The transmission response linearity can be explained as follows. Two magnetically induced symmetric transmission peaks represent clockwise and counterclockwise circular polarization resonances wavelength shifted due to the difference in their refractive indices [see (2)]. Because $g \ll \varepsilon_1$, the refractive indices of two circular polarized waves differ by $\Delta n = g/\sqrt{\varepsilon_1}$. Consequently, the magnetically induced refractive index change is proportional to the medium gyration and, therefore, to its magnetization. At the same time, the resonance wavelength for which the magnetic layer thickness is exactly one quarter of that wavelength is proportional to the refractive index, that is, $\lambda = 4dn$, where $d$ is the layer thickness. Thus, the transmission peak position depends linearly on the medium magnetization.

The effects related to other types of birefringence or the small variations in the refractive index and thicknesses of MPC layers occurring with variations in ambient temperature or strain during measurement will limit the achievable resolution of sensing but should not significantly affect the performance of the proposed sensing scheme. For example, temperature-induced refractive index variations will affect all the MPC layers, but will largely lead to only a common-mode spectral drift of both resonance peaks.

The dynamic range of such a measurement system will depend on the saturating magnetic field and the maximum achievable resolution of the differential frequency measurement. The latter will be determined by the achievable signal-to-noise ratio and the electronic signal processing scheme. Although the light transmitted through the MPC sensor is significantly filtered in the spectral domain, which reduces the transmitted optical power, the electrical oscillations generated by the beat between the separated lobes could be distinguishable in the presence of noise. We intend to undertake the MPC sensor system development work in order to characterize the performance of such systems and report the obtained results elsewhere.

## IV. CONCLUSION

The properties and predicted performance of several MPC structures with multiple phase shifts optimized for infrared-range integrated optics applications have been discussed. The optimization process has accounted for the material absorption effects and focused on reducing the number of layers required for achieving the desired MPC properties for use in intensity modulators. Several features of the optimized MPCs have been 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 a communications-band modulator requiring a very small controlling magnetic field. In addition, we have proposed a new MPC-based scheme suitable for the sensing of magnetic fields with potentially very high resolution and speed of response. Unlike previously developed magnetic field sensors based on the measurement of the Faraday rotation angle, our proposed sensor was based on the field-induced modification of the MPC transmission spectrum and spectral domain processing (Fourier transform heterodyne spectroscopy is expected to prove an efficient signal processing technique for our sensor). The initial steps toward the practical implementation of this MPC-based sensing scheme are now being undertaken.

In addition, improvements in the optimization algorithm for searching larger volumes of the design parameter space (possibly including the reversal of magnetization within selected layers) are the subject of our ongoing research.

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