

Transmission of Non-polarized (Natural) Light by One-Dimensional Magneto-Optical Resonator Structures

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Abstract

The article presents the theoretical studies of the optical properties of such metamaterials as the One-Dimensional Magneto-Optical Resonator Structures. An interaction between non-polarized (natural) light and a magneto-optical resonator structure in a magnetic field was investigated theoretically. The presented theoretical approach is based on matrix multiple-beam summation, taking into account both the phase difference and the difference in polarization direction caused by the Faraday rotation. Attention was paid to the transmission peculiarities of the One-Dimensional Resonator Structures with isotropic zero-field magneto-optic medium inside them. Both spectral and angular distributions of a natural light transmitted through the One-Dimensional Resonator Structure in a magnetic field were investigated. As a result of research, it has been found that, despite the stereotyped view, the magneto-optical rotation of non-polarized light clearly manifests itself in the above optical characteristics of the Resonator Structures. This is explained by the fact that the Faraday rotation changes the conditions of the multiple-beam interference of light inside the Structure. This leads to changes in the interference patterns of the spectral and angular distributions of transmitted natural light and also to the appearance of interference effects for p-polarized part of the light whose reflection coefficient is equal to zero. The results can be used to create new controllable optical devices, for investigation of Faraday-active material properties and for control of parameters of plane-parallel layers and structures.

Keywords

Metematerials, Magneto-Optical Resonator Structures, Faraday Effect, Interference, Transmission

1. Introduction

Recent years, considerable attention is paid to the study of the optical properties of such metamaterials as the plane-parallel mono- and multilayer resonator structures based on dielectric, semiconductor and metallic media. Interference effects in these structures set conditions for their selective properties with respect to wavelength, direction of propagation and polarization of light. These effects result in modification of the spectral and angular characteristics of the intensity of transmitted and reflected light. Applications of magneto-optical materials as a component of the structures makes it possible change dynamically its optical characteristics by magnetic field. These effects are caused by the Faraday rotation under optical resonance conditions.

Recently, investigations of the Faraday effect have been carried out in the Fabry–Perot cavities [1-4], 1D [5-12], 2D [12-18] and 3D [12, 19-21] magnetophotonic crystals as well as in the optical Tamm structures [22-24]. Studies of such magneto-optical resonator structures (MORS) open up a number of possibilities, which have both scientific and applied importance.

Since the Faraday effect is a rotation of the light polarization plane in magnetic field, all previous studies of MORS were carried out with the linearly polarized light. In this paper, a possibility to use non-polarized light in magneto-optical phenomena observed in the resonator structures was considered. Attention was paid to theoretical studies of the transmission of non-polarized (natural) light through the one-dimensional magneto-optical resonator structure with isotropic (at zero magnetic field)

magneto-optical medium inside. The presented here theoretical approach for describing the interaction of light with a magneto-optical medium under optical resonance conditions uses multiple-beam summation taking into account the Faraday rotation. The studies cover both the spectral and angular dependences of a transmitted through MORS light in a magnetic field. Interest in these studies is related with developing new magnetically-operated optical devices for controlling external non-polarized light passing through them.

2. Modeling and Mathematical Formulation

Let us consider 1D-MOR that consists of a magneto-optical layer sandwiched between two non-absorbing mirrors, as it is shown in Figure 1. In general, the mirrors can be either single-layer or multi-layer Bragg structures. They are characterized by a reflection coefficient R (at normal light incidence). The magneto-optical layer is characterized by an isotropic (in zero magnetic field) refractive index n , absorption coefficient α , Verdet constant V and thickness d . The external magnetic field (B) is directed along the normal to the surfaces of MORS.

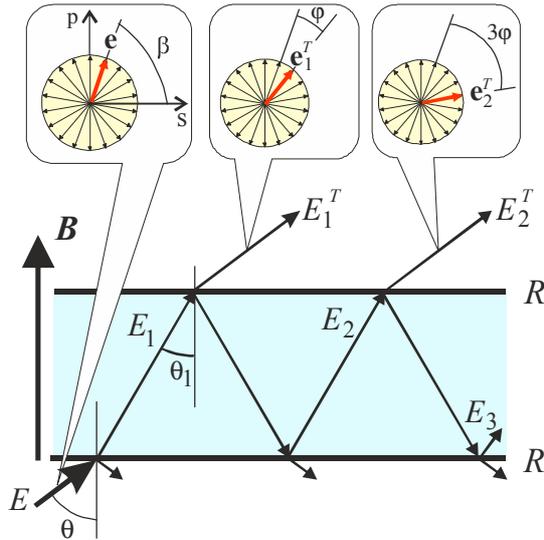


Figure 1. Demonstration of light propagation through a magneto-optical resonator structure. The azimuths of the linearly polarized components are shown on the insertions. They are shown such as at a normal incidence for visualization and convenience.

The non-polarized wave with the electric field amplitude E and the wavelength λ falls on the MORS at an angle θ (see Figure 1). As it is non-polarized, it contains equal quantities of the linearly polarized components with any planes of polarization. Spreading in the plate, they refract and reflects back in a volume and splits into the series of secondary waves E_ξ ($\xi = 0, 1, 2, \dots$). Moreover, in magnetic field B the polarization planes of the linearly polarized components turn on the Faraday angle ϕ :

$$\phi = VdB \cos(\theta_1) \quad (1)$$

where θ is a refraction angle: $\sin \theta_1 = \sin(\theta) / n$.

Under conditions of optical resonance, all secondary waves E_ξ are coherent. It is determined by a coherence of their corresponding linearly polarized components. For the calculation of light the matrixes formalism was used. The electric field vector of an arbitrary linearly polarized component \mathbf{e} (see Figure 1) of the wave E is [25]:

$$\mathbf{e} = e \begin{bmatrix} \cos(\beta) \\ \sin(\beta) \end{bmatrix} \quad (2)$$

where β is an polarization azimuth. The superscripts determine electrical field direction perpendicularly to incidence plane (s) and parallel to it (p). Time dependence of \mathbf{e} is omitted. Spreading of the linearly polarized component in MORS is described by following matrixes:

$$\mathbf{R} = \begin{bmatrix} r^{(s)} & 0 \\ 0 & -r^{(p)} \end{bmatrix} \quad (3)$$

$$\mathbf{F} = \chi \begin{bmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \exp(i\delta) \quad (4)$$

$$\mathbf{P} = \begin{bmatrix} t^{(s)} & 0 \\ 0 & t^{(p)} \end{bmatrix} \quad (5)$$

Here $\delta = 2\pi nd \cos(\theta) / \lambda$ is a phase difference, $\chi = \exp(-\alpha d / 2 \cos(\theta))$, $r_{1,2}^{(s,p)}$ and $t_{1,2}^{(s,p)}$ are, respectively, the reflection and transmission amplitudes for the mirrors. The indices (s) and (p) determine the polarization direction perpendicular to the plane of incidence and parallel to it, respectively. The matrixes \mathbf{R} and \mathbf{P} describe the mirrors reflection and refraction, respectively, \mathbf{F} is a transmission matrix with the Faraday rotation.

The electric vector \mathbf{e}_ξ^T of the corresponding linearly polarized component of ξ -th transmitted wave E_ξ^T is as follows:

$$\mathbf{e}_\xi^T = \mathbf{P}(\mathbf{FR})^{2\xi-1} \mathbf{FPe} \quad (6)$$

The electric vector \mathbf{e}^T of the total transmitted light is the sum of matrix series

$$\mathbf{e}^T = \mathbf{P} \left(\sum_{\xi=0}^{\infty} (\mathbf{FR})^{2\xi-1} \right) \mathbf{FPe} \quad (7)$$

It is easy to determine that for the eigenvalue μ of matrix \mathbf{FR} the condition $|\mu| < 1$ is always true. Hence, the sum in Eq. (9) can be replaced with the expression [26]:

$$\mathbf{e}^T = \mathbf{P}[\mathbf{I} - (\mathbf{FR})^2]^{-1} \mathbf{FPe} \quad (8)$$

where \mathbf{I} is the unity matrix.

The summarized wave \mathbf{e}^T is a linearly polarized component of a total summarized wave with the electric vector E^T . Since the separate linearly polarized components are not coherent, to determine E^T it is necessary to sum them all up:

$$E^T = \frac{2}{\pi} \int_0^{\pi} e^T d\beta \quad (9)$$

And dividing the intensity of the transmitted light by the intensity of the incident light, it is possible to obtain an expression for the total transmittance of MORS in a magnetic field:

$$T = |E^T|^2 / |E|^2 = \sum_{k,m=1}^2 |u_{km}|^2 \quad (10)$$

where u_{km} are the elements of the matrix $\mathbf{P}[\mathbf{I} - (\mathbf{FR})^2]^{-1} \mathbf{FP}$. And for s- and p-polarized parts of the transmitted light, the corresponding transmittances can be written as

$$T^{(s)} = \frac{1}{2} \sum_{m=1}^2 |u_{1m}|^2, \quad T^{(p)} = \frac{1}{2} \sum_{m=1}^2 |u_{2m}|^2 \quad (11)$$

3. Results and Discussions

3.1. Spectral Dependences of Transmission at Normal Incidence

Figure 2 shows the dependences of transmission spectra of MORS on the Faraday angle for non-polarized light at normal incidence. The following MORS parameters were taken for calculation: $|r^{(s)}|^2 = |r^{(p)}|^2 = R = 0.8$, $\eta = 1$. To generalize this description, the phase difference δ was plotted along the abscissa axis. It is seen that for $\phi = 0$ ($B = 0$) the

$$T = \frac{1}{2} \left(\frac{\chi^2 (1-R)^2}{(1-\chi^2 R)^2 + 4R\chi^2 \sin(\delta_+)^2} + \frac{\chi^2 (1-R)^2}{(1-\chi^2 R)^2 + 4R\chi^2 \sin(\delta_-)^2} \right) \quad (12)$$

where $\delta_{\pm} = \delta \pm \phi$. In Eqs (14), we took into account that in the case of non-absorbing mirrors for normal light incidence $|t^{(s)}|^2 = |t^{(p)}|^2 = (1-R)$, $R = |r^{(s)}|^2 = |r^{(p)}|^2$. As it is seen, the transmission spectrum can be described as a superposition of two selective spectra. Positions of a maxima of each of them is determined by conditions $\delta_{\pm} = \pi j$ (here $j = 0, 1, 2, \dots$) correspondingly. When the magnetic field increases, the sidebands move in different direction from an initial spectral position.

Thus, the obtained results for non-polarized incident at normal light agrees with results [4] for linearly polarized one.

distributions of transmittance has a narrow-band character with high contrast.

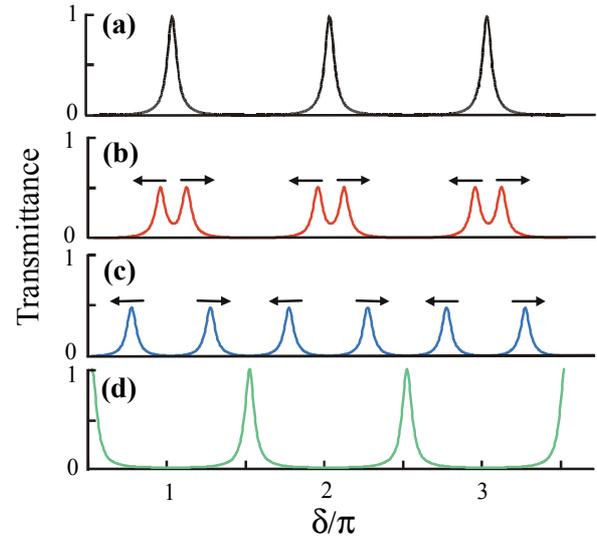


Figure 2. Transmission spectra of MORS for non-polarized normally incident light at different values of the Faraday angle. The phase difference is plotted along the abscissa axis. (a) $\phi = 0$; (b) $\phi = \pi/12$; (c) $\phi = \pi/4$; (d) $\phi = \pi/2$. The following MORS parameters were used for calculation: $R = 0.8$, $\eta = 1$.

In magnetic field, the interference line of transmitted light splits into two secondary lines, which diverge and decrease in their amplitude with increasing the field. With increasing ϕ , the secondary lines begin to merge pairwise with the neighboring one, and when $\phi = \pi/2$ the transmission spectrum takes a pronounced narrow-band character again. However, there is an inversion of the interference extremes. Positions of the lines correspond to the zero-field minima.

At normal incidence of light, it is possible to obtain from Eqs (10) and (11) the following sufficiently compact analytical expressions for the transmittance of MORS in magnetic field:

The result is very important for application in optics of incoherent light. It shows that the MORS can be locked and opened via magnetic field for external natural light.

3.2. Spectral Dependences of Transmission at Brewster's Angle

In the theoretical studies of the transmission with oblique incidence of light, a free plane-parallel magneto-optical plate was used as a MORS. Its mirrors are the interfaces, the reflection and transmission amplitudes of which are described by the Fresnel coefficients:

$$\begin{aligned}
r^{(s)} &= \frac{n \cos(\theta) - \cos(\theta_1)}{n \cos(\theta) + \cos(\theta_1)} \\
r^{(p)} &= \frac{\cos(\theta_1) - n \cos(\theta)}{\cos(\theta_1) + n \cos(\theta)} \\
t^{(s)} &= \frac{2n \cos(\theta)}{n \cos(\theta) + \cos(\theta_1)} \\
t^{(p)} &= \frac{2n \cos(\theta)}{\cos(\theta_1) + n \cos(\theta)}
\end{aligned} \quad (13)$$

This made it possible to take into account correctly changes in the reflection amplitude in the study of the angular dependences of transmission. A refractive index of the plate supposed to be $n = 2$ and absorption coefficient $\alpha = 0$.

Figure 3 shows the theoretical spectral dependences of polarized parts of the transmitted light. In order to generalize the description, the phase difference δ is plotted along the abscissa axis. The calculations were made for the incidence angle of light equal to the Brewster's angle θ_B . As is well known, when p-polarized light is incident at the Brewster's angle, its reflection is zero. And there are conditions for the multi-beam interference only for s-polarized light. However, as it is seen (Figure 3 (b) curve 2), dependence $T^{(p)}(\delta)$ oscillates in magnetic field, that indicates a presence of the multi-beam interference of p-polarized light. At the same time, the contrast of an interference pattern for s-polarization decreases. When the Faraday angle is equal to $\phi = \pi/2$, the interference is absent both for p- and s-polarized light (dependences $T^{(p)}$ and $T^{(s)}$ do not oscillate).

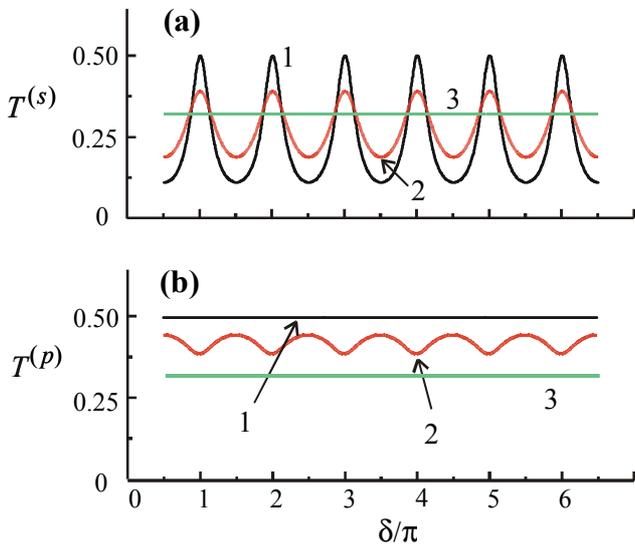


Figure 3. Transmission spectra of MORS of the s- (a) and p- (b) polarized parts of the transmitted light. Incidence angle is equal to the Brewster's angle $\theta = 63.43^\circ$. $n = 2$, $\eta = 1$. 1 (black lines) - $\phi = 0$; 2 (red lines) - $\phi = \pi/4$; 3 (green lines) - $\phi = \pi/2$. In order to generalize the description, the phase difference δ is plotted along the abscissa axis.

The changing of the dependences $T^{(s,p)}(\theta)$ is the consequence of the Faraday effect: the Faraday rotation redistributes the light regarding the polarization directions. As

a result, when $0 < \phi < \pi/2$, p-polarized coherent waves out of the MORS and form the interference pattern. At the same time, the amplitude of s-polarized waves decreases and contrast of an interference pattern decreases.

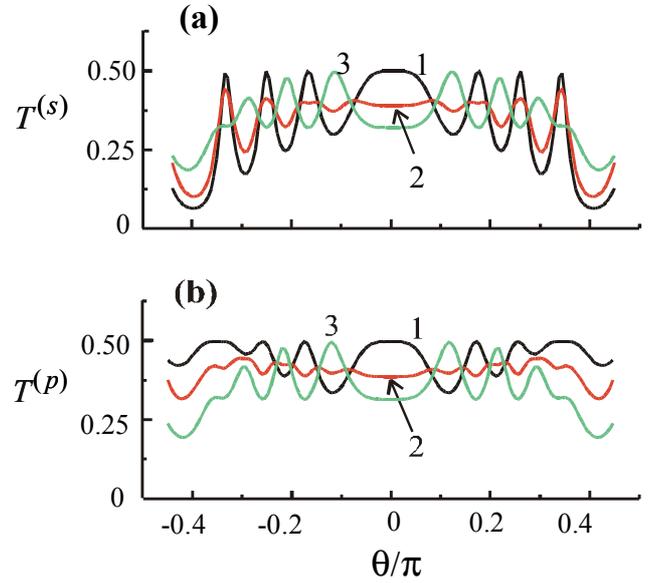


Figure 4. Angular dependences of MORS transmittance for s- (a) and p- (b) polarized parts of the transmitted light. 1 (black lines) - $\phi = 0$; 2 (red lines) - $\phi = \pi/4$; 3 (green lines) - $\phi = \pi/2$.

When $\phi = \pi/2$, initially s-polarized light becomes p-polarized and leaves out through the back face lost-free. The interference pattern is absent for both polarizations.

3.3. Angular Dependences of Transmission

The angular dependences of transmittance of the same MORS are shown on Figure 4. The decreasing of effective magnetic field is taken into account as $B \cos(\theta)$. When θ increases, contrast of the zero-field dependence $T^{(s)}(\theta)$ increases and contrast of zero-field dependence $T^{(p)}(\theta)$ decreases (curves 1 on Figure 3). In a region $\theta \approx 0.35\pi$ (region of the θ_B) a plateau is present in the dependence $T^{(p)}(\theta)$. Such behavior of $T^{(s,p)}(\theta)$ are caused by dependences $r^{(s,p)}(\theta)$ correspondingly.

In the magnetic field (curves 2), the dependences $T^{(s,p)}(\theta)$ distort. Their contrast decreases. However, there are interference peaks in $T^{(p)}(\theta)$ in θ_B region. When value of the Faraday angle is $\phi = \pi/2$, the dependences $T^{(s)}(\theta)$ and $T^{(p)}(\theta)$ become identical (curves 3). They are characterized by rather high contrast and inversion of interference extremes. Such behavior of angular dependences $T^{(s,p)}(\theta)$ is explained by redistribution of light in directions of polarization.

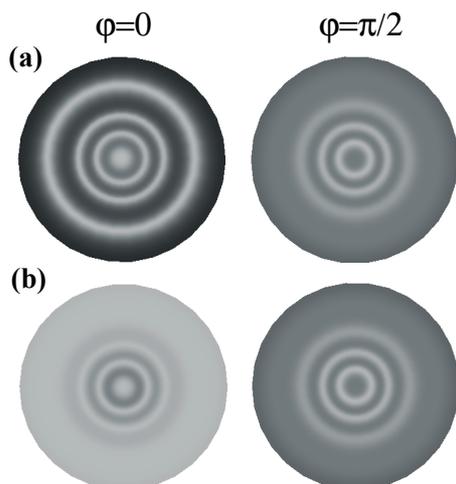


Figure 5. Isoclinic fringes of MORS for s- (a) (on the left) and p- (b) (on the right) polarized parts of the transmitted light when the Faraday angle is $\phi = 0$ (on the right) and $\phi = \pi/2$ (on the left).

The calculated isoclinic fringes of this MORS in the magnetic field for s- (a) and p- (b) polarization are shown on Figure 5. In the absence of magnetic field (on the left) their images depend on the polarization. It is caused by the angular dependences $r^{(s)}(\theta)$ and $r^{(p)}(\theta)$. At $\phi = \pi/2$ (on the right) their images are the same.

4. Conclusions

To sum it up, in the paper the propagation of non-polarized (natural) light through the one-dimensional magneto-optical resonator structures considered theoretically. The presented here theoretical approach for describing the interaction of light with a magneto-optical medium under optical resonance conditions uses multiple-beam summation taking into account the Faraday rotation. The angular and spectral distributions of transmission of MORS in a magnetic field are studied in detail.

It has been shown that, despite the stereotyped view, magneto-optical rotation of non-polarized light clearly manifests itself in the above optical characteristics of MORS. It has been determined, that the interaction of natural light with a Faraday-active medium under conditions of optical resonance results in the changing of conditions of a multi-beam interference. As a result, a magnetic field substantially changes the interference pattern of the spectral and angular distributions of transmitted light. It has been shown, that the form of interference pattern of transmitted light depends both on the phase characteristics of the resonator, and on Faraday angle value (magnetic field) and change depending on magnetic field. It has been observed the change of contrast and also the inversion of interference extremes in the applied magnetic field: maxima are transformed into the minima and vice versa.

It has been shown, the change of the conditions of multi-beam interference by the Faraday rotation leads to the appearance of a clear interference pattern of a p-polarized light at the Brewster's angle.

The obtained results can be applied for determination of the parameters of materials and for the creation of new controllable optical and spectroscopic devices.

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