Conference Paper

Plasmonic Magnetooptic Structures for Visualization of Magnetic Information

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Abstract

Optical head with magnetized garnet layer is used to detect presence of thin ferromagnetic layers such as printed text. Mathematical model of the system was created. Incident P-polarized light affected by garnet layer changes its polarization due to Faraday effect. We can detect presence or absence of magnetic information after studying changes in polarization of the reflected light.

Keywords: Magnetoplasmonic, Faraday effect, magnetoplasmonic structure, Magneto-optic plasmon resonance.

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1. INTRODUCTION

The development of experimental and applied physics is connected with the increasing technological potential of the growth of artificial materials. New technologies allow the production of periodic structures with dimensional characteristic less than the lengths of electromagnetic waves. Studies of these structures impacted the theory of plasmon magneto-optical materials. Recently, more interest has been attracted by studies of the resonance enhancement of the transmittance and the Faraday effect in magneto-optical plasmonic nanostructures.

Magneto-optic (MO) effects describe the changes in the polarization state that occurs as a result of the light interaction with a magnetized substance [1]. M. Faraday in 1845 discovered the phenomenon of linearly polarized light plane rotation. The angle of rotation of the polarization plane is proportional to the magnitude of the magnetic field, the length of the light path in matter and the Verde constant. Verde constant, depending on the magnetic properties, is defined as the specific rotational power per unit path with the unit of the applied field (rad/A). It should be noted that the Faraday effect is nonreciprocal which means that the rotation angle θ changes its sign when the direction of magnetization of substance M changes (Fig. 1). For a fixed direction M, the angle θ increases multiple times if the light passes several times through a

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substance placed, for example, between mirrors. The refractive indices for light with left-handed and right-handed circulation of the vector E are not equal $n_+ \neq n_-$. This means that such circularly polarized waves propagate in matter at different rates.

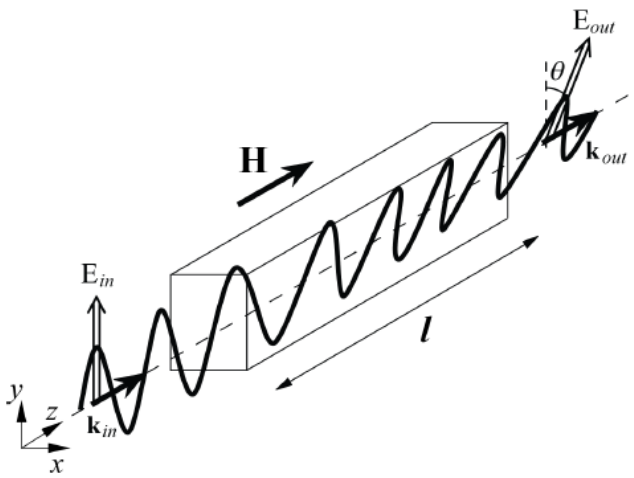

Figure 1: Faraday geometry and rotation of the plane of polarization.

By transforming the Maxwell equations and taking into account the magnetic permittivity tensor, it is possible to obtain two circular modes propagating in a magnetized substance describing one of the MO effects, the Faraday effect:

$$E_+ = \frac{E_0}{\sqrt{2}} \begin{pmatrix} 1 \\ -i \end{pmatrix} \exp[-i\omega(t - c^{-1} n_+ z)]$$

$$E_- = \frac{E_0}{\sqrt{2}} \begin{pmatrix} 1 \\ +i \end{pmatrix} \exp[-i\omega(t - c^{-1} n_- z)]$$

Earlier, an increase in the magneto-optical response in bismuth-substituted iron-garnet garnet $Bi_xY_{1-x}Fe_5O_{12}$ was already proved. This garnet is one of the main MO materials. The elementary cell of iron-yttrium garnet is shown in Fig.2. At the moment, there is no consensus on electronic transitions in ferrites and other oxides. MO activity of iron-garnet garnet can be explained by several processes: (a) electronic transitions involving d shells of Fe^{2+} ions with tetrahedral or octahedral surrounding of oxygen ions, (b) transitions in the Fe-O-Fe connection accompanied by charge transfer by $2p^5$ $3d^6$ excitons, (c) above the energies of 3.4 eV, 2p-3d transitions with charge transfer followed by creation of wandering one-electron states and (d) transfer of charge between pairs of iron ions in different oxygen surrounding. A detailed information can be found in [2] and [3].

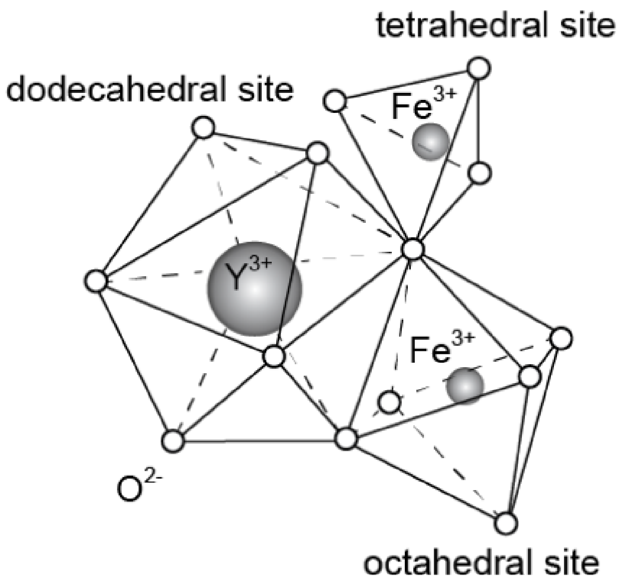

Figure 2: Elementary cell of iron-yttrium garnet.

Doping the iron-yttrium garnet cell with bismuth substantially increases MO activity, although the absorption of light increases too. In the general, MO effects arise as a result of the different polarizability of the magnetized substance.

Extremely promising and new artificial materials are periodic structures based on noble metals. Such structures support localized surface plasmon resonance (LSPR), which leads to an increase in the amplitude of the electromagnetic field at the metal interface. Surface plasmons possess a number of properties, the most important of which is a strong localization near the media interface.

Let us consider the case with one metal-dielectric interface. In this case the Maxwell equations may be solved in the form of:

$$E_m = E_0 \left\{ 1, 0, \frac{k_{sp}}{k_{zm}} \right\} \exp \left\{ i \left(k_{sp} x - k_{zm} z - \omega t \right) \right\}$$

$$H_m = -E_0 \frac{\varepsilon_m}{k_{zm}} \left(\frac{\omega}{c} \right) \{0, 1, 0\} \exp \left\{ i \left(k_{sp} x - k_{zm} z - \omega t \right) \right\}$$

in the region with metal, and

$$E_d = E_0 \left\{ 1, 0, \frac{k_{sp}}{k_{zm}} \right\} \exp \left\{ i \left(k_{sp} x + k_{zd} z - \omega t \right) \right\}$$

$$H_d = E_0 \frac{\varepsilon_d}{k_{zd}} \left(\frac{\omega}{c} \right) \{0, 1, 0\} \exp \left\{ i \left(k_{sp} x + k_{zd} z - \omega t \right) \right\}$$

in the region with dielectric. It is important to note that surface plasmons are excited only with TM polarized light.

Described geometry of the surface plasmons at the metal-dielectric interface is shown in Fig.3.

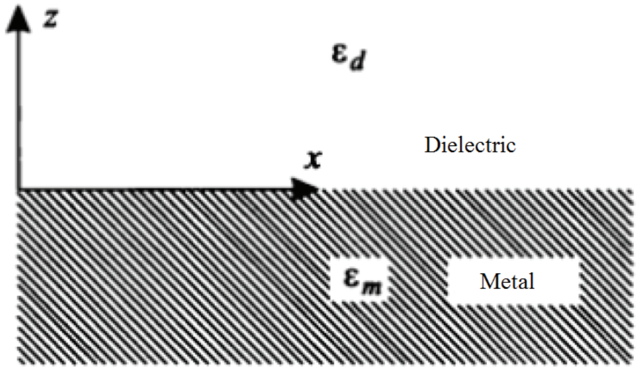

Figure 3: Described geometry.

The wave vectors in the transverse direction from the boundary for metal and dielectric can be expressed as follows:

$$K_{zm} = \sqrt{\varepsilon_m(\omega)\left(\frac{\omega}{c}\right)^2 - k_{sp}^2}$$

$$K_{zd} = \sqrt{\varepsilon_d(\omega)\left(\frac{\omega}{c}\right)^2 - k_{sp}^2}$$

Based on the condition of continuity of the tangential components of the electric and magnetic field, the following can be affirmed:

$$\frac{\varepsilon_m}{k_{zm}} + \frac{\varepsilon_d}{k_{zd}} = 0$$

Then the dispersion expression is represented in the form of:

$$K_x = k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_d(\omega)\varepsilon_m(\omega)}{\varepsilon_d(\omega) + \varepsilon_m(\omega)}}$$

The components of the wave vector in the direction perpendicular to the boundary take the form:

$$K_{j,z}^2 = \frac{\varepsilon_j^2}{\varepsilon_d + \varepsilon_m}\left(\frac{\omega}{c}\right)^2, \quad j = m, d$$

The condition under which localized surface waves could exist is that the expression under square root must be positive, so that the component of the wave vector along the interface would be real. In order to find localized near medium boundary waves, the normal components of the wave vectors must be imaginary. In this case, the fields exponentially decrise with the distance from the boundary.

Relying on the said above, one can come to the conclusion that localized plasmons exist when the following conditions are fulfilled:

$$\varepsilon_d(\omega)\varepsilon_m(\omega) < 0$$

$$\varepsilon_d(\omega)\varepsilon_m(\omega) < 0$$

For the existence of surface plasmons, one of the dielectric functions must be negative and in absolute magnitude exceed the other. As noble metals have a large negative dielectric permeability they are suitable [4].

One of the pioneer works on the optical properties of the MO materials supporting the LSPR was [5]. It was found in [6–8] that an increase in the surface fraction attributable to gold particles in the Bi:YIG-Au structures results in an increase in light absorption due to excitation of the LSPR and an increase in the polarization angle rotation.

Figure 4 shows that the angle of rotation of the plane of polarization grows proportionally to a decrease in the intensity of the wave transmitted through the Bi:YIG-Au structure [9]. Thus, it can be said that the increased MO response of garnet-noble metal structures is associated with a strong absorption of a linearly polarized wave due to excitation of LSPR.

2. MATERIALS AND METHODS

In this paper, we consider mathematical models of MO plasmonic structures and a change in the polarization angle rotation spectrum as a function of the geometric parameters of the structure. The model of the measuring stand is shown in Fig. 5 [10, 11].

The light from the radiation source passes through the polarizer becoming P-polarized. Such polarization is required to excite plasmon resonance. Further, the plane of polarization in a magneto-optical substance undergoes rotation due to the Faraday effect and its amplification by LSPR. The magneto-optical substance used is magnetized bismuth-substituted iron-yttrium garnet with 500 nm thickness.

We have investigated the plasmon resonance that arises on grating made of a noble metal with various geometric parameters, including period, thickness of the metal layer, and duty cycle.

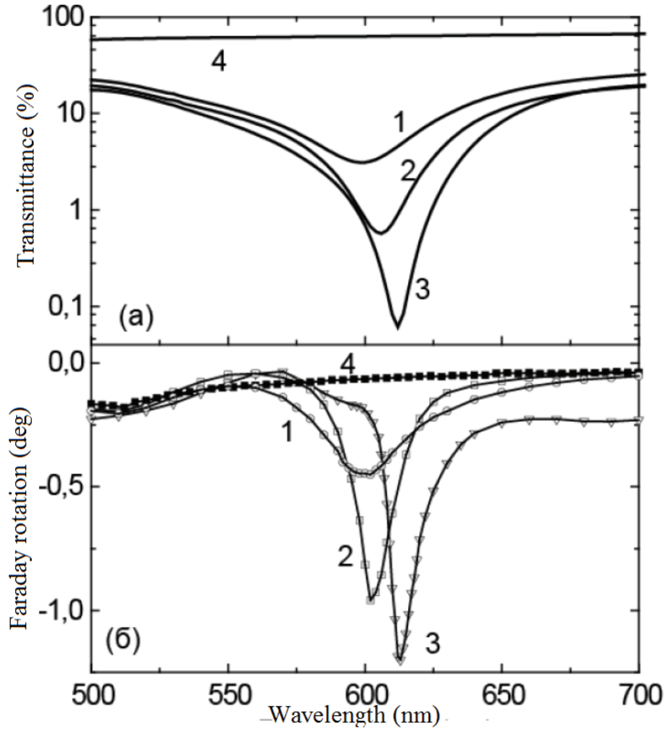

Figure 4: Spectra of transmittance and plane of polarization rotation of the Bi: YIG-Au composite films. 1 - an array of gold particles was produced by a four times melt of a gold film, 2 - five times and 3 - six times, 4 correspond to the Bi:YIG

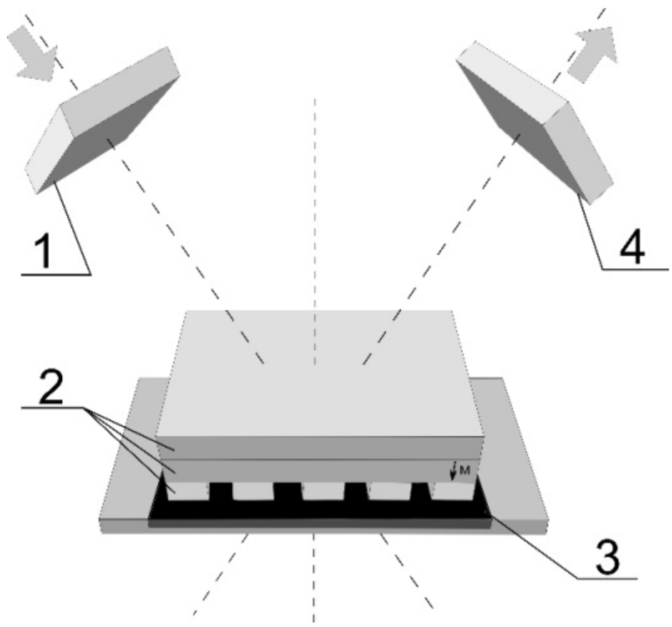

Figure 5: Model of the experimental setup. 1 - polarizer, 2 - magneto-optical structure, 3 - magnetic information carrier, 4 - analyzer.

3. RESULTS

Figure 6 shows the results of mathematical modeling of a structure with and without a noble metal grating. There is a distinct difference in the plane of polarization rotation amplitude. However, at the frequencies of the localized surface plasmon resonance happening at the boundary between the metal and the garnet, the transmittance of the structure undergoes a severe drop (Fig. 7).

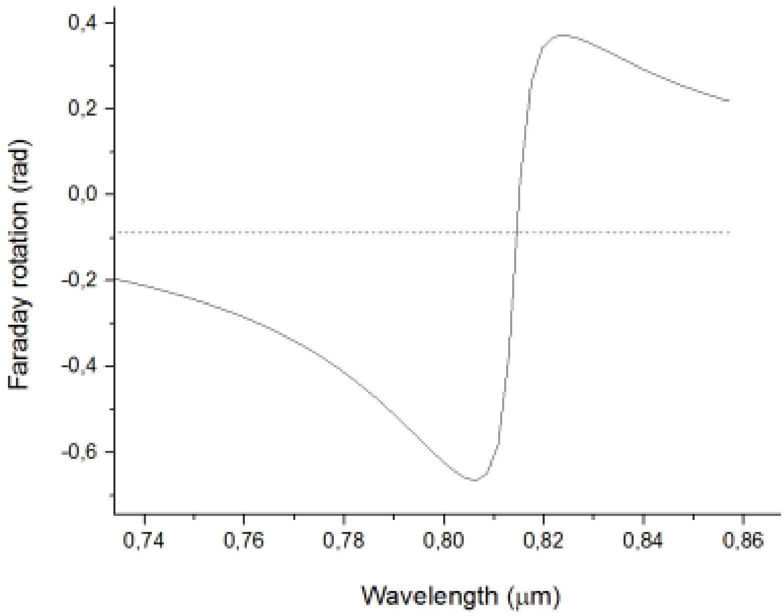

Figure 6: Rotation of the plane of polarization. Solid line - with the noble metal grating, dotted - without one.

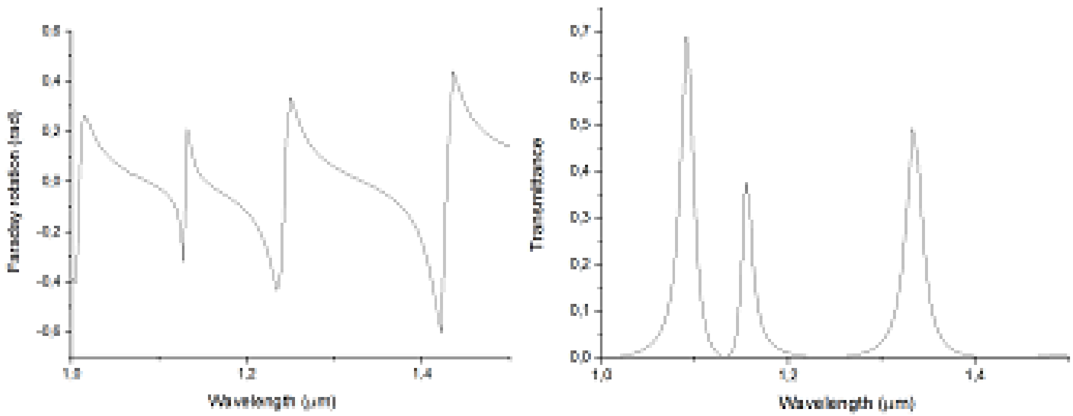

Figure 7: Spectral dependence of the rotation angle of the plane of polarization (on the left) and the spectral dependence of the transmission coefficient of the structure (on the right).

The high power of the radiation is expended on the excitation of the LSPR and at the peak of the rotation of the plane of polarization the percentage of the transmitted energy is close to zero. Taking this into account, the optimal ratio of the angle of rotation of the plane of polarization and the power of the transmitted radiation has to be calculated.

Considering the effect of the change in the lattice period on the rotation spectrum (Fig. 8), one can observe the shift of the resonance to the long-wavelength region of the spectrum. In the case of using silver as a metal lattice for a period of about 0.25 μm and further additional peaks begin to appear (Fig. 9).

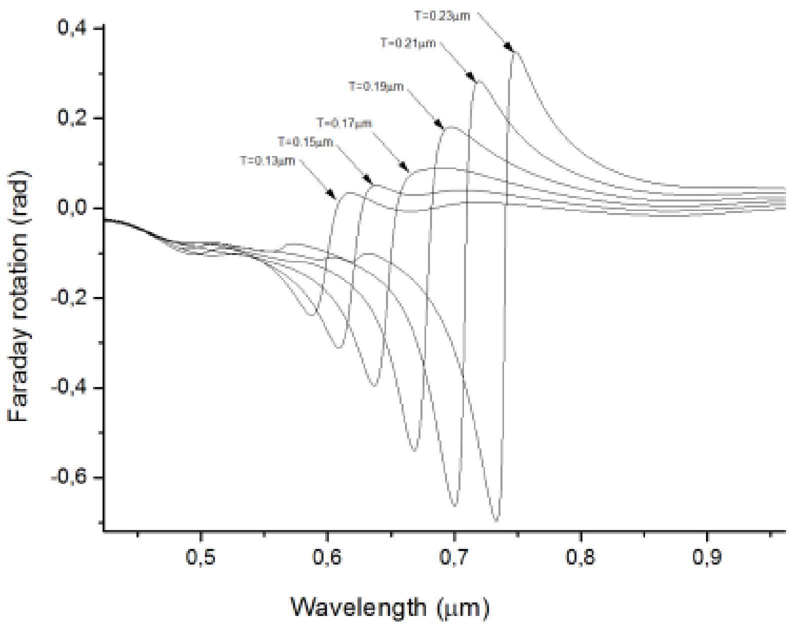

Figure 8: Rotation of the polarization plane for the structures with periods 0.13-0.23 μm.

Figure 10 shows an example with a lattice period of about 600 nm. Several resonance frequencies of rotation in the IR region of the spectrum are observed. As we increase the period further, peaks observed in the visible range gradually disappear.

Investigation of the change in the thickness of the metal indicates an increase in the resonance amplitude and its small shift to the long-wave region with the decrease in thickness (Fig. 11). The increase in the duty cycle indicates the shift of the peak to the short-wave region with a slight amplitude change (Fig. 12).

Based on the obtained results, we have modeled the structure that performs its best when working with the helium-neon laser (λ = 632.8 nm). Geometric characteristics of the structure are shown in Table 1 and graph of the spectral dependence of the Faraday rotation in Fig. 13.

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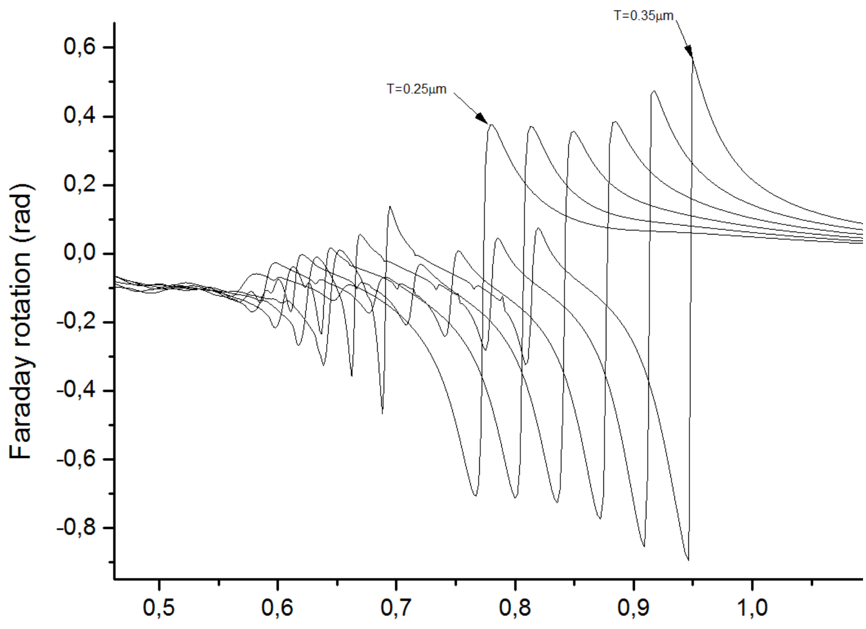

Figure 9: Rotation of the polarization plane for the structures with periods 0.25-0.35 µm.

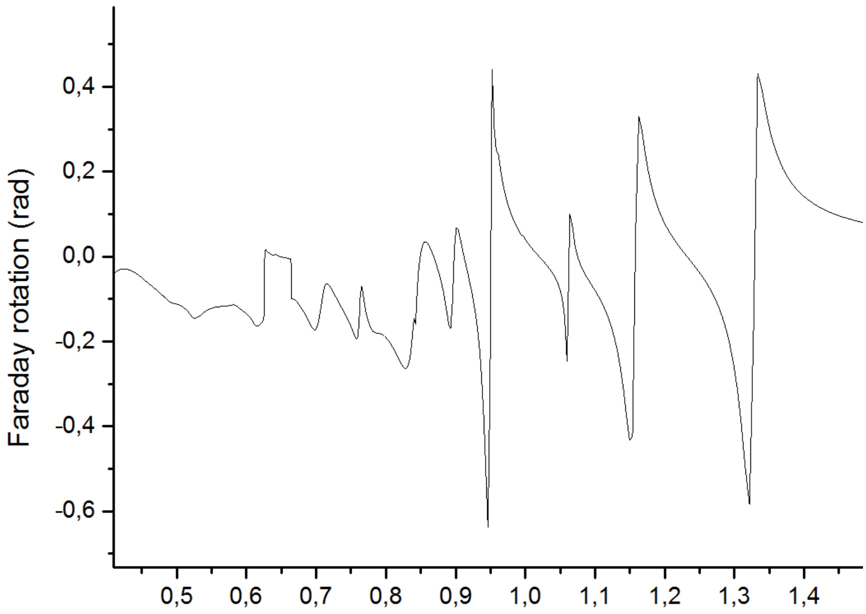

Figure 10: Rotation of the plane of polarization for a structure with a period of 0.6 µm.

4. DISCUSSION

The purpose of this work was to determine the feasibility of practical implementation of these effects in systems for visualization and recording of magnetic images from magnetic information carriers as super sensitive to small magnetic fields sensors. The carriers of magnetic information can be valuable documents (banknotes, money bills), audio-video recording, protective holograms, the study of which involves the use of

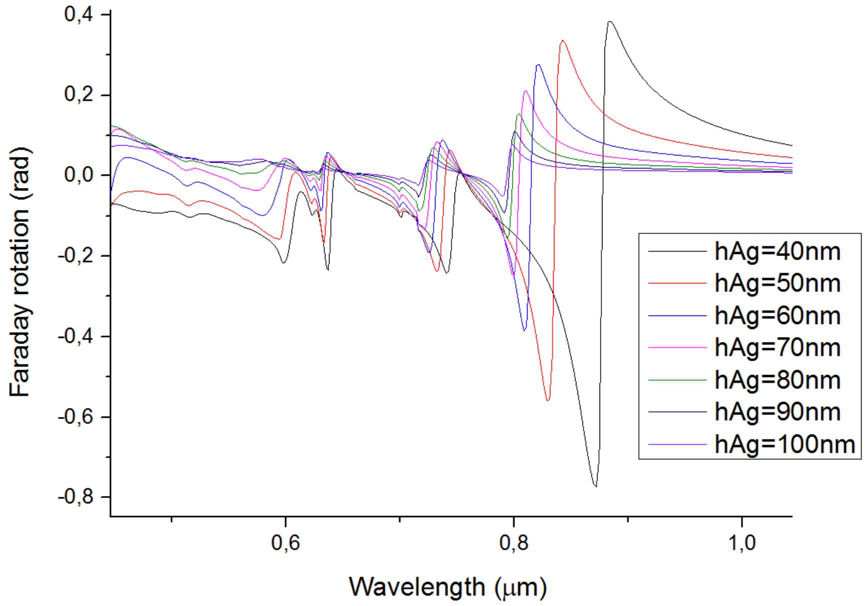

Figure 11: Rotation of the polarization plane for the structures with different grating thicknesses.

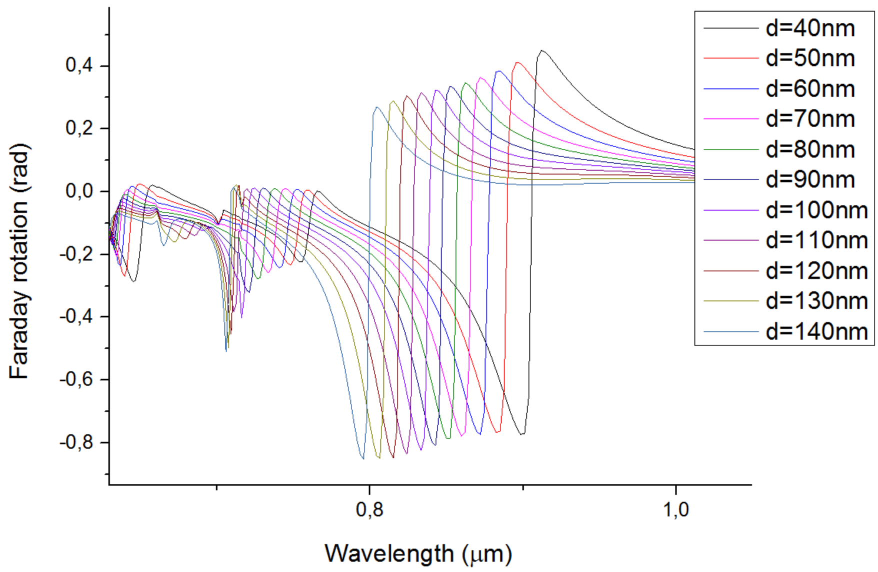

Figure 12: Rotation of the polarization plane for the structures with different duty cycles.

the Faraday magneto-optical effect [12-14]. The idea is that if we move these magnetized substances (magnetic information carriers) to the structures described above some changes will occur with the coefficients in the garnet dielectric permittivity tensor, responsible for the magnetization, the gyration vector. This leads to a change in the rotation of the plane of polarization passing through the light structure. Setting an analyzer in front of the radiation receiver, which is rotated in such a way as to transmit a maximum of radiation in the case when there is no extraneous magnetic

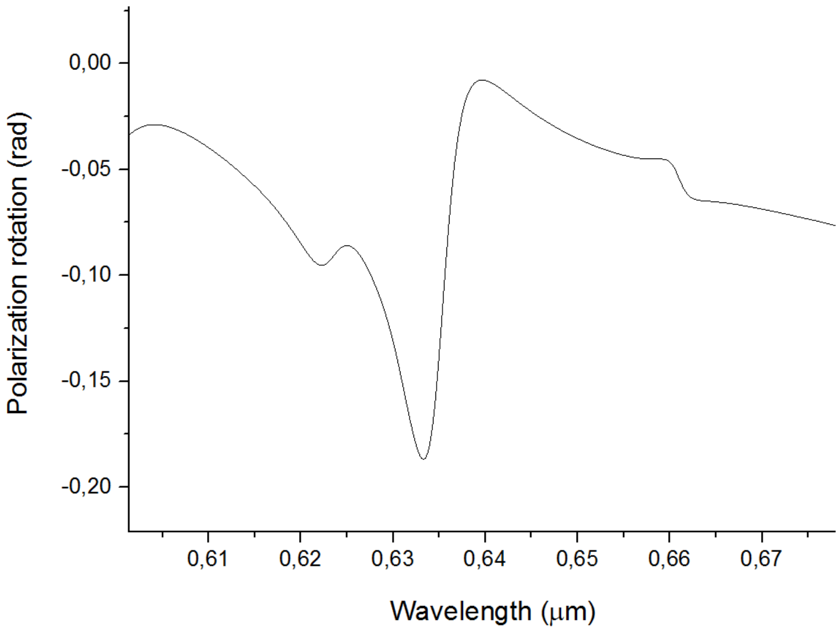

Figure 13: Spectral dependence of the Faraday rotation.

Table 1: Parameters of the optimal structure geometry.

Parameter	Value / Tolerance
T	310 nm / ± 20 nm
d	60 nm / ± 10 nm
h_{BiYIG}	500 nm / ± 10 nm
h_{Ag}	40 nm / ± 5 nm
Substrate	GGG

field, we can see the darkening in those areas where there is a magnetized substance (information carrier). In this way we would have a magnetic image of the carrier.

5. CONCLUSION

Studies indicate a wide range of possibilities for manufacturing magneto-optical plasmonic structures for the study of magnetic interactions in a wide spectral range. The increase in the MO response due to the use of the noble metal gratings is extremely large, but it is necessary to take into account the resonance losses of the radiation power when passing through the structure. The optimum ratio of the MO response and the allowable losses should be calculated beforehand.

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