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Enhanced magneto-optical response with a 1D resonant grating for sensing applications

BSAWMAII Laurea, JAMON Damiena, GAMET Emiliea, NEVEU Sophieb, and ROYER Françoisa

aUniversité de Lyon, CNRS, UMR 5516, Laboratoire Hubert Curien, Université Jean-Monnet, F-42000, Saint-Etienne, France
bSorbonne Universités, UPMC Université Paris 06, CNRS, Laboratoire PHENIX, Case 51, 4 place Jussieu, F-75005 Paris, France

ABSTRACT

Significant enhancement of the longitudinal magneto-optical effect accompanied with high transmission was demonstrated by experimental measurements and confirmed by numerical simulations for small angles of incidence.

The work was led with a subwavelength resonant structure consisting of a 1D dielectric grating structured on top of a magneto-optical waveguide. The simplicity of the fabricated structure associated to the significant achieved magneto-optical effect, make the structure a promising tool for applications like magnetic field sensors or in non-destructive testing.

Keywords: Magneto-optics, Faraday effect, Kerr effects, subwavelength resonant gratings, waveguide mode resonance

1. INTRODUCTION

Magneto-optical (MO) photonic devices are currently highly desirable because they can improve the sensitivity of biosensors,1–3 or due to their sensitivity to the magnetic field. To further improve the sensitivity of these devices, it is relevant to enhance MO effects4 which can manifest as light polarization rotation (Faraday, polar or longitudinal Kerr) or intensity modification (transverse Kerr) under magnetic field. Such enhancement can be achieved with magneto-photonic crystals,5–7 dielectric metasurfaces8 or with subwavelength resonant gratings. These latter are formed by a combination of a dielectric or metallic grating with a dielectric MO material. Under certain conditions giving by Equation (1), the incident light is coupled into the MO waveguide. Then, the interaction between the MO material and the light is higher than a single path through the MO thin film.

\[
\frac{2\pi}{\lambda_0} n_1 \sin \theta_{inc} + \frac{2m\pi}{\Lambda} = \beta
\]

Where \( \beta \) is the propagation constant of the guided mode, \( n_1 \) is the refractive index of the incidence medium, \( \theta_{inc} \) is the incident angle, \( m \) is the diffraction order, \( \Lambda \) is the period of the dielectric grating and \( \lambda_0 \) is the vacuum wavelength for the incident light.

Furthermore, the periodic nanostructuring with optimized opto-geometric parameters can lead to the phase matching condition \((\beta_{TE} = \beta_{TM})\).9 It is well known that this TE-TM mode conversion, employed in Longitudinal and Faraday effects, is maximum when the phase matching condition is satisfied.10

Enhancement of the different MO effects were theoretically and experimentally demonstrated through a simple metallic structure formed by a gold grating deposited on a layer of BIG,11–16 Moreover, significant enhancement of the Faraday effect was achieved numerically and experimentally through more complex metallic structures.17–19

The excitation of eigenmodes of the structure, such as propagated surface plasmon polaritons (SPP),11 localized surface plasmon (LSP),12 cavity modes13 or waveguide modes,17 is responsible of the resonant enhancement of

Further author information: (Send correspondence to J.D)
J.D.: E-mail: damien.jamon@univ-st-etienne.fr
the MO response in the metallic structures. In addition to that, the enhancement of MO effects were theoretically demonstrated through 1D dielectric gratings consisting of alternating MO dielectric and nonmagnetic dielectric materials.\textsuperscript{20, 21} Bai el al\textsuperscript{22} have also demonstrated numerically large values of Faraday and Kerr polar effect through a 2D dielectric structure. The use of symmetric 2D grating allows to fully degenerate the polarization at normal incidence: in such a case TE and TM resonance wavelengths will always match ($\Delta \beta = \beta_{TE} - \beta_{TM} = 0$). The phenomenon of the waveguide mode resonance,\textsuperscript{23} which manifests in a dip in the transmittance spectrum\textsuperscript{24} at the resonance wavelength ($\lambda_0$), is responsible of the MO enhancement in the dielectric structures.

In this paper, significant enhancement of the longitudinal MO effect in transmission,\textsuperscript{4} are presented for small angles of incidence (AOI) with a simple 1D dielectric resonant grating.

### 2. MATERIAL AND METHODS

![Diagram](https://example.com/diagram.png)

**Figure 1.** (a) Schematic drawing of the sample geometry, the incidence conditions and the longitudinal magneto-optical effect in transmission. The geometrical parameters of this structure are $w = 400$ nm, $\Lambda = 1000$ nm, $h_{PR} = 300$ nm, $t_{PR} = 130$ nm and $t_{MO} = 460$ nm. (b) Example of measurements of the polarization rotation at a fixed wavelength ($\lambda = 1580$ nm) for a varied applied magnetic field, in the longitudinal configuration.

The fabricated dielectric structure consists of a photoresist (PR) grating structured on top of a MO waveguide deposited on a glass substrate. The structure geometry is illustrated on Fig. 1a.

The used PR is a S1805\textsuperscript{©} owing several advantages: it has a good adhesion on the MO waveguide and it requires a low annealing (60°C). In addition to that, the grating height can be controlled by diluting the S1805\textsuperscript{©} in ethyl-lactate in order to change its viscosity and thus the thickness of the deposited layer. Finally, the fabrication of PR gratings is simple which leads to low costs devices. The PR grating with height $h_{PR}$, width $w$ and period $\Lambda$, was structured on top of the MO film by a classical photolithographic process using a periodic quartz-supported chromium amplitude mask.

The MO material was prepared by a liquid sol-gel preparation of Tetraethyl orthosilicate ($\text{C}_8\text{H}_{20}\text{O}_4\text{Si}$) doped with a ferrofluid containing cobalt ferrite ($\text{CoFe}_2\text{O}_4$) nanoparticles (NPs). For details on the MO composite elaboration, the readers are referred to Ref. 7. To obtain the MO waveguide, a layer of MO composite with thickness $t_{MO}$ was deposited on a glass substrate by dip coating then treated thermally at 90°C for 1 hour. With the MO composite, it is possible to deposit uniform thin layers on a large scale substrate and with a 100°C thermal treatment. Such composite has been used for the fabrication of integrated MO converters\textsuperscript{25} and 3D magneto-photonic crystals.\textsuperscript{26} An important feature of this material is that the whole permittivity tensor can be tuned by modifying the volume fraction ($\phi$) of NPs in the sol-gel.
In order to control the effective indices of TE and TM modes \((N_{\text{eff}} = \frac{\lambda_0}{2\pi\beta})\), in other words \(\Delta\beta\) for larger MO effects, different MO films were deposited under magnetic field (denoted as \(\vec{B}_{\text{gel}}\)) with different orientations with respect to the waveguide plane. During the MO composite coating, the NPs magnetic moments tend to align with the magnetic field. Once the film is dry, the NPs are frozen.\(^{27}\) As \(\text{CoFe}_2\text{O}_4\) NPs are both optically and magnetically anisotropic, the applied magnetic field has two consequences: a permanent anisotropy is created whose optical axis is parallel to the direction of \(\vec{B}_{\text{gel}}\). And, the magnetic behavior of the composite is modified with an easy axis of magnetization also aligned with \(\vec{B}_{\text{gel}}\). Tab. 1 summarizes the four fabricated MO structures and inset Fig. 2 illustrates their schematic geometries, each of which consists of 400 nm wide and 300 nm of height structured on top of 460 nm thick MO waveguide. Due to fabrication imperfections, these parameters may be slightly different from a sample to another. At the wavelength \(\lambda = 1550\,\text{nm}\), the diagonal elements of the tensor permittivity \((\epsilon_{11} = \epsilon_{22} = \epsilon_{33})\) of the PR, the substrate and the MO composite are 2.5281, 2.2801 and 2.6896-i0.0144 (for \(\phi = 26\%\)) respectively. The off-diagonal elements of the MO composite’s permittivity (the term responsible for the MO effect) is \(\epsilon_{23} = -\epsilon_{32} = -i0.0064\) at \(\lambda = 1550\,\text{nm}\) and for \(\phi = 26\%\).\(^{20}\) These opto-geometric parameters were chosen to insure a good coupling of the incident light into the MO waveguide with a good light confinement in this latter. In order to have the two guided modes (TE and TM) in the structure, the grating is not dug to the bottom and a thin layer of PR with thickness \(t_{PR} = 130\,\text{nm}\) is kept since its refractive index is close to that of the MO film.

The thicknesses and the refractive indices were measured by ellipsometry (Horiba Jobin Yvon UVISEL) and the grating parameters \((w, \Lambda)\) were measured by Atomic Force Microscopy (AFM). In order to obtain a resonance around \(\lambda = 1550\,\text{nm}\) with the given refractive indices and small AOI, the period was chosen to be 1000 nm (this value was confirmed by Littrow mount measurements). Hence, the structure is a subwavelength grating: only the zero diffraction order exists in the substrate and the upper air cover, and the \(\pm 1\) diffracted orders in the MO waveguide.

The polarization rotation was measured at room temperature with a homemade MO setup, where a tunable laser (1480 nm-1630 nm) is used as a source of light, a longitudinal magnetic field \(\vec{B}\) (see Fig. 1a) is applied and a photoelastic modulator is used to increase the sensitivity of the measurements. For every wavelength, the longitudinal applied magnetic field is varied from \(-360\,\text{mT}\) to \(360\,\text{mT}\) and the polarization rotation in transmission is measured (see Fig. 1b). Then, the saturated polarization rotation is plotted as a function of the wavelength. For more information concerning the MO characterization methodology, the readers are referred to Ref. 26. The transmittance was measured by a near infrared spectrophotometer. The simulations have been carried out with a homemade RCWA code, taking into account the whole permittivity tensor.\(^{28}\)

### 3. RESULTS AND DISCUSSION

The transmittance measurements for TE (y-direction) and TM (x-direction) polarized incident light as a function of the wavelength at normal incidence, are plotted on Fig. 2 for the four samples described in Tab. 1. One can see dips in transmittance down to 35\% and 40\% for TE and TM polarizations respectively, revealing the waveguide mode resonance.\(^{23}\) The wavelength shift between TE and TM resonances is not the same for the different samples: the smallest shift (6 nm) is for the out of plane field sample and the largest one (14 nm) is for the sample of in-plane field with grooves parallel to this latter. This behavior is explained as follows: inside the MO waveguide the electric field of the TE mode is along Oy, while that of the TM mode has a component following

<table>
<thead>
<tr>
<th>MO structures</th>
<th>Magnetic field ((\vec{B}_{\text{gel}})) orientation</th>
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<tbody>
<tr>
<td>sample 1</td>
<td>Zero field</td>
</tr>
<tr>
<td>sample 2</td>
<td>Out of plane</td>
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<tr>
<td>sample 3</td>
<td>In-plane with grating grooves perpendicular to the field direction</td>
</tr>
<tr>
<td>sample 4</td>
<td>In-plane with grating grooves parallel to the field direction</td>
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z direction and a small one following x direction. For sample 1, there is no a created anisotropy but there is an intrinsic property of the dielectric waveguide, where the effective indices of TE and TM modes are not equal and a difference in resonance wavelengths ($\Delta \lambda = 10$ nm) is obtained as seen in Fig. 2a. For sample 2 (Fig. 2b), the NPs optical anisotropy axis is oriented along z direction which increases the refractive index in this direction ($n_z$) and decreases $n_x$ and $n_y$ as compared to the first case. Therefore, the refractive index related to the small component of TM mode following x direction is decreased, while that of the component following z direction is increased giving a rise to the resonance wavelength of TM ($\lambda_{TM}$) according to Equation (1) as compared to the first case. However, the resonance wavelength of TE ($\lambda_{TE}$) is decreased due to the decreasing of $n_y$. This behavior explains the decreasing of $\Delta \lambda$ to a value of 6 nm as compared to that of zero field sample. For sample 3 (Fig. 2c), the refractive index related to the small TM component is increased while that of the component following z direction and the refractive index of TE mode are decreased according to the case without applied $\vec{B}_{gel}$, which explains the slight decreasing of $\Delta \lambda$ to 8 nm. However, for the last case (sample 4) $n_{TE}$ is increased and $n_{TM}$ is decreased explaining the increasing of $\Delta \lambda$ to 14 nm as compared to the sample 1.

Hence, an important feature of the magnetic field assisted deposition process is that the TE-TM phase shift can be controlled by the NPs orientation in the waveguide.

The created permanent anisotropy can be also verified by ellipsometry measurements in transmission of the in-plane phase shift and by the hysteresis loops of the Faraday rotation. Fig. 3a illustrates the phase shift in the xy plane as a function of the wavelength for the different $\vec{B}_{gel}$ orientations. As seen in this figure, for the zero field sample non anisotropy is detected, however it is not the case for the parallel field where an anisotropy is measured and its amplitude depends on the incident wavelength. The amplitude of the anisotropy is more important in the visible region than in the infrared and this is related to the dispersion of the MO film’s refractive index (see inset Fig. 3a). For the out of plane field case, the anisotropy cannot be measured by ellipsometry but it can be detected by the hysteresis loops of the Faraday rotation.

The normalized Faraday rotations for the different samples under magnetic field at a fixed wavelength are...
Figure 3. (a) Ellipsometry measurements of the in-plane phase shift (xy plane) as a function of the wavelength for the in-plane, out of plane and zero field samples. Inset: the dispersion of MO film's refractive index for $\phi = 26\%$. (b) Hysteresis loops of the normalized Faraday rotation for the different samples under $\vec{B}_{gel}$. Inset: the Faraday configuration.

It is clear from this figure that the hysteresis loops are not overlapped, what proves that a permanent magnetic anisotropy is created during the gelation under magnetic field. One can see that the hysteresis loop of the out of plane field sample is the largest one and that of the parallel field is the thinner. In the case of out of plane $\vec{B}_{gel}$, the NPs easy axis of magnetization is oriented in a direction parallel to that of the measurement field $\vec{B}_{meas}$ (the measurement configuration of the Faraday effect is illustrated in inset Fig. 3b), resulting as higher Faraday rotations remanence compared to that of the zero field. While, in the case of the in-plane field, the NPs easy axis of magnetization is oriented perpendicularly to the direction of $\vec{B}_{meas}$ resulting as lower polarization rotation remanence. For the case of zero field the NPs are randomly oriented and the behavior is in the middle. Same analysis can be applied to the coercitive field values.

Figure 4. (a) Measurements and (b) numerical simulations of the transmittance for TE and TM-polarized incident light and the polarization rotation in the longitudinal configuration for TE-polarized incident light, as a function of the wavelength for the sample 2 and for an angle of incidence equal to $2^\circ$.
The longitudinal MO effect in transmission was studied for the different resonant structures described in Tab. 1 but only the results for the sample 2 with the smallest phase shift (largest MO effects) will be presented. Hence, a longitudinal field \( \vec{B} \) in x direction (referring to Fig. 1a) is applied, and due to symmetry reasons the longitudinal effect is zero at normal incidence,\(^{29}\) hence an oblique incidence is needed. The experimental measurements of the transmittance (\( T \)) for TE and TM polarized incident light and the polarization rotation (\( \theta \)) in transmission for TE polarization, are plotted on Fig. 4a as a function of the incident wavelength for AOI=2°. As seen in Fig. 4a, the TE-TM wavelength shift (12 nm) is increased as compared to the normal incidence (Fig. 3b) and this is related to the fact that the TE-TM phase shift is not constant as a function of the incident angle according to the propagation equations of the guided modes. The presence of large opposite peaks in the polarization rotation spectrum is linked to the transmission resonances for both polarizations (TE and TM). The measured polarization rotations reach 0.4° and −0.64° as highest values at \( \lambda = 1540 \) nm and \( \lambda = 1553.4 \) nm respectively with transmittance larger than 60%. Furthermore, a good agreement can be observed between simulations (Fig. 4b) and measurements, and the small difference can be explained by the imperfection of the fabricated structure. We should mention that for a single MO film, the longitudinal effect in transmission is in order of 0.001° for small AOI. Hence, a giant enhancement is demonstrated for the MO longitudinal effect at an AOI=2°. The same order of rotation is obtained for TM-polarized incident light (not shown here).

![Figure 5](https://ebooks.spiedigitallibrary.org/conference-proceedings-of-spie)

**Figure 5.** (a) Measurements of transmittance for TE and TM-polarized incident light and measurements of polarization rotation for TE polarization for an angle of incidence equal to 0.4° as a function of the incident wavelength. (b) Calculated values of figure of merit for the experimental measurements of (a) for TE polarization.

As we mentioned before, the TE-TM wavelength shift is 12 nm, hence the optimized condition where these two resonances should overlap for a maximum MO effect is not achieved. However, an overlap can be simply obtained by the angle of incidence. Fig. 5a illustrates the transmittance measurements at AOI=0.4° for TE and TM polarized incident light, for a sample with zero \( \vec{B}_{gel} \) owing the same opto-geometric parameters than those of sample 1. As seen in this figure, the TE and TM resonances resulting from opposite diffraction order sign \( (m = \pm 1) \) are overlapped. According to Equation (1), it is not a phase matching, the TE and TM modes still have different propagation constant. Nevertheless, the two modes are excited simultaneously in the structure resulting in a higher MO effect. This latter is illustrated on Fig. 5a for TE polarization, where a large polarization rotation (1.1°) is reached for the longitudinal effect with high transmittance (60%) at \( \lambda = 1506 \) nm.

With such significant MO enhancements the structure is promising for applications such as magnetic field sensors or in non-destructive testing based on magnetic field sensing.

For a reliable analysis, a compromise between the transmittance (\( T \)) and the polarization rotation (\( \theta \)) should be take into consideration, through the study of the figure of merit defined as \( FoM(°) = \sqrt{T|\theta(°)|} \).\(^{30}\) Fig. 5b
illustrates the values of FoM for the experimental measurements of the polarization rotation and the transmittance at AOI=0.4° and for TE-polarized incident light. One can see three peaks of FoM which are related to the peaks of the polarization rotation spectrum (see Fig. 5a). High values of FoM are reached and the highest one is 0.83°. This value is higher than that demonstrated by Chetvertukhin et al., who experimentally demonstrated a value of 0.018° for the longitudinal effect but in reflection. The work was done with a magnetoplasmonic crystal consisting of a 2D array of nickel nanodisks arranged into hexagonal lattice. The off-diagonal element of the tensor permittivity of the nickel is around: \( \epsilon_{23} = +i0.24. \) Kalish and Belotelov, have numerically demonstrated a value of FoM equal to 2.53° through a metallic structure formed by a gold grating deposited on a magnetic layer of rare-earth iron garnet containing bismuth. Here, the off-diagonal element is: \( \epsilon_{23} = +i0.016. \) Hence, same order of FoM was demonstrated in our work with a MO material owing an off-diagonal element \( (\epsilon_{23} = +i0.0064) \) of one or two orders of magnitude smaller as compared to these works.

4. CONCLUSION

A significant enhancement of the longitudinal MO effect was numerically and experimentally demonstrated in transmission and for small angles of incidence, through a subwavelength resonant structure consisting of a PR grating structured on top of a MO composite waveguide made of cobalt ferrite NPs embedded in a silica matrix. A permanent anisotropy was created in the MO waveguides coated under magnetic field, allowing the control of the TE-TM phase shift. We can say that this structure is a promising structure for non-destructive techniques based on primary or secondary magnetic field detection. Indeed, the three MO effects in reflection are enhanced by such device that offers the possibility to measure different components of the magnetic field. Moreover, one can note the simplicity of fabrication that leads to low cost devices.

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