Angle dependence of the photonic enhancement of the magneto-optical Kerr effect in DMS layers

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Abstract – We investigate theoretically an angle dependence of the enhancement of the polar magneto-optical Kerr effect (MOKE) obtained thanks to a deposition of a paramagnetic Diluted Magnetic Semiconductor (DMS) layer on a one-dimensional photonic crystal layer. Our transfer-matrix-method–based calculations conducted for TE and TM polarizations of the incident light predict up to an order of magnitude stronger MOKE for a (Ga,Fe)N DMS layer when implementing the proposed design. The maximum enhancement for TE and TM polarization occurs for the light incidence at the normal and at the Brewster angle, respectively. This indicates a possibility of tuning of the MOKE enhancement by adjustment of the polarization and of the incidence angle of the light.

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Introduction. – The magneto-optical Kerr effect (MOKE) \cite{1}, manifested by a rotation of a linear polarization plane of the light reflected from the magnetized material’s surface, provides an excellent tool for probing metals \cite{2} or dilute magnetic semiconductors (DMS) \cite{3,4} magnetization. The DMSs have been intensively studied recently \cite{5–9} due to a wide range of valuable functionalities resulting from a combination of properties specific to a semiconductor and to a magnetic material. In particular, weak losses typical for a semiconductor host and a strong magnetic circular dichroism (MCD) specific to ferromagnetic metals are profitable for implementation of the DMS in optical isolators or spatial light modulators in advanced spintronic or photonic applications. Alike the MCD, the MOKE results generally from a difference in the absorption of the left- and the right-circularly polarized light in the magnetized material. In the case of the DMS, the MOKE in the fundamental gap spectral region originates from a splitting of interband transitions in magnetic field induced by spin-orbit and s, p-d exchange interactions between band carriers and localized spins of the magnetic dopant ions.

Practical applications in magneto-optical devices necessitate strong magneto-optical effects from possibly thin DMS films. This could be, in principle, achieved through the increase of a concentration of a magnetic dopant, $x$ \cite{3,10,11}. However, the optical performance of the DMSs typically drops down with increasing $x$ \cite{3,12}. As recently shown, the magneto-optical response of DMS can be efficiently enhanced while keeping $x$ at a reasonably low level by boosting the light-matter interaction exploiting photonic \cite{13–16} or plasmonic \cite{17} effects. In particular, a significant enhancement of a Faraday rotation or MCD related to (Ga,Mn)As layers has been obtained thanks to embedding a DMS layer in a resonant microcavity formed by two distributed Bragg reflectors (DBR) \cite{14,16}.

Here, we theoretically investigate angle dependences in a photonic enhancement of the MOKE in a paramagnetic (Ga,Fe)N. The enhancement is obtained thanks to a deposition of a (Ga,Fe)N layer on top of a single, (Al,Ga)N-based, DBR layer. Through a systematic study we determine first a design of the structure assuring the highest degree of the MOKE enhancement in the fundamental gap spectral region. We find a strong impact of the Fabry-Perot light interferences on the MOKE magnitude, contrarily to the case of optically thick magnetized metal layers, where interference effects are precluded.

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by a small light penetration depth. Next, we analyze a dependence of the MOKE in the DMS and of its enhancement on the light incidence angle. The angle dependences of the MOKE have been studied so far only for magnetized metallic films [18,19]. We show that with the proposed design, the MOKE enhancement for both transverse electric (TE) and transverse magnetic (TM) polarizations remains insensitive to the angle of the light incidence in a wide angle range. However, the maximum of the MOKE enhancement for TM polarization is obtained for the Brewster angle, similarly to the case of magnetized metal layers [18,19].

The possibility of enhancement of the MOKE in (Ge,Fe)N is especially appealing in view of wide-range applications foreseen in [5,9] for a whole class of wide-band gap DMSs [6,12,20,21]. The photonic approach to applications foreseen in [5,9] for a whole class of wide-band gap DMSs [6,12,20,21]. The photonic approach to applications foreseen in [5,9] for a whole class of wide-band gap DMSs [6,12,20,21]. The photonic approach to applications foreseen in [5,9] for a whole class of wide-band gap DMSs [6,12,20,21]. The photonic approach to applications foreseen in [5,9] for a whole class of wide-band gap DMSs [6,12,20,21].

Structures. – We consider a magneto-optical response of two structures: one involving a DMS layer deposited on a DBR layer (referred to as “DMS/DBR”), and the other one (“DMS/buffer”) serving as a reference, involving the DMS layer deposited on a buffer layer (see fig. 1). The DMS/DBR structure consists of the paramagnetic (Ga,Fe)N layer ($x_{Fe} = 0.2\%$) of thickness $d_{DMS}$, the Bragg mirror constituted by $N = 5$ periods of alternating $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}/\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ layers, and the $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ buffer (thickness $d_{buffer} = 200\text{nm}$) deposited on a sapphire substrate. The assumed relatively small number of periods and a low difference of Al content in the layers within the DBR mirror are sufficient for a significant MOKE enhancement in DMS [22]. At the same time, such design is advantageous from the point of view of an epitaxial growth of good-quality (with a low dislocations density) structures [23]. In the reference DMS/buffer structure, the DBR layer is replaced by the $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ buffer layer of thickness equal to the overall thickness of the DBR layer, as shown in fig. 1(b).

Model. – In this work, we consider the case of polar MOKE, where the magnetization vector is perpendicular to the sample reflection surface and parallel to a plane of the light incidence. The angle between the linear polarization direction of the incident light and the major axis of the elliptical polarization of the reflected light defines the Kerr rotation angle $\Theta_{K}$, given by (e.g., ref. [24]):

$$\Theta_{K} = \frac{1}{2} \arg \frac{r^{-}}{r^{+}}, \quad (1)$$

where $r^{-}$ and $r^{+}$ represent complex, wavelength-dependent amplitudes of reflection coefficients for $\sigma^{-}$ and $\sigma^{+}$ circular polarizations, respectively. We start with the determination of a reflection coefficient $r$ in a general case of an arbitrary stack of dielectric layers (see fig. 2). We assume that all layers constituting the structure shown in fig. 2 are uniform, isotropic, and infinite in the plane parallel to the sample surface. The $i$-th layer of thickness $d_{i}$ is described by a wavelength-dependent, complex refractive index $n_{i}(\lambda)$. $n_{i}(\lambda)$ is calculated as a square root of a dielectric function $\varepsilon_{i}(\lambda)$ for the $i$-th layer taking into account contributions from interband optical transitions to the absorption. Namely, transitions to discrete ground and excited excitonic states with a Lorentzian line shape, as well as to a continuum of unbound states [25,26], are taken into account. Since we deal with a wurtzite-type semiconductor, where the valence band at $k = 0$ is split into three sub-bands, the $A$, $B$, and $C$ excitonic states are included to the model [27–29]. The same value of a background dielectric constant $\varepsilon_{0}^{B} = 5.2$ is assumed for all GaN-based layers [29]. Polaritonic effects [25] are neglected [30]. Parameters of excitonic transitions (i.e., energy positions, linewidths and oscillator strengths) in the DMS layer as a function of the magnetic field for $\sigma^{-}$ and $\sigma^{+}$ circular polarizations of the light are taken from the reflectivity experiment performed at $T = 2\text{K}$ on the $\text{Ga}_{1-x}\text{Fe}_{x}\text{N}$ ($x_{Fe} = 0.2\%$) layer grown on a GaN buffer (fig. 4 in ref. [30]). With a direct link to the experiment, our simulations are expected to describe properly a real structure performance. In particular, a contribution to MOKE originating from the variation of not only energy, but also a shape (i.e., oscillator strength and linewidth) of the excitonic transitions in magnetic field is taken into account. The variation of all three parameters describing the excitonic transition has been shown recently to contribute with a comparable weight to a Faraday rotation [31] and to the MCD [30] effects.

We consider TE and TM polarizations of the light incident on the interface between the first (0) and the
second (1) layer at an arbitrary angle $\theta_0$ (see fig. 2). Within the transfer matrix method [32] formalism, the tangential electric ($E$) and magnetic ($H$) fields at the first (0/1) and the last ($(m-1)/m$) interface are related by

$$
E_{0/1} = M E_{(m-1)/m}
$$

(2)
The characteristic matrix of the structure $M$ is defined as $M = \left[ \begin{array}{cc} M_{11} & M_{12} \\ M_{21} & M_{22} \end{array} \right] = \prod_{i=1}^{m-1} M_i$, where matrix $M_i$ is defined for the $i$-th layer as

$$
M_i = \begin{bmatrix}
\cos \beta_i & (-i \sin \beta_i)/q_i \\
-i q_i \sin \beta_i & \cos \beta_i
\end{bmatrix}
$$

(3)
where

$$
\beta_i = \frac{2 \pi d_i}{\lambda_i} (n_i^2 - n_0^2 \sin^2 \theta_0)^{1/2},
$$

(4)
and

$$
q_i = \frac{(n_i^2 - n_0^2 \sin^2 \theta_0)^{1/2}}{n_i^2}
$$

(5)
for the TM polarization, while

$$
q_i = \frac{(n_i^2 - n_0^2 \sin^2 \theta_0)^{1/2}}{n_i^2}
$$

(6)
for the TE polarization. The reflection coefficient $r$ is finally obtained as

$$
r = \frac{(M_{11} + M_{12}q_0)q_0 - (M_{21} + M_{22}q_0)}{(M_{11} + M_{12}q_0)q_0 + (M_{21} + M_{22}q_0)}.
$$

(7)

The $r$ for TM or TE polarizations is obtained by an appropriate substitution of eq. (5) or (6) into eq. (7). Reflectivity coefficients $r$ and $r^+$ for the particular case of our structures are obtained from eq. (7) solved with excitonic parameters corresponding to a given magnetic field and circular polarization of the light.

In the initial step of our investigation of the angle dependence of photonic MOKE enhancement we consider the normal incidence case and determine a design of the structure providing the strongest MOKE related to the DMS layer. We calculate the wavelength-dependent Kerr rotation angle $\Theta_K(\lambda)$ in the (Ga,Fe)N fundamental bandgap spectral region for the DMS/DBR and DMS/buffer structures described in the previous section. We vary the DMS layer thicknesses $d_{DMS}$ between 50 nm and 350 nm. The central wavelength of the mirror $\lambda_{DBR}$ is tuned between 345 nm and 365 nm by tuning thicknesses $d_m$ of the layers constituting the DBR so that the condition $d_m = \lambda_{DBR}/(4n_m)$ is fulfilled. Once the $\Theta_K(\lambda)$ is determined, the MOKE magnitude is calculated as an integral of the absolute value of the $\Theta_K(\lambda)$ over the wavelengths within the region of (Ga,Fe)N excitonic transitions. The integral describes properly the MCD [30] or the MOKE magnitude in the case when neighboring excitons of finite linewidths contribute to the dielectric function. In addition, a difference between extrema of the MOKE curve in the excitonic region (peak-to-peak amplitude) is also determined from the $\Theta_K(\lambda)$ curve.

**Numerical results.** — The calculated magnitude of the MOKE for the normal incidence case ($\theta_0 = 0$) vs. the Bragg mirror central wavelength $\lambda_{DBR}$ and the DMS thickness $d_{DMS}$ is depicted in fig. 3(a) and fig. 3(b) for DMS/DBR and DMS/buffer structures, respectively. The magnetic field is fixed at $B = 1$ T, corresponding to the magnetization of the sample close to its saturation value [25,30]. A comparison of figs. 3(a) and (b) allows for a discussion of the impact of the sample design on its magneto-optical response.

First, fig. 3 shows that the MOKE magnitude generally increases with increasing DMS layer thickness. The apparent oscillatory character of the dependence results from the light interference effects. In the case of the DMS/DBR structure (fig. 3(a)), boundaries accounting for the interferences are constituted by the DBR mirror and a DMS/air interface. For the $d_{DMS}$ corresponding approximately to a multiple of $\lambda_{DBR}/(2d_{DMS})$, the partial reflections sum up in phase and the light interfere constructively, accounting for a multiple passage of the light through the DMS layer. This enhances the absorption and the resulting MOKE magnitude. The oscillations fade with increasing $d_{DMS}$ due to a saturation of the light absorption within the DMS layer. The interference effects are less pronounced in the case of the DMS/buffer structure, as is well seen in fig. 3(c) showing a cross-section of the plots in figs. 3(a) and (b) at $\lambda_{DBR} = 354.9$. Indeed, due to a relatively small difference of the refractive indices, the reflectivity coefficient of the (Ga,Fe)N/(Al,Ga)N interface is an order of magnitude smaller than the one of the DBR mirror in the DMS/DBR structure.

Second, fig. 3(b) indicates that the MOKE integral is particularly sensitive to the $\lambda_{DBR}$ when the DMR stop band overlaps spectrally with the excitonic transitions. The highest MOKE magnitude is obtained at around $\lambda_{DBR} = 355$ nm, where both real and imaginary parts of the DMS refractive index exhibit sharp extrema due to a contribution to the dielectric function coming from excitonic absorption peaks [26,29,30]. As seen in fig. 3(c), thanks to the implementation of the resonant DMR, a substantial (around twofold) enhancement of the MOKE integral yet for thin ($\sim 100$ nm) semimagnetic layers is obtained.

The impact of the sample design is typically not taken into account when discussing the MOKE or other magneto-optical phenomena in the observed in experiments on DMS layers. The above discussion shows that the MOKE magnitude depends not only on the properties of the DMS layer itself, but also on the design of the whole structure involving the DMS layer. Our calculations indicate thus a possibility of interference enhancement of the MOKE magnitude even in the structures with no photonic crystal. Moreover, a difference between the MOKE in DMSs (where the light penetrates the structure) and the MOKE in optically thick metallic layers (where the light probes mainly the surface) is clearly highlighted here.
After a demonstration of the photonic enhancement of the MOKE in the normal light incidence case, we now pass to an analysis of the oblique incidence angles case. We set the (Ga,Fe)N layer thickness to \( d_{\text{DMS}} = 100 \text{ nm} \). The thicknesses of the layers within the DBR are set equal to, respectively, 27.6 nm and 33.1 nm for \( \text{Al}_{0.96}\text{Ga}_{0.04}\text{N} \) and \( \text{Al}_{0.2}\text{Ga}_{0.8}\text{N} \) layers, yielding \( \lambda_{\text{DBR}} = 354.9 \text{ nm} \). This assures that the DBR mirror stop band overlaps spectrally with the \( A \) and \( B \) excitons. To analyze an evolution of the Kerr rotation angle \( \Theta_K(\lambda) \) curve with the angle of incidence \( \theta_0 \), we first present in fig. 4 the \( \Theta_K(\lambda) \) for \( \theta_0 = 0 \) at \( B = 1 \text{ T} \) for both DMS/DBR and DMS/buffer structures. The MOKE amplitude, much larger in the case of the DMS/DBR than for the DMS/buffer structure and a peak-to-peak enhancement reaching a factor of \( \sim 3 \), is evidenced.

We note that despite the fact that two spectrally close (Ga,Fe)N excitons, \( A \) and \( B \), contribute to the MOKE, the \( \Theta_K(\lambda) \) curves exhibit a Lorentzian-like shape, similar as it would be in the case of a single excitonic transition [10,24]. The exciton \( C \) of a small oscillator strength [30] is neglected in the discussion.) It can be understood taking into account a non-zero energy difference between \( A \) and \( B \) excitons at \( B = 0 \text{ T} \) and their opposite splitting in the magnetic field. In such a case their antisymmetric, Lorentzian-type contributions [24,31] to the MOKE do not cancel out, but rather sum up, similarly as in the case of the excitonic MCD in the wurtzite structure (Ga,Fe)N [30].

Figures 5(a) and (b) show the \( \Theta_K(\lambda) \) curves as a function of the wavelength and the angle of incidence \( \theta_0 \) of TE polarized light for the DMS/DBR and DMS/buffer structures, respectively. It is seen in figs. 5(a) and (b) that the spectral shape of the MOKE curve for both structures practically does not change with \( \theta_0 \) within the full range of the incidence angles. The resulting integrals of the absolute value of MOKE, as well as a peak-to-peak amplitude of \( \Theta_K(\lambda) \) in the excitonic spectral region are plotted vs. \( \theta_0 \) in fig. 5(c). Figure 5(c) indicates that for both structures, the MOKE magnitude (independently of how parameterized) keeps approximately a constant value for \( \theta_0 \) from 0 to \( \sim 0.8 \text{ rad } (\sim 46 \text{ deg}) \), it drops considerably for larger angles and, as expected, it reaches 0 for \( \theta_0 \to \frac{\pi}{2} \text{ rad } (90 \text{ deg}) \). However, in the whole range of the incidence angles the magnitude of the MOKE determined for the DMS/BBR structure remains much larger as compared to the case of the DMS/buffer structure. This confirms the advantage of the implementation of 1-D photonic crystal for the enhancement of the MOKE related to (Ga,Fe)N.

Figure 6 shows an analogous set of plots such as in fig. 5, but for the TM polarization of the incident light. A comparison of either integrated MOKE curves (blue lines in fig. 6(c)) or peak-to-peak amplitudes (green lines
Fig. 5: (Colour on-line) Calculated Kerr rotation angle $\Theta_K(\lambda)$ vs. $\theta_0$ of the TE polarized light at $B = 1$ T, for (a) DMS/DBR and (b) DMS/buffer structure. (c) Left axis: integral of $\Theta_K(\lambda)$ over the wavelengths in the excitonic region as a function of $\theta_0$ for DMS/DBR (thick blue solid line) and DMS/buffer (thick blue dashed line) structures. Right axis: peak-to-peak amplitude of $\Theta_K(\lambda)$ in the excitonic region as a function of $\theta_0$ for DMS/DBR (thin green solid line) and DMS/buffer (thin green dashed line).

Fig. 6: (Colour on-line) The same as in fig. 5, but for TM polarized light. The dashed line in (a) and (b) indicates the Brewster angle at $\theta_0 \sim 1.14$ rad ($\sim 65.3$ deg).
The implementation of the DBR layer leads to a significant enhancement of the MOKE in the DMS, which is maintained for a wide range of the light incidence angles. The maximum (an order of magnitude) enhancement of the MOKE is obtained for the TM polarized light incident at Brewster angle. This indicates the possibility of an effective tuning of the degree of the MOKE enhancement through the adjustment of the light incidence angle and polarization.

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