Efficiency evaluation of the transverse magneto-optical Kerr effect in magnetoplasmonic structures

S I Pavlov¹, A B Pevtsov¹, S A Dyakov², D A Yavsin¹ and A V Nashchekin¹

¹ Ioffe Institute, Polytecheskaya Str. 26, St. Petersburg, 194021, Russia
² Skolkovo Institute of Science and Technology, 143025, Moscow, Russia

e-mail: Pavlov_sergey@mail.ioffe.ru

Abstract. In this study the new approach to the efficiency evaluation of the transverse magneto-optical Kerr effect is considered. To assess the prospects for the practical use of structures based on TMOKE, the Figure of Merit (FOM) parameter is introduced, which is the product of the reflected/transmitted light intensity and the Kerr signal of the structure. Kerr signal defined as absolute value of the difference of light intensities at opposite magnetizations. It is shown that parameter Figure of Merit (FOM) in proposed form can give more information than the most commonly used relative value of TMOKE. The advantages of the introduced parameter are demonstrated on the example of a magnetoplasmonic structure with thin magnetite films.

1. Introduction

Transverse magneto-optical Kerr effect (TMOKE) describes a change in the intensity of reflected/transmitted light when changing magnetization perpendicular to the light plane of incidence. This effect attracts researcher’s attention due to its potential for such applications as data storage, optical filtering, magnetic and bio- sensors.

The most of modern magneto-optical devices are based on the Faraday and longitudinal Kerr effects, i.e. rotation of the polarization plane in magnetic materials. Thus, measured signal intensity depends on the angle of rotation of polarization plane in a magnetic medium between crossed polarizers. The TMOKE allows one to control the light intensity directly, i.e. without polarizers. This is one of the perspective ways to create more compact and simple devices.

The main limiting factor for TMOKE being applied is a low magnitude of this effect. Indeed, in smooth ferromagnetic films the TMOKE value is about $1 \cdot 10^{-3}$ [1]. There are different ways to enhance the TMOKE magnitude, for example, one can use a multilayer structure “noble metal/ferromagnet” [2], or a magnetic dielectric/plasmon grating [3]. In such structures the TMOKE magnitude enhancement up to $10^3$ has been achieved. Reference [4] describes the magnetoplasmonic structure in which the Kerr effect amplitude reaches the maximum value $\pm 1$.

An important shortcoming of the above-mentioned studies is that they do not consider the difference between the change in the light intensity and absolute value of the light intensity. Meanwhile, the transmitted or reflected intensity plays an important role for the practical application of TMOKE in optical devices. According to [4] TMOKE signal defined as:

$$TMOKE = \frac{I(M) - I(-M)}{I(M) + I(-M)}$$
where \( I(M) \) denotes reflectance or transmittance. According to this definition, the relative value of TMOKE reaches the highest values when \( R \) is close to zero. Such an artificial TMOKE enhancement which cannot be used practically.

In this paper the new approach to the efficiency evaluation of the transverse magneto-optical Kerr effect is considered based on our previous paper [5], where TMOKE calculation for plasmonic structure on the Fe\(_3\)O\(_4\) thin film is in good agreement with experimental results. Similarly to [6, 7], figure of merit (FOM) parameter is defined as:

\[
FOM = I \times S_k
\]  

where \( I = I(0) - \) reflectance/transmittance at zero magnetization and \( S_k = |I(M) - I(-M)| \) is the absolute value of the difference of light intensities at opposite magnetizations.

Since the change in \( I(M) \) relative to \( I(0) \) is symmetric, light intensity at zero magnetization can be written as:

\[
I(0) = \frac{I(M) + I(-M)}{2}
\]

So if we would define \( FOM = I \times TMOKE \), we get just change in intensity, losing information about intensity magnitude. Alternatively FOM can be defined in other form, e.g. \( FOM = I \times S_k^2 \), \( FOM = I^2 \times S_k \), etc. Such expressions define which parameter is more important in particular case – intensity of light or change in intensity.

Thus FOM defined in equation (1) is the simplest form that takes into account the intensity and change in intensity equally.

2. Results

The sketch of the structure for calculations is shown in figure 1.

![Figure 1. Magnetoplasmonic structure sketch: magnetite films covered with periodic array of gold nanostrples.](image)

Parameters of the structure were used as follows: Fe\(_3\)O\(_4\) film thickness \( h = 100 \) and 150 nm, grating period \( a = 600 \) nm, gold stripe widths \( w = 500, 400 \) and 300 nm, gold thickness 40 nm.

The impact of the magnetic field on the optical spectra is accounted for by means of non-diagonal dielectric tensor given by

\[
\hat{\varepsilon} = \begin{bmatrix}
\varepsilon_0 & -ig & 0 \\
ig & \varepsilon_0 & 0 \\
0 & 0 & \varepsilon_0
\end{bmatrix}
\]

where \( \varepsilon_0 \) is the dielectric permittivity of the non-magnetized film, \( g \) is the value of the gyration. Spectral dependencies for the \( \varepsilon_0 \) and \( g \) for magnetite was taken from [8]. Optical constants for gold were taken from [9]. Quartz refractive index was taken as constant \( n = 1.45 \) in the entire spectral range.

Representative transmission and TMOKE spectra for the described structure are shown in figure 2. On the transmission spectra, the two main dispersion curves are clearly seen which is attributed to surface plasmon-polariton (SPP) on gold-air surface and gold-magnetite surface. The TMOKE spectra contain more information, such as the spectral position of quasiguided modes [10], that are not clearly
visible in transmission spectra. More detailed explanation of the resonances and TMOKE spectra in such structures can be found elsewhere, see for example [11, 12].

**Figure 2.** Transmission (a) and TMOKE (b) spectra of the structure in figure 1. Parameters of the structure: $h=100\text{nm}$, $w=500\text{nm}$.

From the figure 2 one can see that TMOKE signal reaches maximal magnitudes around SPP lines, but transmitted light intensity differs significantly for different spectral regions. For more clear visualization, the transmission, the relative value of TMOKE as well as FOM spectra in reduced spectral range are presented in figure 3. It is clearly seen that even though the relative value of TMOKE reaches almost equal values of about $1.2\times10^{-2}$ in two regions (wide one over wavelength $\lambda=1000-1100$ nm and narrow region over $\lambda=800-900$ nm), the second region is better for practical usage due to very low transmittance in the first region.

**Figure 3.** Transmission (a), TMOKE (b) and FOM (c) spectra of structure with parameters: $h=100\text{nm}$ $w=500\text{nm}$

Another example for structure with $w=400$ nm is shown in figure 4. Despite the greater relative value of TMOKE up to $1.8\times10^{-2}$ at $\lambda=900-1000$ nm and angle of incidence $\theta$ above $30^\circ$, the FOM in this region is only $1\times10^{-6}$. At the same time, in the region where TMOKE value is about $1\times10^{-2}$ ($\lambda=900$ nm, $\theta=2-5^\circ$), the FOM reaches $1.1\times10^{-4}$. This suggests that the second example is more valuable for practical usage.

**Figure 4.** Transmission (a), TMOKE (b) and FOM (c) spectra of structure with parameters: $h=100\text{nm}$ $w=400\text{nm}$

Yet another example of applying the TMOKE-FOM approach is considered in figure 5. In this picture the TMOKE in transmission and reflection are compared. The transmission and reflection spectra as well as the corresponding TMOKE and FOM spectra are shown in upper and lower panels of figure 5.
respectively. One can see that for equal TMOKE values of about $9 \times 10^{-3}$ the FOM value is almost three orders of magnitude greater in case of reflection. This is because the lowest intensity of reflected light is greater than the highest intensity of the transmitted light for considered spectral and angular range.

![Figure 5](image-url)

**Figure 5.** Transmission (a), TMOKE (b) and FOM (c) spectra of structure with parameters: $h=150\text{nm}$ $w=500\text{nm}$; reflection (d) TMOKE (e) and FOM (f) spectra of structure with parameters: $h=100\text{nm}$ $w=300\text{nm}$

Thus, from the considered examples one can see that the FOM approach in proposed form can give more information than the most commonly used relative value of TMOKE. It can be useful for proper parameters selection in development of TMOKE-based devices.

3. **Conclusions**

In this study the new approach to the efficiency evaluation of the transverse magneto-optical Kerr effect is considered. It was shown in some examples that even when the relative value of TMOKE is high, the applicability of the effect is limited because of low transmitted/reflected light intensity. Thus, the parameter Figure of Merit in the proposed form can give more information than relative value of TMOKE. At equal relative values of the TMOKE, the FOM can differ by more than order of magnitude depending on the structure parameters.

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