Analytical expression of the magneto-optical Kerr effect and Brillouin light scattering intensity arising from dynamic magnetization

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Abstract
Time-resolved magneto-optical Kerr effect (MOKE) and Brillouin light scattering (BLS) spectroscopy are important techniques for the investigation of magnetization dynamics. In this paper, we analytically calculate the MOKE and BLS signals from prototypical spin-wave modes in a ferromagnetic layer. The reliability of the analytical expressions is confirmed by optically exact numerical calculations. Finally, we discuss the dependence of the MOKE and BLS signals on the ferromagnetic layer thickness.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Optical techniques based on the magneto-optical Kerr effect (MOKE) such as time-resolved MOKE (TR-MOKE) or Brillouin light scattering (BLS) spectroscopy are routinely used for the investigation of magnetization dynamics. Whereas TR-MOKE provides information on the magnetization dynamics within the time domain, BLS informs on magnetization dynamics within the frequency domain.

BLS measures light intensity scattered by a spin wave. In a phenomenological (wave) picture a spin wave is a periodic displacement of magnetization with respect to the saturated state, oscillating at a spin-wave frequency \( \omega_{sw} \), and propagating at a given spin-wave \( k \)-vector. The spin waves result from the coupling between the spins, dominated by exchange and dipolar interactions [1–3]. Any periodic variation of the optical properties (namely, periodic variation of the permittivity tensor \( \varepsilon(t, \vec{r}) \)) works as an effective oscillating and propagating optical grating [4–7]. Hence, due to the spatial periodicity of the effective grating, the reflected light is scattered and changes its propagation direction. Furthermore, the oscillation of the effective grating changes the light frequency of the scattered light, a quantity detected in a BLS spectrometer [8]. In a (pseudo-)particle picture, the scattering of light by a spin wave can be interpreted as inelastic scattering of photons on magnons [9], where the photon is gaining (losing) its energy as it absorbs (creates) a magnon, respectively. Therefore, in contrast to TR-MOKE, BLS can also detect non-coherent spin waves such as thermal spin waves. Note, that the BLS technique usually provides a larger experimental sensitivity when compared with the TR-MOKE technique. For example, it has been demonstrated to detect thermal spin waves on a Co monolayer [10].

TR-MOKE investigations are based on repeated excitations of magnetization dynamics, usually by magnetic field pulses or by intense light pulses [11–13]. The resulting

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excitations are then stroboscopically detected making use of the MOKE. Therefore, TR-MOKE provides an insight into the magnetization dynamics within the time domain. Using Fourier transformation, the TR-MOKE signal can be easily transformed to the frequency domain [14]. Hence, in the case of externally excited systems, TR-MOKE and BLS investigations are complementary. This was nicely demonstrated by Perzlmaier et al investigating confined spin-wave modes in a square permalloy element [15].

The numerical models to calculate the BLS light intensity were elaborated by Cochran et al [4, 5], followed by Giovannini et al [6]. Later, a simple relation between the complex Kerr angle and the BLS intensity was expressed by Buchmeier et al [7]. However, all those treatments of the BLS intensity are numerical ones, and up to now, there exists no analytical expression of the MOKE and BLS signals originating from spin-wave modes.

In this paper, we present the analytical dependence of the TR-MOKE and BLS signals for several types of spin-wave modes. Such calculations can serve either for the separation of MOKE and BLS signals from a single ferromagnetic (FM) material in a stack of FM layers [16–19], or for the quantitative determination of the energy carried by each spin-wave mode.

The paper is organized as follows: in section 2 we establish a relation between the BLS intensity and the strength of the MOKE effect. In the section 3 the analytical expression of the MOKE depth sensitivity function is developed, and we discuss its validity and properties. Section 4 provides the analytical expressions of the MOKE and BLS signals. Finally, section 5 compares analytical expressions with optically exact numerical models, and we discuss in detail the FM layer thickness dependence of the MOKE and BLS signals.

2. Relation between MOKE and BLS signals

As light travels through a FM layer, the light intensity is attenuated and the phase of the light is delayed. Therefore, sublayers of the FM material situated at different depths of the FM layer provide a different MOKE response to a given magnetization state. Due to the fact that the MOKE is linear in magnetization, the result can be written as a superposition of the single contributions coming from different depths of the FM layer [17, 20–22]:

\[
\Phi_{s/p}(t) = \int_0^d [L_{s/p}(z)m_L(z, t) + P_{s/p}(z)m_p(z, t)]\, dz
\]

where \( \Phi_s = r_{sp}/r_{ss} \) and \( \Phi_p = -r_{sp}/r_{sp} \) are the s- and p- complex Kerr angles, arising from the FM film when the incident light is s and p polarized, respectively. The terms \( r_{xy} \), \( x, y = [s, p] \) stand for components of the reflection matrix. \( L_{s/p}(z) \) and \( P_{s/p}(z) \) are the complex MOKE depth sensitivity relations functions related to longitudinal and polar magnetization, respectively, \( d \) being the FM layer thickness. \( m_L(z, t) \) and \( m_p(z, t) \) are the depth profiles of the magnetizations in the FM film having longitudinal (i.e. in-plane and parallel to the plane of light incidence) and polar (i.e. normal) directions. In the case of spin waves, those magnetizations correspond to profiles of the dynamic magnetization (i.e. spin-wave amplitudes), precessing at the frequency \( \omega_{sw} \):

\[
m_p(z, t) = m_p(z) \sin \omega_{sw} t,
\]

\[
m_L(z, t) = m_L(z) \cos \omega_{sw} t.
\]

According to [7, 23], the BLS intensity \( I_{s/p}(\omega_{sw}) \) of the backscattered light can be expressed in a rather similar way to the complex Kerr angle \( \Phi \):

\[
I_{s/p}(\omega_{sw}) = I_0 \int_0^d \left| r_{ss/p} L_{s/p}(z)m_L(z) + P_{s/p}(z)m_p(z) \right|^2 \, dz.
\]

Within the depth sensitivity, the main difference between the complex Kerr angle \( \Phi \) and the BLS intensity \( I_{s/p}(\omega_{sw}) \) is given by the fact that, whereas MOKE is a linear combination of \( m_L(z) \), \( m_p(z) \), respectively, the BLS intensity has a quadratic form.

From comparing the equations expressing the complex Kerr angle (equation (1)) and the BLS intensity (equation (4)), their close similarity is apparent. With exception of the sign of the longitudinal contribution, the BLS intensity is basically a quadratic form of MOKE. Therefore, the BLS intensity can be expressed as being proportional to the square of the off-diagonal reflection coefficients \( r_{sp/ps} \):

\[
I_{s/p}(\omega_{sw}) = I_0 \left| r_{sp/ps} \right|^2 \equiv I_0 \left| \pm r_{ss/pp} \Phi_{s/p} \right|^2,
\]

where we must reverse the sign of the longitudinal contribution when expressing \( \Phi_{s/p} \). For example, this can be achieved either by reversing the sign of \( m_L \) in the calculations. The complex Kerr angle (i.e. the magnitude of the MOKE) is denoted by \( \Phi_{s/p} \), neglecting its time dependence (i.e. omitting the term \( \sin(\omega_{sw} t + \Phi_{s/p}) \) in equation (1)).

3. Analytical expression of the MOKE depth sensitivity function

In the case of an optically thick FM layer (i.e. the FM film thickness \( d \) is larger than the MOKE probing depth \( \Delta_{MOKE} = \lambda/(4\pi |Im(N)|) \), \( \lambda \) being the vacuum light wavelength and \( N \) (defined just below), \( L_{s/p}(z) \) and \( P_{s/p}(z) \) can be analytically expressed as [21]

\[
P_{s/p}(z) = P_{s/p}(0) \exp[-4\pi iN z/\lambda],
\]

\[
L_{s/p}(z) = L_{s/p}(0) \exp[-4\pi iN z/\lambda],
\]

where we define \( \gamma_{s/p} \) to be the ratio of the LMOKE and PMOKE response at the upper interface (i.e. \( z = 0 \)) of the FM layer, \( L_{s/p}(0) = \gamma_{s/p} P_{s/p}(0) \), \( N \) is the normalized wavevector of light in the polar (i.e. normal) direction, \( N = \sqrt{(N^0)^2 + (N^\perp \sin \psi)^2} \), where \( N^0 \) and \( N^\perp \) are the refractive indices of the FM layer and air, respectively, and \( \psi \) is the angle of light incidence with respect to the sample normal, respectively. In general, metals provide a relatively large value of the optical permeability \( \epsilon_0 \equiv N^2 \), \( N \) being the...
are 810 nm and 25

amplitude. It can be considered a general rule that the PMOKE is stronger than the LMOKE. Additionally, in our example, the small incidence angle of \( \varphi = 25^\circ \) also contributes to the small value of the LMOKE (LMOKE vanishes at \( \varphi = 0 \)). But even for an incidence angle of about 60–70°, when the LMOKE reaches its maximum, its amplitude would increase only by a factor of 2, still much smaller than the PMOKE.

Figure 1(b) shows an agreement between the analytical expressions of the MOKE depth sensitivity functions \( L_{s/p}(z) \), \( P_{s/p}(z) \) as given by equations (6) and (7) and as determined from optically exact 4 \( \times \) 4 matrix calculations for various Ni thicknesses. The starting point, \( L_{s/p}(0) \), \( P_{s/p}(0) \) is determined by the optical 4 \( \times \) 4 calculations in both cases. It is demonstrated that there is nearly a perfect agreement for large Ni thicknesses 40 and 60 nm, whereas there is a disagreement for Ni thicknesses below 30 nm. It is because the analytical expressions of \( L_{s/p}(z) \) and \( P_{s/p}(z) \) are valid when the thickness of the FM layer \( d \) is larger than the MOKE probing length, \( \Lambda_{\text{MOKE}} = \lambda / (4 \pi \text{Im}(N'_z)) \) \( (\Lambda_{\text{MOKE}} = 14.5 \text{ nm} \) for Ni at \( \lambda = 810 \text{ nm} \). On the other hand, for very small thicknesses of the FM layer (when \( d \ll \Lambda_{\text{MOKE}}, \) i.e. below \( d = 3 \text{ nm} \)), the FM layer can be neglected from the optical point of view. Hence, \( P_{s/p} \), \( L_{s/p} \) can be considered constant so that the expressions of \( L_{s/p}, P_{s/p} \) are valid for a very small thickness of the FM layer (so-called ultrathin FM layer approximation [26]).

Therefore, the MOKE depth sensitivity functions \( P_{s/p}, L_{s/p} \) are described well by the analytical expressions (equations (6) and (7)) with the exception of the FM thickness range from 3 to 30 nm. However, even in this range, the analytical expression describes basic features of the depth sensitivity functions. Namely a reduction in \( |P_{s/p}|, |L_{s/p}| \) and an increase in the phase \( \text{arg}(P_{s/p}), \text{arg}(L_{s/p}) \) with increasing depth inside the FM film. Hence, deviation of the simple analytical calculations from optically exact calculations is not large even in the case of this thickness interval, as shown later.

We finally note that \( L_{s/p}(z), P_{s/p}(z) \) are nearly independent of the incidence angle as their angular dependence is governed solely by \( N'_z \), whose angular dependence is very weak in the general case of metals.

4. MOKE and BLS from Damon–Eshbach and perpendicular standing spin-wave modes

To obtain the MOKE or BLS response of a given spin-wave mode, the profile of the dynamic magnetizations \( m_L(z), m_P(z) \) through the FM film must be determined first. Those calculations are usually based on phenomenological models of magnetization inside the FM layer [1, 7, 27, 28]. Then, the complex Kerr angle \( \Phi \) or the BLS intensity \( I_{\text{BLS}}(\omega) \) coming from a given spin-wave mode can be expressed using equations (1) and (4), respectively.

In general, the profile of a spin-wave mode must be calculated numerically. However, prototypical spin-wave modes have rather simple analytical expressions of their amplitude profiles. Here we work out the magneto-optical response of three spin-wave modes, the Damon–Eshbach (DE) mode (including the homogeneous ferromagnetic resonance
(FMR) mode) bounded to the upper (figure 2(a)) and lower (figure 2(b)) interface, and the perpendicular standing spinwave (PSSW) mode (figure 2(c)).

The DE mode occurs when \( M \) lies in plane and the spin wave propagates in a direction perpendicular to \( M \). This mode can be bounded either to the upper (figure 2(a)) or lower (figure 2(b)) interface, depending on the mutual direction of the saturation magnetization and \( k\)-vector propagation [29].

In the case of DE mode bounded to the upper interface (figure 2(a)), the polar and longitudinal profiles of the dynamic magnetizations are [29]

\[
m^\text{(DE1)}_L(z, t) = m^0_L \epsilon \exp(-k_{z,sw}z) \cos \omega_{sw} t, \tag{9}
\]

where \( \epsilon = m^0_L/m^0_p \) describes the ellipticity of the precessing magnetization, assumed to be constant over the whole FM layer thickness, \( k_{z,sw} \) is the normal direction of the spin-wave vector. In the case of a homogeneous FMR mode, \( k_{z,sw} = 0 \). Substituting the dynamic magnetization profiles (equations (8) and (9)) into the expression of MOKE effect (equation (1)), we get

\[
\Phi^{\text{(DE1)}}_{s/p}(d, t) = m^0_p P_{s/p}(0) \sqrt{1 + \gamma^2_{s/p} \epsilon^2} \times \frac{1 - \exp(-k_{z,sw} d - \text{i} \alpha)}{k_{z,sw} \epsilon \sin \omega_{sw} t + \phi_{s/p}}, \tag{10}
\]

where \( d \) is the thickness of the FM layer and \( \alpha = 4\pi N_z d / \lambda \). As the detected MOKE signal is a mixture of both LMOKE and PMOKE, it results in a phase shift \( \phi_{s/p} \) between the phase of the spin-wave mode and the detected MOKE signal, \( \tan \phi_{s/p} = \gamma_{s/p} \epsilon \). Moreover, the term \( \sqrt{1 + \gamma^2_{s/p} \epsilon^2} \) originates from Pythagorean sum of PMOKE and LMOKE.

In the case of a DE mode bounded to the lower interface (figure 2(b)), the profiles of dynamic magnetizations are analogous to equations (8) and (9):

\[
m^\text{(DE2)}_L(z, t) = m^0_L \epsilon \exp(-k_{z,sw}(d - z)) \cos \omega_{sw} t, \tag{12}
\]

leading to the MOKE effect

\[
\Phi^{\text{(DE2)}}_{s/p}(d, t) = m^0_p P_{s/p}(0) \sqrt{1 + \gamma^2_{s/p} \epsilon^2} \times \frac{\exp(-\text{i} \alpha) - \exp(-k_{z,sw}d)}{k_{z,sw} \epsilon \sin \omega_{sw} t + \phi_{s/p}}. \tag{13}
\]

The last type of the spin-wave mode to be discussed here is the PSSW modes (figure 2(c)), described approximately as a cosine function with its maxima pinned at the FM interfaces. Then, the amplitudes of dynamic magnetizations are

\[
m^\text{(PSSW)}_L(z, t) = m^0_p \epsilon \exp(m \pi z / d) \cos \omega_{sw} t, \tag{14}
\]

\[
m^\text{(PSSW)}_0(z, t) = m^0_p \epsilon \exp(m \pi z / d) \cos \omega_{sw} t, \tag{15}
\]

where integer \( m \) denotes the mode number of a given PSSW mode. Substituting those magnetization profiles (equations (14) and (15)) into equation (1) leads to the MOKE effect

\[
\Phi^{\text{(PSSW)}}_{s/p}(d, t) = m^0_p P_{s/p}(0) \sqrt{1 + \gamma^2_{s/p} \epsilon^2} \times \frac{\text{i} \alpha d [1 - \exp(-\text{i} \alpha) - 1]^m}{m^2 \pi^2 - \alpha^2} \sin(\omega_{sw} t + \phi_{s/p}). \tag{16}
\]

5. MOKE and BLS signal from spin waves in a Ni film

Figure 3 shows the MOKE effect from various spin-wave modes as a function of the Ni film thickness in air/Cu(2 nm)/Ni(4 nm)/Cu(5 nm)/Si structure. The investigated modes are the DE mode, bounded to both the upper (DE1) and the lower (DE2) interfaces, expressed for \( k_{z,sw} = 10^7 \, \text{m}^{-1} \). Furthermore, the investigated modes are the FMR mode and several PSSW modes with different mode numbers. Within those calculations, for demonstration purposes, we keep the spin-wave ellipticity \( \epsilon \) constant, although obviously the spin-wave ellipticity is different for different spin-wave modes.

(i) First, the calculations demonstrate good agreement between the exact optical calculations based on 4 × 4 matrix formalism and analytical formulae (equations (10), (13) and (16)). The largest disagreement is for Ni thicknesses in the range of about 3–30 nm, as for this range the analytical expressions of \( L_{s/p}(z) \) and \( P_{s/p}(z) \) are not exact, as already discussed in section 3.

(ii) As the Ni thickness increases, the MOKE signals increase and then saturate. In figure 3, the saturation is clearly visible only for the FMR, DE1 and PSSW1 modes. The saturation roughly appears when the depth of the unique sign of the dynamic magnetization corresponds to the length \( 2 \Delta_{\text{MOKE}} \). In the case of the FMR or DE1 mode, the MOKE signal saturates roughly at \( 2 \Delta_{\text{MOKE}} \approx d \). Within our Ni example,
The spin-wave ellipticity \( \epsilon \) is defined in equations (10), (13) and (16). In Figure 3, the MOKE signals \( |\Phi| \) originating from different types of spin waves as a function of the Ni thickness, assuming the spin-wave ellipticity \( \epsilon = 2 \). \( \Phi \) denotes the DE modes bounded to the upper and lower FM interfaces, respectively, with \( k_{s,sw} = 10^3 \text{m}^{-1} \). \( \Phi \) denotes the FMR mode (i.e. the DE modes with \( k_{s,sw} = 0 \)). \( \Phi \) denotes the PSSW modes. Incidence angle is \( 25^\circ \). Light wavelength is 810 nm. For values of optical and magneto-optical parameters, see text. Symbols are the optically exact \( 4 \times 4 \) matrix formalism, solid lines the analytical expressions (equations (10), (15) and (16)).

For smaller Ni thicknesses, the MOKE signals for PSSW modes are strongly reduced with increasing number of PSSW modes. The reason is analogous to the discussion in point (i) for a large thickness of the FM layer, which is probed by light, has nearly constant amplitude of the dynamic magnetization. Hence, obviously, in the case of PSSW modes, such saturation appears for larger thicknesses of the FM layer, as compared with DE1/FMR modes.

Substituting \( \lambda_{MOKE} = 15 \text{ nm} \), the reduction in MOKE signal is for Ni thicknesses below 15 nm, 30 nm, 45 nm for PSSW1, PSSW2 and PSSW3, respectively, in agreement with figure 3.

Figure 4 demonstrates the MOKE and BLS signals originating from the spin waves inside the Ni film, where the spin-wave profiles and frequencies are calculated using phenomenological models [27, 28]. The used magnetic properties of Ni are saturation magnetization \( \mu_0 M_s = 659 \text{ mT} \) (i.e. \( M_s = 520 \text{ kA m}^{-1} \)), exchange constant \( A = 4.7 \text{ pJ m}^{-1} \) (i.e. exchange stiffness \( D = 2.46 \text{ meV nm}^2 \)), Landé g-factor \( g = 2.1 \), out-of-plane anisotropy \( K_I = 0 \text{ kJ m}^{-3} \) [30]. The in-plane spin-wave wavevector is \( q_i = 0 \), and the external magnetic field \( \mu_0 H = 50 \text{ mT} \) is applied parallel to the plane of incidence. The optical parameters of the Ni film as well as its optical surrounding are described in section 3. The dependence of the MOKE signals on the Ni thickness and the related spin-wave frequencies are presented in figure 4 for the FMR mode as well as for several PSSW modes. The MOKE signals are expressed as \( |\Phi| \), Kerr rotation \( \theta = \text{Re}(|\Phi|) \) and Kerr ellipticity \( \epsilon = \text{Im}(|\Phi|) \). The amplitude of the in-plane dynamic magnetization of the FMR mode is chosen to be one, \( m_{(\text{FMR})}^1 = 1 \). The amplitudes of the dynamic magnetizations of the other spin-wave modes are normalized in a way that their energies per unit area are equal [4, 7].

All expressions of the MOKE signals (\( |\Phi|, \theta, \epsilon \)) provide very similar dependences. As the external field \( H \) was applied
parallel to the plane of incidence, the longitudinal contribution to the MOKE effect is zero, as there is no dynamical magnetization in the longitudinal direction. However, as discussed in section 3, the longitudinal depth sensitivity function is here about 12 times smaller than the polar one. As the normal spin-wave amplitudes are about 1–2 times smaller than the in-plane amplitudes, the polar contribution would be dominant even in the case of $H$ perpendicular to the plane of incidence, where the LMOKE contributes to the outgoing MOKE signal.

The MOKE signals in figure 4 are compared with the normalized BLS intensity (dashed magenta line). As the BLS signal is basically square of the MOKE signal (equation (5)), the behaviour of scaled BLS and MOKE signals is very similar, while the BLS signal is reduced more significantly for smaller Ni thicknesses or for higher orders of the PSSW modes.

6. Conclusion

In conclusion, we have analytically expressed the MOKE and BLS signals originating from prototypical spin-wave modes, namely the DE and PSSW modes. The calculations are based on the additivity of the MOKE effect, on analytical expression of the depth sensitivity function of the MOKE signal, as well as on a straightforward relation between the MOKE and BLS signals. As a showcase, we have expressed the MOKE and BLS signal in a Ni film. It is shown that analytical calculations describe well the physical behaviour, as follows from the comparison with exact magneto-optical calculations. Furthermore, we have demonstrated that the dependence on the FM layer thickness of both the MOKE and BLS signals is very similar. Namely, with increasing FM layer thickness, the MOKE and BLS signals saturate, where for PSSW modes with a higher mode number, the saturation is provided for larger FM layer thicknesses. Furthermore, the MOKE and BLS signals reduce significantly as the PSSW mode number increases.

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