Equatorial Kerr effect in magnetite magnetic fluids

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Abstract. In this research the equatorial Kerr effect is represented within the theoretical Maxwell-Garnett model. A theoretical analysis has shown that in the case of magnetic oxides, for which the condition $k^2 \ll n^2$ is fulfilled, the equatorial Kerr effect for magnetic fluids is related to the equatorial Kerr effect on the material of particles by the simple relation. Therefore, the amount of effect is proportional to $q$, which is the occupancy of the volume of the magnetic fluid with magnetic particles. Besides, the spectral dependences of magneto-optical effects are similar on the magnetic fluids and on the substance of particles. The experimental and theoretical results of the magnetite magnetic fluids are in good agreement.

1. Introduction

Nowadays, magneto-optical research methods are widely used for examination of ultrafine magnetic structures, which include those substances having the sizes of structural and magnetic heterogeneities less than 1000 Å. Magneto-optical investigation of these types of structures are surrounded by an active interest, which is proved to be significant both theoretically and practically. A scientific interest is explained by the unique qualities of ultrafine magnetic structures compared to the solid ones [1]. On the other hand, practical interest is determined by the widespread use of the ultrafine magnetic structures such as: magnetic fluids, thin discontinuous metal films, ferrite-garnet films, implanted magnetic surfaces and etc in industry and in everyday life. It has been discovered in the course of magneto-optical investigation of ultrafine magnetic structures that they are exception to the classic rules of physics. This compounds the task of interpretation of the derived experimental data as well as of establishment of the appropriate rules.

2. Theory

The magneto-optical reflection effects are successfully used to study the processes in the surface regions of magnetic fluids [2]. In considering the magneto-optical effects, which are odd functions of magnetizations, in magnetic fluids, it should be kept in mind that magnetic fluid is a variety of the ultrafine medium [3].

The magneto-optical properties of ultrafine media were analyzed in refs. [2,3] where it was shown that in considering the magneto-optical properties of medium consisting of magnetic colloidal particles the sizes of which are much less than the light wavelength, one should introduce the tensor of the effective dielectric permittivity.
\[
\varepsilon_{\text{eff}} = \begin{bmatrix}
\varepsilon_{\text{eff}} & -i\varepsilon'_{\text{eff}} & 0 \\
-i\varepsilon'_{\text{eff}} & \varepsilon_{\text{eff}} & 0 \\
0 & 0 & \varepsilon_{\text{eff0}}
\end{bmatrix},
\]  

(1)

where, \( \varepsilon_{\text{eff}} = \varepsilon_{\text{eff0}} - i\varepsilon_{2\text{eff}} \), \( \varepsilon_{0\text{eff}} = \varepsilon_{0\text{eff0}} - i\varepsilon_{02\text{eff}} \) and \( \varepsilon_{\text{eff}} = \varepsilon_{\text{eff0}} - i\varepsilon_{2\text{eff}} \).

Diagonal component is connected to reflective index \( n_{\text{eff}} \) and absorption index \( k_{\text{eff}} \) of ultrafine media by formula

\[
\varepsilon_{\text{eff}} = (n_{\text{eff}} - ik_{\text{eff}})
\]

(2)

For magnetic fluids with a low concentration of magnetic colloidal particles and with no direct contact between them the tensor components of the effective dielectric permittivity within the framework of the theoretical Maxwell-Garnett model of an effective medium, extended to include the case of magnetic media, can be written as:

\[
\varepsilon_{\text{eff}} = \frac{2q(e_m - e_0) + (e_m + 2e_0)}{(e_m + 2e_0) - q(e_m - e_0)}; \quad \varepsilon'_{\text{eff}} = \frac{-9q\varepsilon_0^2 e'_m}{(e_m(1-q) + e_0(2+q))^2}
\]

(3)

where \( e_m = e_{1m} - i\varepsilon'_{2m} \) and \( e'_{m} = e_{1m} - i\varepsilon_{2m} \) are the diagonal and nondiagonal tensor components of the dielectric permittivity of the material of magnetic colloidal particles, \( e_0 \) is the dielectric permittivity of the fluid phase, and \( q \) is the ratio of the volume occupied by magnetic particles, to the total volume of the magnetic fluid.

The equatorial Kerr effect (EKE), like the other magneto-optical effects which are odd functions of magnetization, occurs only in the presence of a ferromagnetic phase in the medium under investigation and is related to the tensor components of the effective dielectric permittivity as follows

\[
\delta = \frac{2\sin 2\varphi (A\varepsilon_{\text{eff}} + B\varepsilon_{2\text{eff}})}{A^2 + B^2},
\]

(4)

where \( A = \varepsilon_{2\text{eff}} (2\varepsilon'_{1\text{eff}} \cos^2 \varphi - 1) \) and \( B = (\varepsilon_{2\text{eff}} - \varepsilon_{1\text{eff}}^2) \cos^2 \varphi + \varepsilon_{1\text{eff}} - \sin^2 \varphi \), where \( \varphi \) is the angle of light incidence on the sample.

In general, the magneto-optical properties of magnetic fluids are very different from the properties of the bulk ferromagnetic. This fact causes the changes of the magneto-optical effects of the spectral and angular dependences. This occurs because magnetic fluids represent an example of a magnetic ultrafine medium composed with magnetic particles, the sizes of these magnetic particles surrounded by the carrier fluids, are much less than the light wavelength. Therefore, it is important to define the conditions of the magneto-optical experiment. In this case it occurs much easier to interpret the magneto-optical spectrums, which provides information on magnetized magnetic fluids surface layer, electronic energy structure of fine magnetic particles and the properties of carrier fluids.

In the present paper, using magnetite magnetic fluids as examples, we consider theoretically and experimentally the optical and magneto-optical properties of magnetic fluids based on particles of magnetic oxides, for the optical constants of the material of which, \( n \) and \( k \), the relation \( k^2 \ll n^2 \) holds.

In the research the EKE is represented within the framework of the theoretical Maxwell-Garnett model. In this case, considering the following relation \( k^2 \ll n^2 \) and formula (2), \( A \) and \( B \) in the formula (3) can be expressed in this way:

\[
A = 2n_{\text{eff}} k_{\text{eff}} (2n_{\text{eff}}^2 \cos^2 \varphi - 1); \quad B = (n_{\text{eff}}^2 - 1)(1 - (n_{\text{eff}}^2 + 1)\cos^2 \varphi)
\]

(4)

The analysis of these indications shows that in some areas of the angles of light incidence \( \varphi \) (for magnetite particles with different \( q \), \( \varphi=69-72^\circ \)), \( A \ll B \), which allows us to rewrite formula (3) in more simple way:
\[ \delta_e = \frac{2 \sin 2\varphi}{B} \varepsilon_{2\text{eff}} \]  

(5)

Imaginary part of nondiagonal component \( \varepsilon_{2\text{eff}} \) of the tensor of the effective dielectric permittivity \( \varepsilon_{2\text{eff}} \) (3) can be written down in following way:

\[ \varepsilon_{2\text{eff}} = q \varepsilon_0^2 \left[ \frac{\varepsilon_{2\text{eff}}}{(Y(\varepsilon_{1\text{m}} - \varepsilon_0) + \varepsilon_0^2)} - \frac{2Y \varepsilon_{2\text{eff}} \varepsilon_{1\text{m}}}{(Y(\varepsilon_{1\text{m}} - \varepsilon_0) + \varepsilon_0^2)^3} \right] \]  

(6)

where, \( Y = \frac{1-q}{3} \)  

(7)

Taking into account that dielectric permittivity for isotropic and transparent surrounding area is \( \varepsilon_0 = n_0^2 \), formula (6) takes:

\[ \varepsilon_{2\text{eff}} = qn_0^2 \left[ \frac{\varepsilon_{2\text{eff}}}{(Y(n_m^2 - n_0^2) + n_0^2^2)} - \frac{4Yk_m n_m \varepsilon_{1\text{m}}}{(Y(n_m^2 - n_0^2) + n_0^2^2)^3} \right] \]  

(9)

where \( n_m \) and \( n_0 \) are the reflective indexes particles and liquid carrier accordingly.

If \( n_0 \approx n_m \), formula (9) can be composed as:

\[ \varepsilon_{2\text{eff}} = qn_m^4 \left[ \frac{\varepsilon_{2\text{eff}}}{n_m^2} - \frac{4Yk_m \varepsilon_{1\text{m}}}{n_m^2} \right] \]  

(10)

From (7) comes that \( Y \) takes definition lying at \( 0 - 0.3 \) interval that is less or equal to \( k_m \). This goes to the fact that previously discussed case when \( k^2 \ll n^2 \), in (10) there is a possibility to ignore the second member in the right part and write down expression for the EKE in simpler way:

\[ \delta_e(q) = q \delta_m \]  

(11)

where, \( \delta_e(q) \) is EKE for magnetic fluids with the ratio of the volume occupied by magnetic particles \( q \); \( \delta_m \) - EKE on the material of particles.

It is necessary to say that received results (11) represent truth if only these three conditions are followed: 1) \( k^2 \ll n^2 \); 2) angle of light incidence \( \varphi \) fulfills the requirement \( A \ll B \); 3) \( n_0 \approx n_m \).

It follows from the relation obtained that in the specific experimental conditions the amount of EKE is proportional to \( q \) and therefore on magnetization itself. Also, the character of spectral dependences of magneto-optical effects, are similar for the magnetic fluids and the substance of particles.

3. Experiment

For experimental investigation of magnetic fluids we have chosen the EKE. The EKE consists in a change in the intensity of linearly polarized light reflected from the sample in the case of reversal of magnetization. It can be written as:

\[ \delta = \frac{I_H - I_{H=0}}{I_{H=0}}, \]  

(12)

where, \( I_H \) and \( I_{H=0} \) are, respectively, the intensities of light reflected from the magnetized and demagnetized sample. We have investigated magnetite magnetic fluids with different carrier fluids (water, kerosene, silicon-organic compound) and its sediments.

4. Results and discussion

Figure 1 represents the results of calculations of \( \delta_e(q) \) made by the formula (4) for magnetite particles in the air (a) and in the liquid silicon-organic compound (b), and by the formula (11) (c) with different \( q \) at the angle of light incidence \( \varphi = 70^\circ \). It is obvious from the figure 1 that the magneto-
optical maxima for magnetite particles shift to the side of big energy. If we increase $\varepsilon_0$, this shift diminishes, and for the liquid silicon-organic compound ($\varepsilon_0 = 2.56$) the shift in fact approximates to the zero. The results derived from our research indicated that calculations in the region of the angle of light incidence $\varphi = 69 - 72^\circ$ and big $\varepsilon_0$, $n_0 \approx n_m$, conducted according to (4), coincide with the calculations carried out by the simplified formula (11).

![Figure 1. Dependences of the EKE on the quantum energy of incident light $h\omega$, calculated by formula (4) for magnetite particles in the air (a) and in the liquid silicon-organic compound (b), and by the formula (11) (c) with $q = 0.1(1); 0.3(2); 0.5(3); 1(4)$ and experimental dependences (d) of the EKE on $h\omega$ for magnetic fluids based on magnetite particles in the liquid silicon-organic compound (1), for its sediments (2) and for a bulk film $Fe_3O_4$ (3).](image)

The experimental results obtained for the most of the magnetite fluids investigated are in a good agreement with the calculations made by the formula (11). For example, figure 1 (d) gives the experimental dependences of the EKE on the incident light quantum energy $h\omega$ for one of the investigated magnetic fluids based on magnetite particles in the liquid silicon-organic compound, for its sediments and for a bulk film $Fe_3O_4$.

From measurements of the EKE at two angles of light incidence and of the optical constants using the Every method, we determined the spectral dependences of the really $\varepsilon_{1m}$ and imaginary $\varepsilon_{2m}$ parts of the nondiagonal components $\varepsilon_{m}$ of the tensor of dielectric permittivity for the bulk magnetite with a view to checking the correlation (5) and (10) which makes a linear link between $\delta_{m}(q)$ and $\varepsilon_{2m}$. These calculations showed that the dependences of the EKE and the imaginary part of the nondiagonal component of the tensor of dielectric permittivity of magnetite are in good correlation with each other, which also is in accordance with the formulations (5) and (10).

5. Conclusion

In the present paper, on the example of magnetite magnetic fluids we have considered theoretically and experimentally the optical and magneto-optical properties of magnetic fluids based on particles of magnetic oxides. Within the framework of the theoretical Maxwell-Garnett model the simple relation is made between the EKE for ultrafine medium and the EKE on the according bulk material. The conditions of the magneto-optical experiment have been defined for the essential analytical simplification of the subsequently received results. Moreover, it has clearly been illustrated that the experimentally derived data are well compatible with the above discussed theory. In conclusion, we would like to underline that this result will also be suitable to all magnetic ultrafine medium having the optical constants $n$ and $k$ with the following relation: $k^2 \ll n^2$.

References

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