

## Correlation of light polarization in uncorrelated disordered magnetic media

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Light scattering in a magnetic medium with uncorrelated inclusions is theoretically studied in the approximation of the ladder diagram. Correlation between polarizations of electromagnetic waves that are produced by an infinitely distant dipole source is considered. Here a white-noise disorder model with Gaussian distribution is taken into account. In such a medium the magneto-optical interaction leads to correlation between perpendicular light polarizations. A spatial field correlation matrix with nonzero nondiagonal elements is obtained in the first order on gyration.

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### I. INTRODUCTION

Recently there has been increased research interest in the polarization effects of light in scattering disordered media [1–3]. Light scattering was considered both in theory [4–7] and in experiment [8,9]. This is mainly because of possibility for light localization [10]. So far only weak localization has been observed [11,12] probably due to the vector nature of light [13].

At the same time medium magnetization provides additional peculiarities in the scattering properties. For example, there is a photonic Hall effect in magnetic media [14]. Magnetic field could lead to light localization in a cold-atom gas [15]. There are multiple papers that study influence of magnetization on coherent backscattering. It was demonstrated that coherent backscattering decreases with magnetization increase due to the Faraday effect [16]. The albedo problem is considered in the case of strong [17] and small [18] magneto-optical effects in comparison with disorder fluctuations.

One of the most popular systems under investigation is represented by magnetic metal-dielectric nanostructures [19]. Such material leads to Faraday effect enhancement due to the scattering [20–22]. Media with natural optical activity as well as magneto-optical media were studied in Ref. [23].

The classical model of light scattering ignores phase and polarization correlation on distances longer than the mean free path. The elastic scattering in macroscopic samples is considered as diffusion. But in many cases the interference between scattered light cannot be omitted. This fact highlights the need for a well-described theoretical approach.

The key quantity for theoretical description of light propagation is a spatial field correlation matrix [24]. It is connected with observable quantities [25]. The correlation matrix can be used to determine Stokes parameters [26,27] and the speckle pattern [3].

A theoretical description of Faraday rotation in scattering media was demonstrated in Ref. [1]. In the present paper we are going beyond this model. We propose a theoretical description for light scattering in infinite disordered magnetic media without absorption accurate to the ladder diagram [28]. We do not consider subleading correction of maximally crossed diagrams which is important for the backscattering.

Results are demonstrated up to the linear approximation on gyration. In an uncorrelated nonmagnetic disordered medium only parallel field correlation components exist. In the magnetic medium the correlation matrix acquires nonzero nondiagonal elements. In other words the magneto-optical interaction leads to correlation of perpendicularly polarized components of scattered light at two different points. The nondiagonal part of the field correlation matrix is antisymmetric. Strict consideration of the magneto-optical effect in scattering medium was demonstrated up to first order on gyration.

The paper is organized as follows. In Sec. II we introduce the theoretical model of light propagation in a disordered magnetic medium. We briefly present the way of obtaining the electric-field correlation matrix. Results obtained by this approach for different medium magnetization directions are shown in Sec. III. Section IV is devoted to the discussion and conclusion.

### II. THEORETICAL MODEL

#### A. Electric field in a disordered magnetic medium

Electric field  $E_i$  in a bulk medium, characterized by  $\epsilon_{li}(\mathbf{r})$ , is described by the Helmholtz equation

$$(\partial_l \partial_l - \partial_k \partial_k \delta_{li} - \epsilon_{li} k_0^2) E_i = i \mu_0 \omega j_l, \quad (1)$$

where  $\partial_k \equiv \partial / \partial r_k$ ,  $\delta_{li}$  is the Kronecker symbol,  $k_0 = \omega / c$  is the light wave vector in vacuum,  $\omega$  is the wave frequency,  $c$  is the speed of light,  $j_l$  is the electric current. Summation by repeated symbols is assumed here and elsewhere further. In the simplest case of a nonmagnetic and homogeneous medium the dielectric tensor is a diagonal matrix. In the magnetic medium the dielectric tensor takes the form

$$\epsilon_{li} = \epsilon_l^0 \delta_{li} - i e_{lik} g_k, \quad (2)$$

where  $\epsilon_l^0$  is the diagonal part of the dielectric tensor,  $e_{lik}$  is the Levi-Civita tensor,  $g_k$  is the gyration proportional related to the medium magnetization. Henceforth for simplicity, we assume that  $\epsilon_l^0 = 1$ . This case could be simply generalized by rescaling the relative dielectric tensor.

The Helmholtz equation (1) can be solved by the Green-function method. The Green function is the solution of Eq. (1) with  $\delta$  function in the right side:

$$(\partial_l \partial_l - \partial_k \partial_k \delta_{li} - \epsilon_{il} k_0^2) G_{ij}(\mathbf{r}, \mathbf{r}') = \delta_{ij} \delta(\mathbf{r} - \mathbf{r}'). \quad (3)$$

In that way the electric field for an arbitrary source can be expressed by

$$E_i(\mathbf{r}) = i\mu_0\omega \int G_{il}(\mathbf{r}, \mathbf{r}') j_l(\mathbf{r}') d\mathbf{r}'. \quad (4)$$

The retarded Green function for the magnetic medium in the reciprocal space  $\mathbf{k}$  is given by

$$G_{il}^R(\mathbf{k}) = \sum_{\alpha=\pm 1} P_{il}^\alpha(\hat{\mathbf{k}}) G^{R,\alpha}(\mathbf{k}),$$

$$P_{il}^\alpha(\hat{\mathbf{k}}) = \frac{1}{2}(\delta_{il} - \hat{k}_i \hat{k}_l - i\alpha \epsilon_{ilj} \hat{k}_j),$$

$$G^{R,\alpha}(\mathbf{k}) = [(1 - \alpha \hat{\mathbf{k}} \cdot \mathbf{g}) k_0^2 - k^2 + i0^+]^{-1}, \quad (5)$$

where  $\hat{\mathbf{k}} \equiv \mathbf{k}/k$  is unit vector along the wave vector  $\mathbf{k}$ ,  $G^R(\mathbf{k}) = \int G^R(\mathbf{r}) e^{-i\mathbf{k}\mathbf{r}} d\mathbf{r}$  is the retarded Green function in the reciprocal space,  $\alpha$  is connected to right ( $\alpha = +1$ ) and left ( $\alpha = -1$ ) circular polarizations of scattered light. Such a structure of the Green function with projectors  $\mathbf{P}^{l(-)}$  on the right (left) circular polarization is caused by the magneto-optical interaction. The sign before  $0^+$  in the denominator of  $G^{R,\alpha}(\mathbf{k})$  is selected to obtain only outgoing waves.

Let us consider a magnetic medium with disorder. The disorder is given by a small fluctuation  $\delta\epsilon(\mathbf{r})$  of the dielectric tensor, i.e., we add a diagonal term to  $\epsilon_{li}$  in (2). The disorder model is a white noise:

$$\langle \delta\epsilon(\mathbf{r}) \rangle = 0, \quad \langle \delta\epsilon(\mathbf{r}) \delta\epsilon(\mathbf{r}') \rangle = \frac{6\pi}{lk_0^4} \delta(\mathbf{r} - \mathbf{r}'), \quad (6)$$

where  $\langle \dots \rangle$  means averaging by the Gaussian disorder distribution and  $l$  is elastic mean free path of the medium.

In Eq. (5) the approximate retarded Green function is shown. Indeed, the accurate retarded Green function contains a longitudinal part which is connected to the nontransversality [29]. In Ref. [30] it was demonstrated that in a nonmagnetic medium with optically anisotropic inclusions the longitudinal part of the electric field is proportional to the  $O[\delta\epsilon(\mathbf{r})]$ . In our case if light propagates along the gyration vector ( $\mathbf{g} \parallel \mathbf{k}$ ) then its longitudinal electric-field component is absent [31]. However if light propagates perpendicular to the gyration vector ( $\mathbf{g} \perp \mathbf{k}$ ) then the longitudinal component gives only  $O(g^2)$  terms in the Green function.

Consideration of multiple scattered events on sparse inclusions in the Bouret approximation [32] (i.e., in the first order on  $\zeta = 1/k_0 l$ ) results in substitution of  $0^+$  by  $k_0/l$  in the Green function [17,18,23]:

$$G^{R,\alpha}(\mathbf{k}) = [(1 - \alpha \hat{\mathbf{k}} \cdot \mathbf{g}) k_0^2 - k^2 + ik_0/l]^{-1}. \quad (7)$$

### B. Field correlation matrix

The field correlation matrix  $W_{kl}(\mathbf{r}, \mathbf{r}')$  is defined by

$$W_{kl}(\mathbf{r}, \mathbf{r}') = \langle E_k(\mathbf{r}) E_l^*(\mathbf{r}') \rangle. \quad (8)$$

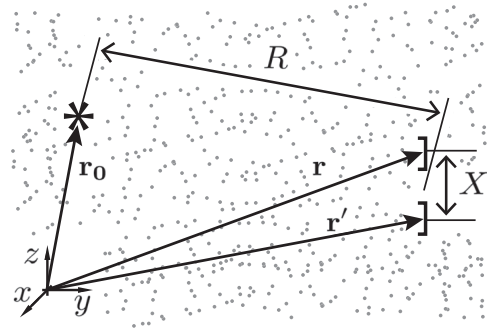


FIG. 1. Observation scheme of light fields correlation in infinite medium with disordered inclusions. The light source at point  $\mathbf{r}_0$  is at a distance  $R$  from the detectors middle point. The detectors at points  $\mathbf{r}$  and  $\mathbf{r}'$  are separated by a distance  $X$ . Hereinafter  $\mathbf{X} \parallel z$ .

It can be described by the Bethe-Salpeter equation which in the ladder approximation [2] reads

$$\langle E_k(\mathbf{r}) E_l^*(\mathbf{r}') \rangle = \langle E_k(\mathbf{r}) \rangle \langle E_l^*(\mathbf{r}') \rangle$$

$$+ k_0^4 \int \langle G_{km}(\mathbf{r}, \mathbf{r}_1) \rangle \langle G_{ln}^*(\mathbf{r}', \mathbf{r}'_1) \rangle$$

$$\times \langle \delta\epsilon(\mathbf{r}_1) \delta\epsilon(\mathbf{r}'_1) \rangle \langle E_m(\mathbf{r}_1) E_n^*(\mathbf{r}'_1) \rangle d\mathbf{r}_1 d\mathbf{r}'_1. \quad (9)$$

We assume that the light source is a point dipole with a dipole moment  $p = 1/\mu_0\omega^2$  located at  $\mathbf{r}_0$ :

$$j_l(\mathbf{r}, \mathbf{r}_0) = -i\omega p_l \delta(\mathbf{r} - \mathbf{r}_0). \quad (10)$$

Equation (9) can be solved in reciprocal space by the Fourier transform on variables  $\mathbf{X} = \mathbf{r} - \mathbf{r}'$  and  $\mathbf{R} = (\mathbf{r} + \mathbf{r}')/2 - \mathbf{r}_0$  with dual variables in the reciprocal space, correspondingly,  $\mathbf{q}$  and  $\mathbf{K}$  (see Fig. 1).

The first step is to solve the Bethe-Salpeter equation with  $\mathbf{X} = 0$ :

$$D_{ijkl}(\mathbf{K}) = S_{ijkl}(\mathbf{K}) + \frac{6\pi}{l} S_{ijmn}(\mathbf{K}) D_{mnkl}(\mathbf{K}), \quad (11)$$

where

$$S_{ijkl}(\mathbf{K}) = \int \langle G_{ik}(\mathbf{q} + \mathbf{K}/2) \rangle \langle G_{jl}^*(\mathbf{q} - \mathbf{K}/2) \rangle \frac{d\mathbf{q}}{(2\pi)^3},$$

$$D_{ijkl}(\mathbf{K}) = \int \langle G_{ik}(\mathbf{q} + \mathbf{K}/2) G_{jl}^*(\mathbf{q} - \mathbf{K}/2) \rangle \frac{d\mathbf{q}}{(2\pi)^3}. \quad (12)$$

We can find  $D_{ijkl}$  by obtaining eigenvalues and eigenvectors  $S_{ijkl}$ :

$$\frac{6\pi}{l} S_{ijkl}(\mathbf{K}) = \sum_{p=1}^9 \lambda_p |p\rangle_{ij} \langle p|_{kl}$$

$$\Rightarrow D_{ijkl}(\mathbf{K}) = \sum_{p=1}^9 \frac{l}{6\pi} \frac{\lambda_p}{1 - \lambda_p} |p\rangle_{ij} \langle p|_{kl}. \quad (13)$$

The next step is to solve Eq. (9) for  $\mathbf{X} \neq 0$ :

$$\begin{aligned} Q_{ijkl}(\mathbf{q}, \mathbf{K}) &= F_{ijkl}^{\alpha\beta}(\hat{\mathbf{q}}, \mathbf{K}) \\ &\times \langle G^\alpha(\mathbf{q} + \mathbf{K}/2) G^{*\beta}(\mathbf{q} - \mathbf{K}/2) \rangle, \\ F_{ijkl}^{\alpha\beta}(\hat{\mathbf{q}}, \mathbf{K}) &= P_{ik}^\alpha(\hat{\mathbf{q}}) P_{jl}^{*\beta}(\hat{\mathbf{q}}) \\ &+ \frac{6\pi}{l} P_{im}^\alpha(\hat{\mathbf{q}}) P_{jn}^{*\beta}(\hat{\mathbf{q}}) D_{mnkl}(\mathbf{K}), \end{aligned} \quad (14)$$

where  $\hat{\mathbf{q}} \equiv \mathbf{q}/q$  is the unit vector along wave vector  $\mathbf{q}$ .

Without loss of generality, we suppose that the source is a point dipole oriented along the  $z$  axis. In such a way the correlation matrix in reciprocal space is

$$W_{ij}(\mathbf{q}, \mathbf{K}) = Q_{ij33}(\mathbf{q}, \mathbf{K}). \quad (15)$$

Finally we have to find the inverse Fourier transform of (15). The Fourier transform of  $W_{ij}(\mathbf{q}, \mathbf{K})$  made only on  $\mathbf{X}$ ,  $W_{ij}(\mathbf{R}, \mathbf{q})$ , is a local density matrix of the radiation with wave vector  $\mathbf{q}$  [17]. Thereby we introduce the quantity  $I_{ij}(\mathbf{R}, \hat{\mathbf{q}})$  by integration  $W_{ij}(\mathbf{R}, \mathbf{q})$  on the absolute value of  $\mathbf{q}$ :

$$I_{ij}(\mathbf{R}, \hat{\mathbf{q}}) = 2 \int q^2 W_{ij}(\mathbf{R}, q\hat{\mathbf{q}}) dq. \quad (16)$$

It is proportional to the light intensity [33].

### C. Solving Bethe-Salpeter equation

First, we have to compute the  $\mathbf{S}$  tensor from Eq. (11). With the aim to compute a result in the analytic form we have to choose certain limited orders in small parameters of our problem. We can compute the  $\mathbf{S}$  tensor at least in orders  $O[(Kl)^2]$  and  $O(g^2)$  but getting eigenvectors is a rather difficult computational task. This can be done in the degenerate perturbation theory.

The main contribution in the small parameter  $Kl$  is  $(1/Kl)^2$ . It rises only from one eigenvalue of the  $\mathbf{S}$  tensor:  $\lambda = 1 - (Kl)^2/3$ . This eigenvalue has only a second-order gyration correction. We neglect such a term assuming that  $g^2 \ll (Kl)^2$ . But  $\mathbf{S}$ -tensor eigenvectors have first order in gyration corrections. For their accounting we assume that  $(Kl)^2 \ll g$ . Thus we have the following relations of small parameters of our problem:  $g^2 \ll (Kl)^2 \ll g \ll \zeta \ll 1$ .

A detailed computation of  $S_{ijkl}$  with  $O((1/Kl)^2)$  terms but without gyration can be found in Vynck *et al.* [2]. To obtain  $\mathbf{S}$  with nonzero gyration we compute the integral on module  $q$  by residue theorem. After that we can expand  $\mathbf{S}$  because  $g \ll \zeta$  and take angular integral. To compute eigenvectors for the first order of gyration we use the degenerate perturbation theory. Since  $\mathbf{S}$  with gyration is a nonsymmetric matrix right and left eigenvectors must be distinguished. We use only eigenvectors which correspond to the unit eigenvalue and coincide. For arbitrary gyration orientation

$$|1\rangle_{ij} = \langle 1|_{ij} = \frac{\sqrt{3}}{3} \delta_{ij} + \frac{\sqrt{3}}{6} e_{ijk} g_k. \quad (17)$$

After computation  $\mathbf{D}$  from (13) we can obtain  $\mathbf{Q}$ . We are interested in the  $1/(Kl)^2$  term which is located only in  $\mathbf{D}$ . Consequently, we can neglect the first term of  $\mathbf{F}$  and  $K$  dependence of the Green function.

From  $\mathbf{D}$  we can find  $\mathbf{W}$  (15):

$$\begin{aligned} W_{ij}(\mathbf{K}, \mathbf{q}) &= \frac{1}{(Kl)^2} \sqrt{3} |1\rangle_{mn} P_{im}^\alpha(\hat{\mathbf{q}}) P_{jn}^{*\beta}(\hat{\mathbf{q}}) \\ &\times \langle G^\alpha(\mathbf{q}) \rangle \langle G^{*\beta}(\mathbf{q}) \rangle. \end{aligned} \quad (18)$$

Summation by repeated symbols is assumed here. In nondiagonal elements there are two distinct contributions of the orders  $O(g/\zeta)$  and  $O(g)$ . We neglect the  $g$ -order term due to the relation  $\zeta \ll 1$ . Inverse Fourier transform of the  $K$ -dependent part of the correlation matrix is proportional to  $1/R$ . Fourier transform from the  $q$  space to  $X$  space leads to (20)–(22).

## III. RESULTS

Further we will consider the following approximation:

$$g^2 \ll (Kl)^2 \ll g \ll \zeta \ll 1. \quad (19)$$

It corresponds to the situation when the light source is located far from the detectors  $R \gg l$ , elastic scattering plays the main role and the magneto-optical effect can be considered as a small correction. The linear on gyration contribution comes from eigenvectors of  $\mathbf{S}$ . As was discovered earlier [23] the eigenvalues contain only  $O(g^2)$  terms. The eigenvectors' computation is a rather complicated task. Only recently eigenvectors without gyration were found up to  $O[(Kl)^2]$  [2]. For the analytic analysis of the linear on gyration contribution we take into account only the largest  $Kl$  terms that are  $O[1/(Kl)^2]$ .

Let us assume that observation points are along the  $z$  axis:  $\mathbf{X} \parallel \mathbf{z}$ . We consider two magnetization directions:  $\mathbf{g}_\parallel$  ( $\mathbf{g} \parallel \mathbf{z}$ ) and  $\mathbf{g}_\perp$  ( $\mathbf{g} \parallel \mathbf{y}$ ). The normalized quantity  $\tilde{\mathbf{W}}(\mathbf{X}) = \mathbf{W}(\mathbf{R}, \mathbf{X})/W(\mathbf{R})$ , where  $W(\mathbf{R}) = \text{Tr}[\mathbf{W}(\mathbf{R}, \mathbf{X})|_{\mathbf{X}=0}] = \frac{k_0 \zeta}{8\pi^2 R}$ , does not depend on the distance from the light source.

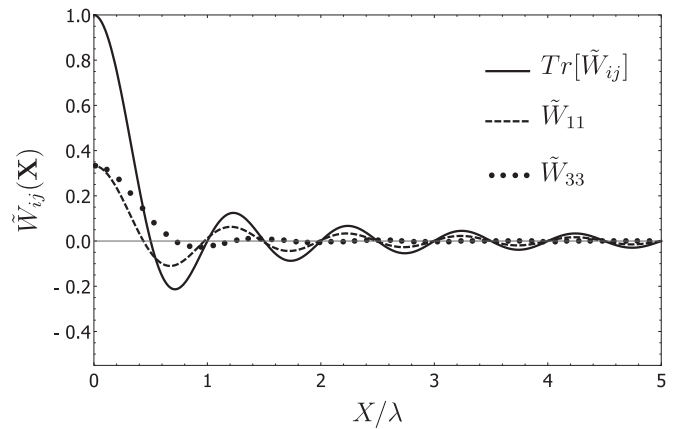


FIG. 2. Dependence of the diagonal normalized field correlation matrix components on the distance between the detectors.  $\mathbf{X}$  is oriented along the  $z$  axis.  $W_{ij}$  shows the correlation between  $E_i$  and  $E_j$  components on the detectors. We assume that the mean free path  $l = 20\lambda$ . The distance between the detectors is normalized on wavelength.

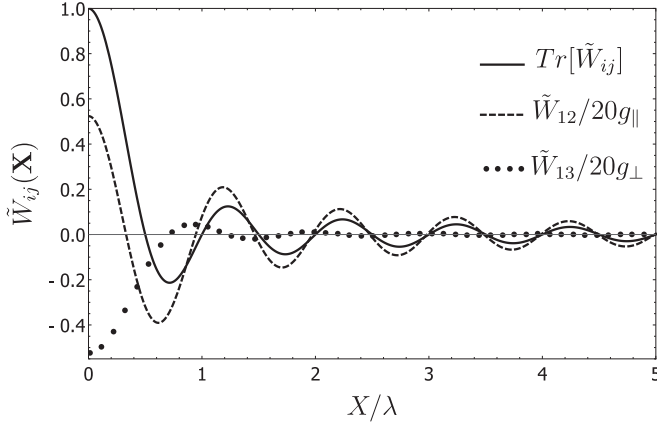


FIG. 3. Dependence of the nondiagonal normalized field correlation matrix components on the distance between detectors.  $\mathbf{X}$  is oriented along the  $z$  axis.  $W_{ij}$  shows the correlation between  $E_i$  and  $E_j$  components on the detectors. Dashed line corresponds to the normalized nonzero element of the correlation matrix divided by  $20g_{\parallel}$  when gyration is directed parallel to  $\mathbf{X}$ . Dotted line corresponds to the normalized nonzero element of the correlation matrix divided by  $20g_{\perp}$  when gyration is directed perpendicular to  $\mathbf{X}$ . We assume that the mean free path  $l = 20\lambda$ . The distance between the detectors is normalized on wavelength.

We obtain the same diagonal elements for both gyration orientations:

$$\begin{aligned} \tilde{W}_{11}(X) &= \tilde{W}_{22}(X) \\ &= \frac{[(k_0X)^2 - 1] \sin k_0X + k_0X \cos k_0X}{2(k_0X)^3} \\ &\quad - \zeta \frac{[(k_0X)^2 - 2](k_0X \sin k_0X + \cos k_0X) + 2}{4(k_0X)^3}, \\ \tilde{W}_{33}(X) &= \frac{\sin k_0X - k_0X \cos k_0X}{(k_0X)^3} \\ &\quad + \zeta \frac{[(k_0X)^2 - 2] \cos k_0X - 2k_0X \sin k_0X + 2}{2(k_0X)^3}. \end{aligned} \quad (20)$$

These diagonal elements have no magneto-optical contribution and coincide with the result with zero gyration [2] (see Fig. 2). However, there are nonzero nondiagonal elements proportional to  $g/\zeta$  (Fig. 3). For  $\mathbf{g}_{\parallel}$  they are

$$\begin{aligned} \tilde{W}_{12}(X) &= -\tilde{W}_{21}(X) \\ &= \frac{g_{\parallel}}{\zeta} \frac{[(k_0X)^2 - 2] \sin k_0X + 2k_0X \cos k_0X}{4(k_0X)^3}, \end{aligned} \quad (21)$$

while for  $\mathbf{g}_{\perp}$ ,

$$\begin{aligned} \tilde{W}_{13}(X) &= -\tilde{W}_{31}(X) \\ &= \frac{g_{\perp}}{\zeta} \frac{(k_0X \cos k_0X - \sin k_0X)}{4(k_0X)^3}. \end{aligned} \quad (22)$$

If  $\mathbf{g} \parallel \mathbf{X}$  only two nondiagonal components  $\tilde{W}_{12} = -\tilde{W}_{21}$  are nonzero. However, for  $\mathbf{g} \perp \mathbf{X}$  only  $\tilde{W}_{13} = -\tilde{W}_{31}$  are nonzero and decay faster.

#### IV. DISCUSSION AND CONCLUSION

To conclude, we have theoretically investigated light scattering in a magnetic medium with uncorrelated inclusions. The spatial field correlation matrix with ladder approximation is used for the light propagation description, so only two-particle interactions are considered. The approximation of the distant light source, when the distance from the source  $R$  is much larger than the elastic-scattering mean free path, is taken into account up to the order  $O[1/(Kl)^2]$ . The magneto-optical interaction is described by terms linear in gyration. The distance between the detectors  $X$  is assumed much smaller than the distance to the source.

Here we studied the correlation matrix dependency on direction and amplitude of the sample magnetization. Explicit calculations of the eigenvalues and eigenvectors were performed in degenerate perturbation theory as it was previously suggested for nonmagnetic medium in Ref. [2]. The first-order magneto-optical effect correction was found. Nonzero values of the nondiagonal field-correlation matrix components are found. Such components are responsible for correlation of the perpendicular polarizations of the scattered light between different points. Influence of the magnetization direction on correlation of light polarization is demonstrated.

This work extends the understanding of light behavior in magnetic scattering medium. The correlation between perpendicular polarizations of light opens the possibility to develop time-reversal-noninvariant systems based on magneto-optical effects enhanced by scattering [20–22]. A rigorous theory of light scattering in the presence of a magnetic field may lead to better understanding of ferrofluid magneto-optics [34]. Moreover, it might be interesting for the study of light scattering in magnetoplasmonic structures [35–37].

Further investigation in this area may go in different directions. First of all, this theory can be applied to various forms of scattering media: scatterers with anisotropic dielectric tensor or inhomogeneous gyration. Second, instead of an infinite medium it is possible to consider half-space or slab geometries. Additional development allows us to obtain better theoretical model up to orders of  $O[(Kl)^2]$  and  $O(g^2)$ . Also it is possible to extend theory to account for backscattered light which requires consideration of maximally crossed diagrams.

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