Quantum Electronics **49** (3) 253–257 (2019)

RADIATION SCATTERING

https://doi.org/10.1070/QEL16834

Circular dichroism in the presence of resonant Mie scatterers

E.E. Gorodnichev, D.B. Rogozkin

Abstract. **Unpolarised light propagation is considered in a circularly dichroic medium with optically isotropic Mie-particles. The degree of passed radiation polarisation is calculated under the assumption that multiple scattering in such a system occurs in the spatial diffusion regime. It is shown that introducing Mie particles into a homogeneous sample with natural optical activity can noticeably enhance the observed circular dichroism, namely, increase a difference between the intensities of right- and left-handed polarised light passed through the medium. If the first Kerker condition is fulfilled for Mie particles, then the effect can be almost ten times stronger as compared to the case of a homogeneous sample.**

Keywords: *multiple scattering, polarised light, circular dichroism, Mie scattering.*

1. Introduction

A medium possessing natural optical activity can exhibit the circular dichroism effect – different absorption indices for light with right-handed and left-handed circular polarisations (see, for example, [1]). The circular dichroism is very sensitive to configurations of complicated molecules and conformation transitions therein. Thus, the measurement of this effect is an important method of stereochemical analysis [2, 3] which is widely used in studying a secondary structure of biopolymers, in particular, peptides and nucleic acids [4, 5].

In view of the fact that determining optical activity characteristics in various media is mainly difficult due to weakness of the effect [4], various methods for enhancing it are interesting [6–9] (for example, heterodyne detection [10]).

In the last decade, in the field of nanophotonics, optical properties of particles with a high refraction index were thoroughly studied in the visible and near-IR spectral ranges [11–19]. It was shown (see, for example, [11–13]) that, in the vicinity of first two Mie resonances (for Mie resonances see [20, 21]), the so-called first Kerker condition characterised by the equality of electric and magnetic polarisabilities of a particle can be fulfilled [22]. For particles possessing the parameters satisfying the Kerker condition, light backscattering is suppressed and, in addition, circularly polarised light does not change its polarisation in scattering [13, 23–25]. Wave depolarisation is so weak that only becomes noticeable after a large number of scattering events. In light diffusion in such a medium, the circular polarisation attenuates anomalously slow [23–25]. Results available [13, 23–25] make us assume that addition of the Mie particles with the parameters satisfying the Kerker condition to a homogeneous medium on the one hand will substantially increase photon path lengths in the medium and on the other hand will not change the state of circular polarisation of the waves propagating through the medium. If the inhomogeneous medium possesses circular dichroism, it results in the substantially greater difference in the intensities of the waves with distinct polarisation passed across the medium. The law of the intensity difference variation for right-handed (I_R) and left-handed polarised (I_L) waves in a homogeneous medium $|I_R - I_L|/(I_R + I_L) = \Delta\kappa L/2$ ($\Delta\kappa$ is the absorption index difference for the corresponding waves, L is the sample length) must be transformed into the law $|I_R - I_L|/(I_R + I_L) = \Delta\kappa S_L/2$, where S_L is the average path of light beams in the sample, in case of adding scatterers to the medium. Since in the diffusion regime the light path is much longer than the sample thickness $S_L \gg L$, a substantial increase in the ratio $|I_R - I_L|/(I_R + I_L)$ will be observed in the considered case. Similarly to such systems as a 'random laser' (see, for example, [26]) and scattering matrices used for measuring weak absorption in liquids and gases [27, 28], a disordered ensemble of Mie particles behaves like a spatially distributed resonator that elongates light beam trajectories in the sample not affecting the circular polarisation.

In the present work, we consider propagation of initially unpolarised light (incoherent superposition of right-handed and left-handed polarised waves) across the system of scattering centres embedded into a medium with circular dichroism. It is assumed, that the optical parameters of the particles fulfil the first Kerker condition. In the diffusion approximation, the degree of circular polarisation as a function of the sample thickness is calculated for passed radiation. It is shown that in a scattering layer with a large optical thickness, a substantially greater circular dichroism should be observed as compared to a layer of the homogeneous medium. The increase factor is analysed as a function of system optical parameters.

2. Transport equation in a scattering medium with circular dichroism

In most practical situations, the natural optical activity can be assumed small; hence, it can be neglected in calculations of the matrix for scattering on Mie particles. As shown in [23–25], near the first Kerker point (which is determined by

E.E. Gorodnichev National Research Nuclear University 'MEPhI', Kashirskoe shosse 31, 115409 Moscow, Russia;
e-mail: gorodn@theor.mephi.ru;
D.B. Rogozkin National Research Nuclear University 'MEPhI', Kashirskoe shosse 31, 115409 Moscow, Russia; Dukhov All-Russian Research Institute of Automatics, Sushchevskaya ul. 22, 127055 Moscow, Russia

Received 7 October 2018; revision received 7 December 2018
Kvantovaya Elektronika **49** (3) 253–257 (2019)
Translated by N.A. Raspopov

the ratio $an/\lambda \approx 0.436$, where a and n are the radius and relative refraction index of the particles, and λ is the light wavelength) the matrix of single scattering has a diagonal form

$$\hat{d} = \begin{pmatrix} a_1 & 0 & 0 & 0 \\ 0 & a_1 & 0 & 0 \\ 0 & 0 & a_2 & 0 \\ 0 & 0 & 0 & a_2 \end{pmatrix}, \qquad (1)$$

where elements a_1 and a_2 are functions of the cosine of angle γ for single scattering, which are expressed in terms of the scattering amplitudes $A_\parallel$ and $A_\perp$ of cross-polarised waves: $a_1 = (|A_\parallel|^2 + |A_\perp|^2)/2$, $a_2 = \mathrm{Re} A_\parallel A_\perp^*$ [27].

The right-handed and left-handed polarised waves are eigenmodes of a medium possessing circular dichroism [29]. Thus, multiple light scattering in such media can be conveniently described by the Stokes vector in the circular representation [30–33]:

$$\hat{I} = \frac{1}{\sqrt{2}} \begin{pmatrix} Q - \mathrm{i}U \\ I - V \\ I + V \\ Q + \mathrm{i}U \end{pmatrix}, \qquad (2)$$

where I, Q, U and V are the standard Stokes parameters in the linear approximation [20]. Within a factor, the values of $I \pm V$ coincide with the intensities of the right-handed and left-handed polarised waves $I_{\mathrm{R,L}} = (I \pm V)/2$.

For scattering matrix (1), the vector transfer equation splits into two independent systems of equations: one for the Stokes parameters $Q \mp \mathrm{i}U$, which are responsible for a linear polarisation of scattered light and the other for circularly polarised components $I_{\mathrm{R,L}}$ [23–25]. Thus, if the first Kerker condition fulfils, the linear and circular polarisations evolve in the process of multiple scattering independently from each other.

In what follows, we will be interested in propagation of an initially unpolarised light (an incoherent superposition of right-handed and left-handed polarised light waves). In this case, the polarisation state of scattered light is described only by the system of equations for intensities I_{R} and I_{L} [31–35]. As applied to a homogeneous medium with circular dichroism into which the Mie particles with the parameters satisfying the first Kerker condition are embedded, the equations for I_{R} and I_{L} have the form

$$\left(\mu \frac{\partial}{\partial z} + n_0\sigma + \kappa\right) I_{\mathrm{R}}(z,\mu) - \frac{\Delta\kappa}{2} I_{\mathrm{R}}(z,\mu)$$
$$= n_0 \int \mathrm{d}\boldsymbol{n}' a_+(\boldsymbol{nn}') I_{\mathrm{R}}(z,\mu') + n_0 \int \mathrm{d}\boldsymbol{n}' a_-(\boldsymbol{nn}') I_{\mathrm{L}}(z,\mu'), \qquad (3)$$

$$\left(\mu \frac{\partial}{\partial z} + n_0\sigma + \kappa\right) I_{\mathrm{L}}(z,\mu) + \frac{\Delta\kappa}{2} I_{\mathrm{L}}(z,\mu)$$
$$= n_0 \int \mathrm{d}\boldsymbol{n}' a_+(\boldsymbol{nn}') I_{\mathrm{L}}(z,\mu') + n_0 \int \mathrm{d}\boldsymbol{n}' a_-(\boldsymbol{nn}') I_{\mathrm{R}}(z,\mu'), \qquad (4)$$

where $a_\pm(\boldsymbol{nn}') = [a_1(\boldsymbol{nn}') \pm a_2(\boldsymbol{nn}')]/2$; $\mu = \boldsymbol{nn}_{\mathrm{int}}$; $\mu' = \boldsymbol{n}'\boldsymbol{n}_{\mathrm{int}}$; $\boldsymbol{n}$ is the unit vector along the light propagation direction; $\boldsymbol{n}_{\mathrm{int}}$ is the unit vector of the internal normal to a sample surface; σ is the cross section of light elastic scattering on Mie particles; n_0 is the particle concentration; k is the average refraction index of the medium [4, 29]; and z axis is directed along the $\boldsymbol{n}_{\mathrm{int}}$.

3. Spatial diffusion of circularly polarised light components

Let us write the solution for system (3), (4) in the form of expansion in a series of Legendre polynomials:

$$I_{\mathrm{R,L}}(z,\mu) = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} I_{\mathrm{R,L}}(z,l) P_l(\mu). \qquad (5)$$

Then for coefficients $I_{\mathrm{R,L}}(z,l)$ in expansion (5) we have

$$\frac{l}{2l+1} \frac{\partial I_{\mathrm{R}}(z,l-1)}{\partial z} + \frac{l+1}{2l+1} \frac{\partial I_{\mathrm{R}}(z,l+1)}{\partial z}$$
$$+ [\Sigma_{\mathrm{R}}^{\mathrm{tot}} - n_0 a_+(l)] I_{\mathrm{R}}(z,l) = n_0 a_-(l) I_{\mathrm{L}}(z,l), \qquad (6)$$

$$\frac{l}{2l+1} \frac{\partial I_{\mathrm{L}}(z,l-1)}{\partial z} + \frac{l+1}{2l+1} \frac{\partial I_{\mathrm{L}}(z,l+1)}{\partial z}$$
$$+ [\Sigma_{\mathrm{L}}^{\mathrm{tot}} - n_0 a_+(l)] I_{\mathrm{L}}(z,l) = n_0 a_-(l) I_{\mathrm{R}}(z,l), \qquad (7)$$

where

$\Sigma_{\mathrm{R,L}}^{\mathrm{tot}} = n_0\sigma + \kappa \mp \Delta\kappa/2$; and

$$a_\pm(l) = \pi \int_{-1}^{1} \mathrm{d}\mu [a_1(\mu) \pm a_2(\mu)] P_l(\mu). \qquad (8)$$

The propagation regime of circularly polarised light components is substantially affected by the relation between the optical medium parameters entering into (6) and (7). It was shown [31–33, 36] that the rate of depolarisation of circularly polarised light is defined by coefficient $a_-(l=0)$, which is proportional to the depolarisation cross section $a_-(l=0) = \sigma_{\mathrm{dep}}/2$, where $\sigma_{\mathrm{dep}} = \int \mathrm{d}\boldsymbol{n}'[a_1(\boldsymbol{nn}') - a_2(\boldsymbol{nn}')]$. The effect of the slow variation of circular polarisation [37–39] occurs if the depolarisation cross section σ_{dep} is substantially smaller that the transport cross section of elastic scattering: $\sigma_{\mathrm{dep}} \ll \sigma_{\mathrm{tr}} = \int \mathrm{d}\boldsymbol{n}'(1 - \boldsymbol{nn}') a_1(\boldsymbol{nn}')$ [24, 36]. In this situation, the circular polarisation state changes in the linear scales of above the transport length of elastic scattering $l_{\mathrm{tr}} = (n_0\sigma_{\mathrm{tr}})^{-1}$, that is, in the spatial diffusion regime of radiation [31–33, 36]. The effect of slow attenuation of circular polarisation was observed in experiments on light scattering in an aqueous suspension of large (with above-wavelength dimensions) latex particles [37–39]. A theoretical description of the results of experiments [37–39] and of numerical simulation [38] was given in [31–33].

The ratio $\sigma_{\mathrm{dep}}/\sigma_{\mathrm{tr}}$ reaches anomalously large values in scattering on the particles possessing a high refraction index with the parameters satisfying the first Kerker condition (typical values are $\sigma_{\mathrm{dep}}/\sigma_{\mathrm{tr}} \approx 10^{-3}$) [23–25]. The smallness of $\sigma_{\mathrm{dep}}/\sigma_{\mathrm{tr}}$ provides the maximal increase in optical light paths in the medium without changing the circular polarisation state of radiation.

In the conditions of light spatial diffusion in a weakly absorbing medium (we assume $\kappa \ll n_0\sigma_{\mathrm{tr}}$) the angular distribution of the radiation intensity is almost isotropic and in expansion (5) it suffices to retain the first two summands with $l = 0$ and 1 [40, 41] (for polarised light see also [31, 32, 36]). In the result, from (6) and (7) we obtain the diffusion-type system of equations for $I_{\mathrm{R,L}}(z) = I_{\mathrm{R,L}}(z, l = 0)$:

$$\left[\frac{\partial^2 I_R(z)}{\partial z^2} - 3n_0\sigma_{tr}\Sigma_R I_R(z)\right] + \frac{3}{2}n_0^2\sigma_{tr}\sigma_{dep}I_L(z) = 0, \quad (9)$$

$$\left[\frac{\partial^2 I_L(z)}{\partial z^2} - 3n_0\sigma_{tr}\Sigma_L I_L(z)\right] + \frac{3}{2}n_0^2\sigma_{tr}\sigma_{dep}I_R(z) = 0, \quad (10)$$

where $\Sigma_{R,L} = \kappa + n_0\sigma_{dep}/2 \mp \Delta\kappa/2$.

The boundary conditions for diffusion equations (9) and (10) have the form

$$\left(I_{R,L} - z_0\frac{dI_{R,L}}{dz}\right)\Bigg|_{z=0} = 0, \quad \left(I_{R,L} + z_0\frac{dI_{R,L}}{dz}\right)\Bigg|_{z=L} = 0, \quad (11)$$

where z_0 is the extrapolated length. In the Marshak approximation $z_0 \approx 2l_{tr}/3$, the exact solution to the Milne problem for isotropic scatterers yields $z_0 \approx 0.71l_{tr}$ [40, 41]. For boundary conditions (11), a solution to system (9), (10) is sought in a standard procedure (see, for example, [42]). For a source in the form of an incoherent superposition of right-hand and left-hand waves, the intensities of the circularly polarised radiation components passed through a layer of thickness L can be presented in the form

$$I_{R,L}(L,\mu) = \frac{1}{4\pi}\left[I_{R,L}(z) - \mu l_{tr}\frac{d}{dz}I_{R,L}(z)\right]\Bigg|_{z=L}, \quad (12)$$

where a relation between $I_{R,L}(z)$ and $dI_{R,L}(z)/dz$ is found from boundary condition (11) and the expressions

$$I_R(L) = \frac{1}{(1+\eta^2)}\left\{(1+\eta)\frac{\varepsilon_-(l_{tr}+z_0)}{\sinh[\varepsilon_-(L+2z_0)]} - \eta(1-\eta)\frac{\varepsilon_+(l_{tr}+z_0)}{\sinh[\varepsilon_+(L+2z_0)]}\right\}, \quad (13)$$

$$I_L(L) = \frac{1}{(1+\eta^2)}\left\{\eta(1+\eta)\frac{\varepsilon_-(l_{tr}+z_0)}{\sinh[\varepsilon_-(L+2z_0)]} + (1-\eta)\frac{\varepsilon_+(l_{tr}+z_0)}{\sinh[\varepsilon_+(L+2z_0)]}\right\}. \quad (14)$$

Here,

$$\eta = \left[\sqrt{(n_0\sigma_{dep})^2 + \Delta\kappa^2} - \Delta\kappa\right]/(n_0\sigma_{dep}),$$

and damping coefficients ε_- and ε_+ are determined by the expression

$$\varepsilon_\mp = \sqrt{3n_0\sigma_{tr}\left\{\kappa + \frac{1}{2}\left[n_0\sigma_{dep} \mp \sqrt{(n_0\sigma_{dep})^2 + \Delta\kappa^2}\right]\right\}}. \quad (15)$$

In (15), the parameters $\kappa + (1/2)\left[n_0\sigma_{dep} \mp \sqrt{(n_0\sigma_{dep})^2 + \Delta\kappa^2}\right]$ play the role of the effective absorption indices for right-hand and left-hand polarised waves in the medium considered. If the depolarisation is negligible ($n_0\sigma_{dep} \ll \Delta\kappa$), we return to the initial definition of the absorption indices for the right-hand and left-hand polarisation waves in a homogeneous medium: $\kappa \mp \Delta\kappa/2$. In the opposite case ($n_0\sigma_{dep} \gg \Delta\kappa$), the difference between the effective absorption indices becomes quadratic in $\Delta\kappa$.

The total intensity $I = I_L + I_R$ and the difference of the right-handed and left-handed polarisation wave intensities $I_L - I_R$ (the fourth Stokes parameter V) are determined by the relationships

$$I(L) = \frac{1}{1+\eta^2}\left\{(1+\eta)^2\frac{\varepsilon_-(l_{tr}+z_0)}{\sinh[\varepsilon_-(L+2z_0)]} + (1-\eta)^2\frac{\varepsilon_+(l_{tr}+z_0)}{\sinh[\varepsilon_+(L+2z_0)]}\right\}, \quad (16)$$

$$V(L) = \frac{1-\eta^2}{1+\eta^2}\left\{\frac{\varepsilon_+(l_{tr}+z_0)}{\sinh[\varepsilon_+(L+2z_0)]} - \frac{\varepsilon_-(l_{tr}+z_0)}{\sinh[\varepsilon_-(L+2z_0)]}\right\}. \quad (17)$$

Without circular dichroism ($\Delta\kappa = 0$), formula (16) for intensity I transforms to the known result of scalar theory (see, for example, [36]). At $\Delta\kappa = 0$, circular polarisation does not arise and the fourth Stokes parameter (17) is zero ($V = 0$).

4. Discussion of the results

In practice, the value of $\Delta\kappa$, which characterises the circular dichroism, is small. The ratio $\Delta\kappa/\kappa$ varies within the range of $3\times10^{-4} - 3\times10^{-3}$ [4]. The minimal values of the depolarisation cross section at the first Kerker point σ_{dep} are $\sim10^{-3}\sigma_{tr}$ [23–25]. One should take into account these restrictions while choosing the concentration of scattering Mie particles.

For observing the effect of enhanced circular dichroism suggested in the present work, the transport scattering factor $n_0\sigma_{tr}$ should be the largest: $n_0\sigma_{tr} \gg \max(\kappa, n_0\sigma_{dep}, \Delta\kappa)$. This provides the maximal elongation of photon paths in multiple scattering. The coefficient of radiation depolarisation in an ensemble of Mie particles $n_0\sigma_{dep}$ should be as small as possible. This is necessary for providing detection of differences in the absorption indices for right-hand and left-hand polarised waves prior to the origin of radiation depolarisation due to scattering. Thus, we arrive at the inequalities determining the choice of the Mie scatterer concentration:

$$n_0\sigma_{tr} \gg \kappa \gg n_0\sigma_{dep}. \quad (18)$$

In view of the estimates given above for parameters $\Delta\kappa/\kappa$ and σ_{dep}/σ_{tr}, in the case of fulfilment of condition (18), the ratio $\Delta\kappa(n_0\sigma_{dep})^{-1} \ll 1$ and values included in (16) and (17) can be expanded into series with respect to parameter $\Delta\kappa/(n_0\sigma_{dep})$.

In this approximation, expressions (16) and (17) take the form

$$I(L) = 2\frac{\varepsilon_I(l_{tr}+z_0)}{\sinh[\varepsilon_I(L+2z_0)]},$$
$$V(L) = -\frac{\Delta\kappa}{n_0\sigma_{dep}}\left\{\frac{\varepsilon_I(l_{tr}+z_0)}{\sinh[\varepsilon_I(L+2z_0)]} - \frac{\varepsilon_V(l_{tr}+z_0)}{\sinh[\varepsilon_V(L+2z_0)]}\right\}, \quad (19)$$

where

$$\varepsilon_I = \sqrt{3n_0\sigma_{tr}\kappa}; \quad \varepsilon_V = \sqrt{3n_0\sigma_{tr}(\kappa + n_0\sigma_{dep})}.$$

The degree of circular polarisation for the passed radiation $P_c = |V|/I$ is determined by the expression

$$P_c = \frac{\Delta\kappa}{2n_0\sigma_{dep}}\left\{1 - \frac{\varepsilon_V}{\varepsilon_I}\frac{\sinh[\varepsilon_I(L+2z_0)]}{\sinh[\varepsilon_V(L+2z_0)]}\right\}. \quad (20)$$

Formula (20) can be presented in the form

$$P_c = \frac{1}{2}\Delta\kappa S_L, \quad (21)$$

where S_L implicitly is the average path length covered by photons in the medium without loss of circular polarisation. At $l_{\rm tr} \ll L < l_{\rm d}$, where $l_{\rm d} = (3n_0\sigma_{\rm tr}\kappa)^{-1/2}$ is the diffusion length [40, 41], the path $S_{\rm L}$ grows quadratically with a sample thickness: $S_L = L^2/l_{\rm tr}$. At $l_{\rm d} < L < l_{\rm circ}$, where $l_{\rm circ} = (\varepsilon_V - \varepsilon_I)^{-1}$ is the characteristic length of circular polarisation damping due to scattering [31–33, 36], the quadratic growth of S_L changes to the linear growth: $S_L = L\sqrt{n_0\sigma_{\rm tr}/(3\kappa)}$. In the high thickness limit $L > l_{\rm circ}$, the average path S_L no more depends on a sample thickness: $S_L = (n_0\sigma_{\rm dep})^{-1}$.

One can observe the increase in the circular dichroism discussed above in the experiment, which schematic diagram is similar to polarisation state measurements in the case of light passing through scattering suspensions [37–39, 43–45]. The optical thickness can be varied by changing length L of the cell with a material under investigation or particle concentration n_0 in the cell.

Results of calculations by formula (20) of the circular polarisation degree for passed beam $P_{\rm c}$ are shown in Fig. 1 as a function of thickness L. For comparison, the polarisation degree dependence is also shown for light passing through a homogeneous (without scatterers) medium with a circular dichroism. One can see that in the interesting range of thicknesses L when the radiation is not yet completely absorbed in the medium $\kappa L \leqslant 3-5$, the addition of scattering and weakly depolarising particles to the initial medium results in a noticeable increase in the polarisation degree for passed radiation. It is convenient to characterise the difference in the values of $P_{\rm c}$ for scattering and homogeneous (without scatterers) media by an enhancement factor $\zeta = P_{\rm c}/P_{\rm c}\ (n_0 = 0)$. In a linear approximation with respect to $\Delta\kappa$, we have $\zeta = S_L/L$. Results of ζ calculation are presented in Fig. 2. The maximal value of ζ under conditions (18) can be approximated as $\zeta_{\rm max} \approx 0.7\sqrt{n_0\sigma_{\rm tr}/\kappa}$. For actual values of the medium absorption index and parameters of Mie-particles, the value of $\zeta_{\rm max}$ may reach ten. Note that the character of the enhancement factor dependence on scatterer concentration noticeably changes with a thickness (Fig. 3). For relatively thin samples, ζ grows with concentration. At a greater thickness L, the dependence changes to opposite: the enhancement factor falls as n_0 increases. The maximal value of factor $\zeta_{\rm max}$ is reached at $n_0^{\rm max} \approx (0.6-0.8)[\kappa/(\sigma_{\rm tr}\sigma_{\rm dep}^2 L^2)]^{1/3}$, when the sample thickness is approximately half the damping length of circular polarisation $L \approx (0.4-0.6)l_{\rm circ}$. In Fig. 3 one can see that at a greater Mie-particle concentration the maximal value of ζ increases and the peak position shifts to lower thicknesses.

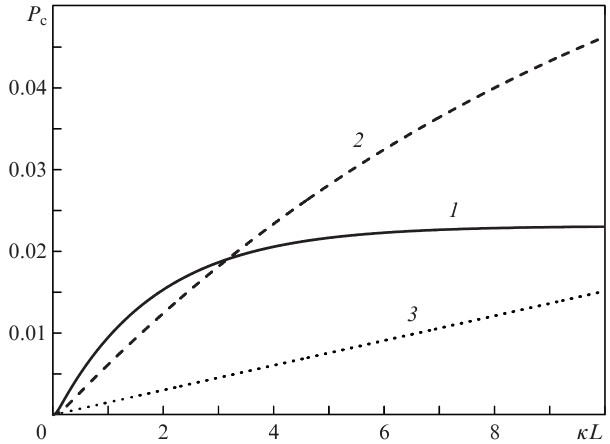

Figure 1. Degree of circular polarisation of initially unpolarised light beam as a function of the sample thickness. The medium parameters are: $n_0\sigma_{\rm tr}/\kappa$ = (*1*) 100, (*2*) 30, and [homogeneous medium (*3*)] 0; $\Delta\kappa/\kappa = 3\times10^{-3}$; $\sigma_{\rm dep}/\sigma_{\rm tr} = 10^{-3}$.

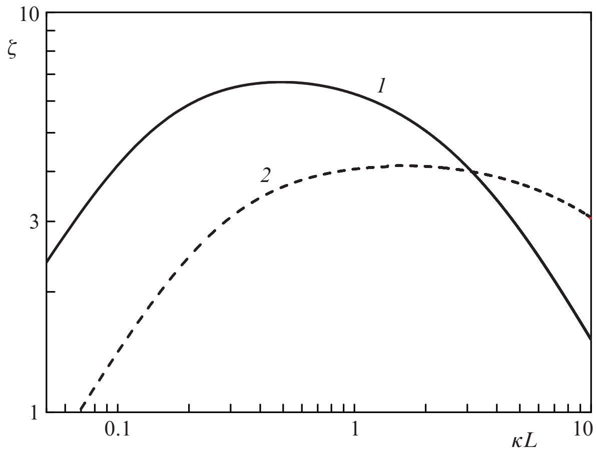

Figure 2. Enhancement factor ζ as a function of the sample thickness. The medium parameters are: $n_0\sigma_{\rm tr}/\kappa$ = (*1*) 100 and (*2*) 30; $\sigma_{\rm dep}/\sigma_{\rm tr} = 10^{-3}$.

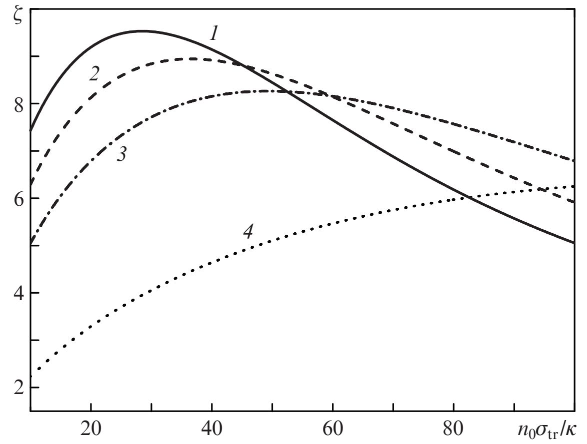

Figure 3. Enhancement factor ζ as a function of the scatterer concentration. The medium parameters are: κL= (*1*) 3, (*2*) 2.5, (*3*) 2, and (*4*) 1; $\Delta\kappa/\kappa = 3\times10^{-3}$; $\sigma_{\rm dep}/\sigma_{\rm tr} = 10^{-3}$.

5. Conclusions

We have considered propagation of initially unpolarised light (an incoherent superposition of right-handed and left-handed polarised waves) in a medium with circular dichroism and randomly disposed Mie particles. It is shown that in the presence of scatterers, the degree of circular polarisation in the passed light beam increases. The effect should be mostly pronounced if the first Kerker condition for Mie particles fulfils, and the ratio of the depolarisation cross section to transport cross section reaches the minimal value. In this case, the disordered ensemble of Mie particles behaves as an optical resonator increasing the photon path inside the medium not affecting the state of circular polarisation. The degree of polarisation for light passed through a scattering sample can increase by a factor of ten as compared to a homogeneous sample of the same size.

Results obtained may form a base for developing a new method of experimental measurement of circular dichroism in liquid optical media.

Acknowledgements. The authors are grateful to A.I. Kuzovlev for interest to this work and useful discussions.

The work was supported by the Programme for increasing competitiveness at MEPhI (Contract No. 02.a03.21.0005 from 27.08.2013).

References

1. Barron L.D. *Molecular Light Scattering and Optical Activity* (Cambridge University Press, 2004).
2. Berova N., Nakanishi K., Woody R.W. *Circular Dichroism: Principles and Applications* (New York: Wiley-VCH Publishers, 2000).
3. Berova N., Di Bari L., Pescitelli G. *Chem. Soc. Rev*., **36**, 914 (2007).
4. Cantor Ch.R., Schimmel P. *Biophysical Chemistry* (New York: W.H. Feeman and Company, 1985) Vol II.
5. Keiderling T.A., Kubelka J., Hilario J., in *Vibrational Spectroscopy of Polymers and Biological Systems* (Boca Raton, FL: CRC Press, 2006).
6. Silverman M.P., Badoz J. *J. Electromagn. Waves Appl*., **6**, 587 (1992).
7. Silverman M.P., Badoz J. *J. Opt. Soc. Am. A*, **11**, 1894 (1994).
8. Ghosh A., Fischer P. *Phys. Rev. Lett.*, **97**, 173002 (2006).
9. Pfeifer M., Fischer P. *Opt. Express*, **19**, 16508 (2011).
10. Preda F., Perri A., Réhault J., Dutta B., Helbing J., Cerullo G., Polli D. *Opt. Lett*., **43**, 1882 (2018).
11. Nieto-Vesperinas M., Gomez-Medina R., Saenz J.J. *J. Opt. Soc. Am. A*, **28**, 54 (2011).
12. Albella P., Poyli M.A., Schmidt M.K., Maier S.A., Moreno F., Saenz J.J., Aizpurua J. *J. Phys. Chem. C*, **117**, 13573 (2013).
13. Schmidt M.K., Aizpurua J., Zambrana-Puyalto X., Vidal X., Molina-Terriza G., Saenz J.J. *Phys. Rev. Lett*., **114**, 113902 (2015).
14. Rodriguez-Fortuno F.J., Engheta N., Martínez A., Zayats A.V. *Nat. Commun*., **6**, 8799 (2015).
15. Kuznetsov A.I., Miroshnichenko A.E., Brongersma M.L., Kivshar Yu.S., Luk'yanchuk B. *Science*, **354**, 846 (2016).
16. Verre R., Shao L., Länk N.O., Karpinski P., Yankovich A.B., Antosiewicz T.J., Olsson E., Käll M. *Adv. Mater*., **29**, 1701352 (2017).
17. Wei L., Bhattacharya N., Urbach H.P. *Opt. Lett*., **42**, 1776 (2017).
18. Barreda A.I., Saleh H., Litman A., Gonzalez F., Geffrin J.M., Moreno F. *Nat. Commun*., **8**, 13910 (2017).
19. Valuckas V., Paniagua-Domínguez R., Fu Y.H., Luk'yanchuk B., Kuznetsov A.I. *Appl. Phys. Lett*., **110**, 091108 (2017).
20. Newton R.G. *Scattering Theory of Waves and Particles* (New York: McGraw-Hill, 1966).
21. Van de Hulst H.C. *Light Scattering by Small Particles* (New York: Dover Publications, 1981).
22. Kerker M., Wang D.-S., Giles C.L. *J. Opt. Soc. Am*., **73**, 765 (1983).
23. Gorodnichev E.E., Kuzovlev A.I., Rogozkin D.B. *JETP Lett*., **104**, 157 (2016) [*Pis'ma Zh. Eksp. Teor. Fiz*., **104**, 155 (2016)].
24. Gorodnichev E.E., Kuzovlev A.I., Rogozkin D.B. *Quantum Electron*., **46**, 947 (2016) [*Kvantovaya Elektron.*, **46**, 947 (2016)].
25. Gorodnichev E.E., Kuzovlev A.I., Rogozkin D.B. *J. Phys.: Conf. Ser*., **788**, 012039 (2017).
26. Gottardo S., Sapienza R., Garcia P.D., Blanco A., Wiersma D.S., López C. *Nat. Photonics*, **2**, 429 (2008).
27. Koman V.B., Santschi C., Martin O.J.F. *Anal. Chem*., **87**, 1536 (2015).
28. Mupparapu R., Vynck K., Svensson T., Burresi M., Wiersma D.S. *Opt. Express*, **23**, 1472 (2015).
29. Bohren C.F., Huffman D. *Absorption and Scattering of Light by Small Particles* (Morlenbach: Wiley-VCH Verlag GmbH, 2007).
30. Kuscer I., Ribaric M. *Opt. Acta*, **6**, 42 (1959).
31. Gorodnichev E.E., Kuzovlev A.I., Rogozkin D.B. *Opt. Commun*., **260**, 30 (2006).
32. Gorodnichev E.E., Kuzovlev A.I., Rogozkin D.B. *JETP*, **104**, 319 (2007) [*Zh. Eksp. Teor. Fiz*., **131**, 357 (2007)].
33. Gorodnichev E.E., Kuzovlev A.I., Rogozkin D.B. *Phys. Rev. E*, **90**, 043205 (2014).
34. Kokhanovsky A.A. *Phys. Rev. E*, **4**, 4899 (1999).
35. Kuzmina M.G., Bass L.P., Nikolaeva O.V., in *Springer Series in Light Scattering* (Cham, Switzerland: Springer, 2018).
36. Gorodnichev E.E., Kuzovlev A.I., Rogozkin D.B. *JETP Lett*., **68**, 22 (1998) [*Pis'ma Zh. Eksp. Teor. Fiz*., **68**, 21 (1998)].
37. MacKintosh F.C., Zhu J.X., Pine D.J., Weitz D.A. *Phys. Rev. B*, **40**, 9342 (1989).
38. Bicout D., Brosseau C., Martinez A.S., Schmitt J.M. *Phys. Rev. E*, **49**, 1767 (1994).
39. Sankaran V., Everett M.J., Maitland D.J., Walsh J.T. *Opt. Lett*., **24**, 1044 (1999).
40. Van de Hulst H.C. *Multiple Light Scattering* (New York: Academic, 1980).
41. Ishimaru A. *Wave Propagation and Scattering in Random Media* (New York: Wiley-IEEE Press, 1999).
42. Korolev L.V., Rogozkin D.B. *JETP*, **86**, 164 (1998) [*Zh. Eksp. Teor. Fiz*., **113**, 291 (1998)].
43. Ghosh N., Pradhan A., Gupta P.K., Gupta S., Jaiswal V., Singh R.P. *Phys. Rev. E*, **70**, 066607 (2004).
44. Ghosh N., Gupta P.K., Pradhan A., Majumder S.K. *Phys. Lett. A*, **354**, 236 (2006).
45. Zimnyakov D.A., Sinichkin Y.P. *J. Opt. A: Pure Appl. Opt*., **2**, 200 (2000).