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Using chiral nano-meta-particles to control chiral molecule radiation

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1. Introduction

Currently, owing to the development of nanotechnologies, new areas of optics have made their appearance — nanooptics and nanoplasmonics, whose subjects are the highly nontrivial properties of optical fields on the nanoscale and their practical applications [1, 2]. Among the most important advantages in this area is the capability of exerting effective control over the radiation of ordinary atoms and molecules with the help of nanoparticles [surface enhanced Raman scattering (SERS), surface enhanced fluorescence (SEF)] [3– 6]. Interesting effects have also been discovered in the investigation of the influence of chiral nanoparticles or nanoparticles of metamaterials with a negative refractive index on the radiation of ordinary molecules [7, 8].

More complex optically active (chiral) molecules are of greater interest because they form the basis of life. This brings up the natural question: Is it possible to efficiently and arbitrarily control the radiation of chiral molecules and use this for various biomedical applications (for instance, for separating racemic mixtures)? We show in our paper that this control is possible if advantage is taken of nanoparticles made of metamaterials (see, for instance, Refs [9, 10]).

2. Chirality and optical activity

Chirality is the property of a system not to coincide with its mirror image under arbitrary rotations and translations [11]. It follows from this definition that, first, chirality is a geometric property of objects and, second, this property may be inherent only in spatial, i.e. three-dimensional, objects. The most important chiral objects are aminoacids and sugars which can exist, in principle, in the form of right or left enantiomers. However, of the utmost significance is the fact that the right enantiomers of aminoacids and the left enantiomers of sugars are not encountered in living nature. It is precisely this asymmetry that makes extremely important the optical investigations of these and kindred phenomena. The possibility of these investigations relies on the circumstance that chiral molecules quite often possess the property of optical activity, i.e. react to light with different polarizations in different ways. In particular, when linearly polarized light is incident on optically active molecules, its plane of polarization changes (rotates) and the degree of this rotation is defined by the factor

$$\frac{n_{\text{left}} - n_{\text{right}}}{n_{\text{left}} + n_{\text{right}}} \sim \frac{\text{molecular size}}{\text{wavelength}} \ll 1 \,, \tag{1}$$

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Uspekhi Fizicheskikh Nauk **182** (10) 1130–1135 (2012) DOI: 10.3367/UFNr.0182.201210k.1130 Translated by E N Ragozin; edited by A Radzig where n_{left} and n_{right} are the refractive indices for the left- and right-polarized waves.

The absorption of waves with different circular polarization is also different, and the degree of this difference is defined by the factor

$$\frac{A_{\text{left}} - A_{\text{right}}}{A_{\text{left}} + A_{\text{right}}} \sim \frac{\text{molecular size}}{\text{wavelength}} \ll 1 , \qquad (2)$$

where A_{left} and A_{right} are the absorption coefficients for the left- and right-polarized waves. Since the molecular size is usually small in comparison with optical wavelengths, the optical activity effects are quite weak. Despite this smallness, the effects of rotation of the polarization plane and circular dichroism enjoy wide application in the exploration of different conformations of biomolecules.

By applying the methods of nanooptics and nanoplasmonics, it is possible to significantly (by 4–6 orders of magnitude!) enhance these extremely weak effects by using nanostructured chiral metamaterials [12] or even the clusters of nonchiral nanoparticles [13].

Our aim is to learn to control precisely the *emission* of light by chiral molecules (and not the *absorption* of light) with the help of chiral nano-meta-particles (see below what this is).

3. Chiral molecules

To solve the problem of controling the light emission by chiral molecules requires, first of all, recognizing the difference between 'ordinary' and 'optically active' (chiral) molecules. Ordinary molecules are characterized only by the electric dipole moment, and their light–matter interaction Hamiltonian is of the form

$$H_{\rm int} = -\mathbf{d}\mathbf{E}\,,\tag{3}$$

where \mathbf{d} is the dipole transition moment between the ground and excited states, and \mathbf{E} is the electric field strength at the point of location of the molecule. This Hamiltonian does not permit describing the effects of optical activity in principle.

Chiral (optically active) molecules possess both electric and magnetic transition moments [14, 15]. In this case, when a spiral is considered as the model of a chiral molecule, for right molecules, in which the electric and magnetic transition moments are parallel, the Hamiltonian for their interaction with an electromagnetic field takes the form

$$H_{\rm int} = -\mathbf{d}\mathbf{E} - \mathbf{m}\mathbf{H}\,,\tag{4}$$

while for left molecules, for which the electric and magnetic transition moments are antiparallel, the Hamiltonian for their interaction with an electromagnetic field is given by

$$H_{\rm int} = -\mathbf{d}\mathbf{E} + \mathbf{m}\mathbf{H} \,. \tag{5}$$

In expressions (4) and (5), **d** and **m** are the dipole transition moments between the ground and excited states in the right molecule, and **E** and **H** are the strengths of the electromagnetic field at the point of its location.

4. Chiral nano-meta-particles

Controling the radiation of chiral molecules calls for the efficient 'mixing' of electric and magnetic fields, chiral nanometa-particles being ideally suited for this purpose. In the simplest case, we may consider for such a particle a plasmon



Figure 1. Chiral plasmon resonance in a spherical particle with $k_0 a = 0.1$: (a) $\chi = 0$, and (b) $\chi = 0.1$.

chiral nanoparticle, i.e., a layered nanoparticle (a nanodimension: a dimension shorter than the wavelength) whose core comprises gold, and the shell consists of natural sugar. In the general case, the constitutive equations of the substance of a chiral nano-meta-particle have the form [16]

$$\mathbf{D} = \varepsilon (\mathbf{E} + \eta \operatorname{rot} \mathbf{E}), \qquad \mathbf{B} = \mu (\mathbf{H} + \eta \operatorname{rot} \mathbf{H}), \tag{6}$$

where **D**, **E** and **B**, **H** are the induction and strength of electric and magnetic fields, respectively, ε , μ are the permittivity and permeability of the material of the chiral medium, and η is the chirality dimensional parameter. The chirality dimensionless parameter is conveniently introduced by the expression $\chi = \omega \eta / c$.

One can see from formulas (6) that, as in the case of optically active molecules [see expressions (4) and (5)], entangling of electric and magnetic phenomena occurs, and such nanoparticles would be expected to efficiently interact with chiral molecules. We note that the constitutive equations correspond to so-called chiral (bi-isotropic) media [17], to state it in more formal terms.

Even a small chirality of a nanoparticle leads to a significant change in its resonance optical properties. Figure 1 shows the dependence of the resonance properties of a chiral plasmon spherical nanoparticle on the permittivity and the permeability. Figure 1a corresponds to the case of a zero-chirality nano-meta-particle. As is evident from this figure, an ordinary plasmon resonance occurs at $\varepsilon \approx -2$, which is hardly dependent on the permeability of the nanoparticle. The situation becomes significantly different when the nanoparticle has an arbitrarily small admixture of chirality (Fig. 1b) because the interaction of electric and magnetic oscillations results in a significant change in the resonance structure, i.e., a chiral plasmon resonance appears. It is precisely the chiral plasmon resonance that makes it possible to exert efficient selective control over the radiation of chiral molecules.

5. Quantum theory of the radiation of a chiral molecule near a chiral nano-meta-sphere

As discussed in the Introduction, the rate of spontaneous emission depends significantly on the nanoenvironment, and in this section we shall consistently describe the quantum theory of spontaneous emission by a chiral molecule residing near a chiral nanoparticle [18].

Fermi's golden rule [19] is fully applicable in the chiral case, and the spontaneous relaxation probability can be described by the well-known expression

$$\Gamma = \frac{2\pi}{\hbar} \sum_{\text{final}} \left| \langle \text{initial} | H_{\text{int}} | \text{final} \rangle \right|^2 \rho(\omega) , \qquad (7)$$



Figure 2. Geometry of electromagnetic field quantization in the presence of a chiral sphere.

where $\rho(\omega)$ is the density of final states, $H_{\text{int}} = -(\hat{\mathbf{d}}\hat{\mathbf{E}}(\mathbf{r}_0)) - (\hat{\mathbf{m}}\hat{\mathbf{H}}(\mathbf{r}_0))$ is the interaction Hamiltonian between the electromagnetic field and the chiral molecule, $\hat{\mathbf{d}} = e\hat{\mathbf{r}}$ and $\hat{\mathbf{m}} = -i\hbar e/(2mc)(\hat{\mathbf{r}} \times \nabla)$ are the electric and magnetic dipole moment operators, and finally

$$\hat{\mathbf{E}}(\mathbf{r}) = \mathbf{i} \sum_{s} \frac{a_{s} \mathbf{e}(s, \mathbf{r}) - a_{s}^{\dagger} \mathbf{e}^{*}(s, \mathbf{r})}{\sqrt{2}} ,$$
$$\hat{\mathbf{H}}(\mathbf{r}) = \sum_{s} \frac{a_{s} \mathbf{h}(s, \mathbf{r}) + a_{s}^{\dagger} \mathbf{h}^{*}(s, \mathbf{r})}{\sqrt{2}}$$

are the quantized electromagnetic field operators (index *s* numbers the modes).

By and large, the quantization of the electromagnetic field reduces to finding the eigenmodes $\mathbf{e}(s, \mathbf{r})$, $\mathbf{h}(s, \mathbf{r})$ of the system, and these modes are termed photons. In our case, unfortunately, the ordinary notions of photons (TE and TM modes) are inapplicable and the entire quantization procedure is to be constructed anew. To do this, we assume that our system, a molecule and a nanoparticle, is placed in an infinitely large spherical resonator with an ideally conducting wall (Fig. 2). After this, the photon mode inside the sphere may be sought in the form of an expansion in terms of vector spherical harmonics [20]:

$$\mathbf{e}_{mm}(\mathbf{r}) = A_{mm}^{\mathrm{L}}(\mathbf{N}\mathbf{\psi}_{mm}^{\mathrm{L}} + \mathbf{M}\mathbf{\psi}_{mm}^{\mathrm{L}}) + A_{mm}^{\mathrm{R}}(\mathbf{N}\mathbf{\psi}_{mm}^{\mathrm{R}} - \mathbf{M}\mathbf{\psi}_{mm}^{\mathrm{R}}), \quad (8)$$

with combinations of TE and TM harmonics entering into this expression, and indices L and R pertaining to left- and right-polarized plane waves in free space with respective wave numbers

$$k_{\rm L} = rac{k_0 \sqrt{arepsilon \mu}}{1 - \chi \sqrt{arepsilon \mu}} \,, \qquad k_{
m R} = rac{k_0 \sqrt{arepsilon \mu}}{1 + \chi \sqrt{arepsilon \mu}}$$

The photon mode outside the particle is sought in the form of a combination of diverging and converging spherical TE and TM waves [20]:

$$\mathbf{e}_{mn}(\mathbf{r}) = C_{mn}^{(1)} \mathbf{N} \zeta_{mn}^{(1)} + C_{mn}^{(2)} \mathbf{N} \zeta_{mn}^{(2)} + D_{mn}^{(1)} \mathbf{M} \zeta_{mn}^{(1)} + D_{mn}^{(2)} \mathbf{M} \zeta_{mn}^{(2)} \,.$$
(9)

)

By imposing the continuity boundary conditions for the tangential field strength components and applying normalization to one photon throughout the space, it is possible to derive explicit expressions for all coefficients entering into expressions (8) and (9) [18]. The resultant dispersion equation has two solutions which correspond to two types of photons. These photon types will be referred to as A and B. For $\chi = 0$, the A type photons reduce to TM photons, and the B type photons reduce to TE photons. The final state density for photons of any type, $\rho(\omega) = \Lambda/(\pi\hbar c)$, is independent, in accordance with the Courant theorem [21], of the presence of finite-sized particles.

By using the derived expressions and writing the molecular transition matrix elements as $\mathbf{d}_0 = \langle e | \hat{\mathbf{d}} | g \rangle$ and $-i\mathbf{m}_0 = \langle e | \hat{\mathbf{m}} | g \rangle$, the spontaneous emission rate (7) for an arbitrary chiral molecule near an arbitrary bi-isotropic sphere may be represented as the sum of decay rates to A- and B-type photons. For instance, for the decay rate to A type photons we have

$$\gamma_{eg}^{A} = \gamma_{eg}^{A, -1} + \gamma_{eg}^{A, 1} + \gamma_{eg}^{A, 0} , \qquad (10)$$

where

$$\begin{split} \gamma_{eg}^{\mathrm{A},-1} &= \frac{k_0}{2\hbar r_0^2} \sum_{n=1}^{\infty} \frac{2n+1}{1+|O_n|^2} \\ &\times \left| (d_{0x} - \mathrm{i} d_{0y}) \left(\psi_n'(k_0 r_0) + T_n^{\mathrm{A}} \zeta_n^{(1)'}(k_0 r_0) \right) \right. \\ &- O_n(d_{0y} + \mathrm{i} d_{0x}) \left(\psi_n(k_0 r_0) + L_n^{\mathrm{A}} \zeta_n^{(1)}(k_0 r_0) \right) \\ &+ O_n(m_{0x} - \mathrm{i} m_{0y}) \left(\psi_n'(k_0 r_0) + L_n^{\mathrm{A}} \zeta_n^{(1)'}(k_0 r_0) \right) \\ &- (m_{0y} + \mathrm{i} m_{0x}) \left(\psi_n(k_0 r_0) + T_n^{\mathrm{A}} \zeta_n^{(1)}(k_0 r_0) \right) \right|^2, \end{split}$$
(11)

$$\begin{split} \gamma_{eg}^{A,1} &= \frac{k_0}{2\hbar r_0^2} \sum_{n=1}^{\infty} \frac{2n+1}{1+|O_n|^2} \\ &\times \left| O_n(d_{0y} - \mathrm{i}d_{0x}) \left(\psi_n(k_0 r_0) + L_n^{\mathrm{A}} \zeta_n^{(1)}(k_0 r_0) \right) \right. \\ &- \left(d_{0x} + \mathrm{i}d_{0y} \right) \left(\psi_n'(k_0 r_0) + T_n^{\mathrm{A}} \zeta_n^{(1)'}(k_0 r_0) \right) \\ &+ \left(m_{0y} - \mathrm{i}m_{0x} \right) \left(\psi_n(k_0 r_0) + T_n^{\mathrm{A}} \zeta_n^{(1)}(k_0 r_0) \right) \\ &- O_n(m_{0x} + \mathrm{i}m_{0y}) \left(\psi_n'(k_0 r_0) + L_n^{\mathrm{A}} \zeta_n^{(1)'}(k_0 r_0) \right) \right|^2, \quad (12) \end{split}$$

$$\gamma_{eg}^{A,0} = \frac{2}{\hbar k_0 r_0^4} \sum_{n=1}^{\infty} \frac{(2n+1)n(n+1)}{1+|O_n|^2} \\ \times \left| d_{0z} \left(\psi_n(k_0 r_0) + T_n^A \zeta_n^{(1)}(k_0 r_0) \right) \right. \\ \left. + O_n m_{0z} \left(\psi_n(k_0 r_0) + L_n^A \zeta_n^{(1)}(k_0 r_0) \right) \right|^2, \tag{13}$$

and T_n^A , L_n^A , and O_n are some coefficients which are expressed in terms of the Bessel functions and which depend only on the properties of the sphere [18]. Similar expressions are obtained for the rate of decay to B photons [18].

6. Analysis of results and illustrations

Expressions (11)–(13) virtually exhaust the problem of spontaneous radiation by an arbitrary molecule residing near a chiral sphere of arbitrary composition and size. Unfortunately, these expressions are cumbersome, which hinders their understanding and interpretation. In the most interesting case of a nanosphere, expressions (11)–(13) may be simplified. However, instead of the formal derivation of

asymptotics, below we consider the spontaneous emission by chiral molecules, which are located near a chiral nanometa-particle, in the framework of a quasistatic (and quasiclassical) approximation [22]. As will be clear, this more physical approach agrees nicely with the exact solution (11)-(13) and permits a complete understanding of the physics of the processes.

The near fields produced by the molecule, which is described by oscillating electric and magnetic dipole moments with amplitudes \mathbf{d}_0 and $-i\mathbf{m}_0$, have the well-known form

$$\mathbf{E}_{0} = \frac{3\mathbf{r}(\mathbf{r}\mathbf{d}_{0}) - r^{2}\mathbf{d}_{0}}{r^{5}}, \quad \mathbf{H}_{0} = -\frac{\mathrm{i}(3\mathbf{r}(\mathbf{r}\mathbf{m}_{0}) - r^{2}\mathbf{m}_{0})}{r^{5}}, \quad (14)$$

where \mathbf{r} is the radius vector emanating from the sphere center to the point of observation. In expressions (14) and further, the factor of monochromatic time dependence is omitted.

The near fields (14) induce dipole moments in the nanoparticle:

$$\delta \mathbf{d} = \alpha_{EE} \mathbf{E}_0(\mathbf{r}_0) + \alpha_{EH} \mathbf{H}_0(\mathbf{r}_0), \qquad (15)$$

$$\delta \mathbf{m} = \alpha_{HE} \mathbf{E}_0(\mathbf{r}_0) + \alpha_{HH} \mathbf{H}_0(\mathbf{r}_0) \,,$$

where the electromagnetic polarizabilities of the chiral sphere are of the form

$$\alpha_{EE} = a^3 \frac{(\varepsilon - 1)(\mu + 2) + 2\varepsilon\mu\chi^2}{(\varepsilon + 2)(\mu + 2) - 4\varepsilon\mu\chi^2},$$

$$\alpha_{EH} = a^3 \frac{3\chi\varepsilon\mu i}{(\varepsilon + 2)(\mu + 2) - 4\varepsilon\mu\chi^2},$$
(16)

$$\alpha_{HH} = \alpha_{FE}(\varepsilon \leftrightarrow \mu), \qquad \alpha_{HE} = -\alpha_{FH}.$$

If it is additionally assumed that the molecule–nanoparticle distance is small in comparison with the wavelength, and the radiation intensity of the particle + molecule system is described by the expression

$$\Gamma \propto \left| \mathbf{d}_0 + \delta \mathbf{d} \right|^2 + \left| -i\mathbf{m}_0 + \delta \mathbf{m} \right|^2, \tag{17}$$

in which the interference between the radiations of the electric and magnetic dipoles does not take place owing to the smallness of phase incursion. Substituting expressions (15) into expression (17) yields

$$\begin{split} \Gamma \propto \left| \mathbf{d}_{0} + \frac{\alpha_{EE}}{r_{0}^{3}} \left(3\mathbf{n}(\mathbf{nd}_{0}) - \mathbf{d}_{0} \right) - \frac{\mathrm{i}\alpha_{EH}}{r_{0}^{3}} \left(3\mathbf{n}(\mathbf{nm}_{0}) - \mathbf{m}_{0} \right) \right|^{2} \\ + \left| \mathbf{m}_{0} + \frac{\mathrm{i}\alpha_{HE}}{r_{0}^{3}} \left(3\mathbf{n}(\mathbf{nd}_{0}) - \mathbf{d}_{0} \right) + \frac{\alpha_{HH}}{r_{0}^{3}} \left(3\mathbf{n}(\mathbf{nm}_{0}) - \mathbf{m}_{0} \right) \right|^{2}. \end{split}$$
(18)

When the orientation of the molecules is not fixed, as is often the case in practice, we must perform averaging over it to obtain

$$\Gamma_{\rm eff} = \frac{4k_0^3 |\mathbf{d}_0|^2}{3\hbar} \left\{ 1 + \frac{2}{r_0^6} |\alpha_{EE} - i\xi \alpha_{EH}|^2 + |\xi|^2 + \frac{2}{r_0^6} |i\alpha_{HE} + \xi \alpha_{HH}|^2 \right\},$$
(19)

where $\mathbf{m}_0 = \xi \mathbf{d}_0$.

The results of calculations in the framework of quantum electrodynamics (QED) and in the quasistatic approximation



Figure 3. Comparison of the results of calculating the spontaneous emission rate for a chiral molecule in the framework of QED and in the quasistatic approximation. The molecule is located near the surface of a chiral spherical nanoparticle with $\varepsilon = \varepsilon' + i0.1$, $\mu = -1.6$, $\chi = 0.2$, and $k_0a = 0.1$. The molecule is radially oriented.

(19) are compared in Fig. 3. One can see from the figure that the results of this simple theory are in perfect agreement with the exact QED calculation [see expressions (11)–(13)] for nanoparticles. The simplicity of interpreting this theory permits determining the explicit conditions whereat the radiation of a chiral molecule of one chirality or other will be suppressed. Realizing this requires that

(i) the system have a chiral plasmon resonance

$$(\varepsilon + 2)(\mu + 2) - 4\varepsilon\mu\chi^2 = 0$$
(20)

(this permits enhancing the magnetic fields);

(ii) the electric moment induced in the nanoparticle be equal to zero:

$$d_0 \alpha_{EE} - \mathrm{i} m_0 \alpha_{EH} = 0 \,. \tag{21}$$

whence, follows the discrimination condition

$$\mu^* \to -\frac{2d_0}{d_0 + 2m_0\chi}, \quad \varepsilon^* \to -\frac{2m_0}{m_0 + 2d_0\chi},$$
 (22)

i.e., the chiral molecule radiation will be suppressed for these μ and ε . At the same time, the radiation from a molecule of

opposite chirality $(m_0 \rightarrow -m_0)$ located near the nanoparticle with parameters (22) will not be suppressed!

To illustrate this effect, Fig. 4 shows the rate of spontaneous emission by the left-hand chiral molecule and its ratio to the rate of spontaneous emission by the right-hand chiral molecule. One can see from this figure that the radiation by the right-hand molecule is almost suppressed, when condition (22) is fulfilled (in this case, when $\varepsilon \approx -0.4$ and $\mu \approx -2$, which corresponds to a metamaterial with a negative refractive index [23]), while the radiation by the left-hand molecule is enhanced by the chiral plasmon resonance. As a result, the decay rate for the left-hand molecule is more than 10 times higher than the decay rate for the right-hand molecule. We emphasize that such chiral metamaterials with a negative refractive index are quite realistic [24].

When it is required to suppress the radiation of the lefthand molecules and enhance the radiation of the right-hand ones, in accordance with condition (22) the nanoparticle metamaterial must have a positive permittivity and a negative permeability. Suchlike metamaterials are also quite possible [9, 10].

7. Applications of the effects discovered

Once we have theoretically shown that it is possible to suppress the radiation of some enantiomers and enhance the radiation of other ones by selecting the parameters of a chiral nanoparticle, many prospects open up for the application of this effect.

First of all, the effect discovered may be employed in the scanning microscope investigation of samples in which one type of enantiomers prevails, and so there is no way to discover and add up by ordinary methods the small amount of the enantiomer of opposite chirality. However, when a particle (Fig. 5), whose material is selected in conformity with conditions (22) so as to suppress the radiation of the bulk of unwanted molecules, is placed on the tip of a scanning microscope, only the sought-after molecules will come into the field of view of the microscope (the quest for extra-terrestrial life, bioterrorist attacks, etc.).

Of even greater importance is the application of the theoretical findings to the purely optical separation of racemic mixtures of biomolecules (Fig. 6). Such mixtures emerge, inter alia, in the chemical synthesis of medicines. However, only one specific enantiomer is required to achieve the correct action. The chemical separation methods in use



Figure 4. Rate Γ_L/Γ_0 of spontaneous emission by a left-hand molecule (a) and its ratio Γ_L/Γ_R to the rate of spontaneous emission by a right-hand molecule (b). The molecules are located near a chiral nano-meta-particle with $k_0a = 0.1$, $\chi = 0.2$, $\xi = m_{0z}/d_{0z} = 0.1$, and $\varepsilon'' = 0.1$.



Figure 5. Detection of separate molecules of a given chirality.



Figure 6. Separation of racemic mixtures of biomolecules.

today are complicated and expensive, and the development of a purely optical method for the separation of enantiomers is, therefore, quite appealing. The findings made above permit, at least in principle, doing this. The schematic of operation of a purely optical facility for enantiomer separation is illustrated in Fig. 6. In one way or another, the synthesized molecules are excited in a chamber, whose surface is covered by nanoparticles corresponding to condition (22). The enantiomers of one type (say, the 'right' ones) rapidly change to the ground state, while the enantiomers of the other type (the 'left' ones) remain in the excited state. By applying an ionizing radiation pulse, it is possible to remove the ionized molecules by an electric field, with the result that only the desired enantiomers will remain in the reaction chamber. It is significant that this synthesis technique is not attended by contamination from by-product chemicals required in the separation by chemical methods.

8. Conclusion

Thus, the problem of describing the spontaneous emission by chiral molecules located near a chiral sphere of arbitrary composition was analytically solved in the framework of QED, as well as in the quasistatic approximation.

As shown above, when a chiral particle has a negative refractive index or a negative permeability, the radiation of nearby right and left molecules may be significantly different. We emphasize that these results are general and are not restricted to the case of only one nanoparticle. It has already been found that the clusters of chiral nano-meta-particles show even greater promise for controling the radiation emitted by enantiomers [25].

These findings open the way to a purely optical separation of drug enantiomers.

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References

- 1. Novotny L, Hecht B *Principles of Nano-Optics* (Cambridge: Cambridge Univ. Press, 2006) [Translated into Russian (Moscow: Fizmatlit, 2009)]
- Klimov V V Nanoplazmonika (Nanoplasmonics) (Moscow: Fizmatlit, 2010)
- Klimov V V Usp. Fiz. Nauk 173 1008 (2003) [Phys. Usp. 46 979 (2003)]
- 4. Kneipp K, Moskovits M, Kneipp H (Eds) Surface-Enhanced Raman Scattering: Physics and Applications (Berlin: Springer, 2006)
- 5. Lakowicz J R et al. J. Phys. D **36** R240 (2003)
- 6. Manno D et al. *Nanotechnology* **21** 165502 (2010)
- 7. Lakhtakia A, Varadan V K, Varadan V V J. Phys. D 23 481 (1990)
- 8. Klimov V V Opt. Commun. 211 183 (2002)
- 9. Cai W, Shalaev V Optical Metamaterials: Fundamentals and Applications (New York: Springer, 2010)
- 10. Noginov M A, Podolskiy V A (Eds) *Tutorials in Metamaterials* (Boca Raton, FL: Taylor & Francis, 2012)
- 11. Kelvin W T (Lord) Baltimore Lectures on Molecular Dynamics and the Wave Theory of Light (London: C.J. Clay and Sons, 1904)
- 12. Hendry E et al. Nature Nanotechnol. 5 783 (2010)
- 13. Govorov A O et al. Nano Lett. 10 1374 (2010)
- 14. Rosenfeld L Z. Phys. 52 161 (1929)
- 15. Barron L D Molecular Light Scattering and Optical Activity (Cambridge: Cambridge Univ. Press, 1982)
- Bokut' B V, Serdyukov A N, Fedorov F I Kristallogr. 15 1002 (1970) [Sov. Phys. Crystallogr. 15 871 (1971)]
- 17. Lindell I V et al. *Electromagnetic Waves in Chiral and Bi-isotropic Media* (Boston: Artech House, 1994)
- 18. Guzatov D V, Klimov V V New J. Phys. 14 123000 (2012)
- 19. Fermi E Rev. Mod. Phys. 4 87 (1932)
- Stratton J A *Electromagnetic Theory* (New York: McGraw-Hill, 1941) [Translated into Russian (Moscow-Leningrad: Gostekhizdat, 1948)]
- Courant R, Hilbert D Methoden der mathematischen Physik (Methods of Mathematical Physics) (Berlin: J. Springer, 1931) [Translated into English (New York: Interscience Publ., 1989); Translated into Russian: Vol. 1 (Moscow-Leningrad: Gos. Tekh.-Teoretich. Izd., 1933) pp. 420, 421]
- 22. Klimov V V, Guzatov D V, Ducloy M Europhysics Lett. 97 47004 (2012)
- Veselago V G Usp. Fiz. Nauk 92 517 (1967) [Sov. Phys. Usp. 10 509 (1968)]
- 24. Kwon D-H et al. Opt. Express 16 11822 (2008)
- Guzatov D V, Klimov V V, Zabkov I V, Pavlov A A "Optical properties of a chiral nanoantenna and their influence on radiation of chiral molecules" (to be published)