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Rotation of an atomic-molecular particle placed into the linearly polarized light field and static electric or magnetic fields

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Rotation mechanisms of an atomic-molecular particle being into the linearly polarized light field and applied static electric or magnetic fields are for the first time shortly analyzed. Exerting of the particle torque is based on the dynamic molecular Hall effect, distinctive features of which are able to expand the resource of the optical-mechanical manipulation by molecular objects.

Keywords: nonlinear optics, nano-photonics, Faraday effect, Hall effect, torque.

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The development and refinement of techniques for control over the motion (rotation) of various nanoobjects introduced into liquid media or placed on a certain surface is one of the active research trends in modern nanophysics [1–3]. A number of physical phenomena (including various effects of interaction with light) are used to manipulate particles and transfer energy needed to perform mechanical work [2,3]. The key advantage of light beams in this context is the remote (non-contact) nature of transfer of energy, momentum, or torque to a target object (or its surroundings). However, since each method of optomechanical manipulation has certain limitations, the issue of expanding the spectrum of available techniques is relevant. The aim of the present study is to analyze phenomenologically new mechanisms of production of torque that illustrate the following assertion: a linearly polarized light wave may impart a constant torque to any atomic-molecular particle affected by its field under the condition of application of a static electric or magnetic field.

The authors of [4] have proposed a mechanism of transfer of torque to a conducting particle via the Lorentz force (under the condition of application of a quasi-static electric ($\mathbf{E}$) and magnetic ($\mathbf{B}$) field) and presented two experimental arrangements: the classical Hall effect geometry ($\mathbf{E}_1 \perp \mathbf{B}$) and the arrangement with additional field $\mathbf{E}_2$ ($\mathbf{E}_2 \parallel \mathbf{B}$ in [4]). Particle torque $\mathbf{T}$ is the result of electrostatic interaction of its dipole moment $\mathbf{d}_H$ (due to the Hall voltage) with $\mathbf{E}_1$ or $\mathbf{E}_2$ and is characterized in the general case by the following double vector product [4]:

$$\mathbf{T} = (\mathbf{d}_H \times \mathbf{E}_2) \propto \big((\mathbf{E}_1 \times \mathbf{B}) \times \mathbf{E}_2\big). \qquad (1)$$

It follows from relation (1) that a constant $\mathbf{T}$ component is also produced when any two fields in (1) are not static; notably, this is illustrated by the experimental arrangement [4] with electric pulses. The question of interest to us is whether light-frequency variable electric and magnetic fields may be used as such fields. The analysis of such phenomena as „optical Hall effect“ [5] and its counterpart [6] Faraday effect in solutions of organic molecules, which was observed with the use of terahertz magnetic field pulses [6], provides an answer to this question. A phenomenological model of the dynamic molecular Hall effect (DMHE) was used in [6] to interpret the obtained results. In contrast to the classical Hall effect, the Lorentz force in DMHE bends displacement current $\mathbf{J}_e$ induced within an individual molecule by electric field $\tilde{\mathbf{E}}(t)$ of a light wave, and the molecule becomes polarized $\mathbf{P}_H(t)$ in the direction orthogonal to vector $\tilde{\mathbf{E}}$ as a result. A similar model is used to characterize another effect that consists in static polarization of an atom (molecule) $\mathbf{P}^{\mathrm{ME}}$ along wave vector $\mathbf{k}$ of an incident linearly polarized light wave [7,8]. It is telling that the authors of [8] referred to this phenomenon as the „longitudinal Hall effect“ (in what follows, we call it the magnetoelectric rectification (MER)).

Analyzing the DMHE model for the Faraday effect proposed in [6], one readily sees that the electrostatic interaction of variable polarization $\mathbf{P}_H(t)$ of an individual particle with orthogonal electric field $\tilde{\mathbf{E}}(t)$ should induce particle torque $\mathbf{T}(t)$

$$\mathbf{T}(t) = \big(\mathbf{d}_H(t) \times \tilde{\mathbf{E}}(t)\big) \propto \big(\mathbf{P}_H(t) \times \tilde{\mathbf{E}}(t)\big) \propto \big[\big(\mathbf{J}_e(t) \times \mathbf{B}\big) \times \tilde{\mathbf{E}}(t)\big], \qquad (2)$$

where

$$\mathbf{d}_H(t) \propto \int (\mathbf{J}_e(t) \times \mathbf{B}) dt,$$

$$\mathbf{J}_e(t) = d\mathbf{P}_e(t)/dt = d\chi(\omega)\tilde{\mathbf{E}}(t)/dt,$$

and $\chi(\omega)$ is the molecule polarizability at light-wave frequency ω (note the similarity with the rotation mechanism implemented in the so-called optical centrifuge [9], where rotating field $\tilde{\mathbf{E}}(t)$ interacts with the induced dipole moment of a molecule). If the imaginary component of $\chi(\omega)$ is negligible, $\mathbf{P}_H(t)$ and $\tilde{\mathbf{E}}(t)$ oscillations are almost in phase (antiphase), and the mean value of torque $\mathbf{T}_c$ of a molecule is nonzero. Figure 1 illustrates the above mechanism of $\mathbf{T}_c$ generation both in the Faraday effect geometry (a) and with

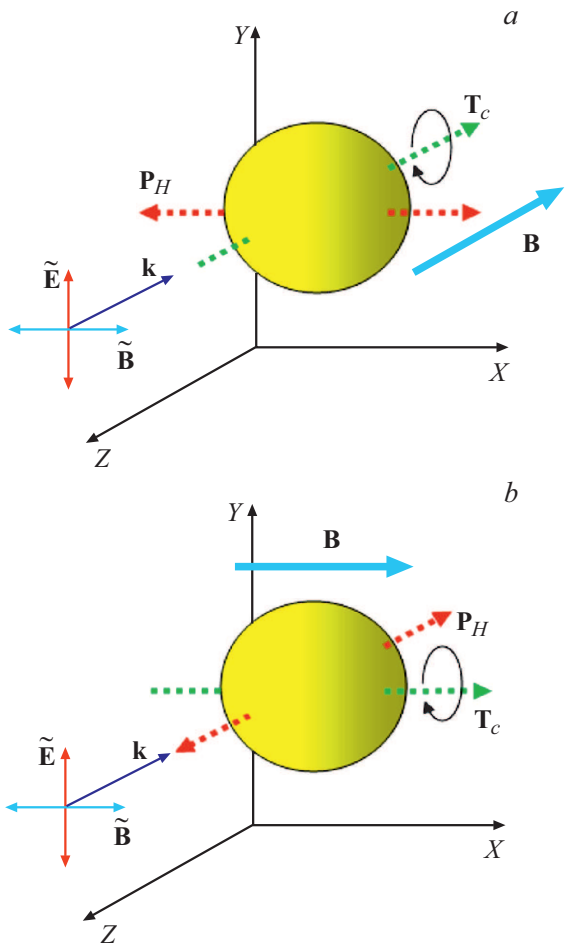

Figure 1. Diagram of transfer of torque $\mathbf{T}_c$ to an isotropic spherical particle in the Faraday effect geometry (a) and the Voigt effect geometry (b). The sphere is affected by the electromagnetic field of a linearly polarized light wave and static magnetic field $\mathbf{B}$. Particle torque $\mathbf{T}_c$ is the result of electrostatic interaction of sphere polarization $\mathbf{P}_H(t)$, which is produced by the Lorentz force, and orthogonal electric field $\tilde{\mathbf{E}}(t)$ of the wave.

an orthogonal orientation of vector $\mathbf{B}$, which corresponds to the Voigt effect geometry (b). Thus, torque should be induced at any orientation of the magnetic field (with the sole exception of $\tilde{\mathbf{E}} \parallel \mathbf{B}$). This is indicative of fundamental differences between the DMHE $\mathbf{T}_c$ generation mechanism and the transfer of torque to a particle by a light wave within the classical model of the Faraday effect. Linearly polarized light may be presented as a superposition of waves with left-hand and right-hand polarizations, which may transfer torques $\mathbf{T}_+$ and $\mathbf{T}_-$ of opposite signs and equal magnitudes to a particle in zero field $\mathbf{B}$. When a magnetic field is applied, the coefficients of absorption of these waves become unequal. Therefore, $|\mathbf{T}_+| \neq |\mathbf{T}_-|$ and a certain constant torque should be applied to a particle.

Moving on to the analysis of the MER effect, one readily sees that a particle torque may be produced in this case by applying static electric field $\mathbf{E}_2$ noncollinear to polarization vector $\mathbf{P}^{\mathrm{ME}}$. The generated torque is then characterized by

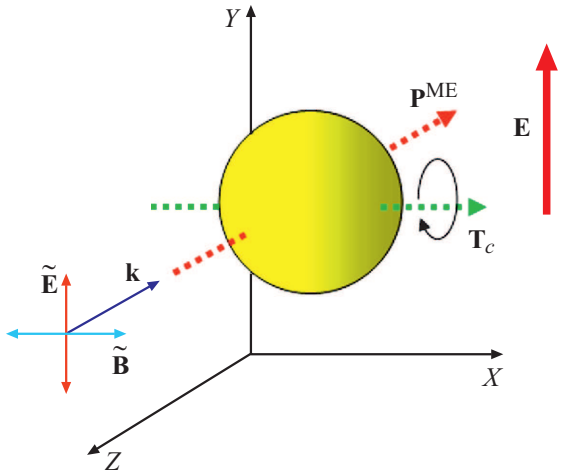

Figure 2. Diagram of transfer of torque $\mathbf{T}$ to an isotropic spherical particle in a static electric field $\mathbf{E}$ that is orthogonal to wave vector $\mathbf{k}$ of a linearly polarized light wave. Particle torque $\mathbf{T}_c$ is the result of electrostatic interaction of field $\mathbf{E}$ and static polarization $\mathbf{P}^{\mathrm{ME}}$ of the sphere induced by the magnetoelectric rectification effect.

the following expanded form of expression (1):

$$\mathbf{T}(t) = \left(\mathbf{d}_H(t) \times \mathbf{E}\right) \propto \left[\left(\mathbf{J}_e(t) \times \tilde{\mathbf{B}}(t)\right) \times \mathbf{E}\right], \qquad (3)$$

where $\mathbf{d}_H(t) \propto \int \left(\mathbf{J}_e(t) \times \tilde{\mathbf{B}}(t)\right) dt$. A particular experimental geometry for an isotropic spherical particle with $\mathbf{E} \parallel \tilde{\mathbf{E}}$ is presented in Fig. 2. It is evident that constant torque $\mathbf{T}_c$ assumes the maximum value at any orientation of vector $\mathbf{E}$ under the condition of its orthogonality to vector $\mathbf{P}^{\mathrm{ME}}$.

It follows from the theory of MER [7,8], this effect does not require the involvement of actual electron transitions (i.e., light absorption). However, it is implied in the Drude–Lorentz model, which is used to characterize MER [7], that $|\mathbf{P}^{\mathrm{ME}}| \propto \sin\varphi_0$, where phase φ_0 is proportional to the oscillator damping coefficient (i.e., to the coefficient of absorption of a light wave in an actual experiment). At the same time, it is preferable to work in the region of transparency of a particle in both experimental and practical terms, since the nonlinear optical nature of MER implies the need for fairly intense light beams [7,8]. This contradiction may be resolved in an experimental arrangement (see an example in Fig. 3) where laser radiation is split into two beams of the same intensity with $\mathbf{k}_1 \perp \mathbf{k}_2$ and orthogonal orientations of their polarization vectors ($\tilde{\mathbf{E}}_1 \perp \tilde{\mathbf{E}}_2$). A particle is positioned in the region of intersection of beams where the phase difference of their electromagnetic oscillations is $\Delta\varphi = \pm\pi/2$. If φ_0 is negligible, the primary contribution to polarization $\mathbf{P}^{\mathrm{ME}}$ is then specified by the interactions of displacement currents induced by $\tilde{\mathbf{E}}_1$ and $\tilde{\mathbf{E}}_2$ with the magnetic field of the orthogonally propagating beam (i.e., $\mathbf{P}^{\mathrm{ME}} = \mathbf{P}^{\mathrm{ME}}_{12} + \mathbf{P}^{\mathrm{ME}}_{21}$). As is shown in Fig. 3, vector $\mathbf{P}^{\mathrm{ME}}$ is orthogonal to vector $\mathbf{k}_1 + \mathbf{k}_2$, and its direction is specified by the sign of $\Delta\varphi$.

In closing, we turn our attention to the academic and technological application potential of the discussed

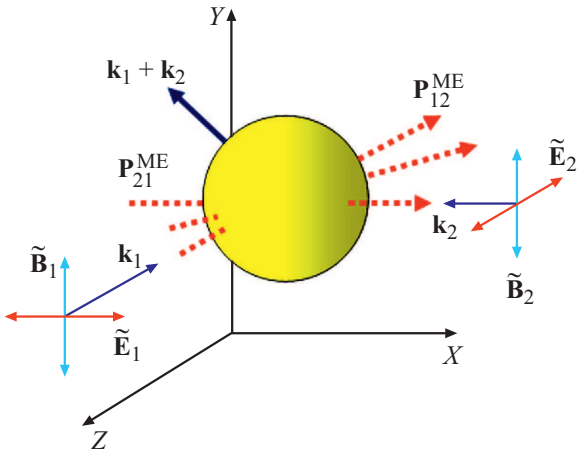

Figure 3. Diagram of an experiment illustrating the method of enhancement of magnetoelectric rectification ($\mathbf{P}^{\mathrm{ME}}$) in the region of optical transparency of a molecular object. A sphere is positioned in the region of intersection of two light beams where the phase difference of their electromagnetic oscillations is $\Delta\varphi = \pm\pi/2$. The primary contribution to $\mathbf{P}^{\mathrm{ME}}$ is produced by components $\mathbf{P}_{12}^{\mathrm{ME}}$ and $\mathbf{P}_{21}^{\mathrm{ME}}$ that are established by the interaction of the displacement current, which is induced by field $\tilde{\mathbf{E}}_1$ of beam *1*, with magnetic field $\tilde{\mathbf{B}}_2$ of beam *2* and vice versa.

methods of rotation of atomic-molecular objects. Although theoretical and experimental data needed to assess the actual potential of the DMHE mechanism are undeniably scarce, a number of its advantages are already evident. The key among them is the capacity to operate in the region of optical transparency of an object. Coupled with the fast response time ($\sim 10^{-12}$ s [6,10]) of DMHE, this should allow one to use relatively high-power optical beams (including ultrashort laser pulses) while minimizing their thermal effect. Another advantage is the symmetry of DMHE, which makes it feasible in almost all inorganic and organic molecular objects. Therefore, the opportunities for control over large organic molecules without relying on their capacity for optically induced spatial transformations [2,3] (e.g., displacement of globular protein molecules) appear promising. It is also of interest to compare DMHE with the above-mentioned optical centrifuge method [9], which allows one to accelerate gas molecules to rotation rates on the order of $10^{12}\,\mathrm{s}^{-1}$. Owing to its ultrafast response, the DMHE mechanism, on the one hand, has the capacity to impart such rotation rates and, on the other hand, provides an opportunity to simplify considerably the experimental arrangement of torque transfer relative to the one implemented in an optical centrifuge.

Conflict of interest

The author declares that he has no conflict of interest.

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