The possibility of creating artificial media possessing optical activity

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(Submitted September 22, 1972)
Zh. Eksp. Teor. Fiz. **64**, 768-770 (March 1972)

It is shown that a Kerr substance in a powerful pumping field consisting of an helical standing wave possesses gyrotropic properties with pronounced dispersion. The magnitudes of optical rotation and circular dichroism that are directly proportional to the pumping intensity are estimated. At field strengths which can be attained in practice these quantities are comparable to those of natural optically active media.

1. The subject of the present communication is a theoretical examination of the possibility of producing artificial gyrotropy with the aid of spatial modulation of the optical properties of certain substances by powerful light radiation. Scalar modulation of the refractive index has already been realized. Its value, according to the data of [1], reaches $\Delta n \propto 10^{-3}$. For our purposes, obviously, a tensor change in the dielectric constant is necessary. Kastler[2] advanced the hypothesis that many substances can rotate the plane of polarization if the modulating field is chosen in the form of a helical standing wave. The mechanisms responsible for this effect may be the Weigert effect or polymerization of the liquids under the influence of the Kerr effect. There are still not enough microscopic data for a detailed analysis of these transformations. It turns out that gyrotropic properties is possessed also by a system consisting of a Kerr substance and a strong pump field of helical structure.

2. The components of the dielectric tensor induced in an isotropic medium by a pump field as a result of the Kerr effect are defined by the expression

$$\varepsilon_{ij} = \delta_{ij}\Big(\varepsilon_0 - a\sum_{k=1}^{3} E_k^2\Big) + 3aE_iE_j. \qquad (1)$$

Let the pump be a standing helical wave

$$E_x = 2E_0 \cos(Kz)\exp(i\omega_L t),\quad E_y = 2E_0 \sin(Kz)\exp(i\omega_L t), \qquad (2)$$

produced by two opposing circularly-polarized waves. Then the wave equation that describes the change of the signal A propagating collinearly with the pump is

$$(d^2/dz^2 + k^2 + \gamma^2 + 3\gamma^2\cos(2Kz))A_x + 3\gamma^2\sin(2Kz)A_y = 0,$$
$$(d^2/dz^2 + k^2 + \gamma^2 - 3\gamma^2\cos(2Kz))A_y + 3\gamma^2\sin(2Kz)A_x = 0. \qquad (3)$$

Here $k^2 = \omega^2\epsilon_0/c^2$, $\gamma^2 = 2aE_0^2\omega^2/c^2$, k is the wave number of the signal wave, and K is the pump wave number. Introducing signal components with circular polarizations $A_\pm = A_x \pm iA_y$, we can reduce the system (3) by a simple transformation to a system with constant coefficients, the characteristic equation of which has four roots:

$$\alpha_{1,2,3,4} = \pm i[k^2 + K^2 + \gamma^2 \pm (4k^2K^2 + 4\gamma^2K^2 + 9\gamma^4)^{1/2}]^{1/2}. \qquad (4)$$

The exact solution of (3) contains four waves each with right-hand and left-hand circular polarizations, among which there are both forward and backward waves. It is natural to specify the boundary conditions in the form

$$A_+^{\rm forw}(0) = A_-^{\rm forw}(0) = A_0,\qquad A_+^{\rm back}(l) = A_-^{\rm back}(l) = 0. \qquad (5)$$

3. The medium exhibits interesting dispersion properties. In the interval $|k^2 - K^2 + \gamma^2| < 3\gamma^2$, two roots of the characteristic equation are real, so that backward waves are produced. Two rapidly-oscillating waves have amplitudes of the order of $\gamma^2/K^2 \sim 10^{-3}$ at $\Delta n \sim 10^{-3}$ ($a \sim 10^{-12}$ cgs esu, $E_0 \sim 10^5-10^6$ V/cm) and can be neglected. As a result we obtain that a forward wave of circular polarization propagates in the medium without undergoing any changes, and corresponds to the given direction of the twist of the helix (is easily "screwed in"):

$$A_+^{\rm forw} = A_0\exp(-iKz). \qquad (6)$$

A wave of opposite circular polarization is reflected in part (Fig. 1). In particular, at the center of the resonance band we have at $k^2 = K^2 - \gamma^2$

$$A_+^{\rm back} = -iA_0\exp(iKz)\,{\rm sh}[\Gamma(l-z)]\,{\rm ch}^{-1}(\Gamma l),$$
$$A_-^{\rm forw} = A_0\exp(-iKz)\,{\rm ch}[\Gamma(l-z)]\,{\rm ch}^{-1}(\Gamma l). \qquad (7)$$

Here $\Gamma = 3\gamma^2/2K \sim 10^2\ {\rm cm}^{-1}$. In sufficiently large $\Gamma l \gg 1$, i.e., $l \gg 10^{-2}$ cm, the wave A_- is totally reflected:

$$A_-^{\rm forw} = A_0\exp[-(iK+\Gamma)z]. \qquad (8)$$

Thus, in this wave-number interval the medium has strong circular dichroism, the magnitude Γ of which drops off to zero towards the edges of the interval. The width of the dichroism band is 0.1% of the pump wave number K.

4. In regions that are adjacent to the dichroism band, the changes of the signal polarization depend almost periodically on the length of the medium, and nothing can be said definitely concerning them, just as for the regions close to natural absorption lines. In the case of sufficient deviation from this band (in practice, already at $|k - K|/K \sim 1\%$), the coupling of the components with opposite circular polarizations vanishes, and they pass through the medium without a change of amplitude, but with different phase velocities, i.e., the polarization plane of radiation that is linearly polarized on entering the medium is rotated:

$$A_+^{\rm forw} = A_0\exp[-i(\tilde{k} + \rho_1)z],\qquad A_-^{\rm forw} = A_0\exp[-i(\tilde{k} - \rho_2)z]. \qquad (9)$$

Here $\tilde{k} = k + \gamma^2/2k$, and the rotation of the polarization plane is $\rho = (9/8)\gamma^4/K(k^2 - K^2)$. At a 1% deviation from the dichroism band we have $\rho \sim 10\ {\rm cm}^{-1}$, i.e., of the same order as natural optical activity of quartz. The

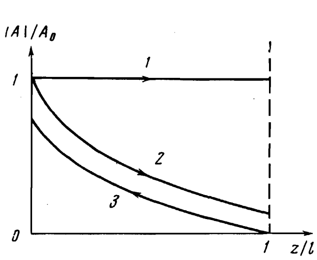

FIG. 1

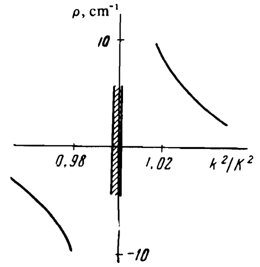

FIG. 2

FIG. 1. Amplitudes of forward and backward waves of two circular polarizations in the dichroism band: 1—$|A_+^{forw}|/A_0$, 2—$|A_-^{forw}|/A_0$, 3—$|A_+^{back}|/A_0$.

FIG. 2. Dispersion curve of optical rotation in a field of a helical standing wave $|k^2 - k^2 + \gamma^2| < 3\gamma^2$ is the shaded region.

rotation angle is then equal to several times 10° per millimeter. The characteristic dispersion curve of the optical rotation in such an artificial medium is shown in Fig. 2.

5. Thus, a powerful helical standing pump wave imparts to a Kerr medium the properties of circular dichroism and optical activity, the magnitudes of which are directly proportional to the pump intensity, and are comparable with the corresponding factors of natural optically active media. There are grounds for assuming that when a Kerr liquid is polymerized in such a pumping field the tensor of the induced dielectric constant will assume the same form, and the optical activity, compared with the known results of scalar modulation of the refractive index, can be more appreciable. It is also of interest to trace the analogy (perhaps not only the outward one) between the natural nonlinear optical activity described by the spatial derivatives of **E** in the dielectric tensor, and the optical activity considered above.

The author thanks S. A. Akhmanov for useful discussions.

[1] W. J. Tomlinson, I. P. Kaminov, E. A. Chandross, R. L. Fork and W. T. Silfast, Appl. Phys. Lett. 16, 12, 486, 1970.
[2] A. Kastler, C. R. Acad. Sci., 271, 19, B999, 1970.

Translated by J. G. Adashko
84