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Refractive index of ferromagnetic semiconductors in a field of coherent light beams

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The influence of intense laser radiation (coherent light beams (CLB)) on refractive index of a ferromagnetic semiconductor (FMSC) has been considered. It is shown that under CLB, in FMSC the grating of a refractive index takes place. A model explaining this effect is proposed. The relevant theoretical calculations have been carried out confirming the new phenomenon, appearance of refractive index grating in FMSC in a field of CLB.

Рассмотрено влияние интенсивного лазерного облучения (когерентных световых пучков, КСП) на показатель преломления ферромагнитного полупроводника (ФМПП). Показано, что под воздействием КСП в ФМПП возникает решетка показателя преломления. Предложена модель для объяснения этого эффекта. Выполнены теоретические расчеты, подтверждающие наличие нового эффекта — появления решетки показателя преломления в ФМПП в поле КСП.

The optical properties (e.g. refractive index, absorption coefficient, light reflection coefficient) of a material become spatially modulated in the interference region of some intense light waves [1]. Permanent gratings have been produced in this way by photographic processes for many years. The experiments of Wiener [2] providing the first demonstration of standing light waves, the use of this effect by Lippmann [3] one year later in the earliest color photography process, and various holographic experiments [4] can be mentioned as examples. Recently, the concern to other kind of laser-induced structures — dynamic or transient gratings was boosted. These gratings disappear after the inducing light source, usually a laser (coherent laser beam (CLB)), is switched off. Such gratings have been obtained in a large number of solids, liquids and gases, and are detected by diffraction of probing beam or by self-diffraction of the light wave inducing the grating. As to technical applications, the laser-induced transient gratings can be used in holography for real-time processing of optical fields. In recent years, this subject has regained interest because of the demonstration of phase conjugation or time-dependent reversal of optical wave fronts [5]. Using this process, it is possible to design self-adaptive optical systems which compensate time-varying phase distortions in high-gain laser oscillators and amplifiers, or in optical transmission lines through atmosphere, water, or optical fibers.

Among laser-induced transient gratings, of a particular interest are the gratings on free carriers in FMSC. For the first time, such gratings in FMSC were considered by one of the authors [6, 7]. These gratings are nearly perfect and almost inertia-free (their inertia is defined by the relaxation times of electrons and magnons). Since gratings in FMSC have those specific properties and also since the parameters of such gratings can be controlled by applied electric fields, the FMSC with laser-induced gratings are of great interest in the physics of dynamic holograms and also as tools suitable to study the properties of non-equilibrium electrons and magnons by highly sensitive optical methods.

In this paper, the influence of intense laser radiation (coherent light beams (CLB)) on refractive index of a ferromagnetic semiconductor (FMSC) has been considered. It is shown that under CLB, in FMSC the grating of a refractive index takes place. A model explaining this effect is proposed. The relevant theoretical calculations have been carried out confirming the new phenomenon, appearance of refractive index grating in FMSC in a field of CLB.

Let a wide-band donor FMSC of EuO type be considered having an average carrier density n_0 in the spin wave temperature range. We shall consider an applied static heating electric field $\mathbf{F}_0 \| OZ$ and assume several CLB incident onto the outer surface $x = 0$ of the FMSC to have the following vector potentials within the FMSC:

$$\mathbf{A}(\mathbf{r},t) = \sum_j \mathbf{A}_j \cos(\omega t - \mathbf{k_j r}). \tag{1}$$

We shall also assume that the frequency ω satisfies the inequality $\bar{\varepsilon} << \hbar\omega << \varepsilon_g$ ($\bar{\varepsilon}$ is the carrier average energy; ε_g, the band gap). In this case, as is known [6], the interference of CLB creates on the FMSC surface an interference pattern, that is, periodical alternation of light (maximum of the CLB intensity and field strength) and dark (minimum of the CLB intensity and field strength) areas as is illustrated in Fig.

Let us consider how the phenomenon may effect the FMSC refractive index. In light areas, the CLB electric intensity will be maximum while in dark ones, minimum. As the CLB quantum energy is $\hbar\omega < \varepsilon_g$, there are no oscillations of charge carriers (electrons) under CLB, so their redistribution is observed only. Those will move out of light areas and accumulate in dark areas, so creating the positive charge areas and negative charge ones. An electric field arises between the areas of positive and negative charge. Under its influence, a strain occurs in the FMSC crystal lattice. Due to that strain, the light will be propagated through one area faster while through another, more slowly. As a result, the refractive index also will be changed periodically. Thus we obtain a spatially periodic laser-induced structure, a grating of the FMSC refractive index. The laser-induced refractive index grating will be shifted in space by a quarter of period as compared to the interference pattern created by CLB on the FMSC surface. Now we shall carry out the relevant analytical calculations confirming the new light refraction effect in FMSC i.e., formation of a laser-induced refractive index grating.

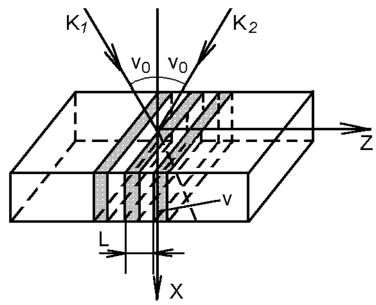

Fig. Interference pattern from two CLB when they illuminated the front surface $x = 0$ of a FMSC sample. ($L = \lambda/2\sin\upsilon$ is the period of interference pattern).

It is known that all substances are characterized by a complex refraction index N, which determines the light speed reduction in a substance in comparison with that in vacuum:

$$N = \sqrt{\varepsilon\mu}, \tag{2}$$

where ε and μ are the FMSC dielectric permittivity and magnetic permeability, respectively. Note that ε and μ are related (in linear approach) to properties of medium by the following relationships:

$$\varepsilon = 1 + 4\pi\chi_e, \quad \mu = 1 + 4\pi\chi_M, \tag{3}$$

where χ_e and χ_M are the FMSC dielectric and magnetic susceptibilities, respectively. Substituting (2) in (3), we obtain the following expression for the complex refractive index:

$$N^2 = (1 + 4\pi\chi_e)(1 + 4\pi\chi_M). \tag{4}$$

Now our task is to calculate the dielectric permittivity ε and magnetic permeability μ or dielectric χ_e and magnetic χ_M susceptibilities of a FMSC. Before to start the calculations, it is necessary to take into account what follows. In FMSC, any volumetric redistribution of current carriers of (electrons) also causes, due to a strong coupling between electron and spin subsystems, in local changes of the spin subsystem. On the other hand, the state of conduction electrons in a FMSC crystal under CLB not only influences the spin subsystem (magnons), but also depends thereon. Therefore, if we consider influence of an external high-frequency electric field of a CLB $\mathbf{E}_j(\mathbf{k},\omega)$ on conduction electrons in FMSC, it is necessary to take into account that it not only gives rise to an internal electric field $\mathbf{F}(\mathbf{k},\omega)$, but also changes the magnetic subsystem state. Thus, the effective electric field acting on a conduction electron in the FMSC volume consists of two fields: internal electric field $\mathbf{F}(\mathbf{k},\omega) = \varepsilon^{-1}(\mathbf{k},\omega)\mathbf{E}_j(\mathbf{k},\omega)$, which is controlled in a FMSC crystal by an external high-frequency electric field of CLB, and a field causing changes in exchange of electrons with magnetic atoms due to changes of their state under an electric field. In the elementary case, the change in magnetization components under an external field is related to its strength by a linear relationship

$$M(\mathbf{k},\omega) = \Lambda(\mathbf{k},\omega)E_j(\mathbf{k},\omega). \tag{5}$$

The effective field, $\tilde{\mathbf{F}}_\sigma(\mathbf{k},\omega)$ acting on an electron with the spin projection σ is

$$\tilde{F}_\sigma(\mathbf{k},\omega) = F(\mathbf{k},\omega) - \frac{JM}{e}(\mathbf{k},\omega)\sigma \equiv \equiv \tilde{\varepsilon}_\sigma^{-1}(\mathbf{k},\omega)E_j(\mathbf{k},\omega), \tag{6}$$

where the following notation for electron spin dependent permittivity is used:

$$\tilde{\varepsilon}_\sigma^{-1}(\mathbf{k},\omega) = \varepsilon^{-1}(\mathbf{k},\omega) - \frac{J\sigma\Lambda(\mathbf{k},\omega)}{e}. \tag{7}$$

It is obvious that the quantities $\varepsilon(\mathbf{k},\omega)$ and $\tilde{\varepsilon}_\sigma(\mathbf{k},\omega)$ differ in physical sense. The first, $\varepsilon(\mathbf{k},\omega)$, characterizes an internal electric field acting on a spin-free particle while the second, $\tilde{\varepsilon}_\sigma(\mathbf{k},\omega)$, a field acting on a conduction electron with a certain spin orientation. It follows therefrom, in particular, that ions composing FMSC are influenced by other field than the conduction electrons.

Thus, to describe the state of conduction electrons in FMSC, it is necessary to know, besides of the usual permittivity $\varepsilon(\mathbf{k},\omega)$, also a permanent-magnet permittivity $\Lambda(\mathbf{k},\omega)$ (nondiagonal response function). For an effective FMSC permittivity, $\tilde{\varepsilon}_{\sigma=\frac{1}{2}}$ it is possible to obtain the following expression [8]:

$$\tilde{\varepsilon}_{\sigma=\frac{1}{2}} = \varepsilon_0[(1 - \Gamma_0) + \frac{\chi_p^2}{q^2}]. \tag{8}$$

As it is seen from the last equation (8), the quantity $\tilde{\varepsilon}_{\sigma=\frac{1}{2}}$ differs from the corresponding quantity characterizing an internal electric field in an antimagnetic crystal by that it contains the feedback function Γ_0. Its occurrence can be explained by existence of positive feedback between a magnetic moment and electric field in a FMSC crystal. Really, for example, the field of the ionization donor increments an electron concentration in its neighborhood, and thus, the ferromagnetic interatomic connection will increase as well as the magnetization. This, in turn, reduces energy of an electron in a neighborhood of the donor, forcing it to approach even more to to the donor, etc. Thus, if the quantity Γ_0 can be neglected, a FMSC, for want of examination of its optical properties, can be considered as the usual nonmagnetic semiconductor. This can be done for unregenerate FMSC in spin-wave temperatures when

$$\Gamma_0 = \frac{3T}{2\nu\mu_p}. \tag{9}$$

Taking this circumstance into account, we now shall initiate with calculation of FMSC permittivity in a high-frequency field of CLB, abstracting from its magnetic properties. For calculation, we shall use the known Lorentz model of a harmonic oscillator. In this model, a medium is considered as plurality of some number of one-electron atoms. The movement of an electron in atom is characterized in approximation of elastic interaction of an electron with a nucleus. The interaction force is considered to be proportional to the electron displacement (bias) from its position in the atom in absence of an external field: $f = -qr$. Here q ($q > 0$) is the coupling constant, and the negative sign means that the elastic force, which arises for want of the electron bias of an, is directed oppositely to bias. The electron instantaneous coordinate $\mathbf{r}$ in the absence of action of force $f_E = -eE$, caused by CLB influence, is determined from the second Newton's law:

$$m\frac{d^2\mathbf{r}}{dt^2} = f + f_E, \tag{10}$$

where m and e are electron mass and charge, respectively. Taking into account in (10) also a force braking the electron, $f_t = 2\gamma\mathbf{r}$ (γ is some constant factor), we obtain:

$$\frac{d^2\mathbf{r}}{dt^2} + (2\gamma + \omega_0^2)\mathbf{r} + \frac{e}{m}\mathbf{E} = 0, \tag{11}$$

where $\omega_0^2 = q/m$.

The electric intensity of a light wave **E**, propagating within the FMSC volume, follows from Maxwell equations. Being restricted for simplicity by one-dimensional case, we obtain the following equation for determination **E**, which follows from combined Maxwell equation:

$$\frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{\varepsilon}{c}\frac{\partial^2 \mathbf{E}}{\partial t^2}, \quad (12)$$

where the permittivity of FMSC, ε, is defined by the dipole moment induced by the light wave field:

$$\varepsilon = +4\pi \mathbf{P}/\mathbf{E}. \quad (13)$$

In the frame of Lorentz model, the dipole moment **P** is equal to product of electron charge ($-e$) and its bias **r**, which is characterized by the equation (11), multiplied with the electron concentration n:

$$\mathbf{P} = -ne\mathbf{r}. \quad (14)$$

Thus, the equations (11) and (12) form combined equations for determination of $\mathbf{r}(t)$ and $\mathbf{E}(t)$. By direct substitution, it is possible to be convinced that such solution will be the following expression:

$$\mathbf{E} = \mathbf{E}(\omega)e^{i\omega t} + h.c.$$

$$\mathbf{r} = -\frac{e\mathbf{E}(\omega)}{m(\omega_0^2 + 2i\gamma\omega - \omega^2)} + h.c., \quad (15)$$

where $h.c.$ means a quantity complex to a conjugate first addend.

Substituting (15) into (13), it is possible to obtain the obvious expression for polarization vector **P**:

$$\mathbf{P} = \frac{ne^2\mathbf{E}(\omega)e^{(i\omega t)}}{m(\omega_0^2 + 2i\gamma\omega - \omega^2)} + h.c.. \quad (16)$$

Substituting (16) into (14), we obtain the following expression for FMSC permittivity at frequency ω

$$\varepsilon(\omega) = 1 + \frac{ne^2}{m}(\omega_0^2 + 2i\gamma\omega - \omega^2)^{-1}. \quad (17)$$

The FMSC refractive index change ΔN in a field is easy to obtain from the (17) under conditions of $\omega > \omega_0$, $\omega > 2\gamma$:

$$\Delta N \approx \frac{ne^2}{2\overline{N}m\omega^2}. \quad (18)$$

Hence, any redistribution (or the change) in concentration of charge carriers (electrons) in semiconductors (including FMSC) results in a refractive index change. Thus, the occurrence of a laser-induced grating of carriers concentration in FMSC should result a laser-induced refractive index grating. As is known [1] , under certain conditions ($\overline{\varepsilon} << \hbar\,\omega << \varepsilon_g$) in FMSC volume, as well as in any other semiconductor, CLB redistribute the charge carriers, creating a static laser-induced grating of charge carriers concentration. Or else, in this case, the charge carrier concentration can be written as [6]:

$$n = n_0(1 + \xi_1\cos 2k_{1z}z + \xi_2\sin 2k_{1z}z) \quad (19)$$

(k_{1z} is the CLB wave vector inside of FMSC).

Now, using (18) and (19), we obtain the following expression for ΔN,

$$\Delta N \approx \frac{e^2 n_0(1 + \xi_1\cos 2k_{1z}z + \xi_2\sin 2k_{1z}z)}{2\overline{N}m\omega^2}. \quad (20)$$

Thus, it follows from (20) that the change of the FMSC refraction index due to redistribution of charge carrier concentration (electrons) in a field of CLB will be modulated in space under the periodic law, that is, a CLB interference pattern forms in FMSC a laser-induced grating of refractive index.

Now we shall consider, as the FMSC magnetic subsystem state will influence its refractive index. Let us consider a FMSC, exhibiting in external stationary electrical field $F_0 \| OZ$ both magnetic fields $\mathbf{H}_0 \| \mathbf{F}_0$ and a weak variable homogeneous magnetic field $\mathbf{h} = \mathbf{h}_0\cos\omega_1 t$ perpendicular to $\mathbf{H}_0$. The components of the effective magnetizability tensor χ in such FMSC far from resonance are considered in detail in [9], where the following expression has been obtained for Hermitian component of this tensor:

$$\mathrm{Im}\chi_{xx} = -\frac{\omega_1}{\omega}\left(\frac{M_0}{H_0}\right)^2 \frac{\lambda_1\beta_0^2}{(2\pi)^3}\left(\frac{\Theta_m}{\Theta_c}\right)^2 \times$$
$$\times [1 + \frac{R\,(2\pi)^3 M_0}{\lambda_1\ \beta_0^2\ H_0}\left(\frac{\Theta_c}{\Theta_D}\right)\left(\frac{T}{\rho a^2 v_s^2}\right)^3]. \quad (21)$$

Here $\omega_0 = 2\mu_b H_0(1 + \beta_0 H_0/M_0)$, μ_b is the Bohr magneton; β_0, the anisotropy constant; v_s, the sound speed; ρ, the FMSC crystal density; R and λ are the numbers, Θ_c, Θ_D the Curie and Debye temperatures, respectively; Θ_m, the magnon temperature.

The complex refractive index of FMSC, N, in this case be defined as

$$N^2 = (1 + 4\pi\chi_e)(1 + 4\pi\chi_M(\Theta_m))$$

and, as it follows from a ratio (21), becomes the function of magnon temperature.

Now we shall look, as the presence of a laser-induced grating of magnon temperature will influence the FMSC refractive index. In the presence of interference field of CLB magnon temperature, Θ_m, as it was shown in [6], can be written as

$$\Theta_m = T_m^{(0)} + T_2 = T_m^{(0)}(\mu_0 + \mu_1\cos 2k_{1z}z + \mu_2\sin 2k_{1z}z). \quad (22)$$

Using (21) and (22), it is easy to obtain a resultant expression for refractive index of FMSC with a laser-induced grating of magnon temperature:

$$N^2 = \varepsilon_0 \left[\frac{1 + 4\pi\frac{\omega_1}{\omega_0}\left(\frac{M_0}{H_0}\right)^2 \frac{\lambda_1\beta_0^2}{(2\pi)^3}\left(\frac{T_m^{(0)}}{\Theta_c}\right)^2}{\left(1 + \frac{R\,(2\pi)^3 M_0}{\lambda_1\ \beta_0^2\ H_0}\left(\frac{\Theta_c}{\Theta_D}\right)^3 \frac{T}{\rho a^2 v_s^2}\left(\begin{matrix}1 + \mu_0 + \mu_1\cos 2k_{1z} \\ z + \mu_2\sin 2k_{1z}z\end{matrix}\right)^2\right)} \right]. \quad (23)$$

Thus, as it follows from (23), in FMSC with a laser-induced grating of magnon temperature probably the refractive index nonlinearity causes the nonlinearity of a FMSC magnetizability and refraction index oscillations should be observed, which will result in occurrence of complementary dark domains. To conclude, as a result of the examinations, it is shown, that there are at least two formation mechanisms of refractive index nonlinearity in FMSC: (i) the refractive index changes caused by redistribution of free electrons in an interference field in FMSC; and (ii) the refractive index nonlinearity caused by nonlinearity of FMSC magnetizability. The contribution form each of these nonlinearity mechanisms depends on various factors (concentrations of electrons, the spontaneous magnetization value, heating degree of carriers and magnons, etc.).

On completion of this work, we shall conduct some numerical valuation. So, for example, if the concentration of carriers is assumed to be about 10^{15}–10^{16} cm^{-3}, $T = 0.5 \cdot 10^{-21}$ J, $\omega = 5 \cdot 10^{14}$ s^{-1}, and the CLB electric intensity 1000 V/cm, it has been obtained for typical FMSC such as EuO [8], that the modulation depth of the laser-induced refractive index grating may attain 1–3 % and it can easily be observed experimentally for optical measuring.

References

1. H.J.Eichler, P.Gunter, D.W.Pohl, Laser-Induced Dynamic Gratings, Springer-Verlag, Berlin, Heidelberg, New York, Tokyo (1985).
2. M.Born, E.Wolf, Principles of Optics, Pergamon, Oxford (1973).
3. G.Lippmann, *Compt. Rend. Seanc. Acad. Sci. Paris*, **112**, 274 (1891).
4. D.Gabor, *Nature (London)*, **161**, 77 (1948).
5. B.Ya.Zel'dovich, N.F.Philipetsky, V.V.Shkunov, Principles of Phase Conjugation, Springer Ser. Opt. Sci., v.42, Springer, Berlin, Heidelberg (1985).
6. A.E.Levshin, O.Yu.Semchuk, P.M.Tomchuk, *Sov. Phys. Solid State*, **28**, 229 (1986).
7. A.Yu.Semchuk, L.G.Grechko, V.M.Ogenko, *Phys. Stat. Sol.(b)*, **157**, 451 (1990).
8. E.L.Nagaev, Physics of Magnetic Semiconductors, Nauka, Moscow (1979) [in Russian].
9. O.Yu.Semchuk, S.S.Rozhkov, *Sov. Phys. Solid State*, **24**, 1730 (1982).

Показник заломлення феромагнітних напівпровідників у полі когерентних світлових пучків

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Розглянуто вплив інтенсивного лазерного опромінення (когерентних світлових пучків, КСП) на показник заломлення феромагнітного напівпровідника (ФМНП). Показано, що під впливом КСП в ФМНП виникає гратка показника заломлення. Запропоновано модель для пояснення цього ефекту. Виконано теоретичні розрахунки, які підтверджують наявність нового ефекту — виникнення гратка показника заломлення в ФМНП в полі КСП.