MODULATION OF AN ELECTRON BEAM BY A LIGHT WAVE

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When a beam of electrons passes through a light beam whose intensity varies abruptly over the cross section or drops off sharply at the edge, the density of the electron current becomes modulated at the optical frequency. When such a beam is incident on a target, it may produce radiation at the optical frequency and its harmonics [cf. [1]).

Let us consider a monoenergetic narrow beam of electrons moving with velocity V along the OX axis (cf. Fig. 1). Assume that at the point O it crosses a narrow monochromatic linearly polarized beam of light of frequency ω, the electric vector of which is directed along the X axis and varies in amplitude from zero at the point P to E at the point O (the right-hand curve in the figure). We assume that its intensity vanishes jumpwise on passing through O across the beam. At the point x = L the electron flux is incident on a metallic screen perpendicular to the X axis.

If its intensity varies slowly in the transverse direction in the interior of the beam, then the velocity of electrons leaving the beam at the point O at the instant of time t can be expressed in the form (the electrons are assumed to be nonrelativistic)

$$v(t) = V + \frac{eE}{m\omega}\sin\omega t, \tag{1}$$

where e and m are the charge and mass of the electrons. For very moderate electron energies, up to very strong optical fields, the following inequality holds:

$$eE/m\omega \ll V. \tag{2}$$

On the other hand, the concentration of the electrons at the point O remains practically constant and equal to their concentration in the incident beam. We shall designate it N.

Thus, the modulation to which the electrons are subjected under the foregoing conditions is perfectly analogous to the processes occurring in a klystron [2]. We can therefore write down immediately an expression for the current density (I_p is a Bessel function)

$$j(x,t) = \mathrm{Re}\left\{eNV\left[1 + 2\sum_{p=1}^{\infty} I_p\left(p\frac{xeE}{mV^2}\right)e^{ip\omega(t - \frac{x}{V})}\right]\right\}. \tag{3}$$

We note that when the parameter xeE/mV^2 is of the order of unity, the amplitudes of a number of harmonic components of the current density (including the fundamental, optical frequency) are comparable with the dc component enV.

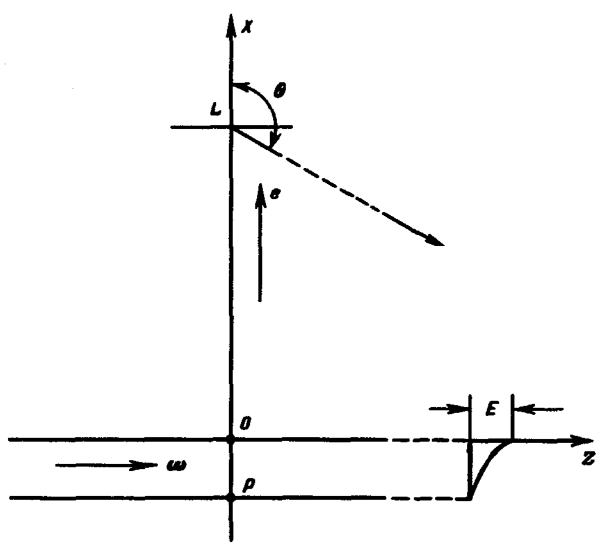

Fig. 1

The electron beam incident on the screen produces transition radiation on the screen surface [4]. We assume for simplicity that the screen has infinite conductivity[1]. Then the radiation of an electron moving inside the screen is completely absorbed, and the vector potential of the radiation field produced by the current (more accurately, its X-component) can be written in the form [3]

$$A_X = \frac{S}{cR_0}\int_0^L i\left(x, t - \frac{R_0}{c} + \frac{x\cos\theta}{c}\right) dx\,. \tag{4}$$

Here R_0 is the distance to the observation point, the angle between the X axis and the observation direction, and S the cross section area of the electron beam. When (3) is substituted in (4), the factors containing the Bessel functions vary much more slowly with changing x than the exponential factor. We can therefore calculate (4) by integrating by parts. We then obtain for the p-th harmonic

$$A_X^{(p)} = \frac{2eNV^2S}{R_L} I_p\left(p\frac{LeE}{mV^2}\right)\frac{1}{ip\omega(V\cos\theta - c)}\, e^{ip\omega\left(t - \frac{R_L}{c} - \frac{L}{V}\right)}.$$

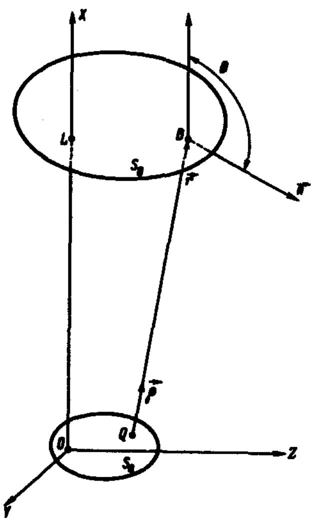

Fig. 2

Here R_L is the distance from L to the observation point. In fact $A_X^{(p)}$ must also be doubled, in order to take into account the charges induced on the surface of the screen (the "electric image" of the current, cf. [4]).

We consider now an electron beam whose transverse dimension is larger than the wavelength of light (see Fig. 2; S_Q and S_B are respectively the cross sections of the electron beam as it emerges from the light beam and on the screen, respectively). Assuming the electron wavelength h/mV to be much shorter than the light wavelength, we shall describe the electron beam with the aid of geometrical optics. We consider an infinitesimally narrow electron beam passing through an area element dS_Q in the S_Q plane in the direction QB. We introduce an analogous brightness coefficient ν_{QB}, equal to the ratio of the concentration dN_B produced by this beam at the point B in the absence of light-wave modulation, to the area dS_Q:

$$dN_B = \nu_{QB}\, dS_Q.$$

The field of the light wave can be obtained by summing the fields from such elementary infinitesimally narrow beam, one of which was considered above. It turns out that at large distances the light field can be described with the aid of an integral of the Huyghens-Fresnel type [3], evaluated over the area of the electron beam on the screen. The field (magnetic, for concreteness) of the p-th harmonic on the screen should be taken in the form

$$H_B = \frac{8\pi i}{p\omega} I_p\left(p\frac{LeE}{mV^2}\right)\int_{S_Q} \vec{\rho}\times n\, \frac{e\nu_{QB}V^2}{(\vec{\rho}n)V - c}\, e^{ip\omega\left(t - \frac{r}{V} - \frac{z_Q}{c}\right)} dS_Q.$$

Here $\vec{n}$ and $\vec{\rho}$ are unit vectors in the observation direction and in the direction

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[1] If the screen material is sufficiently transparent, then bremsstrahlung must be taken into account in addition to the transition radiation.

of the vector $\vec{r}$, respectively. The remaining notation is clear from Fig. 2.

It can be assumed that the process described here explains the appearance of radiation on a non-luminescent screen under the influence of an electron beam, which was observed by Schwarz and Hora [1]. Jumps of the amplitude of the normal component of the electric field of the light wave occurred on the boundaries of a thin crystal plate placed by them in the light beam. The parameter LeE/mV^2 (see above) could, under the conditions of [1], be of the order of unity (the presence of two jumps on the two faces of the plate could change only the amplitude of the electron-velocity modulation, cf. [2]).

Without a detailed knowledge of the electron beam geometry, the light intensity can be estimated only very approximately. At an electron-beam divergence angle 10^{-4} rad (see [5]) the visual brightness under the conditions of [1] can be estimated at about 10^{-4} nit.

In conclusion, the author thanks G.A. Askar'yan and I.V. Tyutin for a discussion of the work.

[1] H. Schwarz and H. Hora, Appl. Phys. Lett. 15, 349 (1969).
[2] V.I. Kalinin and G.M. Gershtein, Vvedenie v radiofiziku (Introduction to Radiophysics), GITTL, 1957.
[3] L. D. Landau and E.M. Lifshitz, Teoriya Polya, Fizmatgiz 1960 (Classical Theory of Fields, Addison-Wesley, 1965].
[4] I.M. Frank, Usp. Fiz. Nauk 87, 189 (1965) [Sov. Phys.-Usp. 8, 729 (1966).
[5] P. Hirsch, A. Hovey, R. Nicolson, D. Pashley, and M. Whelan, Electron Microscopy of Thin Crystals , Butterworth, 1966.

NEW POLARON EFFECT IN THE INTERBAND MAGNETOOPTIC ABSORPTION OF SEMICONDUCTORS

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Singularities of interband magnetooptic absorption, occurring at $\Omega_c = \omega_0$ (Ω_c is the electron cyclotron frequency and ω_0 the frequency of the longitudinal optical phonons interacting with the electrons), have been recently observed experimentally [1] and calculated theoretically [2]. These singularities are connected with the fact that when $\Omega_c = \omega_0$, two branches of the electron-phonon-system spectrum intersect, namely, an electron on the bottom of the Landau band $\ell = 1$ and an electron on the bottom of the band $\ell = 0$ plus one optical phonon.

In principle, the intersection of the branches of the spectrum of the electron-phonon system can occur also without a magnetic field. For example, an electron with momentum $p = p_0 \equiv (2m_c\hbar\omega_0)^{1/2}$ and an electron with $p = 0$ plus a phonon with $\hbar\omega_0$. However, calculation shows that the three-dimensional character of the electron motion leads to a very weak singularity in the absorption coefficient. A much stronger singularity arises in the case of one-dimensional motion of the electron, which can be realized in a quantizing magnetic field.

The effect can be qualitatively understood from Fig. 1. The dashed line in the upper part of the figure (the parabola 1 and the line 2) represent two branches of the electron-phonon-system spectrum (without interaction): an electron in the band $\ell = 0$ with momentum p, and an electron in the band $\ell = 0$ with