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NONLINEAR PULSE MODULATION OF VHF RADIO PULSES AND BEAMS

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Abstract—Feasibility of controlled modulation of VHF radio waves is shown by means of reflecting waves from the surface of an n-type semiconductor with a periodically varying carrier temperature. Heating of the carriers by an external electric field is discussed, and cases of amplitude modulation and polarization of waves passing through the semiconductor plate are considered. The role of external magnetic fields in the formation of the polarization structure of radiation is noted.

The present work is devoted to the complex of controllable processes in the thermal interaction of VHF radiowaves with the collisional plasma of n-type semiconductors. Such processes are associated with the temperature dependent frequency ν_e of electron–photon scattering in semiconductors. The dependence of the reflection and transmission coefficients for GHz radiowaves on ν_e indicates that these coefficients are temperature controllable. In particular cases this relationship may be an increase of ν_e with temperature, typical of Ge [1]:

$$\nu_e = \nu_{e0}\sqrt{\frac{T_e}{T'_{e0}}} \tag{1}$$

or a decrease of ν_0 according to

$$\nu_e = \nu_{e0}\sqrt{\frac{T_{e0}}{T_e}}, \tag{2}$$

typical of InSb [2]. Here ν_{e0} is the value at some initial temperature T_{e0} in degrees Kelvin; T_e is the final temperature such that $T_e \geqslant T_{e0}$.

The association of these temperature coefficients with the pumping effects of thermally self-excited waves and with the interaction of two cross-modulated waves suggests how one may achieve amplitude and frequency-phase modulation through temperature effects.

We should point out the physical features of the phenomena considered which distinguish them from cross-modulation in a gaseous plasma [3, 4]:

(1) The existence of a sharp boundary between the semiconducting plasma and the external medium explains the peculiar dependence of the amplitude and phase of the reflected signal on the electron temperature of the n-type semiconductor. Furthermore, this dependence is different for s and p-polarized waves incident on the semiconductor surface.

(2) In the GHz range of radiowaves the imaginary part of the electric permeability ε of the semiconductor need not be small compared to its real part. The thermal modification of the refracted wave develops in a thin film of the semiconducting plasma, whose thickness may be of the order of a wavelength.

(3) The characteristic time of the above processes is determined by the relaxation time of the electron temperature,

$$\tau_T = \frac{1}{\delta \nu_e}, \tag{3}$$

where δ is the mean fraction of energy transferred in electron–phonon collisions

$$\delta = \sqrt{\frac{2}{\pi}}\cdot\frac{m_e \cdot c_s^2}{kT_{e0}}. \tag{4}$$

Here c_s is the velocity of sound, m_e the effective mass of the electron, and k is Boltzmann's constant. The quantity δ is small: Thus for Ge, $\delta = 10^{-2}$, while for InSb, $\delta = 10^{-3}$. The relaxation time τ_T may range over 10^{-9}–10^{-11} s, with a ν_e of 10^{11}–10^{13} Hz. Such build-up times are of interest in the creation of plasma electron devices.

Let us consider the simple case of modulating a beam of VHF waves of frequency ω incident at an angle on a film of n-type semiconductor. We may represent the dielectric permeability of the semiconductor in the form $\varepsilon = R + iI$, in which

$$R = \varepsilon_L - \frac{V}{1+S^2}, \quad I = \frac{V \cdot S}{1+S^2}; \qquad S = \frac{\nu_e}{\omega}, \quad V = \frac{\Omega^2}{\omega^2}, \tag{5}$$

where Ω is the Langmuir frequency of the electrons.

The temperature dependence of R and I may be expressed in terms of the collision frequency [1, 2] in dimensionless form:

$$S/\mathrm{Ge} = S_0\sqrt{f} \qquad S/\mathrm{InSb} = \frac{S_0}{\sqrt{f}}, \tag{6}$$

where f is characterized by the electron temperature,

$$f = \sqrt{\frac{T_e}{T_{e0}}}. \tag{7}$$

The complex reflection coefficients R_s and R_p corresponding to s and p polarizations and angle of incidence α may be written in terms of the quantities of (5)

$$R_s = \frac{\cos\alpha - \sqrt{R + iI - \sin^2\alpha}}{\cos\alpha + \sqrt{R + iI - \sin^2\alpha}} = |R_s|\, e^{i\varphi_s}; \tag{8}$$

$$R_p = \frac{(R + iI)\cos\alpha - \sqrt{R + iI - \sin^2\alpha}}{(R + iI)\cos\alpha + \sqrt{R + iI - \sin^2\alpha}} = |R_p|\, e^{i\varphi_p}. \tag{9}$$

The temperature dependence of the intensity reflection coefficient $|R_s|^2$ is shown in Fig. 1.

The transmission coefficient through the semiconductor layer is likewise a function of temperature. For a layer of thickness d the intensity transmission coefficient k is given by

$$k = (1 - |R_s|^2)\cdot e - \frac{d}{L_x}, \tag{10}$$

where L_x is a characteristic decay length,

$$L_x l = c/\omega\chi. \tag{11}$$

The temperature dependence of the attenuation decrement χ is shown in Fig. 2.

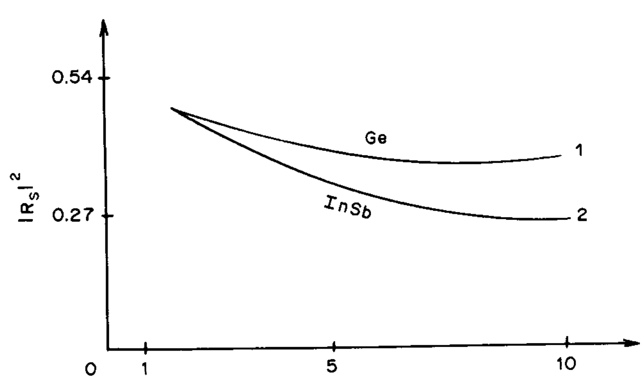

Fig. 1. The modulus of the reflection coefficient $|R_s|^2$ as a function of the electron temperature of the semiconductor plasma for an s-polarized wave.

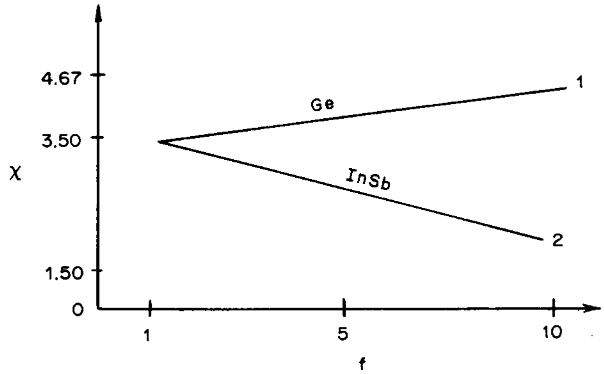

Fig. 2. Temperature dependence of the absorption coefficient χ at normal incidence.

Let us now analyse the effect of an external magnetic field on the interaction of millimetre radio waves with the semiconductor plasma. The effect of the magnetic field is to complicate considerably the frequency and angular dependence of reflection. Let us take a simple case corresponding to normal incidence of the wave on the semiconductor layer, parallel to the magnetic field, in a frequency region that is near gyroresonance. The detuning from resonance is conveniently characterized by the parameter

$$X_0 = \frac{1-\sqrt{U}}{S_0}; \quad U = \frac{\omega_{H^2}}{\omega^2}, \tag{12}$$

where ω_H is the Larmor frequency of the electrons. Near resonance ($\sqrt{U} \to 1$) the dielectric permeability of the semiconductor may be represented in the form

$$\varepsilon_\perp = \varepsilon_L - \frac{V \cdot X_0}{2S_0} \cdot \frac{1}{X_0^2 + \dfrac{S^2}{S_0^2}}; \qquad \varepsilon_\parallel = \varepsilon_L - \frac{V}{1+S^2} + \frac{iVS}{1+S^2}; \qquad \varepsilon_\Lambda = -\frac{V}{2(X_0^2 + S^2/S_0^L)}\left[\frac{iX_0}{S_0} - S\right]. \tag{13}$$

For a normally incident wave the complex refractive index $n + i\chi$ will be different for waves polarized along ($\varepsilon_\parallel$) and perpendicular ($\varepsilon_\perp$) to the magnetic field,

$$(n + i\chi)_\parallel^2 = \varepsilon_\parallel; \qquad (n + i\chi)_\perp = \varepsilon_\perp - \frac{\varepsilon_\Lambda^2}{\varepsilon_\perp}. \tag{14}$$

We substitute the tensor components ε from (13) into (14), calculate n and χ, and then substitute into (8) and (10) in order to calculate the reflection and transmission coefficients. The differences in the reflection and transmission coefficients for $E_\parallel$ and $E_\perp$ waves result in polarization changes for the reflected and transmitted waves. Characterizing the polarization by the angle $\tan \mu = E_\parallel / E_\perp$ between the slopes of the electric and the magnetic wave vectors, we obtain for the reflected wave

$$\operatorname{tg} \mu = \operatorname{tg} \mu_0 \left|\frac{R_\perp}{R_\parallel}\right|. \tag{15}$$

In a similar way, for the transmitted wave

$$\operatorname{tg} \mu = \operatorname{tg} \mu_0 \sqrt{\frac{1-|R_\perp|^2}{1-|R_\parallel|^2}} \cdot e^{-\omega d/c(\chi_\perp - \chi_\parallel)}. \tag{16}$$

It must be emphasized that the magnetic field causes a sharp change in the reflecting properties of the semiconducting film, without heating the electrons. Thus, for an InSb layer with parameters $N_e = 10^{15}\ \mathrm{cm}^{-3}$, $\varepsilon_\perp = 15.8$ for waves with $\lambda = 1$ mm, $S_0 = 0.1$, $\chi_0 = 0.3$ and constant temperature at $f = 1$, we obtain $R_\perp / R_\parallel = 2.1$. In this case the angle μ for reflection increases, while the vector $\vec{E}$ is swung "away" from the magnetic field. In the transmitted wave the vector $\vec{E}$ may be turned "towards" the magnetic field, since the component $E_\perp$ is more strongly absorbed than $E_\parallel$. In the example considered, $\chi_{\parallel} = 0.2$ and $\chi_{\perp} = 13.9$, and at the unperturbed temperature $f = 1$, the angle μ is given by

$$\operatorname{tg} \mu = \frac{\operatorname{tg} \mu_0}{2} \cdot l^{-\omega d/c(\chi_{\perp} - \chi_{\parallel})},$$

in which the exponent equals 0.6 when the film thickness is $d = 5\ \mu$, so that $\tan \mu = 0.3 \tan \mu_0$. Thus the application of a magnetic field leads to different polarizations for the reflected and refracted waves.

The combined modulation effects of the electron temperature and the magnetic field broadens the scope for controlling the rearrangement of VHF radiowaves interacting with semiconductor plasmas.

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