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REAL-TIME SYSTEMS

ADAPTIVE SYSTEMS IN THE SHORT WAVE RANGE

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Abstract—A theoretical study is presented of the modulation of high-frequency radio waves in amplitude and phase by causing them to be reflected from an n-type semiconductor slab while periodically varying the temperature of the carriers. An opportunity to control with heat the angle of total polarization of the reflected waves is reported. It is demonstrated that the amplitude, phase and polarization of the reflected signals can be varied fast enough for the evolution of these processes to be controlled in rapidly adaptive optical devices in the high frequency range.

By means of an example of an n-type semiconductor, specifically InSb and Ge, the paper demonstrates that when the frequency ω of the incident wave, the Langmuir frequency Ω_e of the carriers, and the collision frequency ε are all values of the same order, a significant disturbance of ε takes place. Its real and imaginary parts ($R = \operatorname{Re} \varepsilon$ and $I = \operatorname{Im} \varepsilon$) have values of the same order and disturb, respectively, the amplitude $|R|$ and the phase ϕ of the reflected waves. Thus, the paper demonstrates that by heating the carriers one can control the amplitude and the phase of the reflected beam.

It will be convenient to represent the effect of the electron temperature of the carriers on the amplitude $|R|$ and the phase φ of the complex reflectance coefficient $R \cdot \exp(-i\varphi)$ by separating the real and imaginary parts in the familiar Fresnel formulae [1]. This transformation for S and P-polarized waves incident at an angle α results in

$$|R_S|^2 = \frac{\cos^2 \alpha + a^2 - 2a \cdot \cos \alpha \cdot \cos \theta}{\cos^2 \alpha + a^2 + 2a \cdot \cos \alpha \cdot \cos \theta} \tag{1}$$

$$\begin{aligned} |R_P|^2 = {} & [\cos^2 \alpha (a^4 + \sin^4 \alpha) + 2a^2 \sin^2 \alpha \cos^2 \alpha \cos 2\theta + a^2 - 2a \cos \alpha \cdot \cos \theta (a^2 + \sin^2 \alpha)] \\ & \cdot [\cos^2 \alpha (a^4 + \sin^4 \alpha) + 2a^2 \sin^2 \alpha \cos^2 \alpha \cos 2\theta + a^2 + 2a \cos \alpha \cdot \cos \theta (a^2 + \sin^2 \alpha)]^{-1}, \end{aligned} \tag{2}$$

$$\cos \varphi_S = \frac{\cos^2 \alpha - a^2}{\sqrt{(\cos^2 \alpha - a^2)^2 + 4a^2 \cos^2 \alpha \cdot \cos^2 \theta}}, \tag{3}$$

$$\begin{aligned} \cos \varphi_P = {} & [\cos^2 \alpha (a^4 + \sin^4 \alpha) + 2a^2 \sin^2 \alpha \cos^2 \alpha \cos 2\theta - a^2] \\ & \cdot \{\cos^2 \alpha (a^4 + \sin^4 \alpha) + [2a^2 \sin^2 \alpha \cdot \cos^2 \alpha \cdot \cos 2\theta - a^2]^2 \\ & + 4a^2 \cos^2 \alpha \sin^2 \theta (a^2 \cdot \sin^2 \alpha)^2\}^{-1/2}, \end{aligned} \tag{4}$$

where

$$a^2 = \sqrt{\left[\varepsilon_L\left(1 - \frac{V}{1 + S^2}\right) - \sin^2\alpha\right]^2 + \left[\frac{\varepsilon_L V \cdot S}{1 + S^2}\right]^2} \tag{5}$$

$$\cos 2\theta = \left[\varepsilon_L\left(1 - \frac{V}{1 + S^2}\right) - \sin^2 \alpha\right] a^2, \tag{6}$$

$$V = \frac{4\pi e^2 n_e}{m_e \omega^2},$$

$$S = S_0 / f^{3/2} (q + pf), \qquad S_0 = v_0 / \omega, \qquad S = v_e / \omega, \tag{7}$$

$$v_0 = v_{i0} + v_{P0}, \qquad q = v_{i0} / v_0, \qquad p = v_{P0} / v_0. \tag{8}$$

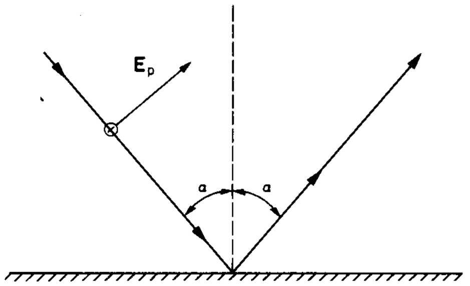

Fig. 1. Geometry of reflection of S- and P-polarizations from a semiconductor slab.

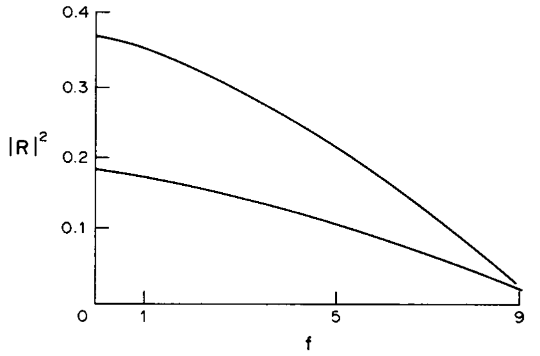

Fig. 2. Variation of the reflectance coefficient (taken as intensity $|R|^2$ of the reflected wave) with carrier temperature f for illumination at $\lambda = 200\ \mu$m incident at $\alpha = 45°$ on the surface of n-InSb at $T_{e0} = 78$ K. The plots refer to S- and P-polarizations.

Fig. 3. Coefficient of reflectance (in terms of intensity) versus the angle of incidence of a 200-μm beam on the surface of an n-InSb slab at $T_{e0} = 78$ K. Curves 1 and 2 refer to the carrier temperatures $f = 1$ and $f = 9$ respectively.

The temperature dependence is represented here by dimensionless collision frequencies

$$\begin{aligned} S_{\mathrm{Ge}} &= S_0\sqrt{f} \\ S_{\mathrm{InSb}} &= S_0/f\sqrt{f} \end{aligned} \tag{9}$$

being the functions of the carrier-heating temperature $f = T_e/T_{e0}$.

Using Eqs (1)–(8) we computed point by point the intensities and phases of S- and P-polarized reflected waves as functions of carrier heating temperature f and angle of incidence α on the surface of Ge and InSb semiconductors. The associated geometry is presented in Fig. 1. The plots in Figs 2–4 vividly demonstrate the possibility of controlled variation of the intensity and phase of the reflected signals.

Figure 3 shows that in the interval 0–30° of the angle of incidence the temperature variations of $|R|^2$ are opposite for S- and P-polarizations, namely, when electrons are heated the intensity of

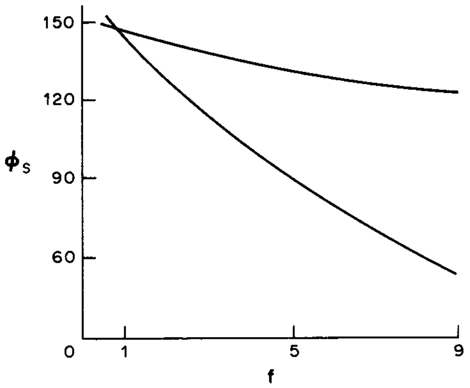

Fig. 4. Dependence of phase of the reflected S-polarization on carrier temperature f for irradiance at $\lambda = 200\ \mu m$ incident on a semiconductor slab at $T_{e0} = 78$ K. The curves relate to angles of incidence $\alpha = 0°$ and $\alpha = 30°$.

the reflected signal falls for S-polarization and rises for P-polarization. A further growth of the angle of incidence ($\alpha = 45°$) is accompanied by a decrease of the reflectance coefficients for both polarizations to small values (see Fig. 2).

The temperature variation of the phase shift for different angles of incidence is presented in Fig. 4. Notice the considerable temperature phase shift

$$\Delta\varphi = \varphi_{S,f=9} - \varphi_{S,f=1} = \pi/2$$

when the carriers are subjected to 9-fold heating.

The relaxation of electronic temperature in the examples considered is worth noting [2, 3]. In our case of thermal heating of the carriers, the collision frequency ν is about 10^{11}–10^{13} s^{-1}; therefore the average fraction of energy δ imparted to an electron in one collision is in the order of 10^{-3} for InSb and 10^{-2} for Ge. Accordingly, the characteristic settling time of these processes, or the electron temperature relaxation time, amounts to $\tau_T = (\delta\nu)^{-1} = 10^{-9}$–$10^{-11}$ s. These settling times may be of interest when the devices of plasma electronics are being considered.

Thus we have demonstrated the theoretical possibilities of controlling the amplitude, phase and polarization of the shortwave beam reflected from an n-type semiconductor slab by heating the free carriers in the slab.

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