OPTICAL CONTROL OF THE TERAHERTZ TRANSMISSION OF GaAs-PRISM

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1. Introduction

The terahertz frequencies region from 100 GHz to 10 THz (or wavelengths of 30 μm – 3 mm), located midway between microwaves and infrared, presents a new frontier containing an abundance of technical applications and fundamental research problems [1-3]. Consequently, THz research solutions and techniques can come from either optics or microwaves or in many cases unique combinations of both. Associated with THz investigations is the need for enabling THz technology and techniques. One outstanding problem is developing of the opto-THz switches and modulators.

For optical control of the medium THz characteristics, the high-resistivity GaAs seems very promising. On the one hand, it has a relatively low (< 0.7 cm^{-1}) absorption below 1.5 THz and its refractive index is practically independent of THz frequency. On the other hand, photoexcited GaAs exhibits a strong interaction with THz radiation through free carriers. Fine tuning of the strength of the interaction by the intensity of optical excitation then leads to interesting phenomena which are directly utilizable for THz-wave modulation and switching. The opportunity to change THz power reflectivity by illumination of a GaAs surface with optical fluence ~10 $\mu J/cm^2$ was recently demonstrated [4]. The major drawbacks are request of high laser fluence; use only the normal incidence on the semiconductor surface, and relatively small range 0.3 – 0.03 of the variation of THz reflectivity. Besides, the decrease in the surface reflectivity does not lead to the increase in the transmission due to appreciable absorption of THz wave in the illuminated layer.

Here for optical control of THz reflection and transmission we suggest to use the GaAs-prism (Fig. 1) operating in the regime of total internal reflection without illumination. It is theoretically shown that photoexcitation of the prism’s basement results in change of its transmission from 1 to practically zero. The required optical fluence is nearly 2 μJ/cm2 that is close to possibilities of modern femtosecond Ti:sapphire oscillators. The obtained results give an opportunity to develop fast THz switches and modulators controlled by optical radiation.

2. Theoretical results and discussion

For a theoretical model, let us consider a structure consisting of three media with plane-parallel interfaces: (1) a lossless undoped semiconductor in the ground state with the refractive index n1, (2) a thin conductive layer with thickness d representing the photoexcited part of the semiconductor, (3) a lossless material with the refractive index n3. The reflection of the THz radiation from this structure is described by the field reflection coefficient r defined as [5]

$$r = \frac{r_{12} + r_{23} t_2}{1 + r_{12} r_{23} t_2}\ , \qquad (1)$$

where r_{ab} are the Fresnel reflection coefficients for an interface consisting of materials a and b, $t_2 = \exp[i(4\pi d/\lambda)\dot{n}_2 \cos\theta_2]$ is the transmission coefficient through the conductive layer, $\dot{n}_2 = \sqrt{\dot{\varepsilon}} = n + ik$ is the complex refractive index of the conductive layer, $\dot{\varepsilon}$ is the complex dielectric constant, λ is the wavelength of THz radiation in vacuum, θ_2 is the angle satisfying Snell's law of refraction: $n_1 \sin\theta_1 = (n+ik)\sin\theta_2 = n_3 \sin\theta_3$.

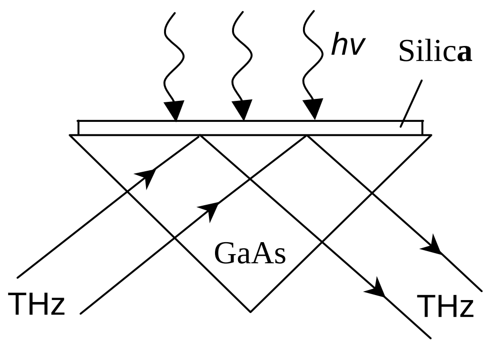

Fig. 1. The schematic view of right-angle GaAs prism illuminated by laser.

The reflection at the interface is suppressed if the nominator of Eq. (1) is equal to zero. Hereinafter the thickness of the conductive layer d is assumed to be equal to the penetration depth of the optical pump beam in GaAs (d = 0.75 μm for the wavelength 0.8 μm [2]) which satisfies the condition d << λ/n. Besides for definiteness we consider that the electrical vector of THz wave is oriented perpendicularly to the incident plane. Under these assumptions, one can obtain that the numerator of Eq. (1) vanishes if

$$\left(\sqrt{\dot{\varepsilon} - n_1^2 \sin^2\theta_1} + n_1 \cos\theta_1\right)\left(\sqrt{\dot{\varepsilon} - n_1^2 \sin^2\theta_1} - \sqrt{n_3^2 - n_1^2 \sin^2\theta_1}\right) = \frac{i\lambda}{2\pi d}\left(n_1 \cos\theta_1 - \sqrt{n_3^2 - n_1^2 \sin^2\theta_1}\right). \qquad (2)$$

Thus, a photoexcited part of GaAs can operate as an antireflective layer for THz waves if $\dot{\varepsilon}$ is close to required by Eq. (2). In special case of the normal incidence of THz-wave ($\theta_1 = 0$), the above formula coincides with the approximate formula presented in [4], where additional assumptions $\dot{\varepsilon} >> n_1^2, n_3^2$, and $n_1 = 1$ have been used as well. By substituting in above $n_1 = 3.6$, $n_2 = 2$ (close to the refractive index of silica), d = 0.75 μm, λ = 300 μm we obtain that the roots of Eq. (2) are $\dot{\varepsilon} = 1.03 - i28.75$ for $\theta_1 = 0$ and $\dot{\varepsilon} = -89.88 - i121$ for $\theta_1 = 45°$. In the first case the corresponding real and imaginary parts of the complex refractive index are approximately the same n = 3.86 and k = 3.72, whereas in the second case the imaginary part k = 11.0 is significantly greater than real n = 5.5. The reason of such behavior is the total internal reflection of THz wave from GaAs – silica interface in the second case without photoexcitation.

The frequency-dependent complex dielectric constant $\dot{\varepsilon}$ in GaAs is well described by the Drude model [6]:

$$\dot{\varepsilon} = \varepsilon_1 - \frac{\omega_p^2}{\omega(\omega - i\gamma_e)}, \qquad (3)$$

where ε_1 = 12.96 is the dielectric constant of high-resistivity GaAs, $\omega p^2 = (Ne^2/\varepsilon_0 m_e)$ is the plasma angular frequency depending on the number of photogenerated electrons N, e is the electron charge, ε_0 is the permittivity of vacuum, me is the electron effective mass, γ_e is the dumping coefficient, and contribution of heavy holes in (3) is neglected for simplicity.

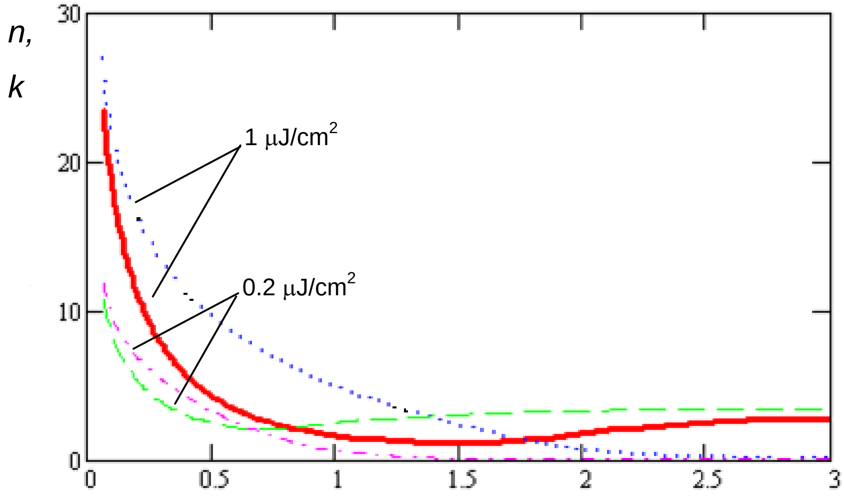

Fig. 2. The dependences of real part n (upper curves at 0.5THz) and imaginary part k (lower curves at 0.5THz) of the complex refractive index on the frequency for different laser fluences and 0.2 $\mu J/cm^2$.

Based on the above formula the dependence of the complex refractive index on the frequency for different optical pump fluence (J_0) may be determined. To roughly estimate the dumping coefficient γe we used the relation $\gamma_e = e/m_e\mu_e$. By substituting m_e=0.067m_0 and drift mobility μ_e=8600 $cm^2/V\cdot s$ [2], the dumping coefficient is estimated $\gamma_e = 2\pi\times$(3THz) that is close to $2\pi\times$(2.86THz) reported in Ref. [6]. Besides we assume a homogeneous distribution of the photocarriers with negligible diffusion on a time scale of picosecond. This allows to determine the concentration of the photogenerated electrons as $N=J_0T/hf_0d$, where $hf_0=2.48\times10^{-10}$ nJ is the energy of the optical photon at 0.8-μm-wavelength, T=0.67 is the transmission coefficient of GaAs surface, J_0 is the optical pump fluence. The dependences of both the real (n) and imaginary (k) parts of the refractive index on the frequency $f=\omega/2\pi$ for optical pump fluences 1 μJ/cm^2 and 0.2 μJ/cm^2 are presented in Fig. 2.

It is seen that the frequency of the crossing of n and k curves lies in the THz region if the optical pump fluence is of the order a few μJ/cm^2. As it follows from Eq. (2), the reflectivity of GaAs surface may be significantly suppressed nearby the crossing of n and k for the normal incidence of THz wave ($\theta_1 = 0$). For 45° angle of THz-incidence ($\theta_1 = 45°$) it is required that k is significantly greater than n. The last may be satisfied in sub-THz region as it is seen from Fig. 2. Obviously in case of right-angle GaAs-prism (see Fig. 1) the violation of condition of the total internal reflection will result in the decrease in the prism transmission. To determine dependence of the reflectivity of GaAs prism on optical pump fluence, we substituted in Eq. (1) the Fresnel coefficients r_{12}, r_{23}, and t_2 for 45° angle of THz-incidence with n and k determined by Eq. (3). The results of calculation are illustrated in Fig. 3, where the dependences of the reflectivity |r| at different frequencies (0.3 and 0.8 THz) on the optical pump fluence are presented.

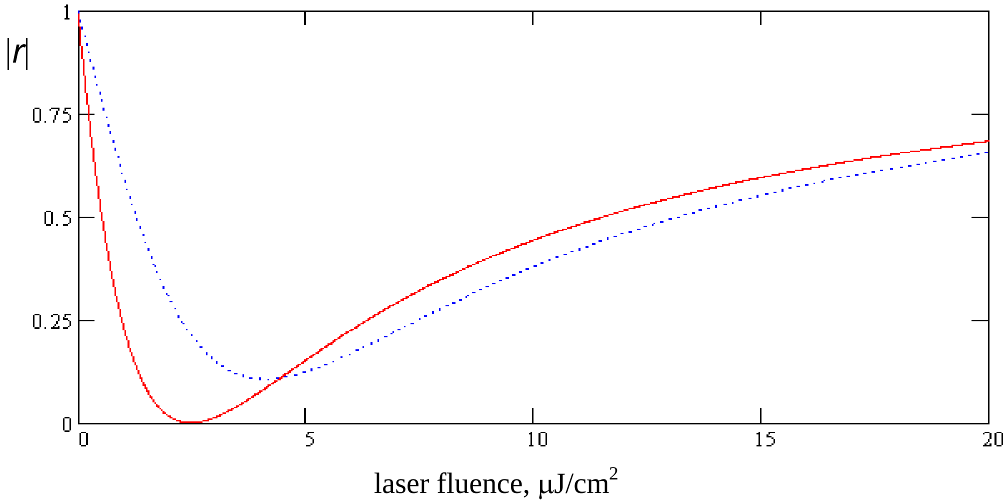

Fig. 3. Dependence of the THz reflectivity of GaAs – silica interface in case of 45° incidence angle.

It is seen that illumination of the GaAs – silica interface with the fluence 2.5 μJ/cm^2 results in total suppression of the reflectivity of 0.3-THz-wave that corresponds to change in the transmission of GaAs prism from 1 to zero. With increasing THz frequency (e.g., 0.8 THz) the both required laser fluence and reflectivity in minimum are increased. The minimum of reflectivity (10%) is realized if the laser fluence is about 4 μJ/cm^2.

3. Conclusion

Thus, illumination of the GaAs – silica interface leads to change of subTHz-wave transmission of the right-angle GaAs prism from 1 to practically zero. The last allows developing the fast THz switches and modulators controlled by optical radiation.

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