PROCEEDINGS OF THE YEREVAN STATE UNIVERSITY

Physical and Mathematical Sciences 2011, № 1, p. 55–59

Physics

COHERENT TERAHERTZ EMISSION FROM PHOTOCONDUCTIVE ANTENNA

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The presence of a resonant medium in the capacitor core essentially changes the character of THz radiation of photoconductive antenna. As a result the coherent radiation at the frequency of elementary excitation (LO phonon or plasmon) is obtained. Though the power of radiation slightly differs from that provided by a usual THz source, the energy of pulse is significantly greater due to longer duration of the pulse. Besides, such a method of THz pulse generation is very useful for THz emission spectroscopy of many materials.

***Keywords*:** THz, antenna, radiowave sources.

1. Introduction. The conventional of THz spectrum investigation for micrometer scale structures meet with problems, as for localization of THz wave in the micrometer range the diffraction limit must be overcome. Recently for solution of this problem in the optical range [1–6], the phenomenon of superfocusing of surface plasmon polaritions [7–9] was proposed. However, the use of such an approach in the THz range is complicated due to problems connected with an effective excitation of the surface Plasmon polaritons and high losses in the process of their propagation.

In the present paper we propose another method of THz spectrum investigation for micrometer particles based on the process of coherent generation of an elementary excitation of LO phonon or plasmon in the crystal. This process of the formation of coherent LO phonons can be realized by fast switching off of an external electrostatic field. In case of LO phonons in the presence of external electrostatic field the lattice ions are displaced from their equilibrium positions. At an abrupt elimination of the field, the ions return to their equilibrium positions making damped oscillations. The frequency of these oscillations corresponds to that of L0 phonons. It is noteworthy that the phenomenon of coherent radiation of THz waves of an elementary excitation frequency has been experimentally observed in a number of semiconductors [10–12].

The photoconductive antennas excited by amplified femtosecond optical pulses have been studied and used for generation of intense terahertz (THz) pulses [13–18]. They can emit half-cycle or monocycle intense THz pulses with a broad

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bandwidth and have been used in real-time imaging and other applications. The THz radiation is generated in the semiconducting structure in consequence of the acceleration of an electron-hole pair produced under the light. The fact is that an ultrafast visible/near-infrared pulse of photon energy greater, than the semiconductor band gap, creates electron-hole pairs close to the surface of the generation crystal. These are accelerated by an applied electric field with the result that a dipole momentum is produced that emits a THz pulse. The radiation proper is provided by two electrodes formed on the surface of semiconductors that emit as an antenna. A strong electric field is applied between the electrodes to accelerate the photocarriers generated by the incident laser pulse focused between the electrodes. In the present paper it will be shown that by simple modernization of this THz source it is possible to obtain the coherent THz emission.

2. Structure of the Source. The structure of the proposed source is shown in Fig. 1. It differs from the conventional structures by the presence of a capacitor in the circuitry. Assume now that a crystal is placed between the capacitor plates and an elementary excitation (phonon or plasmon) is formed in it. In such a media the real part of dielectric permittivity at definite frequencies takes on also negative values.

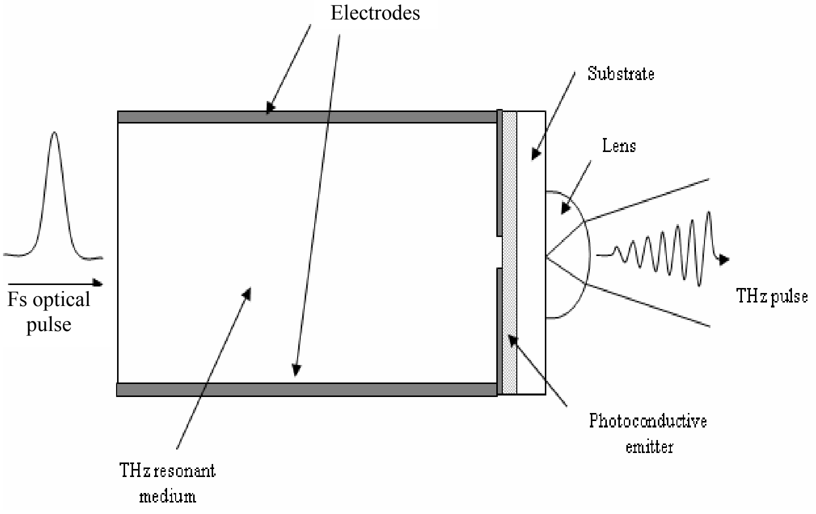

Fig. 1. The structure of the source of THz coherent radiation.

As it follows from the telegraph equation, the wavelength of THz radiation essentially increases in the vicinity of $\mathrm{Re}\,\varepsilon(\omega) \approx 0$. It allows to notably increase he size of the electronic circuit.

The dependence of dielectric permittivity on frequency ω is given by expression

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\omega_0^2(\varepsilon_0 - \varepsilon_\infty)}{\omega_0^2 - \omega^2 + 2i\gamma\omega}. \qquad (1)$$

For many crystals the resonant frequency ω_0 is in THz area. In particular, in ZnTe crystal $\varepsilon_\infty = 6.8$, $\varepsilon_0 = 9.8$, $\omega_0 / 2\pi = 5.45$ THz, $\gamma / 2\pi = 0.028$ THz [19]. Besides that the lifetime of carriers in the semiconductor should be much in excess of picoseconds that is readily approached in ordinary photoconductors.

3. Theory. The electronic circuit of emission system is shown in Fig.2. Here R_0 is much less, than the resistance of the photoconductor prior to the photoexcitation of the electron-hole pairs R_1 and much more, than the resistance of the photoconductor after the photoexcitation of electron-hole pairs R_2 ($R_2 << R_0 << R_1$). Thus, on exposure to an ultrashort laser pulse the R_2C system operates independently of the applied voltage.

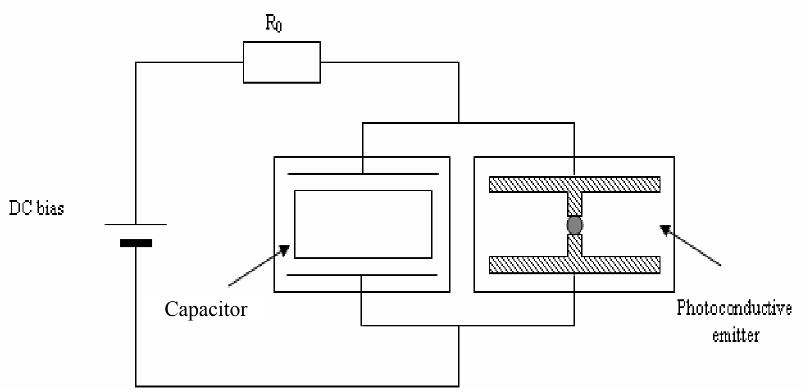

Fig. 2. The electronic circuit of THz emission system.

Under conditions of strong dispersion in the resonant medium the relation between the electric induction D and intensity of electric field $\hat{\varepsilon}$ is given by the integral operator [20]:

$$E(t)=\hat{\varepsilon}^{-1}D(t)=\int_{-\infty}^{0}F(t-\tau')D(\tau')d\tau', \tag{2}$$

where

$$F(t)=\int_{-\infty}^{\infty}\frac{1}{\varepsilon(\omega)}e^{-i\omega t}\frac{d\omega}{2\pi} \tag{3}$$

and $\varepsilon(\omega)$ is the dielectric permittivity of medium. For the structure under investigation we can use

$$D=4\pi\frac{q}{S}, \qquad U=E\Delta, \qquad c_0=\frac{S}{4\pi\Delta}, \tag{4}$$

where q is the charge on the condenser plate, U is the applied voltage, c_0 is the capacity, S is the surface of the plate, Δ is the distance between the plates. After transformation of variables $\tau'=t-\tau$, we find

$$U(t)=\frac{1}{c_0}\int_{0}^{\infty}F(\tau)q(t-\tau)d\tau. \tag{5}$$

As a result we obtain the following equation for the charge

$$R_2\frac{dq(t)}{dt}+\frac{1}{c_0}\int_{0}^{\infty}F(\tau)q(t-\tau)d\tau=0. \tag{6}$$

The first term in (6) defines the voltage drop on the photoconductor and the second term – the voltage drop on the capacitor. After the Fourier transformation we obtain

$$\int_{-\infty}^{\infty}\left[i\omega R_2+\frac{1}{c_0\varepsilon(\omega)}\right]q(\omega)e^{i\omega t}d\omega=0\,. \qquad (7)$$

For $t>0$ we obtain the following equation for (6):

$$q(t)=\int_{-\infty}^{\infty}\frac{Ac_o\varepsilon(\omega)}{1+i\omega R(\omega)c_0\varepsilon(\omega)}e^{i\omega t}\frac{d\omega}{2\pi}\,. \qquad (8)$$

The integral (8) is calculated using the mathematical apparatus of the complex variable theory. In the upper half-plane the poles of subintegral function are determined from the equation

$$1+i\omega R(\omega)c_0\varepsilon(\omega)=0\,. \qquad (9)$$

The first solution of (9) is in the range of low frequencies:

$$\omega_1=\omega_1'+i\omega_1'',\quad \omega_1'=0,\quad \omega_1''=\frac{1}{R_2c_0\varepsilon_0},\quad \gamma,\omega_1''<<\omega_0\,. \qquad (10)$$

The second solution of (9) is in the range of LO phonon frequency:

$$\omega_2=\omega_2'+i\omega_2'',\ \omega_2'=\sqrt{\frac{\varepsilon_0}{\varepsilon_\infty}}\omega_0,\ \omega_2''=\frac{1}{2}\left(\gamma+\frac{\varepsilon_0-\varepsilon_\infty}{\varepsilon_0\varepsilon_\infty c_0R_2}\right),\ \omega_2''<<\omega_0\,. \qquad (11)$$

Note that $\mathrm{Re}\,\varepsilon(\omega_2)\approx 0$ when $\gamma>>(\varepsilon_0-\varepsilon_\infty)/\varepsilon_0\varepsilon_\infty c_0R_2$, and, therefore, we shell have for the charge

$$q(t)=q_0\left\{\exp\left[-\frac{t}{R_2c_0\varepsilon_0}\right]+i\frac{(\varepsilon_0-\varepsilon_\infty)}{2\sqrt{\varepsilon_0\varepsilon_\infty}R_2c_0\omega_0\varepsilon_0}\exp\left[i\sqrt{\frac{\varepsilon_0}{\varepsilon}}\omega_0t-\frac{1}{2}\gamma t\right]\right\}. \qquad (12)$$

Here $q_0=\varepsilon_0c_0U_0$, U_0 is the applied voltage. The high-frequency component of the current is given by expression

$$I_\omega(t)=\mathrm{Re}\frac{dq(t)}{dt}=\frac{U_0}{R_2}\cdot\frac{(\varepsilon_0-\varepsilon_\infty)}{2\varepsilon_\infty}e^{-\frac{1}{2}\gamma t}\cos\sqrt{\frac{\varepsilon_0}{\varepsilon_\infty}}\omega_0t\,. \qquad (13)$$

As a result the characteristic expression for the damped oscillations is obtained.

4. Conclusions. Thus, the presence of a capacitor with the resonant medium in the core essentially changes the character of THz radiation. The radiation field of the photoconductive antenna is determined by the quantity $dI_\omega(t)/dt$, and as a result the coherent radiation is obtained. As it follows from (13), the power of this radiation slightly differs from usual THz sources. The energy of pulse of the proposed source is much more, than that of a usual source, because of the greater duration of radiation. By proper choice of the material in the capacitor it is possible to obtain coherent radiation at different frequencies. As such some doped semiconductors may serve, in which the plasmons are formed in the THz range. Thus, the process under discussion may be used as a new method of spectroscopic research.

Received 03.11.2010

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