

Coherent Terahertz Emission From Photoconductive Antenna

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Abstract: The presence of a capacitor with the resonant medium in a core essentially changes a character of THz radiation of photoconductive antenna. We obtain a coherent radiation at the frequency of elementary excitation (LO phonon or plasmon). The power of this radiation a little differs from a usual THz source. The energy of pulse to the suggested source is much more than the energy of a usual source because of the greater duration of radiation. It is possible to use this process as a new method in spectroscopic investigations.

1. Introduction

Investigation of spectra of micrometer structures by the conventional methods in the THz range meets with problems, as for localization of the THz wave in the micrometer area the diffraction limit must be overcome. Though some reassuring results have been obtained in the way of solving this problem, however they are not sufficient for application in spectral investigations.

Recently, for solving this problem using the phenomenon of superfocusing of surface plasmon polaritons has been suggested [1], which has been theoretically and experimentally analyzed in the optical range [2-7]. However, in the THz range experimentally unsolved problems emerge connected with the excitation of surface plasmon polaritons and their losses in the process of propagation.

In the present paper we suggest some other method of THz spectrum investigation for micrometer particles based on the process of coherent generation of L0 phonons in the crystal. It is noteworthy that the phenomenon of coherent radiation of THz waves at L0 phonon frequency has been experimentally registered in a number of semiconductors [8-10]. In [11] this phenomenon has been explained by the coupling between plasmon and L0 phonon modes excited by the femtosecond laser pulses. Here it will be shown that the mentioned coherent radiation has quite a general nature and can be realized not only in semiconductors and without the presence of plasmons.

The process of coherent generation of L0 phonons can be realized by the sharp switch off of an external electrostatic field. At the presence of such field the ions making up the lattice are displaced from their equilibrium positions. At the sudden elimination of the field, the ions return to their equilibrium positions, making damped oscillations. The frequency of this oscillation corresponds to that of the L0 phonons.

The photoconductive antennas excited by amplified femtosecond optical pulses have been studied and used for generation of intense terahertz pulses [12-17]. They can emit half-cycle or monocycle intense THz pulses with a broad bandwidth, and have been used in real-time imaging and other applications. THz radiation is generated by the acceleration of photoexcited electron-hole pairs in semiconductor structures. Here 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 pairs can be accelerated by an appropriate electric field and the resulting changing dipole leads to generation of THz pulse. Typically suitable surface fields are realized by a lateral antenna comprising two electrodes can be deposited onto a semiconductor surface. A strong electric field is applied between the electrodes which accelerate the photocarriers generated by the incident laser pulse focused

between the electrodes. In this paper we show that it is possible to obtain coherent THz emission by a simple modernization of this THz source.

2. Source structure

The structure of the suggested source is shown in Fig.1. It differs from a usual structure by the presence of a capacitor in the circuit. Let between the electrodes of the capacitor a crystal be placed, where elementary excitation (phonon or plasmon) is finely formed. In such media the real part of the dielectric permittivity in a certain range of frequencies accepts also negative values. From the telegraph equation follows that in the region $\text{Re } \varepsilon(\omega) \approx 0$ the THz wavelength essentially increases. This allows one to increase the sizes of the electronic circuit considerably.(Fig.1)

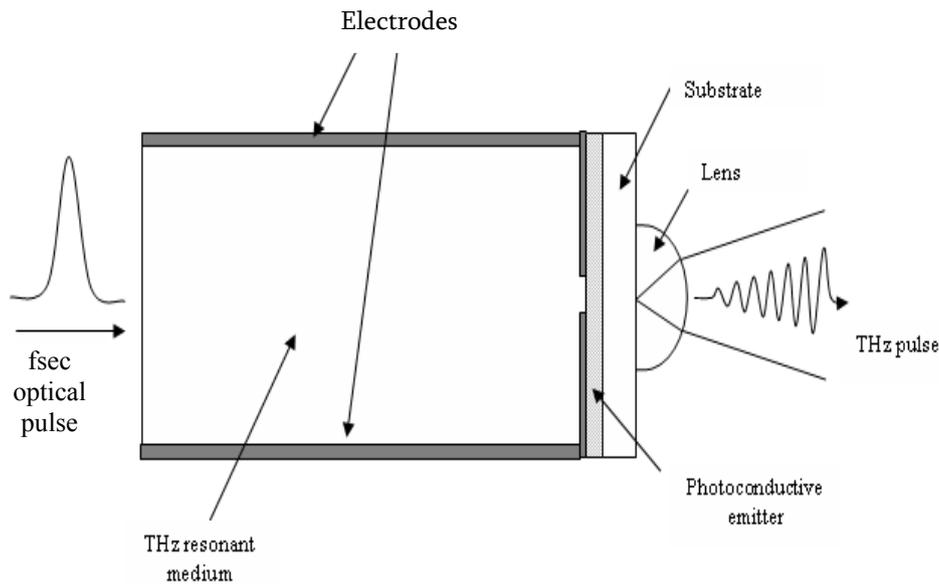


Fig.1. Structure of the source of THz coherent emission.

We present the dependence of the dielectric permittivity on the frequency ω in the following form:

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

In a number of crystals the resonant frequency ω_0 is in the THz region. In particular, in a ZnTe crystal

$$\varepsilon_\infty = 6.8, \varepsilon_0 = 9.8, \omega_0 / 2\pi = 5.45 \text{ THz}, \gamma / 2\pi = 0.028 \text{ THz} [18].$$

Besides, the carriers lifetime in the semiconductor should be much more picoseconds, that in ordinary photoconductors is easily fulfilled.

3. Theory

The electronic circuit of the emitting system is shown in Fig.2. Here R_0 is much less than the resistance of a photoconductor before photoexcitation electron-hole pairs R_1 and much more than the resistance of a photoconductor after photoexcitation electron-hole pairs R_2 ($R_2 \ll R_0 \ll R_1$). Thus, after influence of an ultrashort laser pulse, the R_2C system operates independent from the bias voltage.

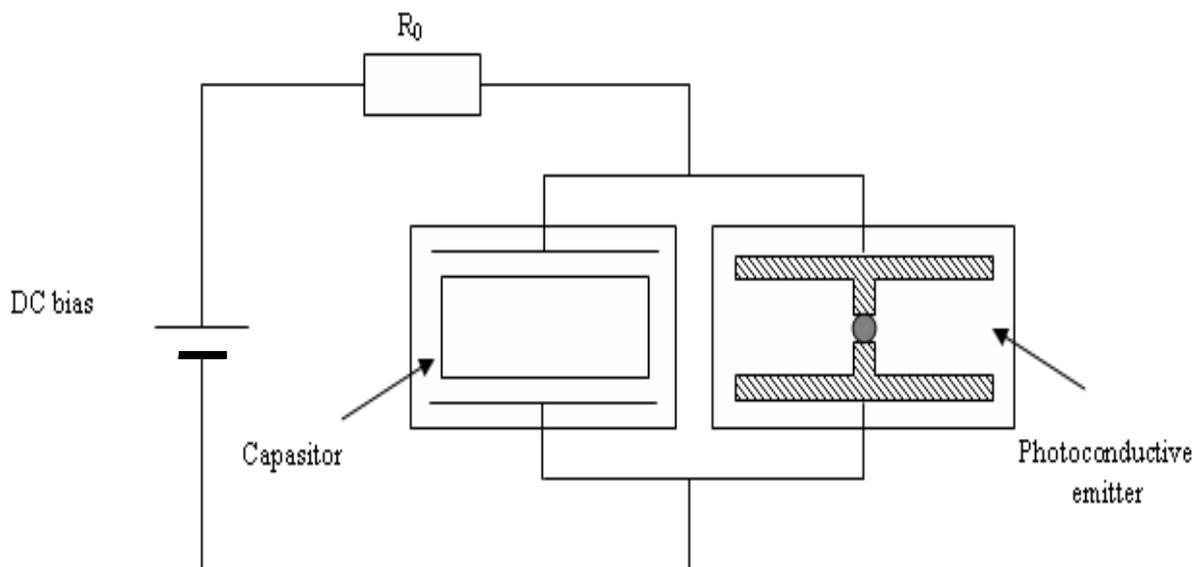


Fig.2. Electronic circuit of the THz emitting system.

In the conditions of strong dispersion in the resonant medium, the connection between the electric induction D and the electric field intensity E is defined by the integral operator [19]:

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

where

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

and $\varepsilon(\omega)$ is the dielectric permittivity of the medium. In the structure investigated here

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

where q is the charge on the plate of the condenser, U is the applied voltage, c_0 is the capacity, S is the area of the plate, Δ is the distance between the plates. By transformation of the variable $\tau' = t - \tau$, we obtain

$$U(t) = \frac{1}{c_0} \int_0^{\infty} F(\tau) q(t - \tau) d\tau. \quad (4)$$

As a result we get the following equation for the charge:

$$R_2 \frac{dq(t)}{dt} + \frac{1}{c_0} \int_0^{\infty} F(\tau) q(t - \tau) d\tau = 0 \quad (5)$$

The first term in Eq.(5) defines a voltage drop on a photoconductor and the second term a voltage drop on the capacitor. After a standard Fourier transformation we obtain

$$\int_{-\infty}^{\infty} [i\omega R_2 + \frac{1}{c_0 \varepsilon(\omega)}] q(\omega) e^{i\omega t} d\omega = 0. \quad (6)$$

At $t > 0$ we obtain for (6) the following solution:

$$q(t) = \int_{-\infty}^{\infty} \frac{A c_0 \varepsilon(\omega)}{1 + i\omega R(\omega) c_0 \varepsilon(\omega)} e^{i\omega t} \frac{d\omega}{2\pi}. \quad (7)$$

The integral (7) is calculated using the mathematical apparatus of the theory of complex variable functions. In the upper half-plane the poles of the integrand are determined from the equation

$$1 + i\omega R(\omega)c_0\varepsilon(\omega) = 0. \quad (8)$$

The first solution of Eq.(8) is in the region of low frequencies:

$$\omega_1 = \omega_1' + i\omega_1'', \quad \omega_1' = 0, \quad \omega_1'' = \frac{1}{R_2c_0\varepsilon_0}, \quad \gamma, \omega_1'' \ll \omega_0. \quad (9)$$

The second solution of Eq.(8) is determined by the frequency of LO phonon:

$$\omega_2 = \omega_2' + i\omega_2'', \quad \omega_2' = \sqrt{\frac{\varepsilon_0}{\varepsilon_\infty}}\omega_0, \quad \omega_2'' = \frac{1}{2}\left(\gamma + \frac{\varepsilon_0 - \varepsilon_\infty}{\varepsilon_0\varepsilon_\infty c_0 R_2}\right), \quad \omega_2'' \ll \omega_0. \quad (10)$$

Let's notice that $\text{Re}\varepsilon(\omega_2) \approx 0$. When $\gamma \gg (\varepsilon_0 - \varepsilon_\infty)/\varepsilon_0\varepsilon_\infty c_0 R_2$, for a charge we obtain

$$q(t) = q_0 \left\{ \exp\left[-\frac{t}{R_2C_0\varepsilon_0}\right] + i \frac{(\varepsilon_0 - \varepsilon_\infty)}{2\sqrt{\varepsilon_0\varepsilon_\infty}R_2C_0\omega_0\varepsilon_0} \exp\left[i\sqrt{\frac{\varepsilon_0}{\varepsilon_\infty}}\omega_0 t - \frac{1}{2}\gamma t\right] \right\}, \quad (11)$$

Here $q_0 = \varepsilon_0 c_0 U_0$ and U_0 is the bias voltage. The high-frequency component of the current is defined by the expression

$$I_\omega(t) = \text{Re} \frac{dq(t)}{dt} = \frac{U_0}{R_2} \frac{(\varepsilon_0 - \varepsilon_\infty)}{2\varepsilon_\infty} e^{-\frac{1}{2}\gamma t} \cos \sqrt{\frac{\varepsilon_0}{\varepsilon_\infty}}\omega_0 t. \quad (12)$$

Thus, we obtain the characteristic expression for damped oscillations.

4. Conclusion

Thus, the presence of a capacitor with the resonant medium in a core essentially changes the character of THz radiation. The radiation field of the photoconductive antenna is defined by the value $dI_\omega(t)/dt$ and as a result we obtain the coherent radiation. From expression (9) follows that the power of this radiation a little differs from a usual THz source. The energy of pulse to the suggested source is much more than the energy of a usual source

because of the greater duration of radiation. By using various materials in the capacitor it is possible to obtain the coherent radiation at different frequencies. As such materials there can be also doped semiconductors in which plasmons are formed in the THz region. Thus, the discussed process can be used as a new method in spectroscopic investigations.

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