Amplification of THz Radiation in the System of Excitons and Biexcitons

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***Abstract* — The new mechanism of terahertz radiation generation (amplification) which is based on the use of quantum transitions between two-exciton and biexciton states is investigated. It is shown, that the enhancement coefficient of terahertz radiation depends on the pump intensity.**

Generation of terahertz radiation in the dimensional-confined structures has attracted a great deal of attention recently. Terahertz radiation was observed in the quantum transitions in the asymmetric coupled-quantum-well structures, in superlattices, in a single quantum well as a result of quantum beats between excitons with light and heavy holes. Recently Kavokin et al and Slavcheva and Kavokin proposed new mechanism of THz lasing based on the pumping of the excited exciton 2p state in semiconductor quantum wells and the stimulated optical transition between excited 2p and ground 1s exciton states. The cavity was pumped optically at half of the self-frequency of the 2p-exciton. Another group of investigators proposed the emission of THz radiation due to the transitions between upper and lower polariton branches in semiconductor microcavity.

We propose a new mechanism of generation (or amplification) of terahertz radiation in bulk or dimensional-confined semiconductor structures which is based on the quantum transitions between exciton and biexciton states. Let the incident pulse of resonant laser radiation on the semiconductor with the frequency ω_1 equal to the frequency of 1s-exciton state ω_0, excites the excitons from the ground state of the crystal. We suppose the exciton state as the macroscopically occupied. The two-exciton state 2ex with the frequency $2\omega_0$ is macroscopically occupied too. These two-exciton states were used for the explanation of the results of four-wave mixing experiments, for the prediction of the possibility of Bose-Einstein condensation using the collective process of two-exciton two-photon absorption of light. It seems that the same states can play an important role in the process of terahertz radiation generation. As the biexciton state with the self-frequency $\Omega_0=2\omega_0-\Omega_m$ is situated below to the two-exciton state with the self-frequency $2\omega_0$ on the value Ω_m, then the population inversion appears between two-exciton and biexciton states. That is why if we inject a weak pulse of THz radiation with the frequency ω_2 equal to Ω_m the such radiation will be amplified because of the induced downthrow of the inversion.

The conservation laws of the energy and momentum of the process of two-exciton – biexciton transition give

$$2E_{ex}(\mathbf{k}_1)=E_{biex}(\mathbf{q})+\hbar\omega_2, \quad (1)$$

$$2\mathbf{k}_1=\mathbf{q}+\mathbf{k}_2, \quad (2)$$

were $\mathbf{k}_1=\mathbf{k}_{phot.}$, $\mathbf{q}$ and $\mathbf{k}_2$ are the wave vectors of the exciton (photon that excites it), the biexciton and the THz quantum of radiation respectively. Then for the quantum of the THz radiation we obtain

$$\hbar\omega_2=I_m+\hbar^2\mathbf{k}_2(2\mathbf{k}_1+\mathbf{q})/4m_{ex}. \quad (3)$$

For $\mathbf{k}_2=0$ we obtain $\omega_2=\Omega_0=I_m/\hbar$, which means that the quantum of the THz radiation is equal to the binding energy of biexciton.

Let two plane electromagnetic waves with the amplitudes E1 and E2 and frequencies ω_1 and ω_2 propagate in the crystal. In this case the Hamiltonian of interaction of the electromagnetic waves with the excitons and biexcitons has the form

$$H=-\hbar g\left(a^+E_1^+ + aE_1^-\right)-\hbar\mu\left(a^+a^+bE_2^+ + b^+aaE_2^-\right), \quad (4)$$

were g is the constant of exciton-photon interaction and μ is the constant of the optical two-exciton – biexciton transition, a and b are the amplitudes of exciton and biexciton polarization of medium.

Using (4) we can obtain the Heisenberg equations for the amplitudes of excitons and biexcitons. Also we obtain the expressions for the density of excitons and susceptibilities of the medium in the ranges of frequencies ω_0 and $2\omega_0-\Omega_m$ correspondingly. We can see that absorptive components of susceptibilities $\chi_1''>0$ and $\chi_2''<0$. It evidences about the amplification of the THz radiation at the expense of the first pulse with the frequency ω_1. The THz susceptibility χ_2 depends on the exciton density and is proportional to n^2. We obtained the bistable behavior of the exciton density on the pump intensity I_1 and on the exciton detuning Δ_1, which appears in the case, when δ exceeds the critical value δ_c.

In the case of exact resonance we have obtained the expressions for the dielectric functions of the medium

$$\varepsilon_1=\varepsilon_{10}\left(1+i\frac{\omega_{LT}\gamma}{\gamma^2+2\mu^2n|E_2|^2}\right),$$

$$\varepsilon_2=\varepsilon_{20}-i\frac{4\pi\hbar\mu^2n^2}{\gamma}, \quad (5)$$

and the equation for the exciton density

$$n\left(\gamma^2+2\mu^2nI_2\right)^2=\gamma^2g^2I_1,$$

where I_1 and I_2 are the intensities of the both fields. Further in the slowly varying envelope approximation we obtain the approximative integral of motion, which links the intensities of both waves

$$J_2 = J_{20} \exp\left[\frac{c}{2}\left(J_{10}^2 - J_1^2\right)\right]$$

and the expression for the spatial distribution of the intensity of the enhanced wave.

We can see that the greater value of the parameter $\beta = cJ_{10}^2/2$, the greater the maximal possible value of the intensity $J_{2\max}/J_{20} = \exp(\beta)$. Taking the approximative solution $J_1 = J_{10}\exp(-\alpha_{10}x)$, where α_{10} is the absorption coefficient on the frequency of pump pulse, we obtain

$$J_2 = J_{20}\exp\left(\beta\left(1 - e^{-2\alpha_{10}x}\right)\right).$$

We can see that normalized intensity J_2/J_{20} at first rapidly increases with the increase of the coordinate *x*. At the very great distances the intensity of this wave saturates and takes the maximal value $J_{2\max}$, while the intensity of pumping wave decreases exponentially. Introducing the gain coefficient *g* of the this wave by formula $J_2(x) = J_{20}\exp(gx)$, we obtain $g(x) = (\beta/x)(1 - \exp(-2\alpha_{10}x))$. At *x*=0 the gain coefficient *g(x)* has the maximal value $g(0) = 2\beta\alpha_{10}$.

So we showed that the population inversion between two-exciton and biexciton states appears under the pumping of the exciton state, in the transition between which the generation of terahertz radiation is possible. The intensity of the terahertz radiation exponentially increases with the increase of the pump intensity.