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Terahertz emitter based on dipolaritons

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ABSTRACT

We study the system with dipolaritons — mixed quasiparticles which are formed in the double quantum well heterostructure in the presence of strong light-matter interaction. These quasiparticles possess large dipole moment due to the resonant coupling between direct and indirect excitons via electronic tunnelling. Using the pulsed pumping of the cavity mode one can induce oscillations of the indirect exciton density. This corresponds to a harmonic change of the dipole moment in time and results in the classical electromagnetic wave emission with frequency being in the terahertz (THz) range. In the current paper we present a simple theory which describes this phenomenon and estimate possible output power of radiation.

Keywords: THz emitter, dipolariton, exciton, superradiance

1. INTRODUCTION

Generation of signals in a different range of frequencies is a crucial aspect of diverse areas of physics. While the sources of radiation in radio frequency and optical range are well established, the terahertz region of frequencies remains less exploited.¹ However, being difficult to realize, emission sources of THz signals are highly required due to numerous possible application spanning from communication technology to medicine and spectroscopy. Therefore, the proposal and realization of THz sources with tunable frequency and high emission power is a hot research topic.

The currently existing THz emitters can be divided into several groups regarding the operation principles of a device.² First, it is possible to realize the conventional solid state oscillator, namely high frequency Gunn or tunnelling diodes.³ However, their operating frequency is limited and only reaches the lower boundary of terahertz frequency range remaining mostly the microwave frequency sources. Second, it is possible to emit signal of infrared to terahertz range with quantum cascade laser (QCL).^{4,5} Exploiting the multiple photon emission from intersubband transition of wide quantum wells,⁶ it covers the upper boundary of THz range with relatively high power of emission. The third group of THz sources represents so-called laser driven terahertz emitters, where femtosecond optical pulse illuminating the semiconductor structure leads to an oscillation of carrier density and consequent conversion of an optical signal to the THz range.⁷⁻⁹ Similar effect can be observed in crystals with a large second-order susceptibility where time-varying polarization induces THz emission.¹⁰ Finally, the wide group of THz emitters are free electron based sources like klystron or free electron laser. Despite being efficient from the point of power, their applicability suffers from large size of the devices. In the following paper we shall focus mainly on the second and third groups of THz emitters.

The theoretical proposals for THz sources in solid state and semiconductor physics present rich diversity. For instance, they can be realized using the carbon nanostructures, in particular carbon nanotubes (CNT's).^{11,12} Another area where possibility of THz generation was widely studied theoretically is polaritonics – the area where quantum optics and condensed matter physics meet.^{13,14} There the essential feature is strong interaction between

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exciton – bosonic quasiparticle consisting of coupled electron and a hole – and photon confined in semiconductor microcavity. Proposals include the polariton based THz emitters where signal is generated from transitions between upper and lower polariton branches, which become allowed after certain symmetry breaking.^{15–17} Next, terahertz transition between $2p$ and $1s$ exciton states, where lower one is coupled to cavity mode, has shown to emit THz photons.¹⁸ Recent theoretical studies also include proposal of a bosonic cascade laser which can be done using multiple THz photon emission from exciton (or exciton polariton) transitions in a parabolic confining potential.¹⁹

The mechanism for terahertz signal generation described in this paper relies on the notion of spatially direct and indirect excitons. Spatially indirect excitons are composite bosons consisting of electron and hole situated in separate layers (QWs).²⁰ They were widely studied last decades, where the main issue of research there was achievement of Bose-Einstein condensate (BEC) state.^{21–23} The key features of indirect excitons are large radiation lifetime due to small electron–hole wave function overlap and possibility to achieve thermal equilibrium (therefore, indirect excitons sometimes are referred as cold excitons). Moreover, they have large dipole moment in the growth direction, which results in the strong interactions between indirect excitons.^{24,25}

Recently, it was shown that physics of exciton polaritons and spatially indirect excitons can be strongly mixed in the specially grown semiconductor heterostructure.^{26–28} In the double quantum well with resonantly coupled electronic levels and cavity mode tuned to excitonic transition, one can achieve situation where quasiparticles being linear superposition of cavity photon (C), direct exciton (DX) and indirect exciton (IX) appear. Thus, three polaritonic modes emerge being upper polariton (UP), middle polariton (MP) and lower polariton (LP). They share properties of bare modes and are called *dipolaritons*.²⁸

Here we study the effect of tunnelling coupling between direct and indirect exciton which is inherited by dipolariton. This can be seen as Rabi flopping between two states when cavity mode pulsed pump excite DX mode, with corresponding harmonic oscillation of IX density. We describe the simple theoretical approach based on coupled oscillators model which allows to capture the main physics of the outlined process. Finally, noting that indirect excitons are elementary dipoles, this process leads to the classical emission of Hertz dipoles array with THz frequency which can be externally tuned. The mechanism therefore is similar to downshift optical-to-THz frequency conversion used in laser driven terahertz emitters. Moreover, using the specific structure, we show the way towards the high power generation.

2. THE MODEL

The geometry of the system represents two coupled quantum wells where electronic tunnelling is resonant (Fig. 1). This corresponds to an electron wave function being delocalized between two QWs. The optical microcavity is tuned to the lower band gap quantum well (left QW in Fig. 1), while right QW remains decoupled from an optical pump. Pulsed pumping creates electron-hole pairs which form the direct excitons. However, an applied voltage in the growth direction leads to a mixing of direct and indirect exciton states, leading to the formation of mixed dipolariton mode.²⁸ The cavity photon to direct exciton coupling was well studied before and gives birth to formation of polariton states.^{13,14} The anti-crossing of DX–IX resonances in electric field is a consequence of the strong tunnelling coupling which was studied intensively for GaAs/AlGaAs heterostructures.^{29–31}

We start from the Hamiltonian which describes dipolariton as three coupled oscillators

$$H = \hbar \begin{pmatrix} \omega_{IX} & \Omega/2 & 0 \\ \Omega/2 & \omega_{DX} & J/2 \\ 0 & J/2 & \omega_C \end{pmatrix}, \quad (1)$$

where $\hbar\omega_C$, $\hbar\omega_{DX}$ and $\hbar\omega_{IX}$ denote cavity mode, direct exciton and indirect exciton energy, respectively. The coupling constant between photon and direct exciton is $\hbar\Omega$ (Rabi energy),³² while the tunnelling rate corresponding to DX–IX coupling is $\hbar J$. They lead to mixing of bare states in the case of strong coupling regime. The corresponding vector state reads as

$$|\Psi\rangle = \begin{pmatrix} \Psi_{IX} \\ \Psi_{DX} \\ \Psi_C \end{pmatrix}, \quad (2)$$

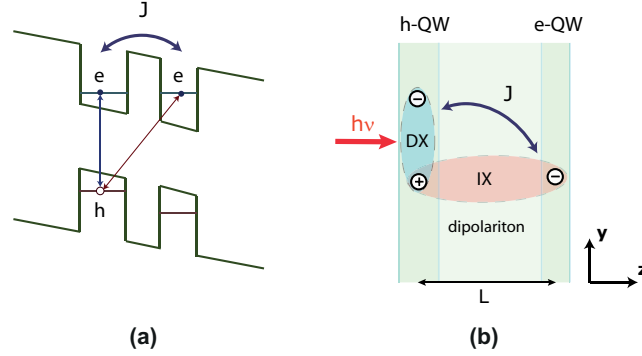


Figure 1. (Color online). Sketch of the system. (a) Double quantum well (DQW) heterostructure with resonantly coupled electron levels and a hole in the left quantum well (QW). The right QW has larger band due to presence of *In* alloy or smaller width of the well. (b) Electron-hole bilayer with schematic picture of coupled spatially indirect and direct exciton which form dipolariton.

with Ψ_C , Ψ_{DX} and Ψ_{IX} being field operators for cavity photon, direct exciton and indirect exciton, respectively. We are interested in the time-dependent response of the system and consider evolution of $|\Psi(t)\rangle$ state after illumination of the sample by short optical pulse. To separate the rapidly oscillating part of dynamics we can go to rotating frame using transformations: $\Psi_{IX}(t) = \psi_{IX}(t)e^{-i\omega_{IX}t}$, $\Psi_{DX}(t) = \psi_{DX}(t)e^{-i\omega_{DX}t}$ and $\Psi_C(t) = \psi_C(t)e^{-i\omega_C t}$.¹³ In the following treatment we assume macroscopic occupation number for each type of particle, and therefore can treat fields as classical. This allows one to write the closed set of time-dependent Schrödinger equations,

$$\frac{\partial \psi_{IX}(t)}{\partial t} = i\frac{J}{2}\psi_{DX}(t)e^{i\delta_J t} - \frac{\gamma_{IX}}{2}\psi_{IX}(t), \quad (3)$$

$$\frac{\partial \psi_{DX}(t)}{\partial t} = i\frac{J}{2}\psi_{IX}(t)e^{-i\delta_J t} + i\frac{\Omega}{2}\psi_C(t)e^{-i\delta_\Omega t} - i\frac{\gamma_{DX}}{2}\psi_{DX}(t), \quad (4)$$

$$\frac{\partial \psi_C(t)}{\partial t} = i\frac{\Omega}{2}\psi_{DX}(t)e^{i\delta_\Omega t} - iP_0(t)e^{-i\Delta t} - \frac{\gamma_C}{2}\psi_C(t), \quad (5)$$

where we defined the photonic detuning $\delta_\Omega = \omega_C - \omega_{DX}$ for cavity photon coupled to direct exciton, and energy distance between spatially indirect and direct excitons $\delta_J = \omega_{IX} - \omega_{DX}$. Here we introduced resonant optical pumping with frequency defined by detuning $\Delta = \omega_P - \omega_C$ [second term in RHS of Eq. (5)], where ω_P represents initial frequency of pumping laser, and pulsed structure is encoded in the $P_0(t)$ function. Except the coupling terms noted before, we phenomenologically introduce the damping rates for each mode $\gamma_i = 2\pi/\tau_i$, $i = C, DX, IX$. They differ drastically due to different typical lifetime for each mode being $\tau_C \approx 3$ ps, $\tau_{DX} \approx 1$ ns and $\tau_{IX} \approx 100$ ns. Here we disregard the spatial dynamics of the system since we are mostly interested in time-dependent density evolution of the fields.

3. RESULTS

We calculate numerically the dynamics of the system with coupled quasiparticles subjected to a picosecond pulsed optical pumping. The presence of mixing terms between different mode implies the oscillating behavior similar to Rabi flopping in classical model with two-level system exposed in the time-varying field. However, the set of Eqns. (5)–(3) which describes dipolariton has several characteristic frequencies, namely, coupling between direct exciton and photonic mode Ω with corresponding detuning δ_Ω , and IX–DX coupling J with δ_J being frequency difference between modes. Additionally, the pumping frequency ω_P defines the efficiency of the pumping. The major role here is played by J and Ω coupling constants. Thus, one can expect that regarding the parameters of the system, there are several possible regimes with different type of oscillations.

We analyze in detail the solutions of the system (3)–(5) for varying coupling constants Ω and J . In particular, we are interested in situation where harmonic oscillations of indirect exciton density $n_{IX} = |\psi_{IX}^2|$ with homogeneous magnitude appear in the system. The first regime (*I*) refers to the case where tunnelling rate dominate over Rabi frequency for C–DX coupling, $J > \Omega$. This situation corresponds to the dipolariton mode being

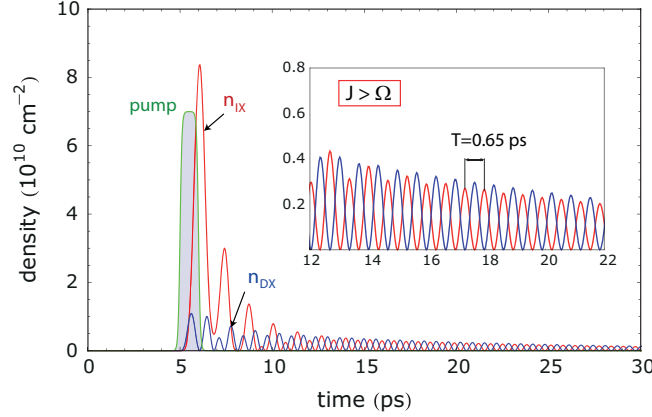


Figure 2. (Color online). Dynamics of the dipolariton system subjected to pulsed optical pumping which shows oscillations of indirect exciton (red line, n_{IX}) and direct exciton (blue line, n_{DX}) density. The coupling constants are equal to $\hbar J = 6$ meV and $\Omega = 2$ meV. The green area represents optical pulse with duration $\Delta\tau = 1$ ps and pulse edge defined by 0.1 ps transient time (pump). The inset shows the long-term term oscillations of $n_{IX} = |\psi_{IX}|^2$ and $n_{DX} = |\psi_{DX}|^2$ density which are in antiphase. The period of oscillations is equal to $T = 0.65$ ps.

superposition of Ψ_{IX} and Ψ_{DX} with corresponding density oscillations (Fig. 2). The plot shows a turning-on behavior and establishing the long-term antiphase harmonic oscillations (Fig. 2, inset). The magnitude of the signal slightly decreases with time due to finite lifetime of the quasiparticles. Finally, the frequency of oscillations can be deduced from Fourier transform of the signal and is equal to $\nu \approx 1.5$ THz. This corresponds approximately to frequency $J/2\pi = 1.45$ THz, and time-dependent density oscillations can be written in form

$$n_{IX}(t) = n_{IX}^0 \cos^2(Jt) e^{-t/\tau}, \quad (6)$$

where n_{IX}^0 denotes the magnitude of established oscillations with frequency J which decreases in time with damping rate τ^{-1} .

Second regime (*II*) describes the case of equal or smaller tunnelling coupling, $J \leq \Omega$. In this case situation corresponds to efficient mixing of all modes and dipolariton exhibits simultaneous oscillation between both C–DX and IX–DX bare particles. Thus, the oscillations of the indirect exciton density become strongly asymmetric, while allow for high-amplitude oscillations in the pulsed regime.

We have shown that in first regime IX and DX density oscillate with THz frequency. Finally, this infers that dipolariton is an oscillating dipole, with dipole moment in z direction d_z changing periodically from value $d_z = d_0$ of indirect exciton (IX) to $d_z = 0$, meaning a zero z projection of direct exciton (DX). We can introduce the quantity corresponding to total dipole moment in the system, which reads as $D_z = N_{IX} d_z$, where $N_{IX} = n_{IX} A$ denotes the number of indirect excitons in the sample of area A . Since we have shown before that density of indirect excitons $n_{IX}(t)$ is a harmonic function of time, the total dipole moment of the system (measured in z direction) yields

$$D_z(t) = d_0 n_{IX}^0 A \cos^2(Jt) e^{-t/\tau}, \quad (7)$$

with J being the frequency of density oscillations. It typically lies in the THz range and can be adjusted by change of spacing between QWs. Moreover, we note that frequency of oscillations depends on the IX–DX detuning, which allows the electrical tuning of THz emission frequency.

The emission of classical Hertz dipole can be described by the electromagnetic flux (Poynting vector) and the general formula for the intensity of emission reads as $I = \ddot{D}_z^2 / 6\pi\epsilon_0 c^3$,³⁴ where D_z is a total dipole moment of dipolariton array, ϵ_0 is vacuum permittivity and c is a speed of light (we use SI units). This formula is written in approximation of far field emission, *i.e.* measuring intensity on the length $l \gg L$ much larger than length of the dipole. For the particular case of harmonic oscillations we can write total power of emission by dipolariton emitter array, $I = N_{IX}^2 d_0^2 J^4 / 3\pi\epsilon_0 c^3$, where $d_0 = eL$ is a dipole moment of indirect exciton with

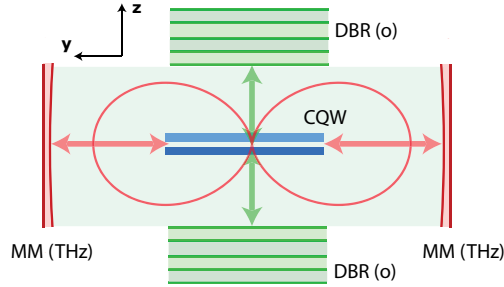


Figure 3. (Color online). Sketch of the geometry where power of THz emission is increased due to Purcell effect (top view). Here DBR(o) represent optical cavity mirrors (green), while MM(THZ) denote metallic mirror cavity tuned to reflect signal of THz frequency (red). The red lines show peculiar polar pattern of dipolariton THz emitter.

L being separation between centers of QWs. Here for simplicity we did not consider damping part $e^{-t/\tau}$ of oscillator array, which can be added straightforwardly if necessary. It will result into damping of total power of emission, and to achieve stable cw radiation one therefore needs to use sequence of pump pulses. Similarly to the conventional case of elementary dipole emitter, the polar pattern is given by relation $I_\theta \sim \sin^2 \theta$, where θ is an angle between direction of radiation and z axis (see Fig. 3). One should note that total intensity is proportional to the square of indirect exciton density and is not linear. This can be seen as a result of *superradiance*³⁵ due coherent in-phase oscillations of elementary dipoles. Namely, the system of dipolaritons represents a “collective dipole”, with corresponding superradiant emission properties emerging due to interference effects. This kind of laser based on the superradiance was experimentally created³⁶ and has shown significant improvement over conventional laser sources. In our case dipolariton system represents coherent superradiant THz emission source.

For $\hbar J = 6$ meV and typical distance between QWs being $L = 12$ nm, the power of the THz emission of one elementary dipole formed by dipolariton is equal to $I_0 = 1.8 \times 10^{-17}$ W = 18 aW. The total power can be increased using the large number of elementary dipoles N_{IX} . The typical concentrations of indirect excitons in experiment lie in the range $n_{IX} = 10^{10}$ cm⁻². Therefore, for 60 μ m diameter of a pumping spot one has $I_{tot} \approx 1.4$ μ W. Then, in a single sample it is possible to grow a stack of double quantum wells $n_{DQW} = 4$. Finally, using several sets of cavities on one chips allows to obtain power in the range achievable by quantum cascade lasers.

To improve properties of THz radiation and increase the efficiency, one can place the system inside the cavity tuned to the THz emission frequency. It can be created using metallic mirrors or using an inductor capacitor circuit.^{6,37} The sketch of the system is shown in Fig. 3. The efficiency of the emission will increase due to multiplication by Purcell factor

$$F_P = \frac{3}{4\pi^2} \frac{\lambda_c^3}{n^3} \frac{Q}{V_{eff}}, \quad (8)$$

where Q is a quality factor of the cavity, V_{eff} is an effective cavity volume, λ_c represents working wavelength and n denotes a refraction coefficient of the cavity. For the chosen frequency 1.45 THz which corresponds to $\hbar J = 6$ meV IX–DX coupling, the experimental value of Purcell factor in a inductor-capacitor cavity is $F_P = 17$.³⁷ Therefore, the total emission power increases one order of magnitude, while spectral properties of the signal can be tuned with parameters of the cavity.

4. CONCLUSIONS

We presented a theory which describes the system of dipolaritons serving as a source of THz emission. It was shown that due to direct-indirect exciton coupling, optically excited dipolariton system exhibits density oscillation with subpicosecond period. This corresponds to emission of the signal in THz frequency range by array of miniature classical dipoles. The spectral properties as well as power output of emission were shown to be competitive with other laser induced THz emitters.

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