Modulation of terahertz radiation based on dc-ac-field tuned coherent dynamics of dipolaritons

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***Abstract*—We propose an effective and convenient way of modulating the THz emission by dc and ac fields based on the coherent dynamics of dipolaritons, quasiparticles formed by the direct exciton, indirect exciton and photon in semiconductor double quantum wells embedded in microcavities. With the help of resonant tunneling, photon-assisted transport, and the dark Floquet states, we may generate efficient THz radiation (with tunable frequency and appreciable radiation power) or quench the THz emission by tuning the ac and dc fields.**

I. INTRODUCTION

Dipolaritons, the quasiparticles formed by the direct exciton (DX), indirect exciton (IX) and cavity photon (C)in semiconductor double quantum wells embedded in microcavities can be used to generate THz radiation due to their tunable energy, suitable optical dipole and lifetime[1,2]. The dynamics of dipolaritons can be tuned efficiently by using both the cavity field (optical method) and coherent tunneling between the two wells (transport method)[1].

We propose to use the combination of dc and ac field to manipulate the coherent dynamics of dipolaritons. The dc field can be used to adjust the energy levels of direct exciton and indirect excition (with electron and hole in different well, thus having large dipole moment), while the ac field leads to interesting time-dependent dynamics. We mainly consider three cases as shown in Figure 1: case I, the resonant tunneling with $E_{DX}=E_{IX}$ (E_{DX} the energy levels of the direct exciton and E_{IX} energy level of the indirect excition); case II, the photon-assisted transport with $E_{IX}-E_{DX}=\hbar\omega$ (ω the frequency of ac field); case III, symmetric configuration with $E_{DX}-E_{IX}=E_{DX}-E_{C}$ (E_C the energy of cavity modes.)

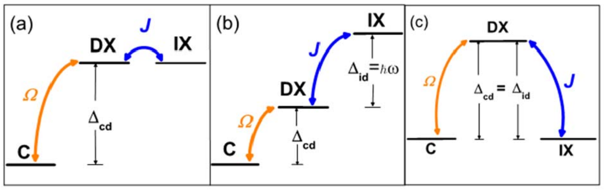

Fig. 1. (a) Energy level structure of case I corresponding to the resonant tunneling. (b) Energy level structure of case II corresponding to photon-assisted transport. (c) Energy level structure of case III related to the presence of dark state.

II. THEORETICAL MODEL AND METHODS

The dynamics of our system consisted of direct exciton, indirect exciton and photon in semiconductor double quantum wells embedded in microcavities can be described by the Hamiltionan

$$H=\hbar\omega_C\hat{a}^+\hat{a}+\hbar\omega_{DX}\hat{b}^+b+(\hbar\omega_{IX}+eV_{ac}\cos\omega t)\hat{c}^+c \\ +\frac{\hbar\Omega}{2}(\hat{b}^+\hat{a}+\hat{a}^+\hat{b})-\frac{\hbar J}{2}(\hat{c}^+\hat{b}+\hat{b}^+c)+P(t)\hat{a}^++P^*(t)\hat{a}, \tag{1}$$

where $\hat{a}^+$, $\hat{a}$, $\hat{b}^+$, b , $\hat{c}^+$, c are the creation and annihilation operators for the modes C, DX and IX, respectively. The first three terms of the Hamiltonian correspond to the energies of the three modes in the presence of the dc-ac field ($\hbar\omega_{IX}=\hbar\omega_{IX}^0+eV_{dc}$, $\hbar\omega_{IX}^0$ the energy level of the indirect excition in the absence of field). In the next two coupling terms, $\hbar\Omega$ is the coupling strength between C and DX, and $\hbar J$ is the coupling strength between DX and IX. The last two terms describe the pumping of the cavity mode with $P(t)=P_0e^{-i\omega_P t}$, ω_P the pumping frequency. The equation of motion of the density matrix of the system is $i\hbar\partial\rho/\partial t=[H,\rho]$. Based on the mean field approximation, which is valid for the case of large population for each mode, we are able to calculate the time evolution of the wavefunction of each mode $\psi_C=\langle\hat{a}\rangle$, $\psi_{DX}=\langle\hat{b}\rangle$, $\psi_{IX}=\langle\hat{c}\rangle$. The dipole moment can be calculated as $D(t)=\langle\Psi(t)|-e\hat{r}\,|\Psi(t)\rangle$, with $|\Psi(t)\rangle=(\psi_C(t),\psi_{DX}(t),\psi_{IX}(t))^T$. The emission spectrum can be obtained by the Fourier transformation $S(\nu)=\left|e^{-i\nu t}D(t)dt\right|^2$.

III. RESULTS

We investigate the quasienergy and the time evolution of our system by analytical and numerical calculations. Figure 2 shows the time evolution of the densities for the modes ($n_C=|\psi_C|^2$, $n_{IX}=|\psi_{IX}|^2$, $n_{DX}=|\psi_{DX}|^2$) and the corresponding emission spectrum. In the calculation, we have used the parameters: $\hbar J=12.7meV$, $\hbar\Omega=6meV$, $\Delta_{CD}=\omega_C-\omega_{DX}=-15meV$, $eV_{ac}=1.8\hbar\omega$, and $\hbar\omega=33meV$.

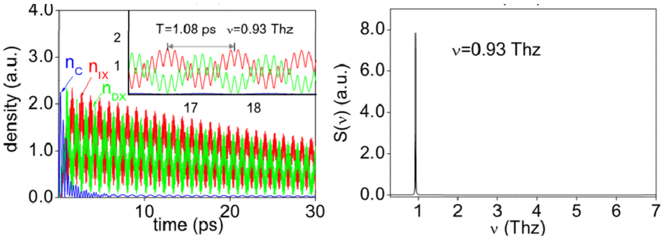

Fig.2. The time evolution of the densities of the modes and the corresponding emission spectrum.

It is found that the

oscillation between the direct exciton an indirect exciton may lead to THz emission. By Floquet theory, we find that the emission frequency matches the quasienergy difference of the related states and the coherent dynamics of dipolaritons may be described by an effective Hamiltonian with effective couplings between the direct exciton, indirect exciton and cavity photon, $\hbar\tilde{\Omega} = \frac{\hbar}{T}\int_0^T \Omega \cdot e^{-i(\Delta_{CD})t} dt$, $\Delta_{CD} = \omega_C - \omega_{DX}$, $\hbar\tilde{J} = \frac{\hbar}{T}\int_0^T J \cdot e^{-i[\Delta_{ID}t + \frac{eV_{ac}}{\hbar\omega}\sin(\omega t)]} dt$, $\Delta_{ID} = \omega_{IX} - \omega_{DX}$.

For the cases I, II with small $\hbar\tilde{\Omega}$, the quasienergies are $\varepsilon = \hbar\Delta_{CD}$, $\varepsilon = (\hbar\Delta_{CD} \pm \hbar\sqrt{\Delta_{CD}^2 + 4|\tilde{J}|^2})/2$. For case III, the quasienergies are $\varepsilon = \hbar\Delta_{CD}$, $\varepsilon = (\hbar\Delta_{CD} \pm \hbar\sqrt{\Delta_{CD}^2 + 4|\tilde{\Omega}|^2 + 4|\tilde{J}|^2})/2$. One can see that the emission frequency can be tuned by dual ways, i.e., by optical channel through $\hbar\Omega$, and/or by transport channel through $\hbar J$. It is also clear that the THz emission frequency can be conveniently tuned by the dc-ac field for the three cases with specific energy level structures, which can be achieved by applying appropriate dc field.

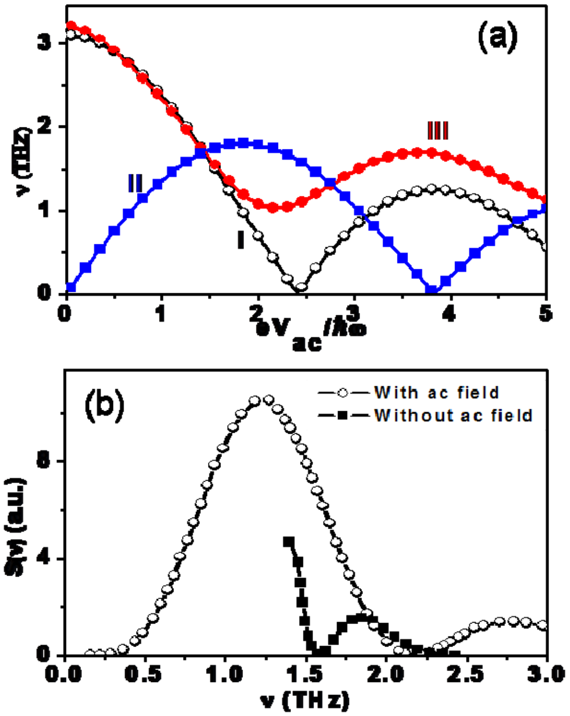

Fig. 3. (a) Emission frequency vs. ac field for case I (resonant tunneling),case II (photon-assisted transport) and case III (symmetric configuration with dark Floquet state). (b) The emission intensities for the cases with and without ac field.

As seen in Fig. 3 (a), we can obtain radiation field with frequency in the most interesting regime 0.1-3THz by tuning the ac field, which can realized conveniently in experiment. More over, our calculation indicates that the THz radiation based on the coherent dynamics modulated by dc and ac field may have appreciable radiation power. Fig. 3(b) shows the emission power of the structure in the presence/absence of ac field, which is in the order of μW [2,3]. The performance of the THz radiation can be further improved by optimizing the quantum well structure, the dc and ac fields. In addition, we have found that the presence of dark Floquet state leads to the quench of THz radiation for the specific ac field in the case III. The generation of this dark Floquet state containing only indirect exciton component provides a useful way of generating pure indirect exciton states.

Our proposal for THz wave generation based on dipolaritons can be generalized to systems with multiple quantum well structure/superlattice within microcavities. By carefully modulating the coherent dynamics of dipolaritons, in particular, the phases of related oscillation of the modes and dipoles, one may obtain strong THz radiation due the constructive superposition of the dipoles based on dipolaritons. Furthermore, interesting Fano resonances can be observed due the interference between the modes with different width/lifetime, which is the consequence of the different characteristic lifetimes of the direct exciton, indirect exciton, cavity photon and the interaction among them.

IV. SUMMARY

We use dc-ac field to modulate the coherent dynamics of dipolaritons (with suitable optical dipole and lifetime) with the help of resonant tunneling, photon-assisted transport, and dark Floquet state. Based on the coherent dynamics of dipolaritons, we find efficient and convenient methods for generation/modulation of THz waves with tunable frequency and appreciable power.

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