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Characteristics of Coherent Photon Transport in Semiconductor Waveguide Cavity System

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ABSTRACT

We have studied the characteristic feature of coherent photon transport in a semiconductor waveguide. We have presented a semiconductor master equation formalism that accurately simulated coherent input or output coupling of semiconductor cavity quantum electrodynamics systems such as planar photonic crystals and micropillar cavities. The role of quantized multiphoton effects pointed out the possible failure of weak excitation approximation, which was found to fail even for low input powers and small mean cavity photon numbers. For increasing field strengths, possible failure of the semiclassical approach was taken into account. In the weak coupling regime, higher order quantum correlation effects, were shown to be significant. We have introduced the general theoretical technique to simulate coherent photon transport outside both the weak excitation approximation and the semi classical approximation. Electron-phonon interactions at a microscopic level were derived using polaron transformation. We have demonstrated that substantial deviations from the weak excitation approximation resulted for very small mean photon numbers. We have modified the master equation approach to include the mechanism of electron-acoustic scattering and studied the impact of electron-phonon interaction on incoherent scattering and coherent renormalization of the exciton cavity coupling rate, qualitative differences from simple Lorentzian decay model containing quantum dot were found. We have also studied the transmission of light in the strong coupling regime and simulated a phase gate. We have found that coupling to an acoustic phonon bath caused considerable qualitative changes in light propagation characteristics modeled by a simple pure dephasing process. We have used the model to simulate a conditional phasegate. The obtained results were found in good agreement with previously obtained results.

KEYWORDS Coherent, Photon Transport, Waveguide, Simulation, Coupling, Photonic, Semiconductor Cavity, Micropillar Cavity, Quantization, Excitation, Interaction, Polaron Transformation, Acoustic Scattering, Lorentzian Decay, Quantum Dot.

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INTRODUCTION

There have been several successful demonstration of coherent light propagation effects in various semiconductor systems, including planar photonic crystals and micropillars. Bose et al. [1] measured the exciton-induced doublet, i.e. polariton splitting through waveguide mode transmission in a photonic crystal waveguide cavity system [2]. Loo et al. [3] probed the strong coupling in micropillar via coherent reflection. Young et al. [4] demonstrated first steps toward a conditional phase gate using light reflection from a micropillar common to the analysis of all of these experiments has been the application of the weak excitation approximation, where at most only one quantum was assumed. Young etal suggested that their experiments were likely at the single photon level for less than 0.1 photon per cavity lifetime, so they applied a weak excitation approximation solution [5]. These useful formalisms have been very successful and certainly help to clarify the basic physics of low intensity photon transport. The validity for the weak excitation approximation was taken and there can be quantum nonlinearities in the systems due to multiphonon correlations. Giant optical non linearities were studied by Auffeves-Garnier et al. [6], their semiclassical approach adiabatically eliminated the cavity mode and included effects outside the weak excitation approximation i.e. the Purcell regime, naturally with such a semiclassical approach. There is no influence from the higher lying levels of the anharmonic Jaynes-cumming ladder, so it cannot be applied in the strong coupling regime. Most photon transport approaches also neglect the details of electron-acoustic phonon scattering [7-11], apart from the inclusion of Lorentzian decay rate for the excition i.e. broadening of the zero phonon line. Several workers have shown that coherent excitation of semiconductor quantum dot systems can easily go into the anharmonic cavity quantum electrodynamics regime [12-13]. The ability to couple waveguides and cavities offers exciting opportunities for integrated quantum optical devices using solids [14-16]. In planar photonic crystals offer a technology platform, when quantum bits or qubits can be manipulated from quantum dots placed at field antinode positions within the cavity or waveguides [17-19]. Integrated semiconductor micropillar systems also shown promise for quantum optical applications [20-21] working at the few photon level. Sattar and Kumar [22] studied impedance concept for waveguiding devices from the microwave frequency regime to optics and plasmonics. The Expression were based on the electromagnetic eigen modes that were excited at the interface of a structure. Alam and Aparajita [23] studied mutual capacitive coupling and tunneling in the silicon single electron transistor coupled to a dopant atom. They observed a spectacular enhancement of the conductance through single electron transistor when transport occurred by resonant tunneling via the dopant atom. They have found that in certain range of temperature the mesoscopic fluctuations of coulomb blockade peaks were suppressed. Kumar and Ranjan [24] studied transmission through surface disorder waveguides in general and solid basis. Their results presented that desired properties on a waveguide through the roughness of its boundaries can be obtained. This surface scattering approach predicted that how mode specific scattering lengths in waveguides dependent on the details of system's surface roughness.

METHOD

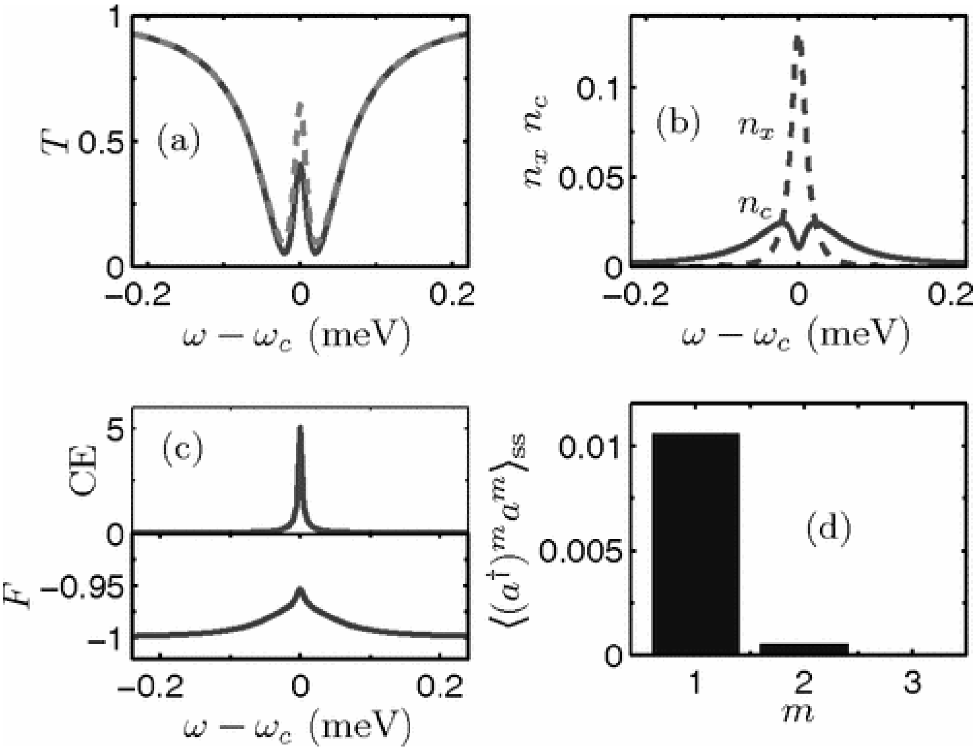
We have considered that light propagation for a quantum dot cavity geometry, where the input and output fields can be indentified separately from the cavity regime in which the quantum dot was assumed to be embedded. For a continuous wave waveguide mode of a photonic crystal system, the classical weak excitation approximation reflectivity has been derived is given below

$$r_{pc}(\omega)=\frac{i\omega\Gamma_c}{\omega_c^2-\omega^2-i\omega(\Gamma_c+\Gamma_0)-\omega\Sigma(\omega)}$$

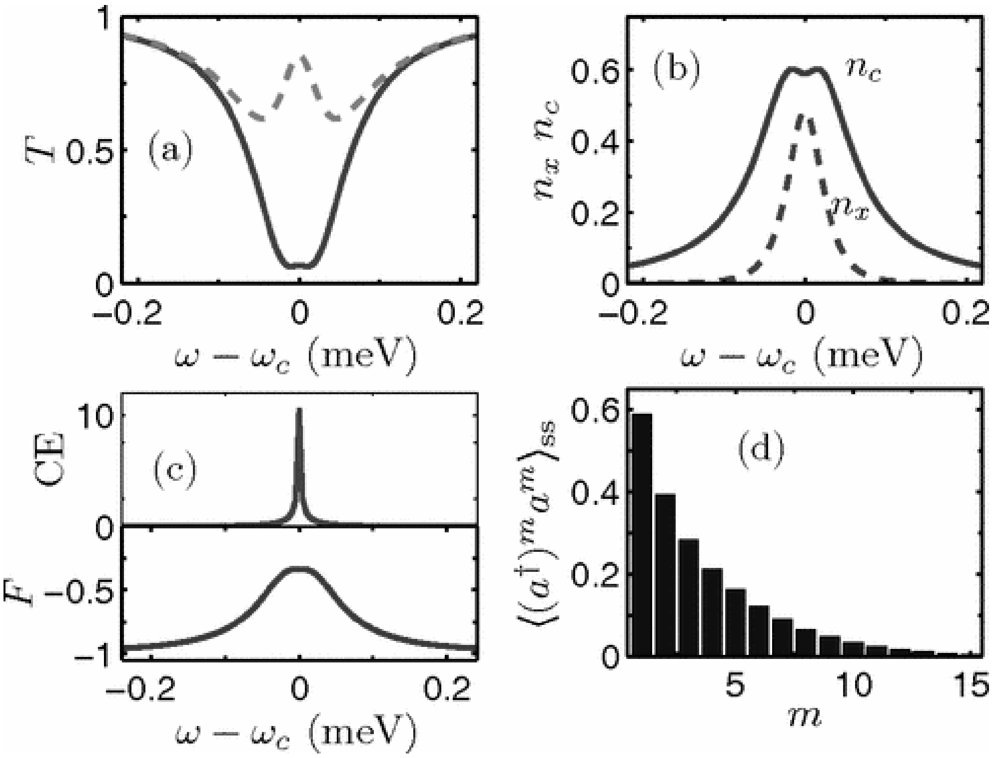
Where the self energy $\omega\Sigma(\omega)=\frac{\omega g^2}{\omega_x}-\omega^2-i\omega\Gamma_x^-\ \Gamma_0=2k_0$ is the cavity decay, $\Gamma_c\equiv 2k_c=2(k_l+k_r)$ is the cavity waveguide coupling rate, which is inversely proportional to the group velocity of the waveguide mode, ω_c is the cavity mode resonance, ω is the target exciton resonance of the quantum dot and $\Gamma_x^{'}=Y+Y^{'}$ is the total decay rate of the exciton, including radiative (Y) and non radiative, pure dephasing $(Y^{'})$ process. The total cavity decay rate in $\Gamma_c^t = \Gamma_0 + \Gamma_c$ and the exciton cavity coupling rate $g \propto \frac{d^2}{V_{eff}}$ is the effective mode volume. The corresponding transmissivity is simply $t = 1 + r$ and transmission through $R = |r|^2$ and $T = |t|^2$. Similar expressions have been derived by other group, e.g. with the dot resonance with cavity, then polariton doublet coincides with the vacuum Rabi splitting which was observed in transmission or reflection, the normal mode doublet occurred even if the dot is not in the strong coupling regime, through ultimately doublet feature is lost at high temperatures due to phonon micropillar system was similar and have $r_{\mu pill} = 1 - \sqrt{\eta pc}$, where η is a measure of in or out efficiency.

RESULTS AND DISCUSSION

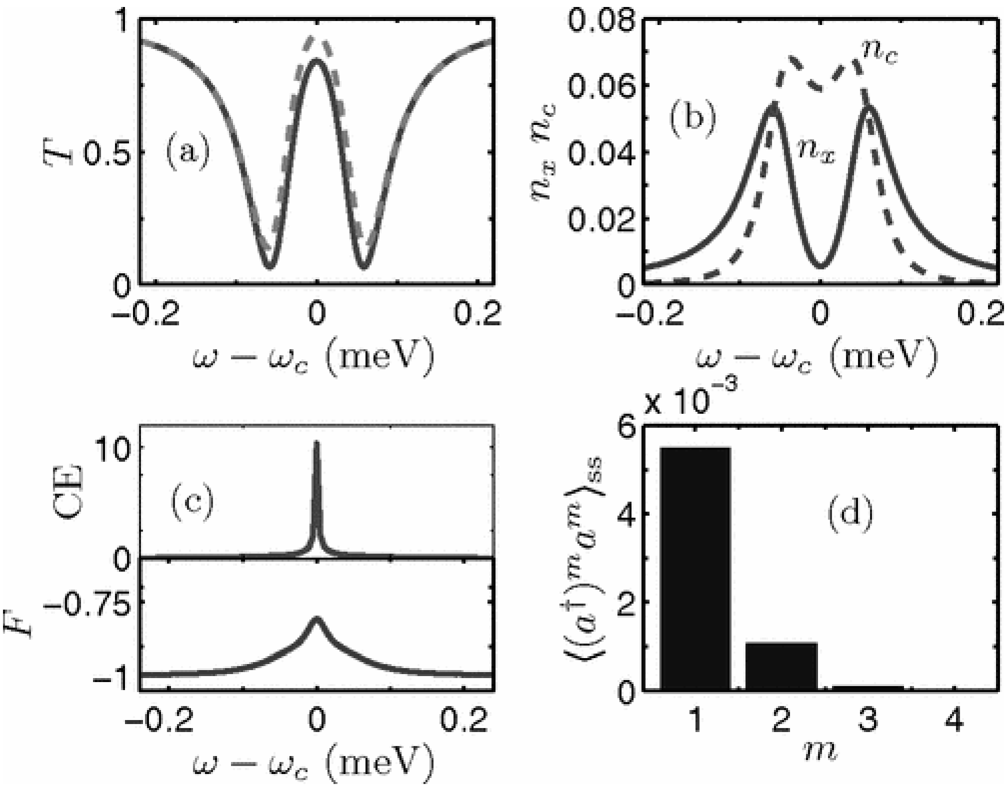
Graph (1) shows the weak coupling regime with $g = 20meV \approx 0.32\kappa_t$, using a fairly weak excitation field of $\eta_x = 0.5g$. This field value was chosen to be small enough that the cavity population is significantly lower than 0.1 but large enough a breakdown of the weak excitation approximation. We have also confirmed that this value of $\frac{g}{k}$ yielded to vacuum Rabi splitting. Graph (1)(a) shows the transmission versus detuning with as shown as dashed line and without the weak excitation as shown by solid line. We have also confirmed that the polariton doublet appeared even though are not in the strong coupling regime. The weak excitation approximation breaks down with qualitative differences of more that 40% near $\omega \approx \omega_c$ and with chosen value of g, the region of transparency is very weak, which is a consequence of the finite quantum dot broadening through Y and $Y^{|}$. This observation is contrast with the results of ref (6), where such broadening were not included, these zero phonon line broadenings are essential to include for a realistic quantum dot system. Graph (1) (b) shows the exciton and cavity mode population, confirming that the largest cavity population is well below 0.1, the fundamental condition for the weak excitation approximation is not low number of photons but a negligible excitation of the dot and excitation population is evidently no longer negligible. Graph (1) (c) shows the correlation error. The non linear quantum aspects of this dot cavity coupling regime is shown in graph (2) which shows the increase in the pump value to $\eta_c = 2.5g$. The weak excitation breaks down dramatically as shown in graph (2)(a). Graph 2 (a) and 2 (d) further confirm that we are accessing a regime where both the weak excitation approximation and the semi classical approximations, even for a weakly coupled system. We have found anharmonic cavity quantum electrodynamics regime. Graph (2) (b) shows the corresponding population. A quantum dot cavity system in the weak to intermediate coupling regime with $g = 60\mu eV \approx k_t$ and $\eta_c = 0.25g$ have been found. Graph (3)(a) shows the transmission with dashed line and without solid line the weak excitation approximation, the population was found. Graph (3)(b) shows the semiclassical error and 3 (c) and 3 (d) dhows the Fano factor. Electron-phonon scattering is seen to manifest in a coherent renormalization in $g \to \langle B \rangle g$ as well as mediate incoherent scattering between the exciton and cavity. We have studied a conditional phase gate. Using a semiconductor micropillar system, conditional phase shifts of around 0.03 were found. In reflection conditional phase changes of around $\pm\frac{\pi}{4}$ were found. One photon resulted i.e. the weak excitation approximation tended to overestimate this value. Including the coupling to the photon bath was seen to qualitatively change the phase characteristics. The obtained results were compared with previously obtained results of theoretical and experimental works and were found in good agreement.



Graph 1: Transmission characteristics for a weakly-coupled Quantum Dot-cavity-waveguide system, with $g = 20meV \approx 0.32\kappa_t$ and $\eta_c = 0.5g$. (a) Transmission with (dashed) and without (solid) the Weak excitation approximation.



Graph 2: With the larger pump field $\eta_c = 2.5g$ multiphoton correlations.



Graph 3: For an intermediate to strongly coupled system, with $g = 60\mu eV \approx \kappa_t$ and $\eta_c = 0.25g$ ..

CONCLUSION

We have studied the characteristics of coherent photon transport in a semiconductor waveguide cavity system using semiconductor master equation technique. We have found that for the regime of coherent photon transport including multiphoton effects and photon scattering within the theoretical formalism in the weak coupling higher order quantum correlation effect were significant. We have demonstrated that for mean photon numbers much less than 0.1 adopted weak excitation i.e. single quantum approximation breaks down even in weak coupling regime. We also explored the role of electron-acoustic-phonon scattering and found that phonon mediated scattering played a qualitatively important role on the light propagation characteristics. A conditional phase gate at a phonon bath temperature of 20k in the strong coupling regime was present. The obtained results were found in good agreement with previously obtained results.

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