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Semiconductor Waveguide-Cavity System Having Coherent Photon Transport Derivation from Master Equation

Pankaj kumar[1]*Dr. Pramendra Ranjan Singh
Research Scholar, JP University, Chhapra[1]

Abstract:
This paper shows the derivation of a master equation procedure to swot the input/output description in a semiconductor waveguide-cavity system having coherent photon transport. For that purpose we pursue a variety of dot-cavity interaction strengths to inspect the possessions of photon propagation and a QED.
Key words: Solid-State Quantum Optics, Cavity QED, Single Quantum Dot, Photons in Semiconductors.

Introduction

In 1916 Albert Einstein formalized a quantum theory of radiation and put forward indispensable originator of spectral lines - spontaneous emission, stimulated emission, and photo-absorption. Since that the properties of atomic spectral lines were always be a curious topic amongst the physicist of quantum mechanics (1-4).

The transition without any external influence were called as "spontaneous" And the phenomenon of emission of a photon by an atom in an excited state making a transition to its ground state is termed as Spontaneous emission and the rate of spontaneous emission from an atom was significantly dependent on the electromagnetic environment(5,6). Unsurprisingly, it turns out to be attention-grabbing and significant to think about structures with controllable electromagnetic environments for instance- *Resonators*. For considerable periods of time an elegant resonator can trap light, and accordingly consented to the study of interactions between trapped light and matter which is analogous to different atomic states(6). Light emitted by an atom in a resonator faces a drastically different electromagnetic environment compared to free space, which has a continuum of electromagnetic states. Further, the electromagnetic environment (i.e., the density of optical states) in a resonator can be modified by varying the cavity geometry, creating possibility to create light-matter coupled states that suppose to be hard or unfeasible to stumble on nature(5).

The impression of "external" control got significantly accustomed with the occupied quantum treatment of particles and fields and result of that the one of the most precise physical theories worked out by humankind "quantum-electrodynamics" (QED) come forward(7,8).

Spontaneous Emission

To understand and calculate the rate at which spontaneous emission happens requires a careful consideration of the interaction between the atom (treated as a two-level system) and the (quantized)electromagnetic fields in which the atom finds itself(4). The interaction energy between an atom and a single electromagnetic mode is equal to the dot product of the atomic dipole moment and the electric field at the atom's position. This, along with the energy of the field and atom, allows the total atom-field Hamiltonian to be written down, as was first done in the Jaynes-Cummings model (6).

Most physical situations give explanation for the use of the rotating wave approximation in the elucidation of this Hamiltonian. The atomic levels are supposingly "dressed" by the electromagnetic field. The time fruition of the system is exertioned out using Schrodinger's equation, enlightening that the atom ops between the excited and ground states with the distinguishing "Rabi" frequency, An attention-grabbing observation at this instant is that in the full quantum treatment illustrated here, an initially excited atom "Rabi-ops" even if there are no photons in the cavity(9). This is for the reason that while the anticipation importance

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of the vacuum electric field faded away, the anticipated value of the field intensity does not, and in consequence, vacuum instability grounds the atom to instinctively emanate (4).

Atom-Optics to Semiconductor Cavity QED

Some definite confident and convinced atomic transitions in cesium or rubidium atoms are characteristically worned, along with micrometer-sized cavities with very-high-reactivity mirrors (10). The nominal methodological confrontations faced are colossal, both in generating the experimental setup and in assembling the observed data. Some urbane and classy trapping modus operandi such as magneto-optic-traps is used to embrace an atom in particularly over a cavity. The atom is then allowed falling into the cavity region, and it interacts with the cavity for a very short period of time (12).

In this moment, a laser pulse is required to excite the atom, at the same time other laser beams cross-examined the state of the coupled atom-cavity system (6). Despite the fact that these experimental arrangement are imperative in appreciative physics and indicative of theory, it is inflexible to envision their exploit in supplementary intricate configurations (e.g., coupling between several cavities), or their portability to industry. In this perspective, semiconductor-based cavity-QED enunciated a invigorating unconventional, notwithstanding (understandably) with its individual set of impediments (11).

At this point, cavities can be created or produced by creating defects in otherwise-intermittent dielectric structures (photonic crystals). It must be eminent illustrious that semiconductor-based, non-periodic configuration such as ring resonators can also be implicate (15). The counterpart of the atom is the quantum dot (QD). A QD is a small-sized semiconductor structure (quite a lot of smaller than the wavelength), which is enclosed in all three dimensions by elevated electronic band-gap material (18).

This spatial and energetic internment show the way to a quantized spectrum of the QD transitions, as a consequence assembling the equivalence with distinct atomic transitions perceptible (16-18). These QD transitions keep up a correspondence to diverse exciton configurations (excitons, charged-excitons, bi-excitons) (19).

Quantum Dots

Quantum dots (QDs) along with the photonic crystals forms elementary Cavity Quantum Electrodynamics or QCED (15). As a consequence of that the field localization boundaries within sub-cubic wavelength volumes subsequently show the leads to vacuum Rabi frequencies An intense and fervent interfacing mid light and matter can be accomplished in this coordination of CQED (16).

Quantum Dot Dynamics

The capability to couple waveguides and cavities proffered exciting opportunities for incorporated quantum optical devices using solids(6). predominantly, planar photonic crystals presumptuous a technology platform, where quantum bits (qubits) can be manoeuvre from quantum dots or QDs positioned at field antinode positions within the cavity or waveguide. quantum optical applications ideas can be withdrawn via Integrated semiconductor micropillar systems while Working at the few photon level(8-10).

Coherent Light Propagation Effects In Various Semiconductor Systems

A huge no of successful research has been done on the coherent light propagation effects in various semiconductor system, including planar photonic crystals and micropillars. According to some literature reviewed (11-14)

- Bose et.al., measured the exaction-induced doublet through wave guide mode transmission in a photonic crystal waveguide cavity system(12).
- Loo et al(13)probed the strong coupling in a micropillar via Coherent reflection.
- Young et al(14)demonstrated first steps towards a conditional phase gate using light reflection from a micropillar.

ISSN:0971-1260
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single photon level and applied a Weak Exitation Approximation of excitation approximation solutions was suggested from the experiments of Young et al were frequently assumpted by many other workers in excitation regimes where the mean photon number is well below those associated with saturating the quantum dot exciton (15).
Under this paper we try to propose the conjectural and speculative formalism of the multi photon effects and phonon scattering with the establishment of coherent photon transport.

Light Propagation For A QD-Cavity Geometry

To correspond to light propagation for QD-cavity geometry, the cavity area in which the QD is simulated to be impacted both the input and output fields can be acknowledged discriminately from (24). Supportingly, Hughes and Kamada derived the conventional WEAK EXITATION APPROXIMATION reflectivity for a unremitting or continuous wave (cw) waveguide mode of a photonic crystal system, (10,23)

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

$\omega\Sigma(\omega)$ =self-energy
and $\omega\Sigma(\omega) = \omega g^2/(\omega_x - \omega^2 - i\omega T^t)$,
Here the note down point is that the cavity-waveguide coupling rate is inverse proportional to the wave guide mode in group velocity
ω_c= cavity mode resonance,
and ω_x= target exciton resonance of the QD,
Γ_0=cavity decay rate throughout vertical scattering
And will be formulized as
$\Gamma_0 \equiv 2\kappa_{0,}$
Γ_c= correspond to the cavity-waveguide coupling rate and can be calculated as
$\Gamma_c \equiv 2\kappa_c = 2(\kappa_l + \kappa_r)$(25-28).
the total decay rate of the exciton represented as
$\Gamma_x^t = \gamma + \gamma'$(29,30).
γ = radiative pure dephasing
γ' = nonradiativepure dephasing process
The total cavity decay rate represented as
$\Gamma_x^t = \Gamma_0 + \Gamma_c$
and the exciton-cavity coupling raterepresented as(36-38)
$g \propto d^2/V_{\mathrm{eff}}$,
where d = dipole moment of the exciton
V_{eff}= effective mode volume.
The corresponding transmissivityis simplyrepresented as
$t = 1 + r$,
corresponding transmissivity the reflectionand transmission, through
$R = |r|2$ and $T = |t|2$.
Pragmatically observed in transmission or reflection, a polariton doublet happen together with the vacuum Rabi splitting afterward With the dot on resonance with the cavity, this *normal mode* doublet can come to mind even though the dot is not in a strong -coupling rigme , despite the fact thateventually thedoublet attribute is vanished at elevated temperatures as a result of phonon bath coupling(30-32).
From a micropillar system, the interpretation of coherent reflection is comparable and analogous;
one has $r\mu_{\mathrm{pill}} = 1 - \sqrt{\eta} r_{\mathrm{pc}}$,

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Vol-22-Issue-14-December -2019

where η=determinant of in/out coupling efficiency,
and that was also formulate the subsequent replacements:
For vertical scattering
$\Gamma_c \rightarrow \Gamma_0$ and
for sidewall scatter
$\Gamma_0 \rightarrow \Gamma_s$.
To make a clear differentiation between radiative and pure dephasing processes of the Quantum Dot exaction the above Weak Excitation Approximation formalism can not suitable; the acoustic phonon bath or multiphoton effects also does not considerate at this situation (38,39).
If we Do not take into account for the intricacy and convolution of phonon scattering we will use a master equation technique where exciton-photon interactions are effortlessly included to all instructions ahead of the Weak Exitation Approximation, and the semiclassical approaches (40-45).

$$\langle a^r_{\text{out}}(t)\rangle = -\langle a_{\text{in}}(t)\rangle + \sqrt{2\kappa_c}\,\langle a(t)\rangle,$$
$$\langle a^l_{\text{out}}(t)\rangle = \sqrt{2\kappa_c}\,\langle a(t)\rangle, \quad (1)$$

Where, for a coherent cw input state,
$\langle a_{\text{in}}\rangle = i\eta_c/(2\sqrt{2\kappa_c}),$
with η_c= cavity pump rate.
Subsequent the explanation of the Master Equation, the *steady-state* transmissivity and reflectivity are obtained

$$t \equiv |t|e^{i\phi_t} = \langle a^r_{\text{out}}\rangle_{\text{ss}}/\langle a_{\text{in}}\rangle \quad \text{and} \quad (2)$$
$$r \equiv |r|e^{i\phi_r} = \langle a^l_{\text{out}}\rangle_{\text{ss}}/\langle a_{\text{in}}\rangle, \quad (3)$$

where *φt* and *φr* are the respective phases. functioning in a frame rotating concerning the laser pump frequency, ω*L*, the model Hamiltonian derived as

$$H = \hbar\Delta_{xL}\sigma^+\sigma^- + \hbar\Delta_{cL}a^\dagger a + \hbar g(\sigma^+ a + a^\dagger\sigma^-) + H^c_{\text{drive}} + \sigma^+\sigma^-\sum_q \hbar\lambda_q(b_q + b^\dagger_q) + \sum_q \hbar\omega_q b^\dagger_q b_q, \quad (4)$$

where bq ($b^\dagger_q$)are the extermination and foundation operators of the photons,
'a'= cavity mode annihilation operator,
σ+ and σ− = Pauli operators of the electron-hole pair or exciton,
$\Delta_{\alpha L} \equiv \omega_\alpha - \omega_L$ (α = x,c)
are the detuning of the exciton (ω_x) and cavity (ω_c) from ω_L,
and H_c drive = ℏηc(a + a†)articulates the coherent cavity drive.
recover the Independent Boson Model (IBM)we have to convert Eq. (4) to a polar on frame To obtain the Master Equation, at priority, (28–30) the IBM is acknowledged to precisely express the distinguishing line shape of a single exciton coupled to a bath of acoustic photons (45,46).
In particular, the polaron Master Equation(20,30,31)commences coherent electron-phonon coupling unerringly, whereas incoherent phonon connections are indulgenced at the level of a

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second-order Born approximation. The time- convolution less Master Equation makes setup (20,31,40-47)

$$\frac{\partial \rho}{\partial t} = \frac{1}{i\hbar}[H'_{\rm sys}, \rho(t)] + \mathcal{L}(\rho) + \mathcal{L}_{\rm ph}(\rho), \quad (5)$$

The system in polaran-transformed Hamiltonian is

$H'_{sys}=\hbar(\Delta_{xL}-\Delta P)\sigma^{+}\sigma^{-}+\hbar\Delta_{cL}a^{\dagger}a+\langle B\rangle X_g+H^{c}_{drive}$

with $\langle B\rangle=\exp[-\frac{1}{2}\int_0^{\infty}d\omega\frac{J(\omega)}{\omega}\coth(\frac{\beta\hbar\omega}{2})](\beta=1/k_bT)$

$X_g=\hbar g(a^{\dagger}\sigma^{-}+\sigma^{+}a)$, and $\Delta P=\int_0^{\infty}d\omega\frac{J(\omega)}{\omega})]$.

whatsoever we taken the polar on shift (ΔP) in the interpretetion of ω_x . The phonon spectral function, $J(\omega)=\alpha_p\,\omega^3\exp(-\omega^2/2\omega_b^2)$,)depicted the electron-acoustic interaction of photons all the way through a coupling of malformation potential (20,31,32). By means of a Markov approach, the term incoherent photon scattering is enunciated as(20, 22, 38)

$$\mathcal{L}_{\rm ph}(\rho) = -\frac{1}{\hbar^2}\int_0^{\infty} d\tau \sum_{m=g,u}\Big(G_m(\tau) \times [X_m, e^{-iH'_{\rm sys}\tau/\hbar}X_m e^{iH'_{\rm sys}\tau/\hbar}\rho(t)] + {\rm H.c.}\Big), \quad (6)$$

where $X_u=-i\hbar g(a^{\dagger}\sigma^{-}-\sigma^{+}a)$,

and $G_{g/u}(t)$ =the respective polaron Green functions(20,28-30).

$G_g(t)=\langle B\rangle^2(\cosh[\varphi(t)]-1)$,

$G_u(t)=\langle B\rangle^2\sinh[\varphi(t)]$, with

$$\varphi(t)=\int_0^{\infty}d\omega\frac{J(\omega)}{\omega}[\coth(\beta\hbar\omega/2)\cos(\omega t)-i\sin(\omega t)]. \quad (7)$$

The weak excitation approximation only comprises the ground state and the first two ladder states of the JC model i.e., a three-state model(48-50).For properly hefty input fields, many JC ladder states may be implicated. To enhanced attention towards the role of quantum statistics in the system and to facilitate enumerate the potential loss of a semi classical approximation (50).

Conclusion

We have employed semiconductor master equation technique for the purpose of research work. Weak excitation approximation has been used in the work. We have present the general theoretical approach to act coherent photon transport covering both the Weak excitation approximation and the semiclassical approximation.

The theory based on a quantum master equation conformity where cavity and dot decays are presented by Lindblad superoperators and phonon synergy will be included from an capable phonon master equation that combined electron-phonon synergy at a atomic level using a polaron transform.

This paper presented a semiconductor ME conformity that can precisely conjure up coherent input/output coupling of semiconductor cavity-QED systems for example planar photonic crystals and micro pillar cavities.

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