Theory of single photon transport in a coupled Semiconductor microcavity waveguide

Yin Zhong, Lei Tan*, Li-wei Liu

Institute of Theoretical Physics, Lanzhou University, Lanzhou 730000, P. R. China

Abstract

We investigate the coherent transport of a single photon in coupled semiconductor microcavity waveguide, which can be controlled by in-plane excitons in quantum well embedded in the antinode of the electromagnetic field in one of the cavities. The reflection coefficient and transmissivity for the single photon propagating in this semiconductor waveguide are obtained. It is shown that the effect of the exciton’s decay plays an important role in the transport properties of the single photon in this microcavity waveguide if we refer to real systems.

PACS numbers: 03.75.Mn, 75.40.Gb

* Corresponding author. Electronic address: tanlei@lzu.edu.cn
I. INTRODUCTION

Recent years, many theoretical and experimental researches have been focused on semiconductor microcavity [1, 2, 3, 4, 5]. Most of these researches are devoted to the Bose-Einstein Condensation of exciton polaritons which are quasi-two dimensional bosons in the semiconductor microcavity and even BEC of polaritons in a trap [6, 7, 8, 9]. But here we are interested in the coherent transport of single photon in semiconductor microcavity waveguide because of the impressive result achieved in one-dimensional resonator waveguide in optical coupled cavities [10, 11, 12]. In Ref. [10], the results show that the controllable two-level system can behave as a quantum switch for the coherent transport of a single photon which may be a good candidate for quantum information processing where controlling of coherent transport for a scattering photon by tuning inner structure of the target is a hot topic [10, 13, 14].

A typical semiconductor microcavity consists of a planar Fabry-Perot cavity sandwiched between so-called Bragg mirror, which is a period structure composed of two semiconductor or dielectric materials with different refractive indices and containing an embedded quantum well (QW). And the semiconductor microcavity waveguide (consists of many cavities) can be fabricated by conventional manufacture technology of semiconductor [15]. Compared with the optical cavities, the semiconductor microcavity waveguide has several XXXX characteristics in application. Firstly, the practical temperature of this semiconductor system can be several orders higher than the counterpart in optical microcavity waveguide in some point, and this is quite important for future applications [16, 17, 18] in quantum information processing. Secondly, the excitons in the QW are Coulomb-corelated electron-hole pairs characterised by discrete transition frequencies, which can be treated as two-level systems [19]. This is very similar with the two-level atom in optical cavity waveguide [10]. At last, the excitons are stationary against quite high temperature [3, 20]. By contrast, the cold atoms are only existing in very low temperature [21, 22, 23], and it is cumbersome for people to prepare a cold atom initially and load it into the cavity waveguide. Considering these reasons, studying the the coherent transport of a single photon in semiconductor microcavity waveguide is very interesting. We will get reflection coefficient and transmissivity for a single photon transporting in the waveguide by solving eigen-equation of this coupled system composed of single photon and exciton. as a matter of fact, we do not add a pump laser to excite a real exciton, even
though the same function as setup in Zhou et al. \[10\] can also be realized. Which is due to
the reasons that, when no exciton is excited, the state is chosen as low-energy level, and if
one exciton (this exciton is only excited by the photon propagate in the waveguide) is excited,
we call this state up-energy level, and more excitons are not necessary. Furthermore the
decay of excitons has also been investigated for its impressive effect on scattering if we refer
to real systems, and this effect plays an important role in the transport properties in this
microcavity waveguide.

This paper is organized as followed. In Section 2 we describe the Hamiltonian for this
system and derive an eigen-equation for propagating of single photon in the waveguide. In
section 3, we use simple wave function to obtain reflection coefficient and transmissivity and
analyze the parameters in these two coefficients, in section 4, we study the effect of decay
for excitons phenomenologically, finally we conclude in section 5.

II. THE MODEL FOR THE COUPLED MICROCAVITY WAVEGUIDE

We describe the system as a single photon propagates in a semiconductor microcavity
waveguide (here the number of cavity is infinite for we consider a ideal situation, however, in
reality a waveguide must have at least a input and a output, so the real one may have several
differences from our ideal system here) and excitons transport in the plane of QW in one of
cavities in the waveguide. And we only restrict ourselves to a single photon propagating
state, this means initially there are no exciton in the cavity and only after a photon is
absorbed by the QW, an exciton is created and then the exciton breaks down and a photon
is recreated but moves in the opposite direction to the incident direction. As we know
there is not a exiting Hamiltonian for this system, so the first step to solve the problem
is to model a Hamiltonian where we must consider propagating of photon in microcavity
waveguide and excitons in the plane of quantum well in one of the cavity. In general, the
widely used Hamiltonian \[9\] is given by

\[
H = H_{\text{exc}} + H_{\text{ph}} + H_{\text{exc–ph}}
\]  \hspace{1cm} (1a)

\[
H_{\text{exc}} = \sum_p \varepsilon_{\text{ex}}(p) b_p^\dagger b_p + \frac{1}{2A} \sum_{p,p',q} U_{q} b_{p+q}^\dagger b_{p'}^\dagger b_{p'} b_{p+q} \] \hspace{1cm} (1b)

\[
H_{\text{ph}} = \sum_p \varepsilon_{\text{ph}}(p) a_p^\dagger a_p \] \hspace{1cm} (1c)
\[ H_{\text{exc-ph}} = \Omega_R \sum_p a_p^\dagger b_p + h.c. \]  

\( H_{\text{exc}} \) is an excitonic Hamiltonian, \( H_{\text{ph}} \) is a photonic Hamiltonian and \( H_{\text{exc-ph}} \) is a Hamiltonian which describes the interaction between photons and excitons. Here, \( a_p \) and \( a_p^\dagger \) are photonic creation and annihilation operators, \( b_p \) and \( b_p^\dagger \) are excitonic creation and annihilation operators which satisfy Boson commutation relation. 

\[ \varepsilon_{\text{ex}}(p) = E_{\text{band}} - E_{\text{binding}} + \varepsilon_0(p) \]  

The energy for single exciton state, \( E_{\text{binding}} = \mu_{e-h} e^4 / \hbar^2 \epsilon \) is the binding energy for interaction between 2D holes and electrons. \( \mu_{e-h} = m_e m_h / (m_e + m_h) \) is the reduced excitonic mass. \( \epsilon \) is the dielectric constant. \( n = \sqrt{\epsilon} \) is refractive index in the cavity. Their coupling of excitons and photons are attributed to the Rabi frequency \( \Omega_R = d a_{2D} \sqrt{N_{\text{exc}}} \lambda_0 / \hbar n \epsilon \), which is proportional to the exciton oscillator strength \( d \) and to the number of QWs embedded in the cavity with \( \lambda_0 \) the resonant wavelength of the cavity. 

This Hamiltonian is widely used to study exciton polaritons, which are the elementary excitations of coupled systems composed of matter (excitons) and light (photons) in strong coupling regime. This Hamiltonian can be modified for the application of considering the single photon transport in the coupled semiconductor microcavity waveguide. Firstly in the original Hamiltonian, the photons propagate in the homogeneous space in the plane of QW, but in the third direction electromagnetic field is confined in cavities. The momentum \( p \) or wave vector (if \( \hbar = 1 \)) is the in-plane one. Exciton-exciton interaction and exciton-photon interaction conserve these in-plane momentums. In this paper we want to analyze the problem of scattering of a single photon in coupled semiconductor microcavity waveguide, the effect of microcavity waveguide must be included in the photonic Hamiltonian and the original photonic Hamiltonian can be replaced by the following one.

\[ H_{\text{ph}} = \omega \sum_j a_j^\dagger a_j - \zeta \left( \sum_j a_j^\dagger a_{j+1} + h. c. \right) \]  

In this Hamiltonian, we only consider one mode whose incident angle is zero toward to the
plane of QW, and in-plane momentum of this mode vanishes too. We use $a_j^\dagger (a_j)$ to denote the creation (annihilation) operator of the $j$th cavity. $\xi$ is the nearest-neighbor evanescent coupling constant of intercavity, and $\omega$ is the energy of photon in each cavity.

Secondly, the photon only couples with the excitons carrying the same momentum as the them. This can be inferred from the interaction Hamiltonian $H_{exc-ph}$. We can get the new Hamiltonian for coupled excitons and photons.

$$H_{exc-ph} = \Omega_R (a_0^\dagger b_0 + a_0 b_0^\dagger)$$  \hspace{1cm} (3)

$a_0^\dagger (a_0)$ is the photonic creation (annihilation) operator in the zeroth cavity for we assume QWs (or excitons) only locate in this cavity (plane). and $b_0^\dagger (b_0)$ creates (annihilates) excitons in the zeroth cavity for momentum is vanished. $\Omega_R$ is Rabi frequency for this coupling. As what we have done in Hamiltonian $H_{exc-ph}$, we are able to have a replaced Hamiltonian for excitons which only stay in the QWs’ plane in the zeroth cavity.

$$H_{exc} = \varepsilon_{ex}(0)b_0^\dagger b_0 + \frac{1}{2A} U b_0^\dagger b_0 b_0^\dagger b_0$$  \hspace{1cm} (4)

then a suitable Hamiltonian for our problem on scattering of a single photon in coupled semiconductor microcavity waveguide can be given as following:

$$H = H_{ph} + H_{exc} + H_{exc-ph} = \omega \sum_j a_j^\dagger a_j - \xi \sum_j (a_j^\dagger a_{j+1} + h.c.) + \varepsilon_{ex}(0)b_0^\dagger b_0 + \frac{1}{2A} U b_0^\dagger b_0 b_0^\dagger b_0 + \Omega_R (a_0^\dagger b_0 + a_0 b_0^\dagger)$$  \hspace{1cm} (5)

In the following, we do not deal with it directly (mean field theory, perturbation theory, Hubbard-Stratonovich transformation and so on [28]). Here we do is to find the scattering of a single photon in this coupled cavity waveguide, so we consider an eigen-equation for this physical process. To get an eigen-equation, we have to assume an eigen-vector and this can be done as follows. We focus on $H_{ph}$, then let the waveguide be infinite and make a Fourier transformation for $a_j (a_j^\dagger)$. $a_j = \frac{1}{\sqrt{N}} \sum_k e^{ikjl} a_k$ [29], where $k$ is the wave vector of photons, $N$ is the number of cavities in the waveguide and $l$ is the distance between neighbor cavities. So, in momentum (wave vector) space the photonic Hamiltonian can be expressed as

$$H_{ph} = \sum_k \Omega_k a_k^\dagger a_k = \sum_k (\omega - 2\xi \cos (kl)) a_k^\dagger a_k$$  \hspace{1cm} (6)

$\Omega_k = \omega - 2\xi \cos (kl)$. For simplicity, we let $l = 1$ below, so $\Omega_k = \omega - 2\xi \cos (k)$. Now we assume the stationary eigen-vector [10, 14] is

$$|\Omega_k\rangle = \sum_j a_k^\dagger \mu_k (j) |0\rangle_c |0\rangle_{exc} + \mu' |0\rangle_c |1\rangle_{exc}$$  \hspace{1cm} (7)
$|0\rangle_c$ is the vacuum state of photons, $|0\rangle_{exc}$ is the state of zero-momentum for excitons in QWs, $\mu_k(j)$ and $\mu'_{j}$ are the probability amplitudes of the excitons in different particle-number state. Then let us make an eigen-equation $H|\Omega_k\rangle = \Omega_k|\Omega_k\rangle$ and we can get a discrete scattering equation

\begin{equation}
(\omega - \Omega_k + \frac{\Omega_R^2}{\Omega_k - \varepsilon_{ex}(0)}\delta_{j,0})\mu_k(j) = \xi\{\mu_k(j+1) + \mu_k(j-1)\}
\end{equation}

We should notice that the eigen-vector only involve two sub-state. One is only a photon in the waveguide and the other is only one exciton excited. Actually, we may go beyond this regime and we add one or more excitons to the QWs’ plane, but the theory we give here fail because more than one photon can exist for excited emission of excitons and this rule out the assumption that only one photon propagate in the waveguide. This is because that if no more than one exciton exist, exciton-exciton interaction can be neglected, so this is not a many-body problem and we can get analytical result for this problem.

**III. REFLECTION COEFFICIENT AND TRANSMISSIVITY**

With the discrete scattering equation, and considering its similarity to standard quantum mechanics scattering problem, we assume the solution of this equation is

\begin{align*}
\mu_k(j) &= \{e^{ikj} + re^{-ikj}\}(j < 0), \\
\mu_k(j) &= se^{ikj}(j > 0)
\end{align*}

$r, s$ are the reflection and transmission amplitudes. Then we insert assumed solution above to eq.(8) and get

\begin{align*}
R &= \vert r \vert^2 \\
T &= 1 - R
\end{align*}

\begin{align*}
R &= \frac{1}{1 + 4(\frac{\xi}{\Omega_R})^2 \sin^2(k)(\omega/\Omega_R - \varepsilon_{ex}(0)/\Omega_R - 2\xi/\Omega_R \cos(k))^2} \\
T &= \frac{4(\frac{\xi}{\Omega_R})^2 \sin^2(k)(\omega/\Omega_R - \varepsilon_{ex}(0)/\Omega_R - 2\xi/\Omega_R \cos(k))^2}{1 + 4(\frac{\xi}{\Omega_R})^2 \sin^2(k)(\omega/\Omega_R - \varepsilon_{ex}(0)/\Omega_R - 2\xi/\Omega_R \cos(k))^2}
\end{align*}

Figs. 1, 2 show the reflection and transmission coefficients as a function of momentum $k$, respectively. Fig.3 combines both of coefficients. From these results, we see the system
can be considered as a semiconductor switch where we might control excitons’ parameters so as to make a giant influence on the photon’s propagating in this semiconductor microcavity waveguide. The corresponding system has been studied in optical system(or called cavity quantum electrodynamics) by using a two-level atom as a controller recently[10]. And our system is a conventional solid state system, this may be achieved at several kelvin[16, 17, 18].

Apparently, this is a good result because we have a parameter-dependence reflection coefficient and transmissivity for all existing quantities, however, in fact we do not know these parameters directly. Instead, we change this into another form

\[ R(\delta) = \frac{1}{1 + 4\left(\frac{\xi}{\Omega R}\right)^2\delta^2\left[1 - \left(\frac{\delta - \omega + \varepsilon_{ex}(0)}{2\xi}\right)^2\right]} \]  

\[ T(\delta) = \frac{4\left(\frac{\xi}{\Omega R}\right)^2\delta^2\left[1 - \left(\frac{\delta - \omega + \varepsilon_{ex}(0)}{2\xi}\right)^2\right]}{1 + 4\left(\frac{\xi}{\Omega R}\right)^2\delta^2\left[1 - \left(\frac{\delta - \omega + \varepsilon_{ex}(0)}{2\xi}\right)^2\right]} \]  

and parameters in this form can be easily measured from photoluminescence experiments[15, 30, 31]. Here \( \delta = \omega - \varepsilon_{ex}(0) - 2\xi \cos(k) \) is detuning of photons and excitons (it is quite different from conventional definition and we will discuss this below). Figs. 4, 5 show result of eq.(14) and eq.(15) where we find detuning is a quite important parameter and an easily controllable quantity in this waveguide[15]. Fig.6 shows two coefficients of reflection and transmission changing with different detuning. Generally, in semiconductor microcavity detuning (there the detuning is defined as \( \delta = \varepsilon_{ph}(k = 0) - \varepsilon_{ex}(k = 0) \)), which is smaller than Rabi frequency(\( \Omega_R \)), and this means that \( \omega - \varepsilon_{ex}(0) \) is smaller than \( \Omega_R \) in our paper[15], so in Figs.1, 2, 3, 4, 5 and 6, we choose \( \omega = \varepsilon_{ex}(0) = 100\Omega_R, \xi = 2\Omega_R \) for the energy of photons or excitons, which is the order of eV while \( \Omega_R \) is two orders lower than them[3, 4] in semiconductor microcavity.

IV. EFFECT OF DECAY FOR EXCITONS

In solid state systems, excitons are elementary excitations of electrons and holes in semiconductor, and they will decay due to interactions with other particles, for example phonons, free electrons or holes. For simplicity, we can let \( \varepsilon_{ex}(0) = \varepsilon_{ex}(0) - i\Gamma \) and \( \Gamma \) is a phenomenological decay rate that accounts for interactions mentioned above (but decay of excitons due to phonons which are excited by temperature is essential for no pumping of other particles).
Then we can get the new reflection and transmission coefficients by using this replacement.

\[ R = \frac{1}{(1 + \frac{2\xi \sin(k)\Gamma}{\Omega R})^2 + 4(\frac{\xi}{\Omega R})^2 \sin^2(k)(\omega/\Omega_R - \varepsilon_{ex}(0)/\Omega_R - 2\xi/\Omega_R \cos(k))^2} \]  (16)

But transmission coefficient \( T \neq 1 - R \) and \( T = |s|^2 = |1 + r|^2 = 1 + r + r^* + R \). This is quite common for we include dissipation in our model system, and particles (here the excitons) may be absorbed by the environment around them. Exciton is excited by the incident photon and conservation for the number of excitation will fail if exciton decays (absorbed by environment). To compare with non-dissipation reflection coefficient, we have to estimate the magnitude of \( \Gamma \). Here, we know the intrinsic exciton lifetime is about 100 ps (for temperature is 4K) \[9\], and we estimate \( \Gamma \sim 0.01 \Omega_R \). This result are shown in Fig. 7, and we see the central peak is nearly unchanged, but intensity of the second peak on the right is not unity (about 90 percent) due to the dissipation (but in optical waveguide proposed by Lan Zhou et al. \[10\], we use conventional parameters \[32\] to estimate the effect of dissipation and we find this value is about 60 percent impressively). However, the second peak on the left do not show this effect, because initially we only consider a photon propagate from left to the right of the waveguide what results in this asymmetry.

One may ask the reason why we here do not consider the decay of photons, this is because in the microcavity, if photons escape from the cavity, we call this decay, but here do not exist this one and it has been included in the hopping term of photonic Hamiltonian \( H_{ph} \), and other channels of decay are so weak in comparison with decay of excitons \[15\].

V. SUMMARY

In this paper we model a Hamiltonian for transport of a single photon in semiconductor microcavity waveguide, then we deal with eigen-equation of this scattering and get reflection and transmission coefficients from this equation. Parameters in two coefficient can be easily measured using usual solid state method (photoluminescence experiments). Two reflection coefficients have been derived and discussed. We show that the photon in coupled semiconductor microcavity waveguide can be controlled by in-plane excitons in quantum well. And we also investigate the effect of decay for excitons and this shows reduction of reflection intensity for various momentum although the reduction is about 10 percent at 4K. For applications, the higher the practical temperature, the more attractive the setup. And this is
the reason we are interested in this semiconductor system. We think it is also a candidate for quantum information process mentioned in the introduction of this paper.

But we here consider the waveguide as an ideal one, in other words, the number of cavity in the waveguide is infinite and in reality this has to be modified, so a more carefully consideration should solve this problem and effect of temperature also has to be more carefully deal with for this will strongly enforce the interaction between excitons and phonons[15] and we here only include this effect in the energy of excitons phenomenologically. After all, we analyze the scattering of a single photon in semiconductor microcavity waveguide and we propose experiments may be done in semiconductor systems for its high practical temperature, easily fabrication and measurement[15].

VI. ACKNOWLEDGEMENTS

This work was partly supported by the National Natural Science Foundation of China under Grant No.10704031, the National Natural Science Foundation of China for Fostering Talents in Basic Research under Grant No.J0730314, the Fundamental Research Fund for Physics and Mathematics of Lanzhou University under Grant No. Lzu05001, and the Nature Science Foundation of Gansu under Grant No. 3ZS061-A25-035.

[1] H. Deng, G. Weihs, D. Snoke, J. Bloch and Y. Yamamoto, Proc. Natl. Acad. Sci. U.S.A. 100 15318 (2003).
[2] D. Snoke, Science 298 1368 (2002).
[3] S. I. Tsintzos, N. T. Pelekanos, G. Konstantinidis, Z. Hatzopoulos and P. G. Savvidis, Nature(London). 453 372 (2008).
[4] J. Kasprzak, M. Richard, S. Kundermann, A. Baas, P. Jeambrun, J. M. J. Keeling, F. M. Marchetti, H. M. Szymanska, R. Andre, J. L. Staehli, V. Savona, P. B. Littlewood, B. Deveaud and Le Si Dang, Nature(London). 443 409 (2006).
[5] G. Khitrova, H. M. Gibbs, F. Jahnke, M. Kira and S. W. Koch, Rew. Mod. Phys. 71 1591 (1999).
[6] N. Y. Kim, Chih-Wei Lai, S. Utsunomiya, G. Roumpos, M. Fraser, H. Deng, T. Byrnes, P.
Recher, N. Kumada, T. Fujisawa and Y. Yamamoto, Phys.Stat.Sol.(b) 245 1076 (2008).
[7] R. Balili, V. Hartwell, D. Snoke, L. Pfeiffer and K. West, Science 316 1007 (2007).
[8] R. Balili, B. Nelsen and D. W. Snoke, Phys.Rev.B 79 075319 (2009).
[9] O. L. Berman, Y. E. Lozovik and D. W. Snoke, Phys.Rev.B 77 155317 (2008).
[10] Lan Zhou, Z. R. Gong, Yu-Xi Liu and C. P. Sun, Phys.Rev.Lett. 101 100501 (2008).
[11] Jung-Tsung Shen and Shanhui Fan, Phys. Rev. A 79, 023837 (2009).
[12] Jung-Tsung Shen and Shanhui Fan, Phys. Rev. A 79, 023838 (2009).
[13] Lan Zhou, Jing Lu and C. P. Sun, Phys.Rev.A 76 012313 (2007).
[14] F. M. Hu, Lan Zhou, Tao Shi and C. P. Sun, Phys.Rev.A 76 013819 (2007).
[15] A. Kavokin and G. Malpuech, Thin films and Nanostructures:Cavity Polaritons (Volume 32,Elsevier) (2003)
[16] P. Senellart, J. Bloch, B. Sermage and J. Y. Marzin, Phys.Rev.B 62 R16263 (2000).
[17] C. Weisbuch, M. Nishioka, A. Ishikawa and Y. Arakawa, Phys.Rev.Lett. 69 3314 (1992).
[18] Hui Deng, D. Press, S. Gôtzingier, G. S. Solomon, R. Hey, K. H. Ploog and Y. Yamamoto, Phys.Rev.Lett. 97 146402 (2006).
[19] P. R. Eastham and P. B. Littlewood, Phys.Rev.B 64 235101 (2001).
[20] J. J. Baumberg, A.V. Kavokin, S. Christopoulos, A. J.D. Grundy, R. Butte, G. Christmann, D.D. Solnyshkov, G. Malpuech, G. Baldassarri Höger von Högersthal, E. Felin, J. F. Carlin and N. Grandjean, Phys.Rev.Lett. 101 136409 (2008).
[21] S. Chu, Rev.Mod.Phys. 70 685 (1998).
[22] C. N. Cohen-Tannoudji, Rev.Mod.Phys. 70 707 (1998).
[23] W. D. Phillips, Rev.Mod.Phys. 70 721 (1998).
[24] R. B. Balili, D. W. Snoke, L. Pfeiffer and K. West, Appl.Phys.Lett. 88 031110 (2006).
[25] C. Ciuti, P. Schwendimann and A. Quattropani, Phys.Rev.B 63 041303(R) (2001).
[26] De-Leon S. Ben-Tabou and B. Laikhtman, Phys.Rev.B 63 125306 (2001).
[27] C. Ciuti, V. Savona, C. Piermarocchi, A. Quattropani and P. Schwendimann, Phys.Rev.B 58 7926 (1998).
[28] A. Altland and B. Simons, Condensed Matter Field Theory (Cambridge University Press) (2006).
[29] N. W. Ashcroft and N. D. Mermin, Solid State Physics (Harcourt College Publishers) (1976).
[30] A. A. Khalifa, A. P. D. Love, D. N. Krizhanovskii, M. S. Skolnick and J. S. Roberts,
Appl.Phys.Lett. 92 061107 (2008).

[31] D. Bajoni, P. Senellart, E. Wertz, I. Sagnes, A. Miard, A. Lemaître and J. Bloch, Phys.Rev.Lett. 100 047401 (2008).

[32] P. Maunz, T. Puppe, I. Schuster, N. Syassen, P. W. H. Pinkse and G. Rempe, Nature(London) 428 50 (2004).
FIG. 1: Reflection coefficient $R$ as a function of momentum $k$ with $\xi = 2\Omega_R, \omega = \varepsilon_{ex}(0) = 100\Omega_R$
FIG. 2: Transmission coefficient $T$ as a function of momentum $k$ with $\xi = 2\Omega_R, \omega = \varepsilon_{\text{ex}}(0) = 100\Omega_R$
FIG. 3: Reflection (dash line) and transmission (solid line) coefficients as a function of momentum $k$ with $\xi = 2\Omega_R, \omega = \varepsilon_{ex}(0) = 100\Omega_R$.
FIG. 4: Reflection coefficient $R$ as a function of detuning $\delta$ with $\xi = 2\Omega_R \omega = \varepsilon_{ex}(0) = 100\Omega_R$
FIG. 5: Transmission coefficient $T$ as a function of detuning $\delta$ with $\xi = 2\Omega_R, \omega = \varepsilon_{ex}(0) = 100\Omega_R$
FIG. 6: Reflection (dash line) and transmission (solid line) coefficients as a function of detuning $\delta$
with $\xi = 2\Omega_R, \omega = \varepsilon_{ex}(0) = 100\Omega_R$
FIG. 7: Reflection coefficient $R$ as a function of momentum $k$ with $\xi = 2\Omega_R, \omega = \varepsilon_{ex}(0) = 100\Omega_R$ and $\Gamma = 0.01\Omega_R$.