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# Abnormal photon-assisted current in a two-level quantum dot system with the time-varying external field

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ABSTRACT

We have studied the photon-assisted current properties in a two-level quantum dot (QD) system, where the QD and two normal metal leads are simultaneously irradiated by the time-varying external field. In contrast to the monotonous variety with the strength of the external field irradiated only on two leads or only on the QD, here the photon-assisted current presents some abnormal properties. The results show that, when the external field on the two leads is symmetrical and the strength is not changed, the current sideband peaks of the ground state become gradually weaker and weaker, whereas the main resonance becomes much stronger as $W_C$ is increased, where $W_C$ is the external field intensity irradiated on the central QD. The current properties of photon-induced excited state get more complicated. Its right sideband peak disappears in the presence of $W_C$. While the external field on the two leads is completely asymmetrical, the accession of $W_C$ could control the photon–electron pumping effect, which is not only a non-monotonic variation but also changes current direction. Moreover, $W_C$ also has an inhibitory influence on the multi-photon process.



## 1. Introduction

Photon-assisted electron transport in quantum dot (QD) systems is one of the hot issues in condensed matter physics and optical domain. The strong interaction with time-varying external field in such low-dimensional systems leads to completely new ways of electron transport and the emergence of novel many-body transport phenomena [1–12]. Kouwenhoven et al. [1] studied photon-assisted tunneling (PAT) through a GaAs/AlGaAs QD. They observed, in current-gate voltage curves, that a shoulder emerges on the left of the Coulomb peak and a negative current (so-called photon–electron pumping effect) emerges on the right when a microwave (MW) field is only applied on one lead of the system, and demonstrated that the change of the shoulder and negative current is related to the intensity of the MW field. Then, these phenomena were theoretically investigated by Sun et al. [2] using the non-equilibrium Green's function method under the wide band limit, while the external MW field is applied to the dot and two leads, respectively. In addition, Chen and Zhao et al. investigated the photon-assisted shot noise due to the charging effect [3] or the Knodo effect [4], and the photon-assisted heat generation [5,6] in the quantum dot device by varying the frequency or the magnitude of the MW field applied to the QD and the two leads. Furthermore, the group of Taranko [7–9] used the evolution operator method to study electron tunneling through the QD system. The external MW field is applied to both the dot and leads. The influence of the singularities of the lead density of states on the PAT peaks was discussed. These reports all pointed out that the height of the shoulder and the magnitude of the negative current were enhanced as the intensities of the MW field only irradiated on the one lead increased. Meanwhile, the PAT through a QD with two states in the presence of MW field was studied in experiment [10] and in theory [11]. Both the sidebands of the photon-assisted tunneling originating from the ground state and, in particular, from the excited state were obtained when the MW field was symmetrically applied only on the two leads. With the increase of the external field intensity, they found the one-photon sidebands of the main resonance as well as those of the excited state resonance coming up and becoming more apparent. Recently, the PAT experiments in a carbon nanotube QD have also been reported with MW [12] and Terahertz (THz) [13] irradiated on the nanotube QD. The results showed that the peaks attributed to the transport through excited states are more apparent at high power while the main resonance decreases. Very recently, Shibata et al. [14,15] have investigated electron transport through single self-assembled InAs QDs under THz wave irradiation, and given

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the current curves as the function of the gate voltage under several THz powers, in which the current at the side-peaks gradually increases with increasing THz power. In a word, the photon–electron pump, sideband effect and photon-induced excited state resonance are more apparent with the enhancement of the intensity of time-varying external field.

However, all the works mentioned above have not investigated the influence of the intensity of time-varying external field irradiated on QD in detail, when the field is applied simultaneously to the two leads and the QD. Although in previous works [2,3,7–9,16] the time-varying external field has been induced simultaneously to two leads and the QD, the external field irradiated on the QD is just fixed. On the view of the development of nanoscience and nanotechnology, the controllability of PAT in the quantum system has been enhanced, which ensures the feasibility of tuning the time-varying external field on the QD and the two leads simultaneously. Moreover, the photon-assisted current has not been paid more attention in a two-levle QD system, in which the photon-induced excited state resonance can be observed, when time-varying external field is applied simultaneously to the QD and two leads but only the intensity of it on QD is controlled. In this sense, it is interesting to take into account this question in detail.

In this paper, we are going to investigate the response of PAT through a two-level QD coupled with two normal metal leads with tuning the intensity of time-varying external field on QD, when it is applied simultaneously to the QD and the two leads. It is found that, when the time-varying external field is symmetrically applied to the two leads, the current sideband peaks of the ground state become gradually weaker and weaker, while the main resonance becomes much stronger as $W_C$ is increased, where $W_C$ is the external field intensity irradiating on the central QD. The photon-induced excited state resonance and its sideband peak on the left of the current curve get more complicated. Its right sideband peak disappears in the presence of $W_C$. For the completely asymmetrical external field case, the accession of $W_C$ could control the photon–electron pumping effect and change the direction of the current. Moreover, $W_C$ also has an inhibitory influence on the multi-photon process.

## 2. Model and formulation

In this paper we discuss a QD system with two levels, i.e., the ground state $\varepsilon_0$and the first excited state $\varepsilon_1$, when the time-varying external field has been applied simultaneously to the QD and the two leads. We also take into account the intradot electron–electron Coulomb interaction U. The system under our consideration is described by the Hamiltonian:

$$H = \sum_{\alpha \in S,D} \varepsilon_\alpha(t) c_\alpha{}^+ c_\alpha + \sum_{j=0,1} \varepsilon_{C_j}(t) d_j{}^+ d_j + U d_0{}^+ d_0 d_1{}^+ d_1 + \sum_{\alpha \in S,D,j} V_{\alpha,j} c_\alpha{}^+ d_j + H.c. \tag{1}$$

where $c_\alpha{}^+(c_\alpha)$ and $d_j{}^+(d_j)$ are the creation (annihilation) operators of the electronic states in the source (drain) electrode and the central QD, respectively. As for the time-varying external field, we take the adiabatic approximation [17–18], in which external field can be described by an oscillating potential and it only causes the single-electron energy spectrum a rigid shift: $\varepsilon_\beta(t) = \varepsilon_\beta + W_\beta(t)$, where $\beta = C,S,D$ denote the central QD, the source, and the drain electrode, respectively. $\varepsilon_\beta$ is the time-independent single electron energy without external field, and $W_\beta(t)$ is the time-dependent external field with $W_\beta(t) = W_\beta \cos \omega t$. The latter two terms denote the tunneling part that is time independent. The current flowing out of the reservoir $\alpha$ can be defined as the rate of change in the number of electrons in electrode $\alpha$, which can be calculated through the commutator of the electron number operator $\hat{N}_\alpha = \sum_\alpha c_\alpha^+ c_\alpha$ with the Hamiltonian. Using the formulism of time-dependent Green's function, the current flowing out of the source electrode is given by ($\hbar = 1$)

$$I_S(t) = -2eIm \int_{-\infty}^{t} dt_1 \int \frac{d\varepsilon}{2\pi} \sum_j e^{-i\varepsilon(t_1-t)} e^{-i\int_t^{t_1} W_S(\tau)d\tau} \Gamma_j^S(\varepsilon)[G_{jj}^<(t,t_1) + f_S(\varepsilon) G_{jj}^r(t,t_1)] \tag{2}$$

where $f_\alpha(\varepsilon) = f(\varepsilon - eV_\alpha)$ is the Fermi distribution function of electrons in the $\alpha$ electrode, $V_\alpha$ is the dc bias, $\Gamma_j^S(\varepsilon) = 2\pi\rho_S(\varepsilon) V_{\alpha,j} V_{\alpha,j}^*$ is the generalized linewidth function, and $\rho_S(\varepsilon)$ is the density of states in the source electron. Here, we take the wide bandwidth approximation [19], which is independent of the energy level. Then using the Keldysh equation, $G_{jj}^<(t,t')$ is related to the retarded Green function $G_{jj}^r(t,t')$, as

$$G_{jj}^<(t,t') = \iint dt_1 dt_2 G_{jj}^r(t,t_1) \textstyle\sum_{jj}^<(t_1,t_2) G_{jj}^a(t_2,t') \tag{3}$$

and the self-energy function $\sum_{jj}^<(t_1,t_2)$ is

$$\textstyle\sum_{jj}^<(t_1,t_2) = i \displaystyle\int \frac{d\varepsilon}{2\pi} e^{-i\varepsilon(t_1-t_2)} \sum_{\alpha \in S,D} f_\alpha(\varepsilon) \Gamma_j^\alpha e^{-i\int_{t_2}^{t_1} W_\alpha(\tau)d\tau} \tag{4}$$

Since $\langle I_S(t)\rangle = -\langle I_D(t)\rangle = \langle I\rangle$, the average current $\langle I\rangle$ is

$$\langle I\rangle = -2e\sum_j \frac{\Gamma_j^S \Gamma_j^D}{\Gamma_j^S + \Gamma_j^D} \int \frac{d\varepsilon}{2\pi} [f_S(\varepsilon)\langle Im A_j^S(\varepsilon,t)\rangle - f_D(\varepsilon)\langle Im A_j^D(\varepsilon,t)\rangle] \tag{5}$$

where

$$A_j^\alpha(\varepsilon,t) = \int_{-\infty}^{t} dt_1 G_{jj}^r(t,t_1) e^{-i\varepsilon(t_1-t) - i\int_{t_2}^{t_1} W_\alpha(\tau)d\tau} \tag{6}$$

By using the Dyson equation and the equation of motion (EOM), we can solve the retarded Green function. Here we take higher-order cutoff approximation to get the photon-induced excited-state resonances. In addition, we make further simplifications: the occupation number of the state $j$ $n_j(t)$is replaced by its average value $n_j$[11].

By the method of iteration, we can get the retarded Green function

$$G_{jj}^r(t,t') = [1-n_{\bar{j}}] g_{\varepsilon_j}^r(t,t') e^{-\frac{\Gamma_j}{2}(1-n_{\bar{j}})(t-t')} + n_{\bar{j}} g_{\varepsilon_j+U}^r(t,t') e^{-\frac{\Gamma_j}{2} n_{\bar{j}}(t-t')} \tag{7}$$

Substituting the expression of $G_{jj}^r(t,t')$into Eq. (6), $A_j^\alpha(\varepsilon,t)$becomes

$$A_j^\alpha(\varepsilon,t) = \sum_{k,k'} J_k\left(\frac{W_C - W_\alpha}{\omega}\right) J_{k'}\left(\frac{W_\alpha - W_C}{\omega}\right) e^{i(k+k')\omega t} \times \left\{ \frac{1-n_{\bar{j}}}{\varepsilon - \varepsilon_j - k'\omega + i\frac{\Gamma_j(1-n_{\bar{j}})}{2}} + \frac{n_{\bar{j}}}{\varepsilon - \varepsilon_j - U - k'\omega + i\frac{\Gamma_j n_{\bar{j}}}{2}} \right\} \tag{8}$$

Substituting $A_j^\alpha(\varepsilon,t)$ into Eqs. (2) and (5), the time-dependent current $I_S(t)$ and the average current $\langle I\rangle$ are obtained immediately. Notice that these formulas of the current satisfy the gauge invariance in the following sense: if the voltages of the left lead, the right lead, and the gate voltage $\nu_g$ (which controls the intradot electron energy levels $\varepsilon_j = \varepsilon_j^0 + e\nu_g$) are shifted by the same amount, the current does not change. The current $\langle I(t)\rangle$ can be separated into two parts $I_0(t)$ and $I_1(t)$, where $I_j(t)(j=0,1)$ is the current through the state $j$.

In numerical studies, we take the following approximations: (1) $U = \infty$, the second term in the bracket of $A_j^\alpha(\varepsilon,t)$, Eq. (8), becomes zero; (2) the symmetrical barriers ($\Gamma_j^L = \Gamma_j^R$), then the average current reduces to

$$\langle I\rangle = \sum_{j=0,1} \langle I_j\rangle = e\sum_j \Gamma_j^S \Gamma_j^D \int \frac{d\varepsilon}{2\pi} \sum_k \left\{ f_S(\varepsilon) J_k^2\left(\frac{W_C - W_S}{\omega}\right) - f_D(\varepsilon) J_k^2\left(\frac{W_C - W_D}{\omega}\right) \right\}$$