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Ultrafast single-electron transfer in coupled quantum dots driven by a few-cycle chirped pulse

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We theoretically study the ultrafast transfer of a single electron between the ground states of a coupled double quantum dot (QD) structure driven by a nonlinear chirped few-cycle laser pulse. A time-dependent Schrödinger equation without the rotating wave approximation is solved numerically. We demonstrate numerically the possibility to have a complete transfer of a single electron by choosing appropriate values of chirped rate parameters and the intensity of the pulse. Even in the presence of the spontaneous emission and dephasing processes of the QD system, high-efficiency coherent transfer of a single electron can be obtained in a wide range of the pulse parameters. Our results illustrate the potential to utilize few-cycle pulses for the excitation in coupled quantum dot systems through the nonlinear chirp parameter control, as well as a guidance in the design of experimental implementation. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4871400]

I. INTRODUCTION

Recent technological advances in ultrafast optics have resulted in the generation of laser pulses as short as a few optical cycles conveniently.[1] The few-cycle pulses have been extensively studied both experimentally and theoretically owing to the wide applications, such as exploring the dynamic behavior of matter on ever-shorter timescales, and studying light-matter interactions at unprecedented intensity levels.[1] Specifically, ultrashort pulses can excite coherence on high-frequency transitions that may be used for efficient generation of extreme ultraviolet radiation.[2] Shaped pulses can control transient population dynamics or create optimal coherence in atomic system.[3–11]

On the other hand, it has been noted that ultrasmall semiconductor quantum dots (QDs), also called "artificial atoms," are analogous to real atoms and possess many intrinsic characteristics of atomic physics.[12] However, it is more advantageous at least from the viewpoint of practical purposes to find, instead of real atom gases, solid media that could provide different energy scales and physical features which can be easily varied over a wide range of parameters. These flexible systems represent an ideal platform for theoretical and experimental investigations, where the interactions between light and matter can be studied in a fully controlled, well characterized environment, and with excellent optical and electrical probes. These features make semiconductor QDs promising candidates for applications in electro-optical devices together with the gate technology. Thus, the study of external influences on quantum dots becomes an important topic.[13]

To date, the effect of time-varying external fields on electronic population transfer in semiconductor QD systems has attracted considerable attention and manifest some interesting effects ranging from photon-assisted tunneling to electron pumping.[13–36] Many theoretical and experimental schemes for controlling transfer of one-electron or two-electron in coupled QD system have been reported,[22–40] and experimental methods to determine the interdot tunnel coupling both for ground and excited states have been developed.[23,24] As an example, stimulated Raman adiabatic passage (STIRAP) is a very popular method to produce completed population transfer in the quantum dot structure.[25–30] The STIRAP technique uses the counter-intuitive delayed laser pulses to adiabatically correlate the initial populated state to the desired target state during the system evolution. However, the adiabatic condition limits the pulse width in the nanosecond time scale. As pointed out in Ref. 1, the use of ultrashort pulse lasers to obtain population transfer may have some spectral benefits, such as easy to control the population distribution on the ultrafast process. However, up to now, there has been little investigations of the use of few-cycle pulses for inducing and controlling a single electron transfer in the semiconductor QD systems.

Motivated by this, we systematically study the dynamics of coherent transfer of a single electron in a coupled double QD system. We focus on the high-efficiency transfer of an electron between the localized ground states of the coupled QDs, driven by the application of a chirped few-cycle pulse. We numerically solve the time-dependent Schrödinger equations, and show that a complete transfer of a single electron between the ground states of the coupled QDs is possible for the values of the chirp rate parameter and the intensity of the pulse. Even in the presence of the decay and dephasing processes, high-efficiency coherent transfer of a single electron can be obtained in a wide range of chirp parameters and intensity of the pulse. Our study not only provide an efficient tool to manipulate the quantum dynamics of QD system with

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adjustable chirped rates but also represents an achievement in this direction, and the results may have potential application in the development of novel optoelectronic devices and solid-state quantum information science.

II. MODEL HAMILTONIAN FOR COUPLED QUANTUM DOTS

The QD system under consideration is illustrated in Fig. 1.[29–38] The device is composed of two nonidentical quantum dots, marked as left (L) and right (R) dots, respectively. Usually, the coupled QD structures are described as a quasi-one-dimensional problem.[12] We consider that the two dots are taken to be widely separated, the wave functions of the lowest states $|l\rangle$ and $|r\rangle$ with the energies ε_l and ε_r, respectively, are localized in the corresponding QDs. The parameters of the system, i.e., the size of the dots, the width of the potential wells, and the height of barriers, are chosen such that this structure supports only one excited state $|e\rangle$ whose energy ε_e lies just below the top of potential barriers separating the QDs, so that the wave function is delocalized over both QDs. Considering the coulomb blockade regime, only a single electron is allowed to enter into the QD system. Since the two dots are widely separated, the energy level $|l\rangle$ ($|r\rangle$) is essentially localized in the left (right) dot. Thus, the tunneling of an electron through the potential barrier between these energy levels is very improbable. As it becomes obvious from Fig. 1, we will study the dynamics of this system by a three-level Λ-type scheme as for certain external applied field, for example, a few-cycle chirped pulse that couples near resonantly the ground states $|l\rangle$ and $|r\rangle$ to the excited state $|e\rangle$. Such a three-level system is available in a realistic QD device.[21,24,28]

The transitions $|l\rangle \leftrightarrow |e\rangle$ and $|r\rangle \leftrightarrow |e\rangle$ are driven by a few-cycle laser pulse. The electric field of the few-cycle pulse $E(t)$ is described by

$$E(t) = E_0\xi(t)\cos[\omega t + \varphi(t)], \tag{1}$$

where $\xi(t) = e^{-(t-2\tau)^2/\tau^2}$ is the laser field envelope, E_0 is the pulse amplitude, τ describes the pulse duration, full width at half maximum (FWHM), and ω is the laser frequency ($T_0 = 2\pi/\omega$ is an optical oscillation cycle time). The carrier envelope phase (CEP), $\varphi(t)$, describes the time-dependent offset of the peak laser pulse relative to the peak position of the envelope. The time profile of the time-varying CEP, $\varphi(t)$, considered in this work, has the following time-varying hyperbolic form:

$$\varphi(t) = -\eta\cosh\left(\frac{t-2\tau}{\tau_c}\right), \tag{2}$$

where η indicates the frequency sweeping range and τ_c indicates the steepness of the chirping function. The chirp form is controlled by adjusting these two parameters η and τ_c. Due to the recent advancement of comb laser technology, it is highly likely that such a time-varying CEP can be achieved in the near future.[41] First of all, we present the effects of chirped frequency on the laser pulse. Fig. 2 shows the electric field form with time-varying CEP $\varphi(t)$ achieved by fixing $\tau_c = 4.84$ ps while varying the η parameter. When $\eta = 0$, the CEP is 0, and the pulse is chirp free. It is evident that reshaping the laser pulse by chirping the frequency of the laser pulse has a direct consequence of breaking the oscillatory of the laser field. On the other hand, the amplitude of envelope for laser pulses remains invariant to the chirped frequency.

The Hamiltonian of our double QD system can be described by

$$\begin{aligned} H = {} & (\varepsilon_l - \varepsilon_e)|l\rangle\langle l| + (\varepsilon_r - \varepsilon_e)|r\rangle\langle r| + \hbar\{\Omega\xi(t) \\ & \times \cos[\omega t + \varphi(t)]|l\rangle\langle e| + q\Omega\xi(t) \\ & \times \cos[\omega t + \varphi(t)]|r\rangle\langle e| + H.c.\}, \end{aligned} \tag{3}$$

where $2\Omega = \mu_{le}E_0/\hbar$ and $2q\Omega$ are the Rabi frequency for the transitions $|l\rangle \leftrightarrow |e\rangle$ and $|r\rangle \leftrightarrow |e\rangle$ with the corresponding electric dipole moments for the corresponding transitions μ_{le} and μ_{re}. The parameter q is defined as the ratio of the transition dipole moments $q = \mu_{re}/\mu_{le}$. The energy for the levels $|j\rangle$ ($j = l,r,e$) is denoted by ε_j. We express the eigenstate of an electron in the double QD structure as a linear combination of the three wave functions ψ_j, i.e., $\psi(t) = C_l(t)\psi_l + C_r(t)\psi_r + C_e(t)\psi_e$, here the coefficients C_l, C_r, and C_e imply the probability for finding the electron in states ψ_l, ψ_r, and ψ_e, respectively. Moreover, the coefficients satisfy the simple normalization $|C_l(t)|^2 + |C_r(t)|^2 + |C_e(t)|^2 = 1$.[42,43]

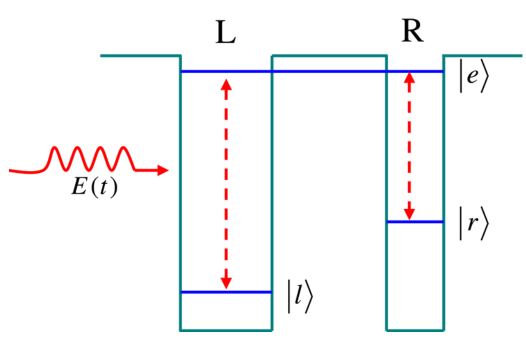

FIG. 1. Schematic diagram of the asymmetric coupled quantum dot structure we studied here. The system possess two non-degenerated lower levels ($|l\rangle$ and $|r\rangle$), and one upper level ($|e\rangle$). A few-cycle laser pulse $E(t)$ couples the ground states ($|l\rangle$ and $|r\rangle$) to an excited state ($|e\rangle$).

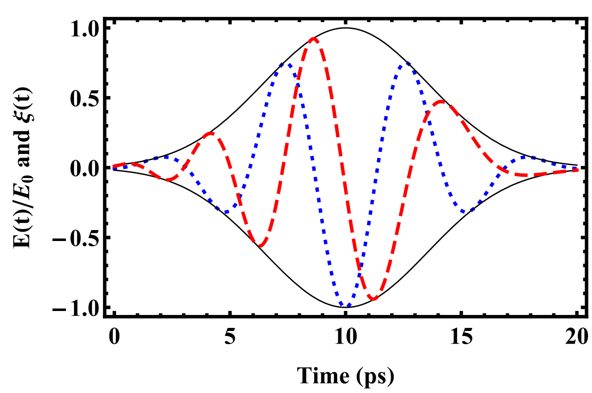

FIG. 2. Effects of the chirped frequency on the electric field of laser pulse $E(t)$. The dotted and dashed lines indicate the corresponding chirp-free ($\eta = 0$) and chirped ($\eta = 0.63$) laser pulses, respectively. The solid lines indicate the envelope of the laser pulse. Other parameters are $\hbar\omega = 0.75$ meV, and $\tau = 5$ ps.

Substituting $\psi(t)$ and H into the Schrödinger equation, $i\hbar\partial\psi(t)/\partial t = H\psi(t)$ and we can obtain a coupled equation of motion for the amplitudes $C_j(t)$ ($\hbar = 1$)

$$\dot{C}_l(t) = i\Omega\xi(t)\cos[\omega t + \varphi(t)]C_e(t) + i(\varepsilon_l - \varepsilon_e)C_l(t), \quad (4)$$

$$\dot{C}_r(t) = iq\Omega\xi(t)\cos[\omega t + \varphi(t)]C_e(t) + i(\varepsilon_r - \varepsilon_e + i\gamma_r)C_r(t), \quad (5)$$

$$\dot{C}_e(t) = i\Omega\xi(t)\cos[\omega t + \varphi(t)]C_l(t) + iq\Omega\xi(t)\cos[\omega t + \varphi(t)]C_r(t) - \gamma_e C_e(t), \quad (6)$$

where the decay rates γ_j ($j=r,e$) are included phenomenologically in the above equations. The decay γ_j comprises the spontaneous emission decay γ_{jp} as well as the phonon-induced dephasing contribution γ_{jd} or $\gamma_j = \gamma_{jp} + \gamma_{jd}$. A more complete theoretical treatment taking into account these processes for the dephasing rates is beyond the scope of this paper, but, as a working approximation, the decay rates can be estimated based on the Ref. 44. In Eqs. (4)–(6), we have used the Schrödinger formalism for describing the dynamics of this interacting system. The density matrix formalism is also adapted for obtaining the desired dynamical observances of the system such as population probability ρ_{jj}, coherence ρ_{ij} by directly solving the density matrix equation numerically. However, using the Schrödinger formalism, one needs a conversion between the probability amplitudes $C_j(t)$ and the probability $\rho_{jj}(t)$, coherence $\rho_{ij}(t)$, i.e., $\rho_{jj}(t) = C_j(t)C_j^*(t) = |C_j(t)|^2$ and $\rho_{ij}(t) = C_iC_j^*(t)$.[45–47]

III. SIMULATION RESULTS

In order to investigate the dynamic response of the ultrafast transfer for a single electron through the coupled QD driven by a time-dependent few-cycle chirped pulse as shown in Fig. 1, we employ the fourth-order Runge–Kutta algorithm approach for solving the time-dependent differential equations (4)–(6) with the initial condition, i.e., $C_l(0) = 1$, $C_r(0) = C_e(0) = 0$. As mentioned above, this initial condition corresponds to the localization of a single-electron in the left dot. Based on above probability amplitudes Eqs. (4)–(6), we calculate numerically the time evolution of population, $|C_j|^2$. It is the value of $|C_r|^2$ used to describe the coherent transfer of a single-electron between the ground states of coupled QD.

Before discussing the numerical results, we address typical values of the parameters for QD system in GaAs/$Al_xGa_{1-x}As$. Coulomb charging energies are of a few meV and set the largest energy scale so that states with more than one additional transport electron can be neglected. Typical excitation energies $\Delta\varepsilon_j$ from the ground states $|j\rangle$ ($j = l,r$) are of the order of a few hundred μeV.[21,24,28] In our simulation, the QD system parameters are estimated by setting $\varepsilon_l - \varepsilon_e = -0.8$ meV, $\varepsilon_r - \varepsilon_e = -0.7$ meV. Both the transition frequencies are contained in the bandwidth of the pulse. First, we consider the QD system driven by a chirp-free few-cycle pulse ($\eta = 0$) with $\hbar\Omega = 0.52$ meV for no time-dependent phase $\varphi(t) = 0$, as shown in Fig. 2. The carrier frequency of the driving few-cycle pulse is chosen at $\hbar\omega = 0.75$ meV, and $\tau = 5$ ps the duration of pulse. Figures 3(a) and 3(b) show the population of the three states $|j\rangle$ ($j = l,r,e$) with the ground state initially in the left dot $|l\rangle$ for $q = 1$. As shown in Fig. 3(a), when the decay terms are absent, i.e., $\gamma_r = \gamma_e = 0$, one can find that the population transfer between the states of left dot ($|l\rangle$) and right dot ($|r\rangle$) is supported but a complete population transfer between the two states does not occur in the calculations. By taking the spontaneous emission and dephasing values nonzero, i.e., $\gamma_r = \gamma_e = 2\,\mu$eV, Fig. 3(b) demonstrates that the population transfer can also be realized. Comparing Figs. 3(a) and 3(b), it is seen that the time evolution of the populations share the similar shape only with a little difference in the final population (i.e., $t = 4\tau$).

As illustrated in Fig. 2, the chirped frequency has a large impact on the Gaussian pulse carrier waves. Now, we turn to investigate the dynamics of the electron transfer under the influence of a nonlinear few-cycle chirped laser pulse. If we take the sweeping parameter as $\eta = 0.63$ rad, the corresponding varying CEP is $\varphi(t) = -0.63\cosh[(t - 2\tau)/\tau_c]$. The amplitude of the Gaussian envelope pulse remains invariant to chirped frequency. However, the oscillatory periodicity of the reshaping Gaussian field is broken due to the chirped frequency. With this chirped driving pulse, Fig. 4 shows the population of three states $|j\rangle$ ($j = l,r,e$), with the initial states in $|l\rangle$. It can be seen that with the same parameter values used in Fig. 3, almost a complete electron transfer (99.8%) can be produced when the decay terms are neglected, i.e., $\gamma_r = \gamma_e = 0$, as shown in Fig. 4(a). In such a process, the excited state $|e\rangle$ plays the role of the intermediate state: it assists the electron transfer between the QDs but remains unpopulated after passing the pulse. Unlike the STIRAP and other adiabatic techniques,[25–30] in this example, the population in the intermediate state $|e\rangle$, can reach large values as the adiabatic criteria is not fulfilled. If the decay damping mechanism due to the spontaneous emission and dephasing contributions is taken into account, i.e., when

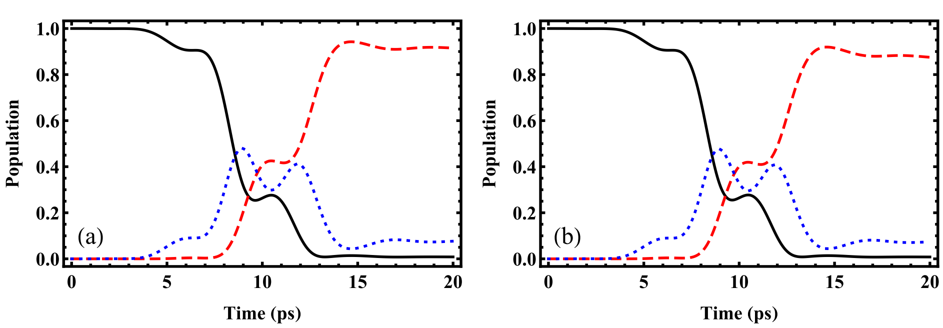

FIG. 3. Time evolution of populations $|C_l|^2$ (solid line), $|C_r|^2$ (dashed line), and $|C_e|^2$ (dotted line) obtained from numerical solution of the coupled equations (4)–(6) for a chirped free pulse $\eta = 0$: (a) Without any decays $\gamma_r = \gamma_e = 0$; and (b) with the decays $\gamma_r = \gamma_e = 2\,\mu$eV. Other parameters are $\hbar\Omega = 0.52$ meV, $\varepsilon_l - \varepsilon_e = -0.8$ meV, $\varepsilon_r - \varepsilon_e = -0.7$ meV, $\hbar\omega = 0.75$ meV, $\tau = 5$ ps, and $q = 1$, respectively.

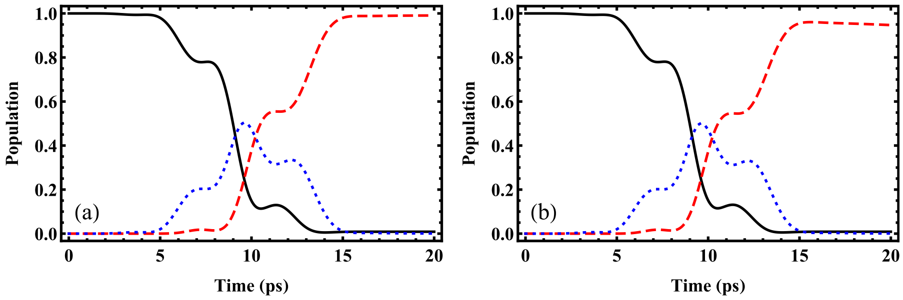

FIG. 4. Time evolution of populations $|C_l|^2$ (solid line), $|C_r|^2$ (dashed line), and $|C_e|^2$ (dotted line) obtained from numerical solution of the coupled equations (4)–(6) for a chirped pulse with $\eta = 0.63$ rad: (a) Without any decays $\gamma_r = \gamma_e = 0$ and (b) with the decays $\gamma_r = \gamma_e = 2\,\mu$eV. Other parameters are $\hbar\Omega = 0.52$ meV, $\varepsilon_l - \varepsilon_e = -0.8$ meV, $\varepsilon_r - \varepsilon_e = -0.7$ meV, $\hbar\omega = 0.75$ meV, $\tau = 5$ ps, and $q = 1$, respectively.

$\gamma_r = \gamma_e = 2\,\mu$eV, from Fig. 4(b), one can find that the final population ($|C_r|^2$) of the state $|r\rangle$ is reduced. Besides, an increase in the rates $\gamma_{r,e}$ will lead to a degradation in the final population in the state $|r\rangle$, as expected. Fig. 4(b) also demonstrates that even if the damping mechanism is present, the electron can be transferred from the ground state ($|l\rangle$) in left dot to the state $|r\rangle$ in the right dot. However, if a reasonable and realistic set of parameters can be found, we should still get high efficiency electron transfer.

As mentioned above, the initial condition corresponds to the localization of electron in the left dot. Based on the above coupled equations (4)–(6), we have calculated numerically the final population in the three states $|j\rangle$ ($j = l,r,e$) as a function of the electric field amplitude Ω and sweeping parameter η after the passing of the few-cycle chirped pulse, as shown in Fig. 5. From Fig. 5(a), we can find that for sweeping parameter η up to 0.63 rad, single-electron transfer from the ground state $|l\rangle$ of the left dot to the ground state $|r\rangle$ of the right dot occurs for a wide range of electric field amplitudes. However, high-efficiency single-electron transfer occurs only for specific values of the electric field amplitude. In presence of the decay and dephasing effects, the maximal single-electron transfer can be 94.7%, and more than 80% single-electron transfer can be achieved for the range of $0.42 < \hbar\Omega < 0.63$ meV. Fig. 5(b) demonstrates that the sweeping parameter η has significant effects on single-electron transfer between the ground states $|l\rangle$ of the left dot and $|r\rangle$ of the right dot. For a negative value of sweeping parameter, we see the single-electron transfer is relatively small. However, high-efficiency electron transfer between the ground states in the QD system occurs for a wide range of positive values for the sweeping parameter.

For a better insight into the effects of electric field amplitudes and chirping frequency on global behavior of single-electron transfer, the contour map of the final population of $|C_r(4\tau)|^2$ as the function of both the electric field amplitude $\hbar\Omega$ and sweeping parameter η/π is shown in Fig. 6. It can be found from Fig. 6(a) that there is a certain region of $\hbar\Omega$ and η/π in which high-efficiency single-electron transfer can be obtained under the condition $q = 1$. As Fig. 6(a) shows, more than 80% single-electron transfer between the ground states $|l\rangle$ and $|r\rangle$ can be obtained for a wide range of parameters in the interaction of few-cycle chirped pulse with the QD system. However, if the ratio of the dipole moment $q \neq 1$, the maximum value of single-electron transfer obtained will decrease. For $q = 0.5$, we plot in Fig. 6(b) the contour map of final population $|C_r(4\tau)|^2$ with the same other parameter values. Compared with Fig. 6(a), the structure is qualitatively very similar, but the maximum value of single-electron transfer becomes much smaller. It is worth noting that the ratio of the dipole moments can vary in a wide range which in experiments can be controlled by adjusting the voltage of the corresponding electrode gate.[21,24] Thus, we may provide more practical opportunities to implement all-optical and electro-optical modulated solid-state devices due to the flexibility in the semiconductor quantum structures.[24] We also investigated the single-electron transfer for different pulse widths. As an example, Figs. 6(c) and 6(d) show the contour map of the final population of $|C_r(4\tau)|^2$ as the function of both the electric field amplitude $\hbar\Omega$ and sweeping parameter η/π for different pulse widths (τ) varying from 1 ps to 15 ps. As shown in Figs. 6(c) and 6(d), the single-electron transfer is very sensitive to the pulse width. If the pulse width becomes longer, the narrower spectrum makes the maximum single-electron transfer less pronounced, which can be explained using the time-dependent perturbation theory.[48]

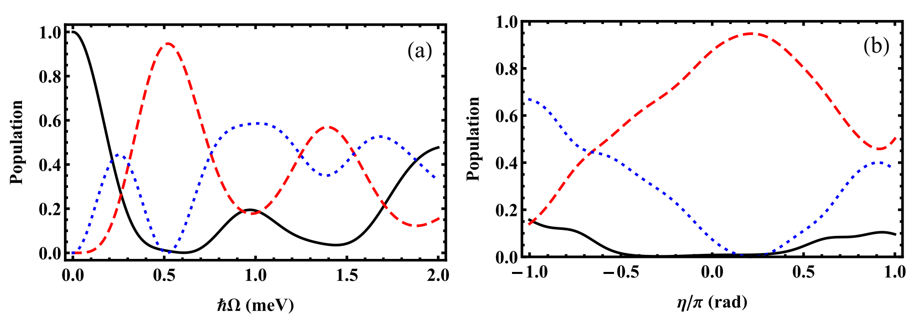

FIG. 5. The final population $|C_l(4\tau)|^2$ (solid line), $|C_r(4\tau)|^2$ (dashed line), and $|C_e(4\tau)|^2$ (dotted line) obtained from numerical solution of the coupled equations (4)–(6) as a function of (a) electric field amplitude Ω (in meV) with $\eta = 0.63$ rad and (b) sweeping parameter η/π (in rad) with $\hbar\Omega = 0.52$ meV for a chirped Gaussian pulse. Other parameters are $\varepsilon_l - \varepsilon_e = -0.8$ meV, $\varepsilon_r - \varepsilon_e = -0.7$ meV, $\omega = 0.75$ meV, $\tau = 5$ ps, and $q = 1$, respectively.

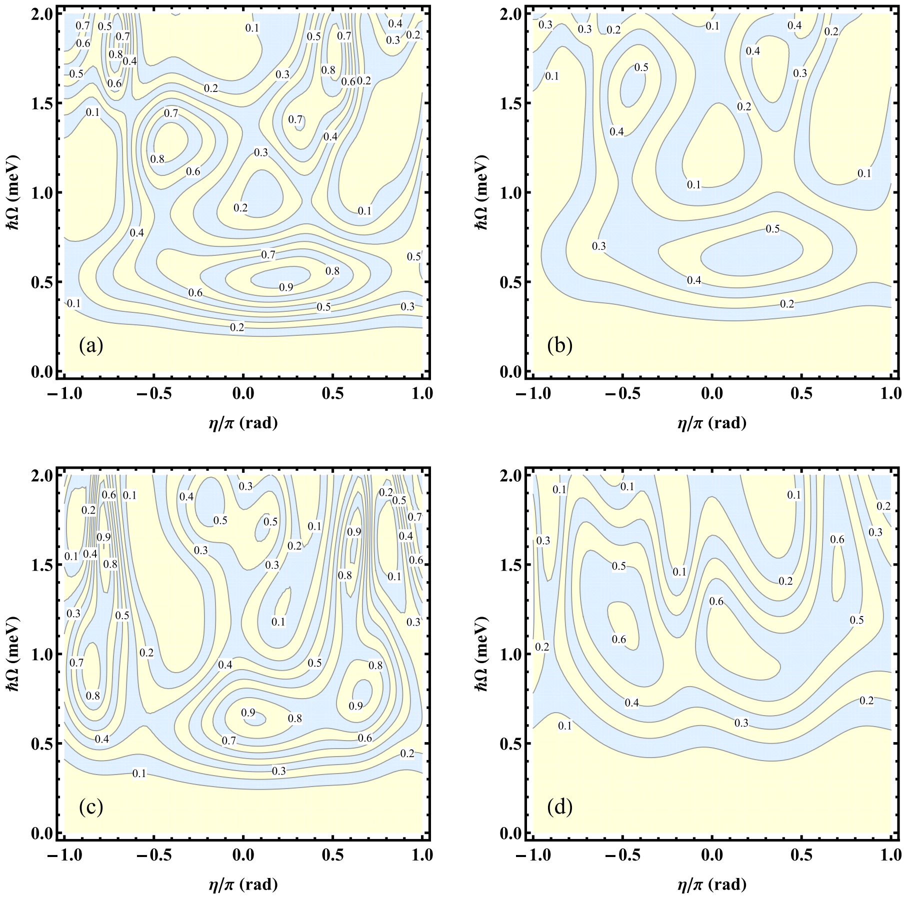

FIG. 6. Contour map of the final population $|C_r(4\tau)|^2$ obtained from numerical solution of the coupled equations (4)–(6) as a function of the electric field amplitudes $\hbar\Omega$ (in meV) and sweeping parameter η/π (in rad) of a chirped Gaussian few-cycle pulse for different ratio of the dipole moments q with fixed pulse width $\tau = 5$ ps: (a) $q=1$; (b) $q=0.5$; for different pulse widths τ with fixed ratio of the dipole moments $q=1$: (c) $\tau = 1$ ps; (d) $\tau = 15$ ps. Other parameters are $\varepsilon_l - \varepsilon_e = -0.8$ meV, $\varepsilon_r - \varepsilon_e = -0.7$ meV, and $\hbar\omega = 0.75$ meV, respectively.

IV. SUMMARY

In conclusion, we have studied the coherent control of the ultrafast single-electron transfer between the ground states of coupled double quantum dots system driven by a chirped few-cycle pulse. We numerically simulated the time-dependent Schrödinger equation without the rotating wave approximation for the description of the system dynamics. In the absence of the decay terms of the QD system, our numerical simulations showed that almost complete single-electron transfer can be achieved if the different transition dipole moments are almost the same and appropriate values of the electrical field amplitude and the chirped parameters are selected. In addition, We found that compared to the STIRAP technique,[25–30] the pulse does not require sufficiently long for the satisfaction of the adiabatic condition here. Furthermore, our numerical simulations also showed that the efficiency of the single-electron transfer reduces even in the presence of the decay terms. Hence, nonlinearly chirped few-cycle laser pulse may be employed for an efficient and ultrafast coherent single-electron transfer with a wide range of laser pulse parameters in semiconductor QD systems.

We should note that the chirp form of the few-cycle pulse is controlled by the time-dependent CEP in the present model, in which we can control the CEP by adjusting the frequency sweeping parameters.[41] The obtained numerical results demonstrated that the single-electron transfer is extremely sensitive to the frequency sweeping parameters as well as the time-dependent CEP if the pulses are only a few cycles in duration. It should be noticed that the time-dependent CEP is used here to control the coherent single-electron transfer in the coupled QD system, which seems to play the similar role as the magnetic flux in an Aharonov–Bohm (AB) ring.[49] However, it is quite different from the AB interferometer. Here, the interaction between the electron and the pulse is time-dependent, while in an AB ring, the non-equilibrium is only due to the bias voltage. But they share the similar physical reason to exhibit phase modulated quantum interference. Compared with the AB interferometer, here, the interaction between the electron and few-cycle pulse provides an alternative approach. Thus, coherent single-electron transfer controlled through the time-dependent CEP provides another feasible mode and a potential application in nanoelectronics and quantum information science in solid-state systems.

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