Optical dipole force on ladderlike three-level atomic systems induced by few-cycle-pulse laser fields

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We report on a study of the optical dipole force in a ladderlike three-level atomic system induced by the trains of few-cycle-pulse laser fields. In the present study, we consider the nonresonant as well as the chirped pulse excitation of three-level atoms. The so-called optical dipole force is calculated by numerically solving the force equation and the density matrix equations self-consistently beyond the rotating wave approximations. By analyzing the center-of-mass motion, it is shown that under nonresonant excitation, the optical dipole force induced by the trains of few-cycle pulses may be used for focusing and defocusing of atoms in an atomic beam. Moreover, we have demonstrated that the chirped nanosecond pulses may be used for both coherent population transfer and focusing or defocusing of atoms simultaneously.

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I. INTRODUCTION

Manipulation and coherent control of atoms and molecules, and various schemes for laser cooling and trapping by using optical force are of tremendous importance in many fields of physics and chemistry [1–6]. Recently, there has been a resurgence of interest in the so-called light or optical force due to the recent progress in the generation of well controlled femtosecond laser pulses [7–10]. Generally, there are two kinds of optical force: the reactive or so-called optical dipole force and the dissipative or so-called spontaneous force [11]. The optical dipole force arises from the interaction between the induced dipole moment and the gradient of the electric field envelope while the dissipative force arises from the impulse experienced by an atom when it absorbs or emits a quantum of photon momentum [12]. Several authors have utilized optical force, through the linearly chirped laser pulses, for slowing down, acceleration [13], and forced rotation [14] of molecules. It is worthwhile mentioning that in the late 1970s, in an experimental study Bornholm *et al.* [15] demonstrated the phenomena of focusing, defocusing, and steering of neutral sodium atoms by using cw laser fields and showed that atoms could be expelled from the laser beam due to the so-called optical dipole force. Recently, the phenomena of focusing, defocusing, and steering of the neutral atoms in the few-cycle-pulse laser field were theoretically analyzed by the authors [16]. The creation of an optical lens for atomic and molecular beam by optical dipole force has also been demonstrated by several authors [17–19]. It may be noted that the spontaneous force can be used for cooling the atoms but cannot be used for trapping the cold atoms. This may be attributed to the fact that the upper limit of the dissipative forces is limited by saturation effects due to the spontaneous emission. Recently, observation of a very strong optical force, the so-called stimulated force, produced by coherent exchange of momentum between atoms and light fields implemented by adiabatic rapid passage (ARP) and bichromatic pulses was reported [20–25]. In the ARP scheme, the laser pulse frequency is swept through a static resonance of an atom or molecule. It may be noted that ARP and the so-called stimulated Raman adiabatic passage (STIRAP) are the most widely used schemes for controlling the population transfer between the quantum states of atoms and molecules. These have found many potential applications in spectroscopy, collision dynamics, and control of chemical reactions, etc. [26–29]. On the other hand, it is reported by some authors that the population oscillations in two-level atomic systems, induced by varying the Rabi frequency of the interacting pulse, can have applications in ultrafast optical switching [30,31]. In the present work, we study the optical dipole force on three-level atoms under three different excitation schemes; firstly, we consider the nonresonant interaction of atoms with the trains of few-cycle pulses, secondly, time-dependent detuned interaction of atoms with the trains of chirped few-cycle pulses, and finally, time-dependent detuned interaction of atoms with chirped nanosecond pulses instead of pulse trains. In Sec. II we present the density matrix equations that describe the interaction of the ladderlike three-level atomic systems with the linearly chirped few-cycle laser pulses. The force equation is also presented. Section III contains our simulated results, and discussions followed by conclusions are in Sec. IV.

II. THE MODEL

The sketch of our scheme for the calculation of optical dipole force on sodium atoms is depicted in Fig. 1. We consider a ladderlike atomic system interacting with two few-cycle-pulse laser fields. In this work the states $|1\rangle$, $|2\rangle$, and $|3\rangle$ respectively refer to $3s_{1/2}$, $3p_{3/2}$, and $4s_{1/2}$ quantum states of neutral sodium atoms.

The total electric field of the trains of collimated pulse laser fields can be written as

$$\overrightarrow{E}_{i(i=1,2)}(t-nt_r) = \sum_{n=0}^{N-1} \widehat{\varepsilon}_i A_i(t-nt_r)\cos[\omega_i(t-nt_r) + \alpha_i(t-nt_r)^2 + \omega_{Di} + \phi_i(z)].$$

Here, $A_i(t-nt_r) = E_{oi}\exp(-\{[(t-nt_r)/\tau]^2 + (r/\omega_0)^2\})$. We assume that the pulse train of electric field E_1 and the pulse train of electric field E_2 are interacting between the states $|1\rangle$, $|2\rangle$ and $|2\rangle$, $|3\rangle$, respectively. Here, $\omega_{Di} = \overrightarrow{k}_i \cdot \overrightarrow{v}$ refers to the detuning of the transition lines of the atom moving

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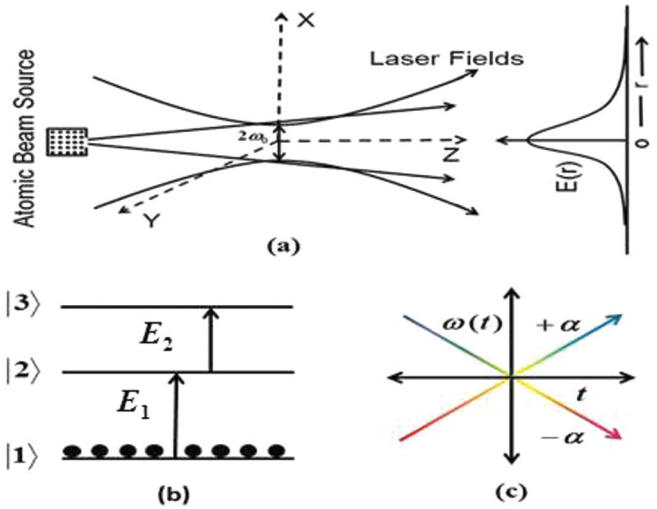

FIG. 1. (Color online) (a) Sketch of the proposed scheme for the calculation of optical dipole force on an atomic beam copropagating with pulsed laser fields; (b) three-level atomic system; (c) time-dependent frequency of up-chirped ($+\alpha$) and down-chirped ($-\alpha$) pulses.

with velocity $\vec{v}$ due to Doppler shift, $\tau = 1.177\tau_p$, where τ_p is the temporal pulse width at full width at half maximum (FWHM), N is the number of pulses, t_r is the pulse repetition time, α_i is the chirp rate, ω_0 is the beam waist, ω_i is the laser frequency, and $\phi_i(z) = k_i z$ represents the longitudinal phases. Here, $k_i (i = 1,2)$ is the wave vector of the corresponding electric fields. The density matrix equations, without invoking the so-called rotating wave approximation, describing the temporal evolution of the density matrix elements, are

$$\begin{aligned}
\frac{d\rho_{11}}{dt} &= i(\Omega_{12}\rho_{21} - \Omega_{21}\rho_{12}),\\
\frac{d\rho_{22}}{dt} &= i[\Omega_{12}(\rho_{12} - \rho_{21}) + \Omega_{23}(\rho_{32} - \rho_{23})],\\
\frac{d\rho_{33}}{dt} &= i(\Omega_{32}\rho_{23} - \Omega_{23}\rho_{32}),\\
\frac{d\rho_{21}}{dt} &= -i\omega_{21}\rho_{21} + i[\Omega_{12}(\rho_{11} - \rho_{22}) + \Omega_{23}\rho_{31}],\\
\frac{d\rho_{32}}{dt} &= -i\omega_{32}\rho_{32} + i[\Omega_{32}(\rho_{22} - \rho_{33}) - \Omega_{12}\rho_{31}],\\
\frac{d\rho_{31}}{dt} &= -i\omega_{31}\rho_{31} + i(\Omega_{23}\rho_{21} - \Omega_{12}\rho_{32}).
\end{aligned} \tag{1}$$

Here, $\Omega_{12} = \Omega_{21} = \mu_{12}E_1(r,t)/\hbar$ and $\Omega_{23} = \Omega_{32} = \mu_{23}E_2(r,t)/\hbar$ are the time-dependent Rabi frequencies for the transition with electric dipole moment μ_{12} and μ_{23}, respectively. It should be noted that $\omega_{ij} = \omega_i - \omega_j$ and $\rho_{ij} = \rho^*_{ji}$. Using an approach based on the density matrix equations and the Ehrenfest's theorem, we derived the following expression for the optical dipole force [16,32]:

$$\begin{aligned}
\overrightarrow{F_t} = \mu_{12}\sum_{n=0}^{N-1} u\{[\overrightarrow{\nabla} A_1(t - nt_r)]\cos[\omega_1(t - nt_r)\\
+ \alpha_1(t - nt_r)^2 + \omega_{D1} + \phi_1(z)]\}
\end{aligned}$$

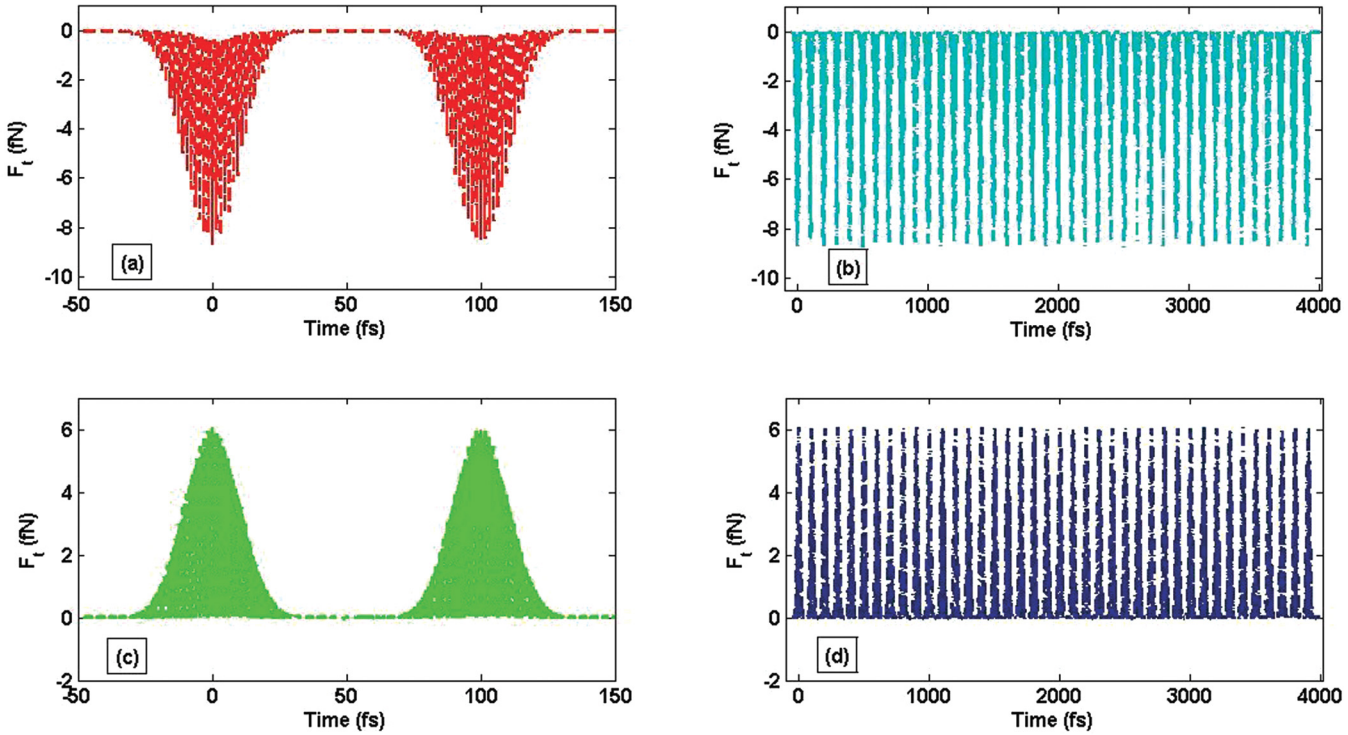

FIG. 2. (Color online) Temporal evolution of optical dipole force under nonresonant excitation: (a) $N = 2$, $\Delta_1 = 1.19$ rad/fs, and $\Delta_2 = 0.65$ rad/fs; (b) $N = 40$, $\Delta_1 = 1.19$ rad/fs, and $\Delta_2 = 0.65$ rad/fs; (c) $N = 2$, $\Delta_1 = -1.19$ rad/fs, and $\Delta_2 = -0.65$ rad/fs; (d) $N = 40$, $\Delta_1 = -1.19$ rad/fs, and $\Delta_2 = -0.65$ rad/fs.

$$+\mu_{23}\sum_{n=0}^{N-1} v\{[\vec{\nabla} A_2(t-nt_r)]\cos[\omega_2(t-nt_r) + \alpha_2(t-nt_r)^2 + \omega_{D2} + \phi_2(z)]\}. \quad (2)$$

Here $u = (\rho_{21} + \rho_{12})$ and $v = (\rho_{32} + \rho_{23})$.

III. RESULTS AND DISCUSSIONS

We solve Eqs. (1) and (2) numerically using a standard fourth-order Runge-Kutta method. We assume that initially all the atoms are in the ground state $|1\rangle$. The following typical parameters are used for simulation: For chirped pulse excitation, $\omega_{21} = \omega_1 = 3.19$ rad/fs, $\omega_{32} = \omega_2 = 1.65$ rad/fs, $\alpha_1 = \alpha_2 = \pm 0.02$ fs^{-2}; on the other hand, for nonresonant excitation of atoms, $\Delta_1 = \omega_{21} - \omega_1 = \pm 1.19$ rad/fs and $\Delta_2 = \omega_{32} - \omega_2 = \pm 0.65$ rad/fs. The rest of the simulation parameters are as follows: $\Omega_{21} = \Omega_{32} = 1.30$ rad/fs, $\mu_{12} = \mu_{23} = 1.85 \times 10^{-29}$ C m [32], $r = 7.07$ μm, $\omega_0 = 10$ μm, and $v_z = 1000$ m/s in the direction of pulse laser fields. The temporal pulse width is taken to be $\tau_p = 23.5$ fs. In the present study, the center of mass is taken to be $M = 22.99$ amu. It could be deduced from Eq. (2) that the transverse force is maximum at $r = 7.07$ μm and minimum at $r = 0$ μm.

In Fig. 2 we depict the temporal evolution of optical dipole force on atoms under nonresonant excitation of atoms. It can be observed from Figs. 2(a) and 2(b) that the optical dipole force is negative for positive detuning which may lead to the focusing of atoms, while Figs. 2(c) and 2(d) show that optical dipole force is positive for negative detuning, and may lead to the defocusing of atoms. In Fig. 3 we depict the temporal evolution of optical dipole force for increased number of pulses, $N = 1000$, compared to the one used in Fig. 2.

One may observe from Figs. 2 and 3 that the magnitude of the optical dipole force remains identical even with the increased number of pulses. Again, the temporal evolution of the optical dipole force remains similar even if the number of pulses is increased. The optical dipole force is negative for positive detuning and positive for negative detuning throughout the interaction time. It is worthwhile mentioning that in the work by Bornholm *et al.* [15] the magnitude of the optical force on neutral atoms, induced by cw laser field, was around 0.01×10^{-18} N or 0.01 aN. On the other hand, in the present study, the time-averaged force is approximately 3.30 fN for $\Delta_1 = \omega_{21} - \omega_1 = 1.19$ rad/fs, $\Delta_2 = \omega_{32} - \omega_2 = 0.65$ rad/fs, and 2.49 fN for $\Delta_1 = \omega_{21} - \omega_1 = -1.19$ rad/fs, $\Delta_2 = \omega_{32} - \omega_2 = -0.65$ rad/fs with $N = 1000$. Clearly, the force considered in this work is much larger than the one considered by Bornholm *et al.*

In Fig. 4, we show the trajectory of atoms subjected to the optical dipole force for $N = 1000$. It can be observed from curves (a)–(c) that due to the optical dipole force with positive detuning, atoms are getting focused. So it appears that the optical dipole force is acting like an ultrafast optical lens for the diverging atomic beam. On the other hand, curves (d)–(f) show that the atoms are getting defocused due to the optical dipole force with negative detuning. Hence the trains of few-cycle-pulse laser fields may be used for effective focusing and defocusing of atoms in an atomic beam. In Fig. 5, we study the temporal evolution of optical dipole force on atoms induced by trains of chirped pulse laser fields.

It can be seen from Figs. 5(a) and 5(b) that the optical dipole force on atoms is negative for each odd number of pulses in the pulse trains, while it is positive for each even number of pulses in the pulse trains for up-chirped pulse trains. On

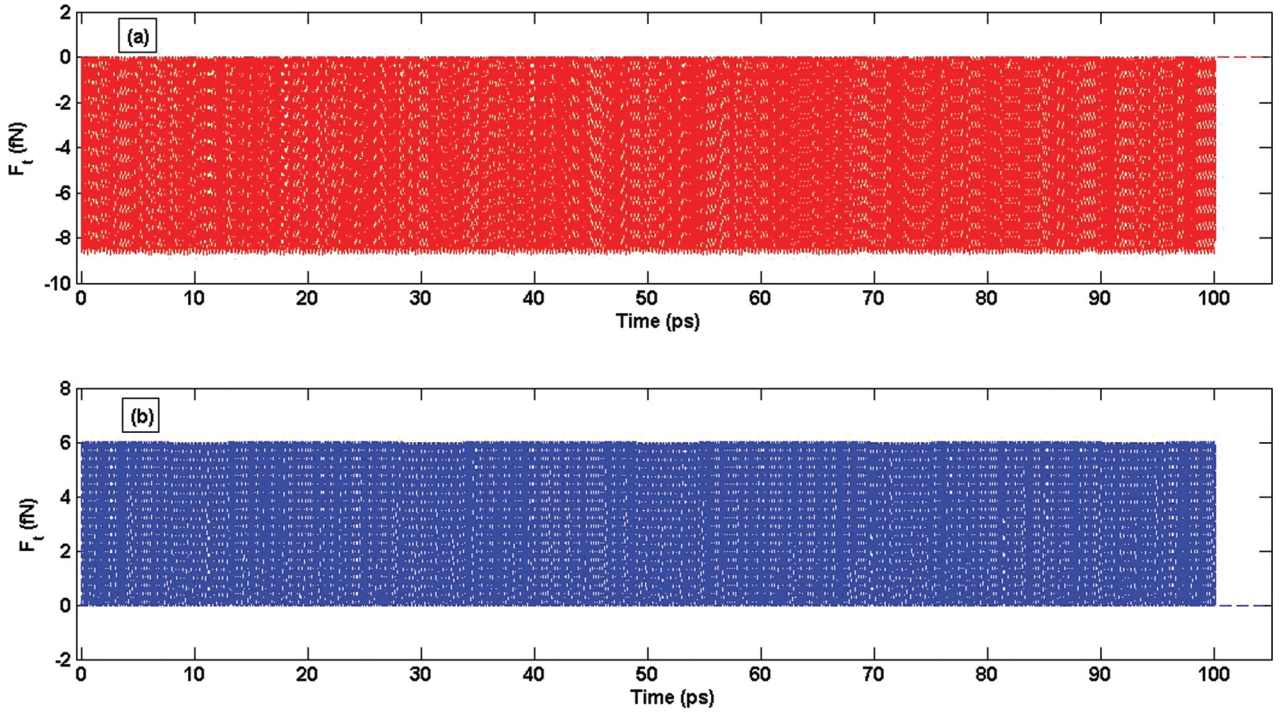

FIG. 3. (Color online) Temporal evolution of optical dipole force under nonresonant excitation: (a) $N = 1000$, $\Delta_1 = 1.19$ rad/fs, and $\Delta_2 = 0.65$ rad/fs; (b) $N = 1000$, $\Delta_1 = -1.19$ rad/fs, and $\Delta_2 = -0.65$ rad/fs.

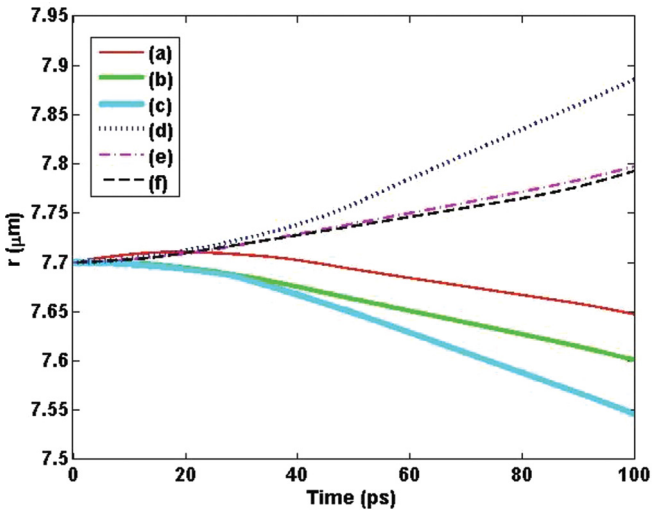

FIG. 4. (Color online) (a)–(c) Focusing and (d)–(f) defocusing of atoms due to optical dipole force: (a) $\Delta_1 = 1.19$ rad/fs, $\Delta_2 = 0.65$ rad/fs, and $v_t = 1000$ m/s; (b) $\Delta_1 = 1.19$ rad/fs, $\Delta_2 = 0.65$ rad/fs, and $v_t = 100$ m/s; (c) $\Delta_1 = 1.19$ rad/fs, $\Delta_2 = 0.65$ rad/fs, and $v_t = 1$ m/s; (d) $\Delta_1 = -1.19$ rad/fs, $\Delta_2 = -0.65$ rad/fs, and $v_t = 1000$ m/s; (e) $\Delta_1 = -1.19$ rad/fs, $\Delta_2 = -0.65$ rad/fs, and $v_t = 100$ m/s; (f) $\Delta_1 = -1.19$ rad/fs, $\Delta_2 = -0.65$ rad/fs, and $v_t = 1$ m/s.

the other hand, the opposite of the above occurs in the case of down-chirped pulse trains, as can be seen from Figs. 5(c) and 5(d). Hence the atoms in an atomic beam will encounter a time-dependent positive and negative optical dipole force induced by the chirped few-cycle-pulse trains in contrast to the optical dipole force induced by the nonresonant interaction of atoms with the few-cycle-pulse trains. So the chirped few-cycle-pulse trains may not be useful for the focusing and defocusing of atoms subjected to the chosen parameters. However, here it is worth mentioning that the chirped few-cycle-pulse trains may be used for some other interesting applications such as ultrafast optical switching and ultrafast coherent population oscillations, etc. [30,33,34]. Finally, we consider the chirped nanosecond pulse excitation of atoms. The pulse duration ($\tau_p = 2$ ns) is considered to be less than all the relaxation times. Figure 6 depicts the temporal evolution of coherent population transfer, optical dipole force, and trajectory of atoms under the influence of the optical dipole force. The chosen realistic simulation parameters are $\Omega_{21} = \Omega_{32} = 300$ rad/ns, $\alpha_1 = \alpha_2 = \pm 10$ ns^{-2}; other simulation parameters remain similar to the ones taken earlier.

It can be seen from Figs. 6(a) and 6(b) that after the interaction, all the atomic populations are in the state $|3\rangle$ and are independent of the sign of the chirping parameters. On the other hand, as is evident from Fig. 6(c), the optical dipole force is negative for $\alpha_1 = \alpha_2 = 10$ ns^{-2}, while it is positive for $\alpha_1 = \alpha_2 = -10$ ns^{-2}. Hence the optical dipole force may be used for focusing and defocusing of atoms with judicious control of the sign of the chirping parameters. Focusing and defocusing atoms are dependent on the transverse velocity of the atoms as well, as can be seen from Fig. 6(d). For the chosen parameters, we find that atoms with transverse velocities up to and below 1 m/s are getting focused due to the optical dipole force. So, the chirped nanosecond pulses may be used for coherent population transfer and focusing of atoms

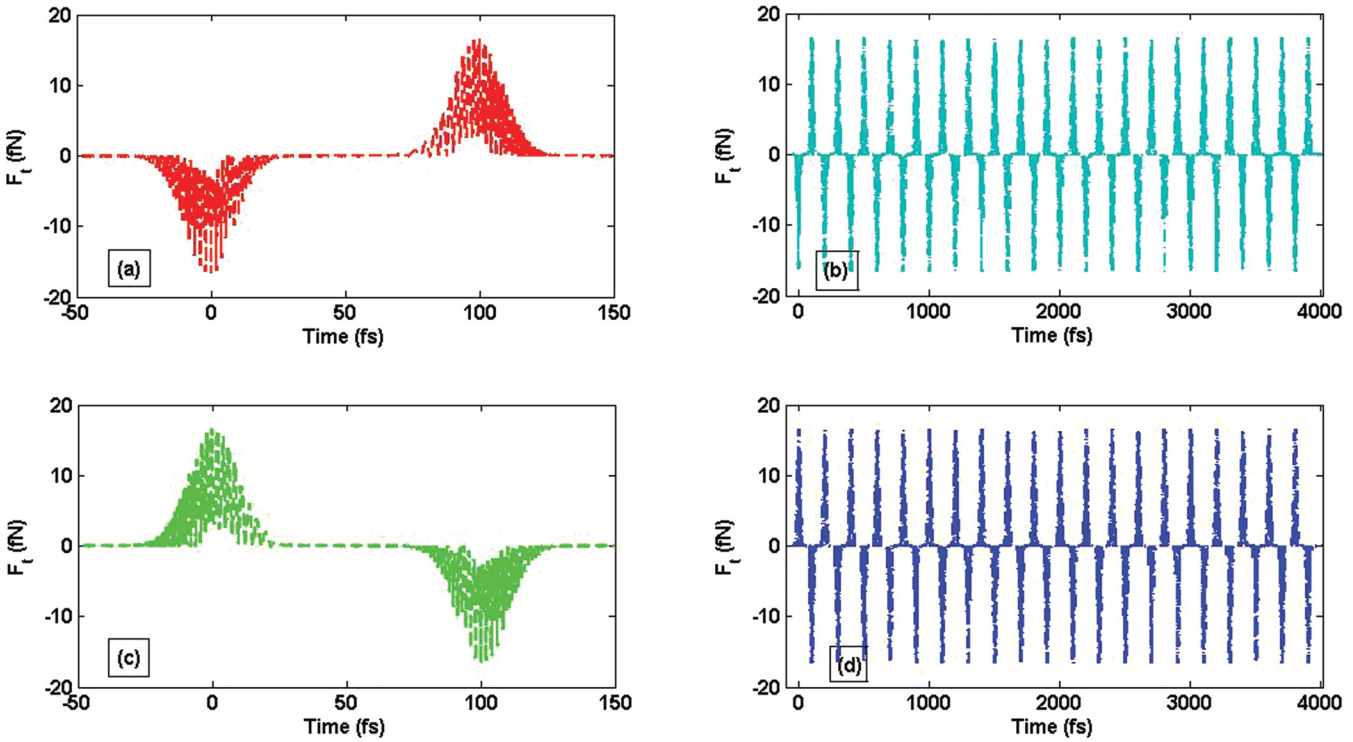

FIG. 5. (Color online) Temporal evolution of optical dipole force under chirped pulse excitation: (a) $N = 2$, $\alpha_1 = 0.02$ fs^{-2}, and $\alpha_2 = 0.02$ fs^{-2}; (b) $N = 40$, $\alpha_1 = 0.02$ fs^{-2}, and $\alpha_2 = 0.02$ fs^{-2}; (c) $N = 2$, $\alpha_1 = -0.02$ fs^{-2}, and $\alpha_2 = -0.02$ fs^{-2}; (d) $N = 40$, $\alpha_1 = -0.02$ fs^{-},^{2} and $\alpha_2 = -0.02$ fs^{-2}.

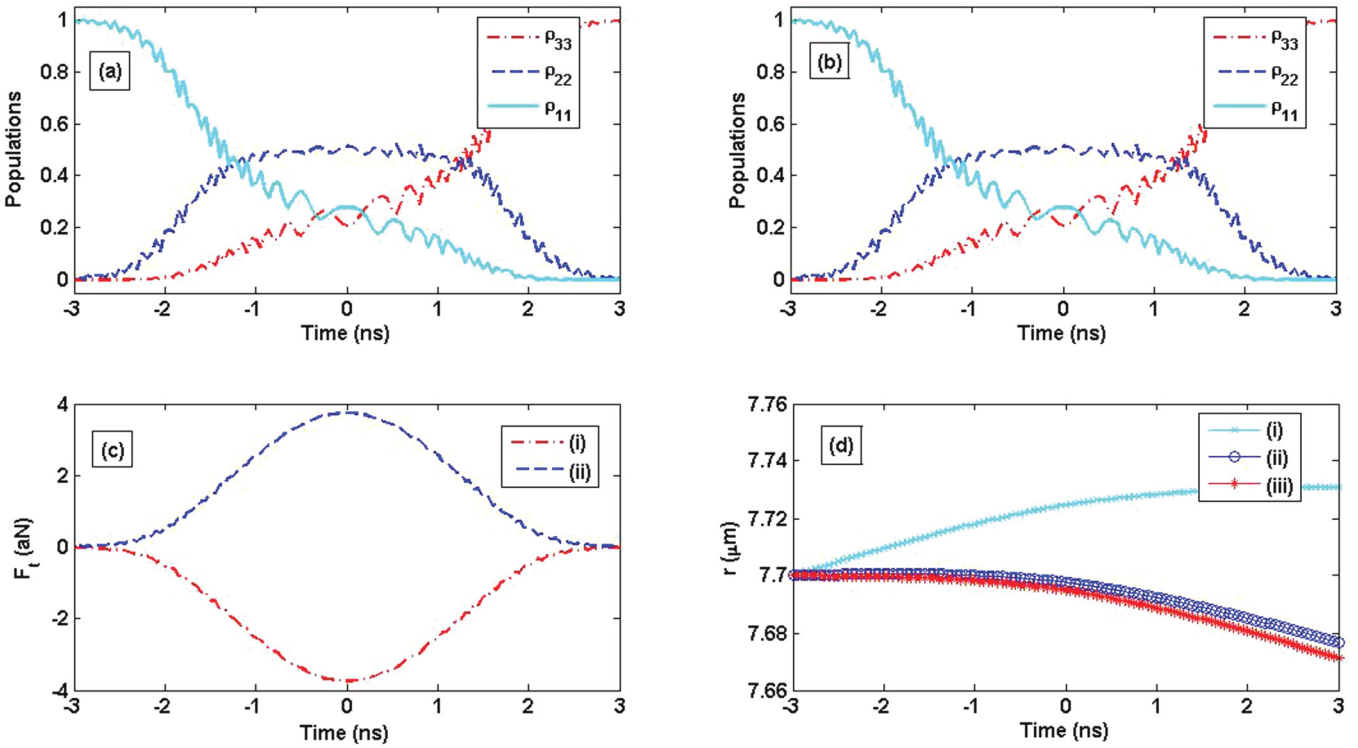

FIG. 6. (Color online) Temporal evolution of (a) populations with $\alpha_1 = \alpha_2 = 10\ \text{ns}^{-2}$; (b) populations with $\alpha_1 = \alpha_2 = -10\ \text{ns}^{-2}$; (c) optical dipole force with (i) $\alpha_1 = \alpha_2 = 10\ \text{ns}^{-2}$, (ii) $\alpha_1 = \alpha_2 = -10\ \text{ns}^{-2}$; and (d) trajectory of atoms with $\alpha_1 = \alpha_2 = 10\ \text{ns}^{-2}$: (i) $v_t = 10$ m/s, (ii) $v_t = 1$ m/s, and (iii) $v_t = 0.1$ m/s.

simultaneously, subject to the appropriate choice of parameters as discussed above. However, the trains of few-cycle pulses may be used for focusing the atoms moving with higher transverse velocities compared to chirped nanosecond pulses, as can be observed from Figs. 4 and 6(d).

IV. CONCLUSIONS

To conclude, we have demonstrated the focusing and the defocusing of atoms with the trains of few-cycle pulses under nonresonant excitation. Our study on the trajectory of atoms subjected to the optical dipole force under nonresonant condition shows that sodium atoms, copropagating with the trains of few-cycle pulses may be used for effective focusing or defocusing. It is also demonstrated that the chirped nanosecond pulses may be used for both coherent population transfer and focusing of atoms simultaneously with judicious choice of parameters.

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