Active manipulation of the selective alignment by two laser pulses*

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This paper solves numerically the full time-dependent Schrödinger equation based on the rigid rotor model, and proposes a novel strategy to determine the optimal time delay of the two laser pulses to manipulate the molecular selective alignment. The results illustrate that the molecular alignment generated by the first pulse can be suppressed or enhanced selectively, the relative populations of even and odd rotational states in the final rotational wave packet can be manipulated selectively by precisely inserting the peak of the second laser pulse at the time when the slope for the alignment parameter by the first laser locates a local maximum for the even rotational states and a local minimum for the odds, and vice versa. The selective alignment can be further optimised by selecting the intensity ratio of the two laser pulses on the condition that the total laser intensity and pulse duration are kept constant.

Keywords: rotational wave packets, femtosecond laser pulses, time delay

PACC: 3300, 3370, 3380P

1. Introduction

The dynamics of molecular rotational wave packet induced by laser pulses with both ultrashort pulse width and ultrahigh laser intensity has been one of the intriguing areas in the last decade. Especially, laser-induced spatial alignment[1,2] and orientation[3,4] are central subjects in molecular science. A sample of aligned or oriented molecules is an excellent quantum logical system, which enables us to investigate quantum phenomena associated with correlations between the molecular anisotropy and the laser polarisation as well as stereodynamics in chemical reactions. The molecular alignment and orientation have paved an effective road for the photodissociation,[5] photoionisation,[6,7] quantum-information processing,[8] nanoscale design,[9,10] molecular imaging,[11] surface processing,[12,13] and attosecond science.[14,15]

In general, there are two ways to align molecular ensembles adiabatically[16] and nonadiabatically.[17] Non-adiabatic alignment of the molecules attracts much attention for being able to study the molecules in a field-free alignment condition. For most applications, it is very important to select the proper parameter of the aligning laser pulse[18−21] and reduce the temperature of molecular ensemble[22,23] to obtain a higher degree of alignment. However, the improvement is often limited by the saturation of molecular alignment and the maximum intensity that can be applied to the molecules without ionising it. Different rotational components exhibit different dynamical behaviours during the evolution of the rotational wave packet. For example, the odd and the even rotational states evolve out of phase around fractional revival times and in phase around full revival times. The coherent rotational wave packet induced by a femtosecond laser pulse can be modified by another femtosecond laser pulse or a train of laser pulses.[24−27] The final rotational wave packet can be manipulated by selecting the intensity ratio or the time delay between the laser pulses. No matter the enhancement or the annihilation of the molecular alignment has been achieved by using two properly time-delayed short laser pulses in experiment. Furthermore, field-free three-dimensional alignment has been observed in experiment by two time-delayed, orthogonally polarised, nonresonant, femtosecond laser pulses.[28]

It is reported that a coherent molecular rotational wave packet can be manipulated selectively by strong femtosecond.[29,30] In the experiment, the first laser pulse induced a coherent rotational wave packet, the second laser pulse manipulated the rotational wave packet. The second laser is introduced just before or after the quarter and three quarters revival of ro-

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tational wave packet, the selective alignment can be achieved, the relative populations between even and odd rotational states can be controlled in the final rotational wave packet, which may find applications for analysis, enrichment, and actual physical separation of molecular spin modifications. On the other hand, as a model scenario of coherent control of rotational states, the rotational wave packet excited by the first laser pulse can be manipulated selectively by the second laser pulse at the quarter or three quarters revival, a general method which relates the selective alignment to their time delay should been developed.

In the present work, a new strategy to actively determine the optimal time delay is proposed. The time-dependent Schrödinger equation is solved at a finite rotational temperature. An obvious selective alignment is obtained by inserting the peak of the second laser pulse at the time when a local maximum of the slope for the alignment curve locates for the even rotational states and a local minimum of that locates for the odds, and vice versa. Under such conditions, the selective alignment can be further optimised by selecting the intensity ratio of the two laser pulses by keeping the total laser intensity and pulse duration constant.

2. Theoretical method

The theoretical method and calculations are similar to those described in Ref. [17]. Field-free alignment is achieved by the excitation of a rotational wave packet, which can be represented by the wavefunction of field-free rotational states $|JM\rangle$ under the rigid rotor approximation

$$\Psi(t) = \sum_J A_{JM}(t)|JM\rangle. \tag{1}$$

The time evolution of the wave packet can be calculated through solving the time-dependent Schrödinger equation

$$\mathrm{i}\frac{\partial \Psi(\theta,\phi,t)}{\partial t} = \left[B\hat{J}^2 - \frac{E^2(t)}{2}(\Delta\alpha\cos^2\theta + \alpha_\perp)\right]\Psi(\theta,\phi,t), \tag{2}$$

where θ is the angle between the laser polarisation and the interatomic axis of the molecule, ϕ is the azimuthal angle of molecular axis in a fixed frame, E is the intensity profile of the aligning laser field, $\Delta\alpha$ is the effective polarisability defined as the difference between $\alpha_{//}$ and $\alpha_\perp$, parallel and perpendicular to the molecular interatomic axis, respectively. B is the rotational constant, $\hat{J}^2$ is the angular-momentum operator. The time-dependent Schrödinger equation (2) can be solved by using the pseudospectral method[31,32] numerically when the molecule interacts with laser pulse.

Finally the time-dependent alignment parameter $\langle\cos^2\theta\rangle$ is obtained from the calculated rotational wave function of the molecules at the finite temperature. In general, the degree of molecular alignment of a whole molecular ensemble is described by $\langle\cos^2\theta\rangle$, in the present case, the quantity $\langle\cos^2\theta\rangle_{JM} = \langle\Psi_{JM} \mid \cos^2\theta \mid \Psi_{JM}\rangle$. At a finite temperature, a statistical ensemble of initial wavefunctions distributed according to the Boltzmann weights ρ_J should be considered, $\langle\cos^2\theta\rangle$ can be written as

$$\langle\cos^2\theta\rangle(t) = \sum_J \rho_J \sum_M \langle\cos^2\theta\rangle_{JM}(t), \tag{3}$$

$\langle\cos^2\theta\rangle = 1/3$ reflects an isotropic distribution, whereas $\langle\cos^2\theta\rangle = 1$ indicates complete alignment. The limiting case in which all molecules are perpendicular to the alignment axis called antialignment is denoted by $\langle\cos^2\theta\rangle = 0$. In general cases, $\langle\cos^2\theta\rangle$ is between 0 and 1.

3. Results and discussion

In the following, the selective alignment of C_2H_2 molecules is calculated by using the above methods. In our calculation, the laser pulse takes the Gaussian form:

$$E(t) = E\,\mathrm{e}^{-2\ln 2((t-t_0)/t_\mathrm{w})^2}\cos(\omega t), \tag{4}$$

where E is peak intensity of the laser, t_w is pulse duration full width at half maximum (FWHM) of the laser, t_0 is the centre of the laser pulse, ω is the frequency of the laser, the wavelength of the laser is 800 nm in our calculation and the first pulse is centred at 0 fs.

Field-free alignment parameter during the first revival and its Fourier transform induced by a single laser pulse with intensity 2×10^{13} W/cm^2 and pulse duration 50 fs at the temperature of 300 K is plotted in Fig. 1. As can be seen from Fig. 1(a), before the aligning pulse is reached, the molecular ensemble is isotropic and $\langle\cos^2\theta\rangle$ is 1/3. When the laser irradiates the molecule, the electric field of the intense laser induces the dipole moment within the molecule. The induced dipole moments impart a torque on the molecular axis that can be large enough to rotate the

molecule to the laser polarisation direction, so the arrival of the aligning pulse is followed by a prompt net alignment. The molecule continues to rotate even after the laser field is switched off and then the periodical alignment appears. The Fourier transform of the alignment parameter gave the beat frequencies ω_{JM} between adjacent rotational states, where $\omega_{JM} = (4J + 6)\omega_1/2$, and $\omega_1 = 4\pi Bc$ is the fundamental rotational frequency, B is the rotational constant of molecule by $B = 1/(2I)$, I is the moment of inertia of a molecule, and c is speed of light. In the present work, the beat frequencies ω_{JM} are replaced by the rotational quantum number J directly. The Fourier amplitude is determined by the corresponding rotational state populations in the coherent rotational wave packet. Figure 1(b) describes the revival structure decomposing into different rotational states. The amplitudes of the Fourier transform from the alignment parameter demonstrated that the even and the odd states were populated differently with a ratio of 1/3 in the rotational wave packet.

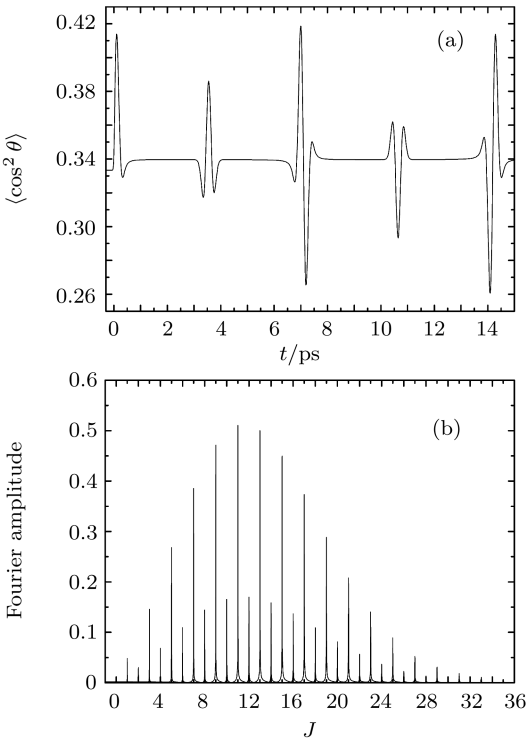


Fig. 1. (a) Calculated time-dependent alignment parameter $\langle\cos^2\theta\rangle$ excited by a 800 nm, 50 fs, 2×10^{13} W/cm^2 laser pulses. (b) The rotational states amplitude from Fourier transform of the alignment parameter.

In fact, the Hamiltonian of the laser-molecule interaction demonstrates that the even and the odd rotational states do not couple to each other. The rotational wave packets induced by a laser pulse can be divided into two components categorized as an even and an odd rotational wave packet, respectively. Figure 2 shows the time-dependent alignment parameter $\langle\cos^2\theta\rangle$ for the odd and even rotational wave packets separately in a revival. Compared with alignment for all rotational states in Fig. 1(a), the odd rotational wave packet and the even rotational wave packet exhibit opposite behaviours around the quarter revival and the three quarters revival. The odd rotational wave packet has the maximum alignment parameter while the even wave packet has the minimum alignment parameter, and vice versa. The odd rotational states are different from the evens in the statistics of nuclei spin, so the opposite localisations of the odd and the even wave packets cancel each other out partially and result in partial alignment for the total rotational wave packet at the time of the quarter revival and three quarters revival after a single laser pulse excitation. Therefore, when the second laser pulse is introduced around the quarter revival or the three quarters revival, the even and odd components can be excited selectively in the final wave packet.[29,30] The effect of time delay between the two pulses on the selective alignment is obviously different at the different times. At the certain time delay, the second laser pulse results in the maximum alignment for the odd rotational wave packets and minimum alignment for the evens, and vice versa.

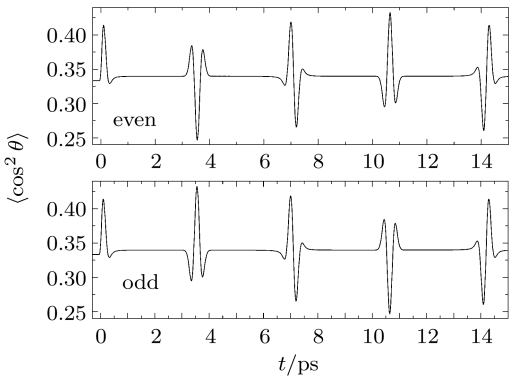


Fig. 2. Calculated time-dependent alignment parameter $\langle\cos^2\theta\rangle$ for the odd and even rotational wave packets excited by a 800 nm, 50 fs, 2×10^{13} W/cm^2 laser pulses.

Our further detailed calculation demonstrates the alignment parameter $\langle\cos^2\theta\rangle$, the slope $\mathrm{d}\langle\cos^2\theta\rangle/\mathrm{d}t$ by the single laser pulse with intensity 2×10^{13} W/cm^2 and pulse duration 50 fs, and peak alignment modified by two laser pulses with different time delays. The zero point of the time is at the peak of the first aligning pulse, we just control the peak of the second pulse by adjusting the time delay, the intensity of second

pulse is 3×10^{13} W/cm^2 and pulse duration is 50 fs. In Fig. 3, from 2.8 ps to 4.2 ps that covers the quarter revival, the second laser pulse is inserted and the selective alignment is resulted. As can be seen, the peak alignment matches with the slope of $\langle\cos^2\theta\rangle$ exactly both for the even and odd rotational states, the peak alignment by two pulses are related closely to the slope of $\langle\cos^2\theta\rangle$ by the first pulse. For example, it is noted that the peak of the second laser is inserted at the time of 3.44 ps when the slope locates a local minimum for the even rotational states and a local maximum for the odds, the minimum alignment degree of 0.3933 is resulted for the even rotational states and the maximum alignment degree of 0.5656 is resulted for the odds, the ratio of the peak alignment $\langle\cos^2\theta\rangle_{\rm odd}/\langle\cos^2\theta\rangle_{\rm even}$ for the odd and even rotational states is about 1.44. Reversely, the peak of the second laser is inserted at the time of 3.62 ps when the slope locates a local maximum for the even rotational states and a local minimum for the odds, the maximum alignment degree of 0.5445 is resulted for the even rotational states and the minimum alignment degree of 0.4121 is resulted for the odds, the ratio of the peak alignment $\langle\cos^2\theta\rangle_{\rm even}/\langle\cos^2\theta\rangle_{\rm odd}$ for the even and odd rotational states is about 1.32.

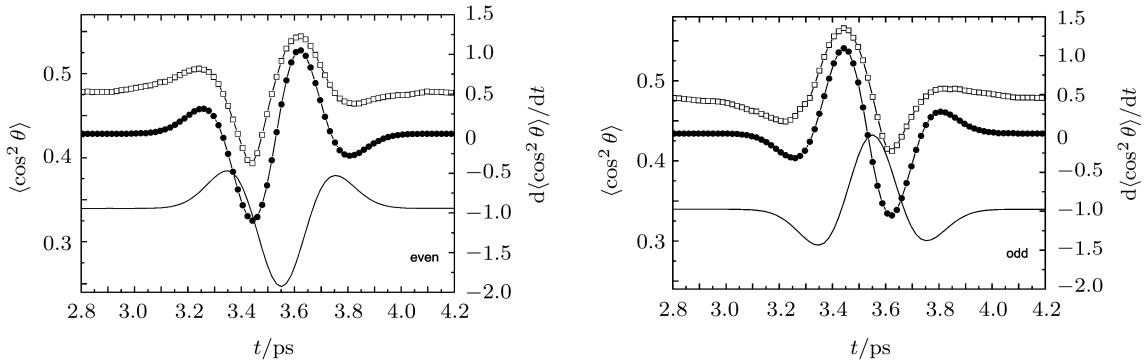


Fig. 3. Calculated time-dependent $\langle\cos^2\theta\rangle$ (the solid black curve, the left axis) and its slope curve (the solid circled markers, the right axis) by the first aligning pulse with intensity 2×10^{13} W/cm^2 and pulse duration 50 fs, the resulted peak alignment (the empty squared markers, the left axis) for the even and odd rotational wave packets when inserting the peak of the second aligning pulse with intensity 3×10^{13} W/cm^2 and pulse duration 50 fs around quarter revival in the shown time range, are shown respectively.

In order to test if the finding about the role of the slope is applicable in general, we calculate the selective alignment when the second laser pulse is introduced around the three quarters revival. Figure 4 demonstrates the alignment parameter $\langle\cos^2\theta\rangle$, the slope $\mathrm{d}\langle\cos^2\theta\rangle/\mathrm{d}t$ by the single laser pulse with intensity 2×10^{13} W/cm^2 and pulse duration 50 fs, and peak alignment modified by two laser pulses with different time delays. The intensity of second pulse and pulse duration are the same as above. In Fig. 4, from 9.9 ps to 11.3 ps that covers three quarters revival, the second laser pulse is inserted and the selective alignment is resulted, the peak alignment also matches with the slope of $\langle\cos^2\theta\rangle$ exactly both for the even and odd rotational states just as showed in Fig. 3, it is noted that the peak of the second laser is inserted at the time of 10.53 ps when the slope of $\langle\cos^2\theta\rangle$ by the first pulse locates a local maximum for the even rotational states and a local minimum for the odds, the maximum alignment degree of 0.5646 is resulted for the even rotational states and the minimum alignment degree of 0.3949 is resulted for the odds, the peak alignment ratio $\langle\cos^2\theta\rangle_{\rm even}/\langle\cos^2\theta\rangle_{\rm odd}$ for the even and odd rotational states is about 1.43. Reversely, the peak of the second laser is inserted at the time of 10.71 ps when the slope locates a local minimum for the even rotational states and a local maximum for the odds, the minimum alignment degree of 0.4125 is resulted for the even rotational states and the maximum alignment degree of 0.5437 is resulted for the odds, the peak alignment ratio $\langle\cos^2\theta\rangle_{\rm odd}/\langle\cos^2\theta\rangle_{\rm even}$ for the odd and even rotational states is about 1.32. It is noted that the peak alignment ratio $\langle\cos^2\theta\rangle_{\rm odd}/\langle\cos^2\theta\rangle_{\rm even}$ reaches a local maximum both inserting the peak of the second laser pulse at the time 3.44 ps and 10.71 ps when the slope locates a local minimum for the even rotational states and a local maximum for the odds, but the degree of

selective alignment modified by the second pulse inserted at 3.44 ps around the quarter revival is more excellent than that inserted the second pulse at 10.71 ps around the three quarters revival. Reversely, the peak alignment ratio $\langle\cos^2\theta\rangle_{\rm even}/\langle\cos^2\theta\rangle_{\rm odd}$ reaches a local maximum both inserting the peak of the second laser pulse at the time 3.62 ps and 10.53 ps when the slope locates a local maximum for the even rotational states and a local minimum for the odds, but the degree of selective alignment modified by the second pulse inserted at 10.53 ps around the three quarters revival is more excellent than that inserted the second pulse at 3.62 ps around the quarter revival.

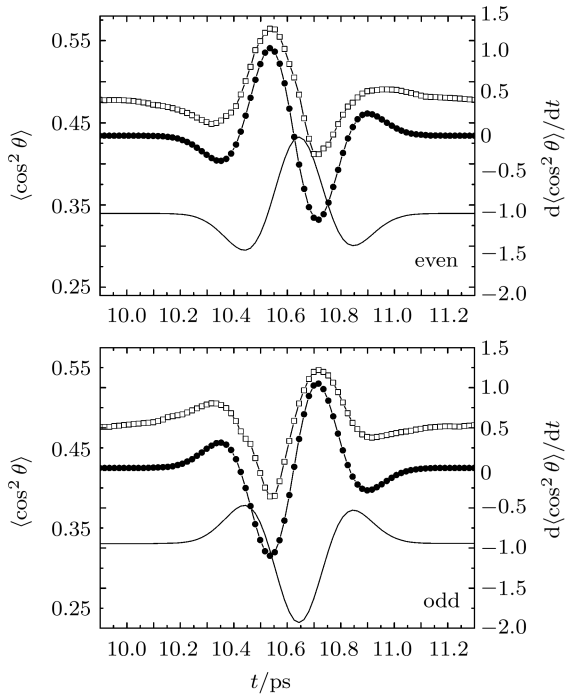


Fig. 4. Calculated time-dependent $\langle\cos^2\theta\rangle$ (the solid black curve, the left axis) and its slope curve (the solid circled markers, the right axis) by the first aligning pulse with intensity 2×10^{13} W/cm^2 and pulse duration 50 fs, the resulted peak alignment (the empty squared markers, the left axis) for the even and odd rotational wave packets when inserting the peak of the second aligning pulse with intensity 3×10^{13} W/cm^2 and pulse duration 50 fs around three quarters revival in the shown time range, are shown respectively.

Figure 5 shows time evolution of rotational wave packet when the peak of the second laser pulse is inserted at the time of 3.44 ps. The alignment $\langle\cos^2\theta\rangle$ by a single pulse varies between 0.2654 and 0.4185 (see Fig. 1). At the time of 3.44 ps, the even wave packet rotates from alignment to antialignment, but the odd wave packet rotates from antialignment to alignment. The second laser pulse decreases even's average rotational energy and stops its motion, but it increases odd's average rotational energy and favours its motion. After the rotational wave packet is modified by the second laser pulse, the opposite effects on the odd and the even wave packets created by the first laser pulse are concealed. The even rotational wave packet is degraded by the second laser pulse. The $\langle\cos^2\theta\rangle$ varies from 0.2690 to 0.3933 for the even wave packet and exhibits a subsequently decreased alignment and antialignment. Reversely, the odd rotational wave packet is promoted by the second laser pulse, the $\langle\cos^2\theta\rangle$ varies from 0.1685 to 0.5656 for the odd wave packet and exhibits a subsequently enhanced alignment and antialignment. Figure 6 shows the amplitude of rotational states from the Fourier transforms of the alignment parameter modified by the second pulse inserted at 3.44 ps, and the difference between the Fourier transforms of the alignment parameter excited by two laser pulses and a single laser pulse. Obviously, after the rotational wave packet is excited by the second laser pulses, the amplitude of even rotational states decreases but the odds increases in comparison with the one excited by a single laser pulse (see Fig. 1). The positive values mean that the second laser pulse has a positive effect on the odd rotational state and increases its population. In contrast, the negative values mean that the second laser pulse has a negative effect on the even rotational state and decreases its population. The results clearly demonstrate the effect of the second laser pulse on the rotational wave packet created by the first pulse. When the peak of the second laser pulse was inserted at the time of 3.44 ps, the odd rotational wave packet was enhanced and the even rotational wave packet was degraded. Thus the final rotational wave packet excited by the two laser pulses was mainly composed of the odd rotational states.

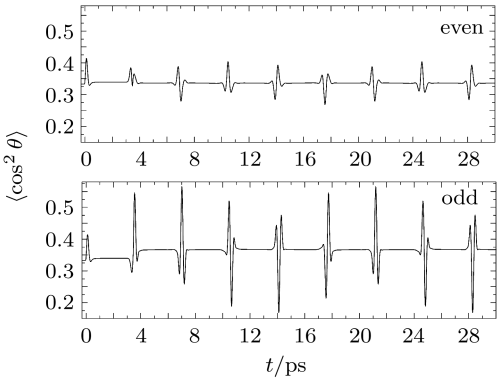


Fig. 5. Calculated time-dependent $\langle\cos^2\theta\rangle$ excited by two laser pulses, the peak of the second laser pulse is inserted at 3.44 ps when a local maximum of the slope locates for the odd rotational states and a local minimum of the slope locates for the evens.

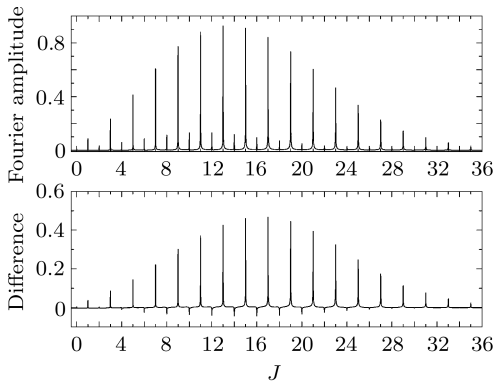


Fig. 6. The rotational states amplitude from Fourier transform of the alignment parameter modified by the second pulse inserted at 3.44 ps, and the difference between the Fourier transforms of the alignment parameter excited by two laser pulses and a single laser pulse.

Figure 7 shows time evolution of rotational wave packet when inserting the peak of the second laser pulse at the time of 10.53 ps. The alignment $\langle\cos^2\theta\rangle$ varies from 0.1694 to 0.5646 for the even wave packet and exhibits a subsequently enhanced alignment and antialignment. Reversely, the $\langle\cos^2\theta\rangle$ varies from 0.2697 to 0.3949 for the odd wave packet and exhibits a subsequently decreased alignment and antialignment. Figure 8 shows the amplitude of rotational states from the Fourier transforms of the alignment parameter modified by the second pulse inserted at 10.53 ps, and the difference between the Fourier transforms of the alignment parameter excited by two laser pulses and a single laser pulse. Obviously, after the rotational wave packet is excited by the second laser pulses, the amplitude of even rotational states is increased but the odd is decreased in comparison with the one excited by a single laser pulse (see Fig. 1). The positive values mean that the second laser pulse has a positive effect on the even rotational state and increases its population. In contrast, the negative values mean that the second laser pulse has a negative effect on the odd rotational state and decreases its population. The even rotational wave packet was enhanced and the odd rotational wave packet was degraded. Thus the even states are increased and the odds decreased in the final rotational wave packet created by the two pulses. We can conclude that the even components prevail on the odds in the final rotational wave packet.

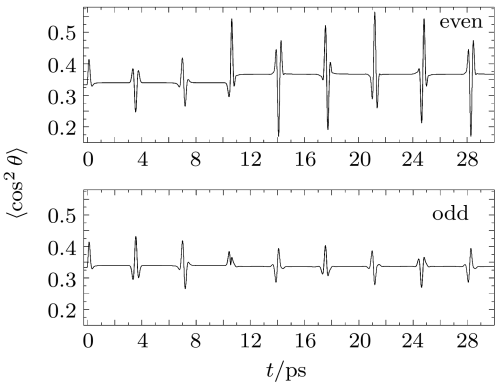


Fig. 7. Calculated time-dependent $\langle\cos^2\theta\rangle$ excited by two laser pulses, the peak of the second laser pulse is inserted at 10.53 ps when a local maximum of the slope locates for the even rotational states and a local minimum of the slope locates for the odds.

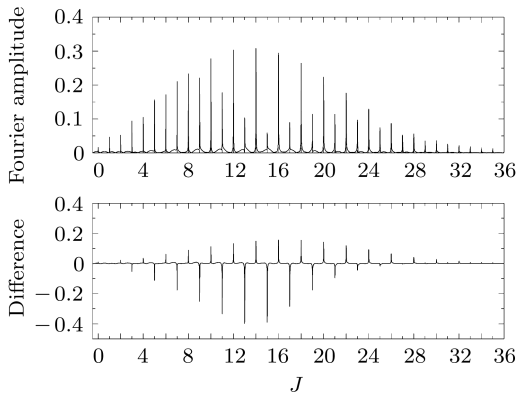


Fig. 8. The rotational states amplitude from Fourier transform of the alignment parameter modified by the second pulse inserted at 10.53 ps, and the difference between the Fourier transforms of the alignment parameter excited by two laser pulses and a single laser pulse.

For optimising the degree of selective alignment, we calculate the ratio of the peak alignment with a set of intensity ratios by fixing the total laser intensity 5×10^{13} W/cm^2 and pulse duration 50 fs. In our calculations, we select the time delay between two laser pulses according to 'the slope rule'. In Fig. 9, the selective alignment degree by two laser pulses with the different intensity ratios I_2/I_1 is demonstrated. As can be seen in Fig. 9(a), the peak of the second laser pulse is inserted at the time around the quarter revival when the slope of alignment by the first pulse locates a maximum for the odd rotational states and a minimum for the evens, the peak alignment ratio $\langle\cos^2\theta\rangle_{\rm odd}/\langle\cos^2\theta\rangle_{\rm even}$ changes for the in-

tensity ratios I_2/I_1 from 0.0 to 4.0, the intensity of the individual pulse is limited to avoid the ionisation of the molecules. The optimal intensity ratio of the pulses should be nearly equal. Meanwhile, when the molecules interacted with the two laser pulses with the same intensity 2.5×10^{13} W/cm^2 and pulse duration 50 fs, the odd rotational wave packet is further promoted and the evens is further degraded. In Fig. 9(b), the peak of the second laser pulse is inserted at the time around three quarters revival when the slope of alignment by the first pulse locates a maximum for the even rotational states and a minimum for the odds. Reversely, $\langle\cos^2\theta\rangle_{\rm even}/\langle\cos^2\theta\rangle_{\rm odd}$ reaches 1.53 when the intensity ratio of the pulses is nearly equal, the even rotational wave packet is promoted but the odds is degraded greatly. The odd and the even rotational states evolve in phase around full revival times but out of phase around the fractional revival times. Inserting the peak of the second laser at the time according to 'the slope rule' to modify the already rotating wave packets around the other fractional revival, we find that the dynamics should be the same as what was discussed above. The scheme should also be applied to most other linear molecules even nonlinear molecules. The selectivity can be further pronounced as long as the laser intensity ratio is selected on the condition that the total laser intensity and pulse duration are fixed, which can also be used in multipulse selective alignment.

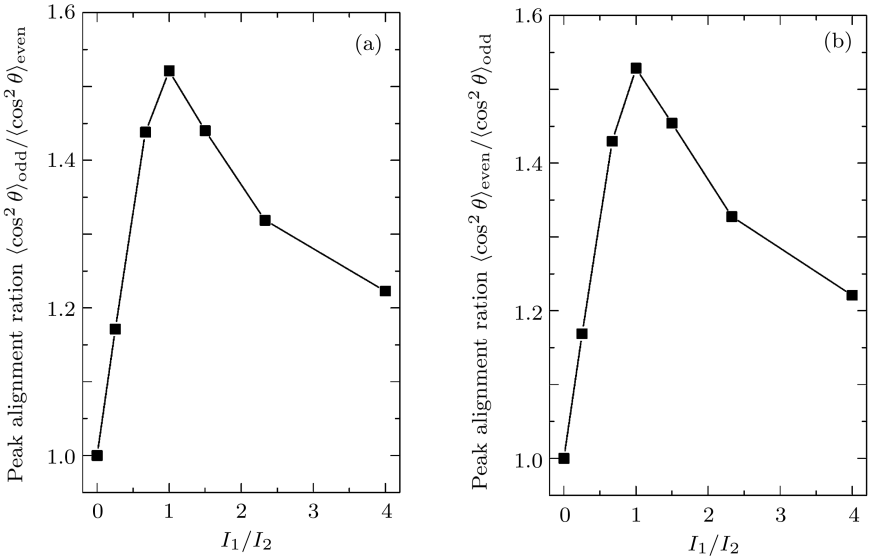


Fig. 9. (a) The ratio of peak alignment $\langle\cos^2\theta\rangle_{\rm odd}/\langle\cos^2\theta\rangle_{\rm even}$, (b) the ratio of peak alignment $\langle\cos^2\theta\rangle_{\rm even}/\langle\cos^2\theta\rangle_{\rm odd}$, by two laser pulse with the different intensity ratios I_2/I_1 while keeping the total intensity 5×10^{13} W/cm^2 and pulse duration 50 fs constant. The second laser pulse is inserted (a) around the quarter revival when a local maximum of the slope locates for the odd rotational states but a local minimum of the slope locates for the evens, (b) around the three quarters revival when a local maximum of the slope locates for the even rotational states but a local minimum of the slope locates for the odds.

4. Conclusion

In conclusion, a novel strategy to determine the optimal time delay of the two laser pulses to manipulate the coherence of the molecular rotational wave packet selectively is demonstrated. The molecular alignment generated by the first pulse can be suppressed or enhanced for the even or odd rotational states, the relative populations between even and odd rotational states can be effectively controlled in a coherent rotational wave packet by adaptively inserting the peak of the second laser pulse at the time when the slope of $\langle\cos^2\theta\rangle$ by the first pulse locates a local maximum for the odd rotational states and a local minimum for the evens. The second pulse stops the motion of the even rotational states and degrades their peak alignment, the odd states is increased and the evens decreased mostly in the final rotational wave packet created by the two pulses. Reversely, when the second laser pulse is inserted at the time when the slope of $\langle\cos^2\theta\rangle$ by the first pulse locates a local maximum for the even rotational states and a local minimum

for the odds. The second laser pulse stops the motion of the odd rotational states and degrades their peak alignment, the odd states is decreased and the evens increased in the final rotational wave packet created by the two pulses. Furthermore, the selective alignment can be optimised by selecting the intensity ratio of the two laser pulses by fixing the total laser intensity. It can be concluded that rotational fractional revivals offer an excellent opportunity to discriminate between the odd and even rotational states as long as inserting the peak of the second pulse at the adaptive time according to 'the slope rule', which can also be applied to most other molecules even nonlinear molecules.

References

[1] Stapelfeldt H and Seideman T 2003 *Rev. Mod. Phys.* **75** 543

[2] Seideman T and Hamilton E 2006 *Adv. At. Mol. Opt. Phys.* **52** 289

[3] Sakai H, Minemoto S, Nanjo H, Tanji H and Suzuki T 2003 *Phys. Rev. Lett.* **90** 083001

[4] Minemoto S, Nanjo H, Tanji H, Suzuki T and Sakai H 2003 *J. Chem. Phys.* **118** 4052

[5] Rakitzis T P, van den Brom A J and Janssen M H M 2004 *Science* **203** 1582

[6] Ohmura H, Saito N and Tachiya M 2006 *Phys. Rev. Lett.* **92** 173001

[7] Yue D G, Zheng X Y, Liu H, Wang C X and Meng Q T 2009 *Chin. Phys.* B **18** 1479

[8] Shapiro E A, Spanner M and Ivanov M Y 2003 *Phys. Rev. Lett.* **92** 237901

[9] Seideman T 1997 *Phys. Rev.* A **56** R17

[10] Dey B K, Shapiro M and Brumer P 2000 *Phys. Rev. Lett.* **85** 3125

[11] Lein M 2007 *J. Phys.* B **40** R315

[12] McClelland J J, Scjolten R E, Palm E C and Celotta R J 1991 *Science* **262** 5197

[13] Tenner M G, Kuipers E W, Kleyn A W and Stolte S 2007 *J. Chem. Phys.* **94** R315

[14] Lan P, Lu P, Cao W, Li Y and Wang X 2007 *Phys. Rev.* A **76** 021801(R)

[15] Gu B, Cui L, Zeng X H and Zhang F S 2006 *Acta Phys. Sin.* **55** 2972 (in Chinese)

[16] Larsen J J, Hald K, Bjerre N, Stapelfeldt H and Seideman T 2000 *Phys. Rev. Lett.* **85** 2450

[17] Dooley P W, Litvinyuk I V, Lee K F, Rayner D M, Spanner M, Villeneuve D M and Corkum P B 2003 *Phys. Rev.* A **68** 023406

[18] Renard M, Hertz E, Guerin S, Jauslin H R, Lavorel B and Faucher O 2005 *Phys. Rev.* A **75** 025401

[19] Yang Z Q and Zhou X X 2008 *Acta Phys. Sin.* **57** 4099 (in Chinese)

[20] Pinkham D and Jones R R 2005 *Phys. Rev.* A **72** 023418

[21] Pinkham D, Mooney K E and Jones R R 2007 *Phys. Rev.* A **75** 013422

[22] Yang Z Q and Zhou X X 2006 *Acta Phys. Chim. Sin.* **22** 932 (in Chinese)

[23] Sakai H, Safvan C P, Larsen J J, Hilligse K M, Hald K and Stapelfeldt H 1999 *J. Phys. Chem.* **110** 10235

[24] Ben Haj-Yedder A, Auger A, Dion C M, Cances E, Keller A, Bris C L and Atabek O 2002 *Phys. Rev.* A **66** 063401

[25] Leibscher M, Averbukh I S and Rabitz H 2003 *Phys. Rev. Lett.* **90** 213001

[26] Lee K F, Litvinyuk I V, Dooley P W, Spanner M, Villeneuve D M and Corkum P B 2004 *J. Phys.* B **37** L43

[27] Xu N, Wu C, Huang J, Wu Z, Liang Q, Yang H and Gong Q 2006 *Opt. Express* **14** 4992

[28] Lee K F, Villeneuve D M, Corkum P B, Stolow A and Underwood J G 2006 *Phys. Rev. Lett.* **97** 173001

[29] Fleischer S, Averbukh I S and Prior Y 2007 *Phys. Rev. Lett.* **99** 093002

[30] Gao Y, Wu C Y, Xu N, Zeng G P, Jiang H B, Yang H and Gong Q H 2008 *Phys. Rev.* A **77** 043404

[31] Tong X M and Chu S I 1997 *Chem. Phys.* **217** 1191

[32] Zhang H, Han K L, Zhao Y, He G Z and Lou N Q 1997 *Chem. Phys. Lett.* **271** 204