Multistage optical Stark decelerator for a pulsed supersonic beam with a quasi-cw optical lattice

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Abstract: We propose a new scheme to realize a multistage optical Stark deceleration for a supersonic molecular beam using a time-varying red-detuned quasi-cw optical lattice with a length of up to 10mm. We analyze the motion of the slowed molecules inside the optical decelerator, and study the dependences of the velocity of the slowed molecular packet on the synchronous phase angle and the number of the deceleration stages (i.e., the number of the optical-lattice cells) by using Monte-Carlo method. Our study shows that the proposed optical Stark decelerator cannot only efficiently slow a pulsed supersonic beam from 230m/s to zero (standstill), but also obtain an ultracold molecular packet with a temperature of sub-mK due to bunching effect in the multistage optical Stark decelerator, which can be trapped in the optical lattice by rapidly turning off the modulation signal of the lattice. Also, we compare the decelerated results of our multistage optical Stark decelerator with a single-stage optical one, and find that our scheme cannot only obtain a colder molecular packet under the same molecular-beam parameters and deceleration conditions, but also be directly used to trap the slowed cold molecules after the deceleration, while don't need to use another molecular trap.

OCIS codes: (020.0020) Atomic and molecular physics; (020.6580) Stark effect; (020.7010) Laser trapping.

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1. Introduction

In the last decade, the manipulation and control of the translational motion of cold or ultracold neutral molecules in gas phase has become one of hot research subjects and would provide a means for the studies of physics and chemistry such as cold molecular high-

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resolution spectroscopy and precision measurements [1, 2], cold chemistry and cold collisions [3-6], quantum computing and quantum information processing [7, 8], and so on.

From dc Stark effect, cold polar molecules will experience an electric dipole force in an inhomogeneous electrostatic field, so this force can be used to decelerate and trap the polar molecules by using the time-varying electrostatic field. That is, so called electrostatic Stark decelerator, which cannot only be used to slow polar molecules in the low-field-seeking states such as CO [9], ND_3 [10], OH [11, 12], OD [13], NH [14], H_2CO [15] and SO_2 [16], but also to slow ones in the high-field-seeking states such as CO [17], YbF [18] and C_7H_5N molecules [19]. Such an electrostatic Stark decelerator can be used to efficiently slow a supersonic molecular beam with a translation temperature of several K from a few 100m/s to zero, and obtain a bunched cold molecular packet with a temperature of a few mK. On the other hand, according to Zeeman effect, a novel Zeeman decelerator using a time-varying magnetic field was proposed and used to slow a supersonic paramagnetic atomic or molecular beam, such as H and D atoms [20, 21], metastable Ne atoms [22] and O_2 molecules [23], etc. To slow all neutral molecules including a kind of neutral molecules without a permanent electric or magnetic dipole moment, in recent years, a pulsed optical Stark decelerator with a far-off-resonance, red-detuned static or moving optical lattice [24, 25], based on ac Stark effect, was proposed and demonstrated. Such an optical Stark decelerator with a well-depth of a few 10K can be used to efficiently slow a supersonic arbitrary molecular beam from several 100m/s to zero, but it cannot be used to obtain a colder molecular packet due to without a so-called bunching effect for slowed molecules in the phase space, this is because its lattice potential depth (22K) [25] is far larger than the translation temperature (1.8K) of NO beam, and there is only a single, time-sequence controlled interaction of the molecules with the lattice light field, so it corresponds to a single-stage optical Stark decelerator for NO molecules. This means that single-stage Stark decelerator, unlike multistage Stark or Zeeman decelerator [9-23], will result in a relative larger velocity distribution width for the slowed molecular packet. So it would be interesting, worthwhile and desirable to find a promising multistage optical Stark decelerator for a supersonic molecular beam and obtain a cold bunched molecular packet with a temperature of sub-mK.

In this paper, we propose a novel multistage optical Stark decelerator for a supersonic molecular beam using a quasi-cw optical lattice, and study the dynamic process of Stark deceleration for a supersonic CH_4 beam by using Monte-Carlo simulation, and obtain some new and important results. This paper is organized as follows: In section 2, we propose a promising scheme to realize a multistage optical Stark deceleration and trapping for molecules with a quasi-cw optical lattice, and introduce the basic principle of our multistage optical Stark decelerator and its theory. In section 3, the scheme of our optical Stark decelerator for a supersonic CH_4 beam is demonstrated by Monte-Carlo method, and some simulated results on molecular deceleration and trapping are obtained. In section 4, we compare our scheme with a single-stage optical-lattice Stark decelerator. Some main results and conclusions are summarized in the final section.

2. Scheme and theory

2.1. Scheme of multistage optical Stark decelerator

Figure 1(a) shows a novel scheme to slow a supersonic molecular beam by using a multistage optical Stark decelerator, which is composed of a stationary red-detuned quasi-cw optical lattice. In this scheme, the optical lattice is created by two nearly counter-propagating quasi-cw single-frequency linear-polarized infrared lasers with the same fixed frequency (i.e. the same wavelength λ) that is far detuned from direct electronic transitions of the molecules. The angle between the two laser beams is β and its value is taken to be about 178^o-175^o in our scheme, and the spatial period Λ of this stable lattice is nearly equal to half of the wavelength. Due to ac Stark effect, the molecules that enter the lattice from the antinode will

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gain the optical Stark energy. This gain in the potential energy will be compensated by a loss in molecular kinetic energy due to the law of energy conservation. If the optical lattice is switched off rapidly before the molecules begin to decrease their potential energy, the molecules will not regain the lost kinetic energy. This shows that the right (or rear) half of each lattice cell in the red-detuned optical lattice can be used to slow the molecules and lose their kinetic energy as they move in the quasi-cw lattice along the z axis, which is similar to the slowing principle of single-stage optical Stark decelerator for molecules using a single pulsed Gaussian laser beam [26] or a pulsed optical lattice [24, 25]. If this process can be repeated again and again by using a time-sequence synchronous and control system, the molecules will be slowed down, even be brought to a standstill. This shows that the time-varying optical lattice forms a multistage optical Stark decelerator, and its slowing principle is similar to one of multistage electrostatic Stark decelerator for molecules.

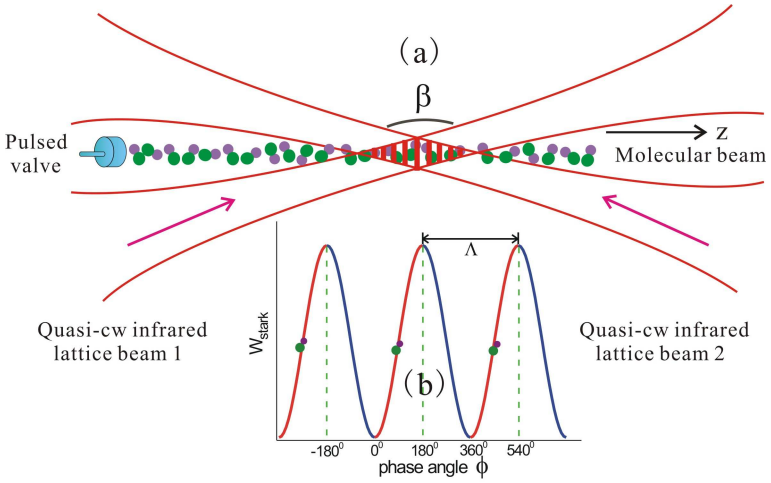

Fig. 1. (a). A schematic diagram of multistage optical Stark decelerator and trap for a supersonic molecular beam using a quasi-cw optical lattice. (b) Longitudinal Stark potential energy generated by the optical lattice for different phase angle ϕ.

2.2. Theory of optical Stark deceleration and its basic principle

We know that the optical lattice has a cosine-squared intensity distribution in the z direction. When a pulsed supersonic molecular beam propagates along the z direction, due to ac Stark effect, the molecules in this red-detuned optical lattice field experience an optical dipole interaction potential as follows

$$U = -(2\alpha I / \varepsilon_0 c)\cos^2(kz/2), \tag{1}$$

where I is the intensity of the Gaussian laser beam, α is the averaged molecular polarizability, ε_0 is the permittivity in free space, c is the speed of light in vacuum and $k = (4\pi \sin(\beta/2))/\lambda$ is the wave number of the lattice [25]. From Eq. (1), when a molecule moves in the optical lattice, it will feel an optical dipole force in the z direction that amounts to

$$F_z = -(\alpha I / \varepsilon_0 c)\sin(kz), \tag{2}$$

which is proportional to the intensity gradient of the optical lattice in the z direction, and then the classical equation of molecular motion in the lattice can be written as

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$$m\ddot{z} = -(\alpha I / \varepsilon_0 c)\sin(kz), \tag{3}$$

where m is the mass of molecules.

For simplicity, we use the phase angle ϕ to describe the molecular position in the optics lattice, which is defined as $\phi = \frac{z}{\Lambda} \times 360^0$, where z is the longitudinal (or axial) position of the molecule. The antinode of the lattice (i.e., the minimum of the lattice potential due to its red detuning) is defined as z =0 (i.e. $\phi = 0^0$). Based on Eq. (2) and Fig. 1(b), we can see that the molecules in a phase-angle region of $0^0 < \phi < 180^0$ will be decelerated because the optical dipole force acted on the molecules is anti-parallel to their moving direction, we call this phase-angle region ($0^0 < \phi < 180^0$) as the deceleration region. While the molecules in a phase-angle region of $180^0 < \phi < 360^0$ will be accelerated because their experienced dipole force is parallel to their moving direction, we call this phase-angle region ($180^0 < \phi < 360^0$) as the acceleration one.

We make a time-varying lattice light field (i.e., a quasi-cw optical lattice, or a time-varying optical Stark potential for the molecules) by employing an electro-optic modulator (EOM) [27], which will be used to simultaneously modulate the intensities of the two cw high-power lasers and form a quasi-cw optical lattice. The lasers (i.e., the optical lattice) are simultaneously switched on when the synchronized molecules approach the antinode of the lattice (i.e. at the phase angle of $\phi = 0^0$). As soon as the synchronized molecule arrives at the position $\phi = \phi_0$ (where ϕ_0 is the phase angle of the synchronized molecules, and we choose $\phi_0 \le 180°$), the lattice is switched off rapidly, and then the synchronized molecules will be slowed during this process ($0° \le \phi \le \phi_0$). It is clear that this process can be repeated many times by using a time-sequence synchronous and control system so as to lower the incident molecular velocity to an arbitrary final value. From the phase stability theory [9, 11], we can only use a time-sequence synchronous and control system to slow a finite portion of molecules in the beam whose velocities are within $\pm \Delta v$ deviation of the synchronized velocity. The time sequence applied to the EOM can remove a fixed amount of kinetic energy per stage from the synchronized molecules, such that the molecular packet maintains tight spatial confinement stage to stage due to bunching effect, which is similar to the concept of longitudinal phase stability in the electrostatic stark deceleration [9, 11]. The appropriate pulse sequence $t_{on}(n)$ of the switched-on signal can be calculated by numerically integrating the equation of Newtonian motion of molecules [i.e. Eq. (3)] in light field, that is

$$t_{on}(n) = \int_{(n-1)\Lambda}^{(n-1)\Lambda + \phi\Lambda/360} (v_0{}^2(n) - (4\alpha I/(\varepsilon_0 cm))(1 - \cos^2(kz/2)))^{-1/2} dz, \tag{4}$$

where $v_0(n) = \sqrt{v_0^2 - (4(n-1)\alpha I/(\varepsilon_0 cm))(1-\cos^2(k\Lambda\phi/720))}$, v_0 is the initial velocity of the synchronized molecules and n is the number of the deceleration stages (i.e., the number of the lattice cells). When the lattice is switched off, the molecules can move freely, and the switched-off time $t_{off}(n)$ of the EOM can be described by

$$t_{off}(n) = (\Lambda - \phi_0 \Lambda / 360^0)/v(n), \tag{5}$$

where $v(n)$ is the final velocity of the slowed molecules after the nth deceleration stage. And then, the total time of the motion of the synchronized molecules in the lattice during the whole of deceleration process is given by

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$$t = \sum_{1}^{n} \left[t_{on}(n) + t_{off}(n) \right]. \tag{6}$$

From Eq. (6), we can estimate the needed time of the whole deceleration process of a supersonic molecular beam. It is clear from Eqs. (4) and (5) that when the parameters of the optical lattice are unchanged, this deceleration time is related to the initial velocity of the synchronized molecules and its synchronous phase angle. This shows that when the parameters of the optical Stark decelerator, the initial velocity of the synchronized molecules and its synchronous phase angle are given in our simulation or experiment, we can obtain an appropriate pulse time-sequence and find that both the switched-on time $t_{on}(n)$ and the switched-off time $t_{off}(n)$ of EOM are increased nonlinearly with the increase of the deceleration stage numbers, so the modulation frequency on EOM is decreased nonlinearly with increasing the deceleration stage numbers, which is the same as that in the case of the electrostatic Stark decelerator [28].

3. Monte-Carlo simulations and results

We use Monte Carlo method to demonstrate our optical Stark decelerator for a supersonic methane (CH_4) molecular beam with a longitudinal temperature of 1K and a mean velocity of u=230m/s [9]. A single-frequency, single-mode linear-polarized ytterbium-doped fiber laser with a power of P=264W and a wavelength of 1060nm is employed to form a stationary infrared optical lattice [29], and the corresponding optical potential (i.e., lattice potential depth) is 6.63 mK. The longitudinal size of the optical lattice is up to 10 mm, and the detection position is at 20 mm away from the center of the optical lattice. The synchronized molecules are assumed to have an initial position z=0 and an initial velocity v_0=u=230m/s.

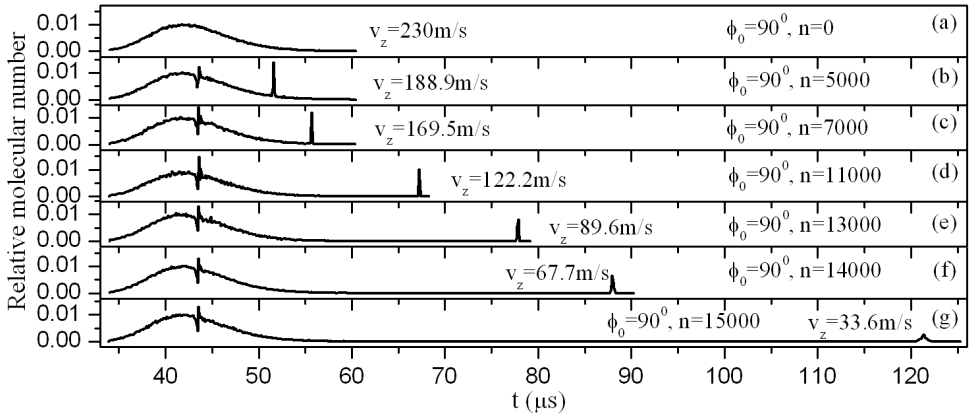

Fig. 2. Simulated time-of-flight signal of CH_4 molecules at the outlet of the decelerator for the synchronous phase angle $\phi_0 = 90^0$ and different deceleration stage n, and other simulation parameters are given in the text.

We first study the dependence of the deceleration effect on the number of the deceleration stages n by Monte-Carlo simulation, and Fig. 2 shows the time-of-flight (TOF) profiles for CH_4 molecules when $\phi_0 = 90^0$, n= 0, 5000, 7000, 11000, 13000, 14000 and 15000, respectively. The width of the TOF profiles is a convolution of the spatial and velocity distributions of the disturbed molecules. We can see from Fig. 2 that with increasing the number of the deceleration stages, the velocity of the slowed packet will be gradually reduced. Such as, when the number of the deceleration stages is increased from 0 to n=15000, the mean velocity of the slowed molecular packet will be reduced from 230m/s to 33.6m/s. Also, with increasing the number of deceleration stages, the peak intensity of the molecular packet

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is gradually decreased, and its velocity width is becoming broader and broader. This shows that the number of the decelerated synchronized molecules keeps unchanged. From our simulated results, we also find that the effective deceleration is limited to the molecules whose velocities are within $\pm 0.5 m/s$ deviation of the synchronized velocity, and about 2% of the molecules in the molecular beam are decelerated and kept staying in the slowed molecular packet.

Shown in Fig. 3 are the simulated phase space plots of the slowed packet for $\phi_0 = 90^0$ after *n*=9000th, 11000th and 13000th stages, respectively. Each hollow circle represents a molecule in the phase space. In according to our above analysis, the size of the phase stable area, which is determined by the phase angle ϕ_0, remains the same for three cases, as shown in Fig. 3. Molecules in the slowed packet oscillate around the synchronized ones in the phase space during the slowing process, which is similar to the case of electrostatic Stark deceleration. For $\phi_0 = 90^0$, the oscillation velocity of the molecules in the slowed packet is about 1m/s.

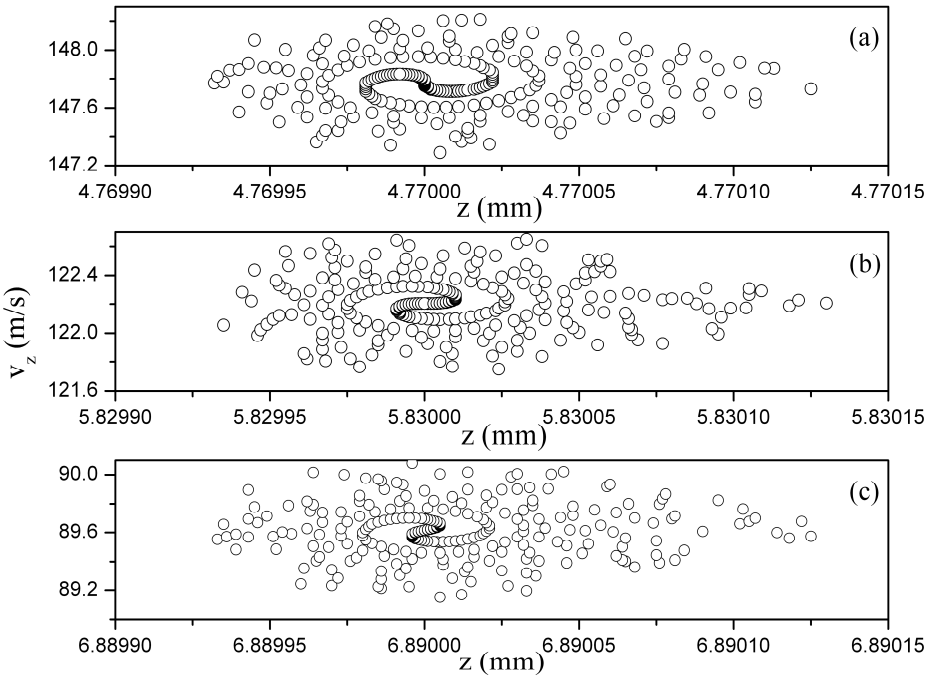

Fig. 3. Simulated phase-space plot for the deceleration stages (a) *n*=9000, (b) *n*=11000 and (c) *n*=13000 with the same synchronous phase angle $\phi_0 = 90^0$.

Afterwards, we study the dependence of the deceleration effect on the synchronous phase angle ϕ_0. In this case, when the synchronous phase angle is varied, both the deceleration effect of the molecular packet and the size of the phase stability region will be changed. Figure 4 shows the simulated TOF signals of the slowed molecules for *n*=7000, $\phi_0 = 75^0$, 90^0, 120^0, 135^0 and 150^0. It is clear from Fig. 4 that with increasing the synchronous phase angle ϕ_0, the velocity of the decelerated molecular packet will be lowered, while the peak intensity of the molecular packet and its number will be gradually decreased. In particular, when the synchronous phase angle is increased from 75^0 to 150^0, the mean velocity of the decelerated molecular packet is reduced from 187.1m/s to 73.7m/s, and the fraction of the slowed cold molecules is decreased from 2.1 % to 0.4%. This shows that the size of the phase

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stability region becomes smaller with the increase of the phase angle, which is accordant with our theoretical predication.

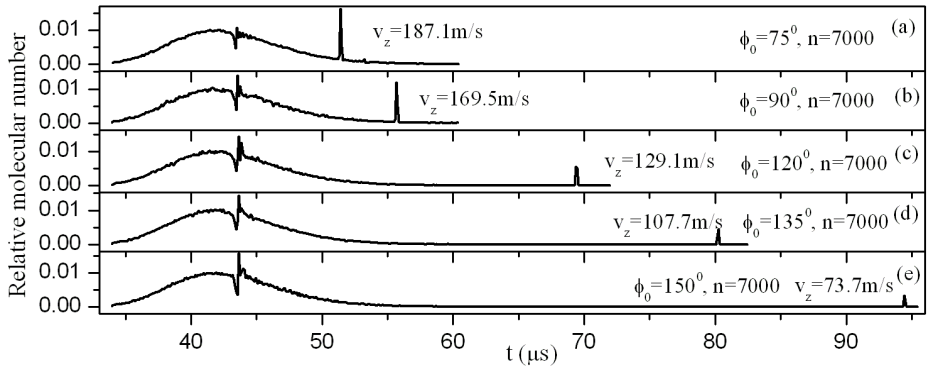

Fig. 4. Simulated time-of-flight signal of CH_4 molecules at the outlet of the decelerator for the deceleration stage *n*=7000 and different synchronous phase angle, and other simulation parameters are given in the text.

We also study the relationship between the phase stable area and the synchronous phase angle ϕ_0 for $\phi_0 = 90^0$, 120^0 and 150^0, and the simulated results (i.e., the phase-space plots of the slowed molecular packet) after the 7000th stage are plotted in Fig. 5. As shown in Fig. 5, the stable area in the phase space of the slowed packet will be decreased with increasing the synchronous phase angle, that is, the number of the decelerated molecules will be gradually reduced.

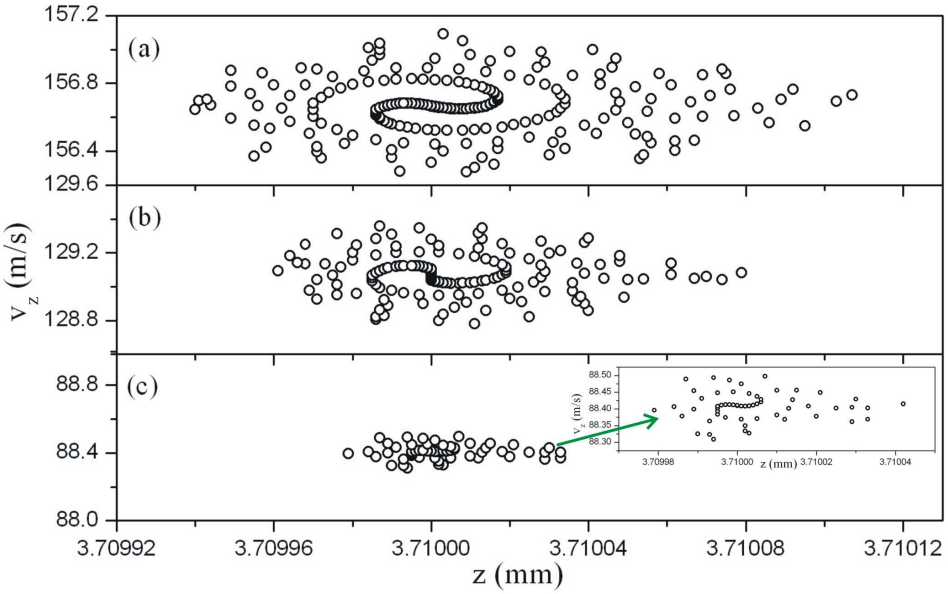

Fig. 5. Simulated phase-space plot for the same deceleration stages *n*=7000 and the synchronous phase angle (a) $\phi_0 = 90^0$, (b) $\phi_0 = 120^0$ and (c) $\phi_0 = 150^0$. The inset figure is the magnified Fig. 5(c).

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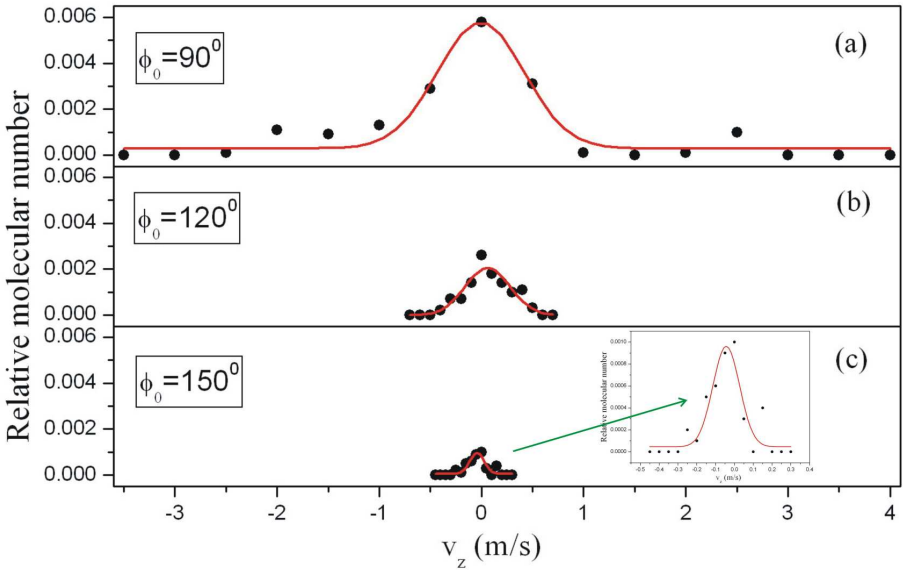

Fig. 6. Simulated velocity distribution of slowed cold methane molecules trapped in the cw optical lattice for the synchronous phase angle (a) $\phi_0 = 90^0$, (b) $\phi_0 = 120^0$ and (c) $\phi_0 = 150^0$. The solid circles are the Monte-Carlo simulated results while the red lines are the Gaussian-fitted lines. The inset figure is the magnified Fig. 6(c).

In principle, if we can keep on increasing the number of the deceleration stages, the bunching molecules in the molecular beam can be decelerated to standstill, and then trapped in the optical lattice. The number of the pulsed optical Stark deceleration stages needed for trapped cold molecules depends on the ratio of the molecular polarizability to its mass as well as its initial phase angle and initial velocity. As soon as the deceleration process ends up, we switch off the modulated signal of the EOM, and the modulated quasi-cw optical lattice becomes a cw one (that is, a stationary periodic optical well will be formed), and then the slowed molecules will be trapped in the cw lattice. The simulated velocity distributions of the trapped cold molecules are shown in Fig. 6 for $\phi_0 = 90^0$, $\phi_0 = 120^0$ and $\phi_0 = 150^0$. We can see from Fig. 6 that when the synchronous phase angle is $\phi_0 = 90^0$, 120^0 and 150^0, the fraction of the trapped cold molecules relative to initial molecular number (the total length of the used optical lattice) are about 2.0% (8.123mm), 1.1% (5.415mm), and 0.4% (4.353mm) respectively, and the corresponding temperature of cold molecules trapped in the lattice are about $1mK$, $48\,\mu K$ and $11\,\mu K$. This shows that our proposed scheme can be directly used to efficiently slow a supersonic molecular beam and obtain a cold molecular sample with a temperature of sub-mK.

4. Comparison and discussion

4.1. Comparison with a single-stage optical Stark decelerator

In 2006, two groups demonstrated the single-stage optical Stark decelerator for molecules with a pulsed optical lattice in the experiment nearly at the same time [24, 25]. Our decelerator looks so similar to the two optical Stark decelerators composed of a pulsed lattice mentioned above, but there is a quite difference between them. Their optical lattices are formed by pulsed lasers with an extremely-high peak power, and the corresponding lattice potential depth is about several 10K, so they can be used to efficiently slow a supersonic molecular beam from ~ 400m/s to zero, but the width of the slowed molecular packet in the

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velocity space is quite broad because there is only a single-time interaction of the synchronized molecules with the pulsed optical lattice (i.e., without bunching effect) in a single-stage optical Stark decelerator. While our quasi-cw optical lattice is formed by the modulated cw lasers and used to form an multistage optical Stark decelerator with a potential depth of up to 6.63mK, so our proposed scheme cannot only used to slow a supersonic molecular beam with a several 100m/s by multi-time interactions of the synchronized molecules with the optical lattice, but also to obtain a very narrowed cold molecular packet due to bunching effect in an multistage optical Stark decelerator. To demonstrate and compare these, we simulate the dynamic processes of both our multistage optical Stark decelerator using the quasi-cw optical lattice and the single-stage optical Stark one with the pulsed optical lattice for a supersonic NO molecular beam, and its initial parameters are the same as ones used in Ref [25], and the simulated results are shown in Fig. 7. In our quasi-cw optical lattice, the phase angle of the synchronized molecule is set to be $\phi_0 = 90^0$, the parameters of the quasi-cw optical lattice are the same as that of our used in Figs. 2 and 4. Figures 7(a) and 7(b) show the results of our multistage and the single-stage optical Stark decelerators [25], respectively. By comparison with Figs. 7(a) and 7(b), we can find that (1) the width of the slowed molecular velocity distribution in our multistage decelerator scheme using the quasi-cw optical lattice with a potential depth of 6.63mK is at least one order of magnitude narrower than that in the previous single-stage Stark decelerator [25] using the pulsed optical lattice with a potential depth of 22K, so the temperature of the slowed molecular packet in our scheme is much lower than theirs because there is an efficient bunching effect in multistage Stark decelerator, and no bunching effect in the single-stage Stark one, which is consistent with our prediction mentioned above; (2) the pulsed lattice can decelerate the molecules from 400m/s to 270m/s by using only one stage while we need 72110 decelerated stages; (3) our cw optical lattice can be directly used to trap the slowed cold molecules after the deceleration, and don't need to use another molecular trap.

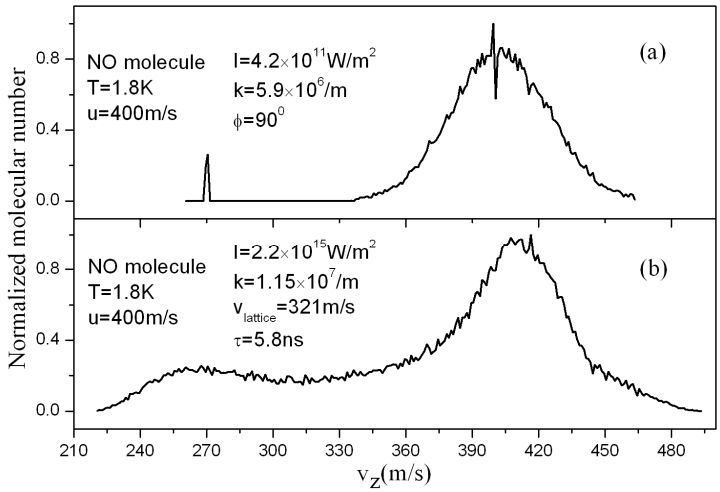

Fig. 7. Simulated NO molecular velocity distribution at the outlet of (a) multistage optical Stark decelerator using a quasi-cw optical lattice for the synchronous phase angle $\phi_0 = 90^0$, the peak intensity I=4.2×10^{11}W/m^2, and the wave vector k=5.9×10^6/m, and (b) a single-stage optical Stark decelerator using a pulsed optical lattice for the synchronous phase angle $\phi_0 = 45^0$, the peak intensity I=2.2×10^{15}W/m^2, the wave vector k=1.15×10^7/m, the lattice's moving velocity $v_{lattice}$= 321m/s, and the laser pulse width t= 5.8ns. The initial translational temperature of supersonic NO molecular beam and its initial flow velocity are T= 1.8K and u= 400 m/s, respectively.

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4.2. Feasibility analysis of our lattice decelerator scheme

The mean velocity of a supersonic molecular beam: It is well known that the mean velocity of a supersonic molecular beam using xenon as an carrier gas is about 380m/s at room temperature (300K) [30], but when the valve housing is cooled to 200K (or 220K) by a temperature-controllable liquid nitrogen (LN) system, the mean velocity of a supersonic ND_3 (or SO_2) beam can be reduced to ~285m/s [31] (or ~300m/s) [16], and the mean velocity of a supersonic metastable CO beam is lowed to 230m/s at a valve-housing temperature of 160K [9]. This shows that a supersonic molecular beam with a mean velocity of 230 - 400 m/s is obtainable.

4.2.1 Generation of a cw optical lattice with a high optical potentia:

To form a cw optical lattice with an optical potential of a few mK to several 10mK, we need a single-mode, single-frequency, linear-polarized high-power cw laser in our proposed scheme. Such as a single-frequency, single-mode, plane-polarized Yb-doped fiber master oscillator power amplifier (MOPA) system with a cw output power of 264W [29] can be used to generate an optical lattice with an optical potential of 6.63 mK, which is used to form our multistage optical Stark decelerator. In recent years, a single-frequency, plane-polarized Yb-doped fiber MOPA source up to 402W was produced [32], and 1kW-class single-frequency plane-polarized fiber MOPA sources were predicted [33], which can be used to form an optical lattice with an optical potential of 10.1 – 25.1mK. This shows that with the fast development of single- frequency, plane-polarized high-power fiber laser technique, it is easy to form a multistage optical Stark decelerator with an optical-lattice potential of higher than 20mK.

4.2.2 Production of a quasi-cw optical lattice and the highest modulation frequency

If assuming that the maximum mean velocity of a supersonic molecular beam is 400m/s (or 230m/s), and the laser wavelength of the optical lattice is 1064nm, the maximum modulation frequency of the quasi-cw optical lattice is ~752MHz (or ~434MHz), which can be realized by using an electro-optic modulator (EOM) with the highest modulation frequency of 1GHz (or 500MHz). Since the single-frequency, plane-polarized Yb-doped fiber MOPA systems with a high power of 264W-1kW has a seed laser source (i.e., a DFB fiber laser) with a power of 80mW [29, 32, 33], it is no problem to modulate the intensity of such a low-power seed laser by using an EOM (1GHz) so as to form a quasi-cw optical lattice with a frequency of up to 752MHz. If our quasi-cw optical lattice is made up by a single-frequency, plane-polarized high-power CO_2 laser, the maximum modulation frequency is only ~ 75.2MHz, so an acoustic-optical modulator (AOM) with the highest modulation frequency of 100MHz can be used to form a quasi-cw CO_2 lattice.

In a real experiment, the used EOM or AOM can not switch off the optical lattice 100% as it has a limited contrast ratio. So we should consider the influence of the contrast ratio of EOM or AOM on the results of our optical Stark decelerator. The contrast ratio of EOM in our scheme is 150:1 [27], when we switch off the optical lattice, the intensity of the residual optical field is much lower than one of the switched-on optical field. When the optical lattice is switched on, the molecules in the decelerated packet will be slowed by the velocity change Δv. While the optical lattice is switched off, the molecules in the decelerated packet will be accelerated by the velocity change $\Delta v'$ due to the residual optical field. It is clear that the relation between the changes of the velocity is $\Delta v >> \Delta v'$. So the influence of the contrast ratio of EOM on the deceleration results in our scheme is very small. To demonstrate this point, we performed the Monte-Carlo simulation for an infinite contrast ratio and a contrast ratio of 150:1 respectively, and find that the synchronous CH_4 molecules are decelerated from 230m/s to 169.5m/s for an infinite contrast ratio, while the CH_4 molecules

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are slowed from 230m/s to 169.9m/s for the contrast ratio of 150:1 when $\phi_0 = 90^0$ and n=7000. This shows that the influence of EOM's (or AOM's) contrast ratio on the deceleration effect in our scheme can be neglected when its contrast ratio is equal to or larger than 150:1.

It is clear from the above analysis that our proposed scheme to form a multistage optical Stark decelerator using a quasi-cw optical lattice is feasible experimentally, which can be directly used to slow a supersonic molecular beam from 400m/s to zero and trap the slowed cold molecular packet with a sub-mK temperature in a cw optical lattice by switching off the modulation signal on the EOM or AOM.

5. Conclusions

In this paper, we have proposed a novel multistage optical Stark decelerator for a supersonic molecular beam using a time-sequence controlled, quasi-cw optical lattice, and described its deceleration principle. By using Monte-Carlo simulation, we have demonstrated the dynamic process of the multistage optical Stark deceleration for a supersonic CH_4 molecular beam, and studied the dependences of the decelerated effect on both the number of the deceleration stages and the phase angle of the synchronized molecules, and obtained some interesting phase-space plots of the slowed molecules. Our study shows that the multistage optical Stark decelerator proposed here can be directly used to slow a supersonic molecular beam from 400m/s to zero in the quasi-cw optical lattice with an interaction length of up to 10 mm and obtain a slowed cold molecular packet with a temperature of sub-mK, even to trap them in its cw optical lattice by turning off the modulation signal of the EOM.

Also, we have analyzed the feasibility of our multistage optical Stark decelerator for a supersonic molecular beam and compared its deceleration effect with a single-stage optical Stark decelerator, and found that our proposed decelerator can yield a narrowed cold molecular packet with a temperature of sub-mK due to bunching effect in a multistage Stark decelerator. This shows that our multistage optical Stark decelerator using a quasi-cw optical lattice cannot only be directly used to slow a supersonic molecular beam with a mean velocity of up to 400m/s and to trap a slowed cold molecular packet with a sub-mK temperature, but also to slow all kinds of neutral molecules (including polar molecules, paramagnetic molecules and those molecules without a permanent electric or magnetic dipole moment), atoms and clusters, and so on. So such a multistage optical Stark decelerator has some important applications in the fields of cold atomic and molecular physics, quantum optics, cold chemistry, quantum computing and quantum information processing [7-8, 34], even can be used to realize an all-optical, chemistry-stabled molecular Bose-Einstein condensates by an optical-potential evaporative cooling [35], etc.

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