

Real-time control of the periodicity of a standing wave: an optical accordion

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Abstract: We report an experimental method to create optical lattices with real-time control of their periodicity. We demonstrate a continuous change of the lattice periodicity from $0.96\ \mu\text{m}$ to $11.2\ \mu\text{m}$ in one second, while the center fringe only moves less than $2.7\ \mu\text{m}$ during the whole process. This provides a powerful tool for controlling ultracold atoms in optical lattices, where small spacing is essential for quantum tunneling, and large spacing enables single-site manipulation and spatially resolved detection.

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OCIS codes: (020.0020) Atomic and molecular physics; (020.7010) Trapping

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1. Introduction

Ultracold atoms in optical lattices are a model system for studying quantum many-body effects in a highly controllable way [1]. They are also promising candidates for quantum information processing [2, 3]. Recently, optical lattices with small periodicity have been used to investigate superfluidity [4], quantum transport [5], the superfluid-Mott insulator transition [6, 7], and the Tonks-Girardeau gas [8, 9]. Small periodicity is essential for these experiments as high tunneling rates between neighboring sites are required. However, small periodicity also makes it very difficult to manipulate and detect single sites of the optical lattice. For example, the number statistics of a single site of the Mott insulator phase has never been measured directly. On the other hand, single-site manipulation and detection has been demonstrated in optical lattices with large periodicity [10, 11]. We can bridge this gap if we are able to change the lattice periodicity while keeping atoms trapped in the lattice.

Several groups have created optical lattices with tunable spacing [12, 13, 14, 15, 16], however, a configuration that is stable enough to allow continuous variation of the lattice periodicity while keeping atoms trapped has yet to be developed. As the optical lattices are normally created by interfering two beams, which is sensitive to the relative phase between beams, it is very difficult to keep the lattice stable while changing its spacing. In this paper, we report the creation of an optical lattice formed by two parallel beams brought together at the focal plane of a lens. We use a novel method to change the distance between the two beams that keeps the optical lattice stable. The center fringe shifts less than $2.7 \mu\text{m}$ while the lattice spacing is changed from $0.96 \mu\text{m}$ to $11.2 \mu\text{m}$ in one second. This stability allows one to change the lattice spacing in real time while keeping atoms trapped. This is also useful in many other applications of optical lattices, such as sorting microscopic particles [17].

2. Theory and Experiment

As shown in Fig. 1, two parallel beams separated by a distance D are brought together by a lens to produce an optical lattice at the focal plane of the lens. If the beams at the focus are plane waves, the lattice spacing will be $d = \lambda / (2 \sin(\theta/2))$, where λ denotes the laser wavelength, and θ is the angle between the two beams at the focus. For a thin lens, if the beams are symmetric with respect to the axis of the lens, the angle will be approximately $\theta \approx 2 \tan^{-1}(D/2f)$. Thus

$$d \approx \lambda \frac{(D^2/4 + f^2)^{1/2}}{D}, \quad (1)$$

where f is the focal length of the lens. We can tune the lattice spacing by changing D . Eq. (1) is commonly used for calculating the lattice spacing [14], however, it is not very accurate when θ is large.

The interference pattern of the two beams and its lattice spacing can be calculated more precisely using Fourier optics. For our setup, we use an achromatic doublet lens, which has much smaller aberrations than a singlet lens, and can be used to achieve a diffraction limited laser spot. It performs a Fourier transformation when an object sits at the front focal plane and the image sits at the back focal plane. Assuming that the field of an incident laser at the front focal plane of a lens is $U(x_1, y_1, -f)$, then the field at the back focal plane of the lens $U_0(x, y, f)$ is the Fourier transform of $U(x_1, y_1, -f)$. For a Gaussian beam, the resulting intensity distribution $I_0(x, y, f) = U_0^*(x, y, f) U_0(x, y, f)$ is still Gaussian and can be calculated easily. If the incident beam is shifted horizontally by $+D/2$ or $-D/2$, the resulted field at the back focal plane will

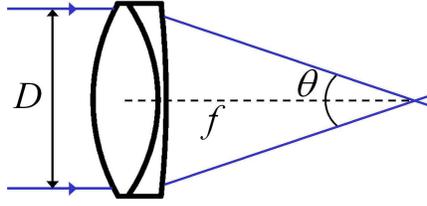


Fig. 1. Two parallel beams separated by a distance D , produce an optical lattice at the focal plane of the lens. We use an achromatic doublet lens to minimize the aberration of the off-axis beams. The highly curved surface faces the incident parallel beams.

become

$$U_{+D/2}(x, y, f) = \exp(-j \frac{\pi D}{\lambda f} x) U_0(x, y, f), \quad (2)$$

$$\text{or } U_{-D/2}(x, y, f) = \exp(+j \frac{\pi D}{\lambda f} x) U_0(x, y, f). \quad (3)$$

Thus the interference pattern created by bringing two identical parallel beams together by a lens (see Fig. 1) is

$$I(x, y, f) = 2 (\cos \frac{2\pi D}{\lambda f} x + 1) I_0(x, y, f), \quad (4)$$

and the period of the interference pattern is

$$d = \lambda f / D. \quad (5)$$

As shown in the derivation, Eq. (4) is independent of the curvature of the laser beams. Both beams can be divergent and have very large waists at the focal plane. Thus we can use this method to produce optical lattices with arbitrary size. Moreover, Eq. (5) is much simpler and more accurate than Eq. (1) when θ is large. From Eq. (5), we get the angle between the two beams at the focus to be $\theta = 2 \sin^{-1}(D/2f)$.

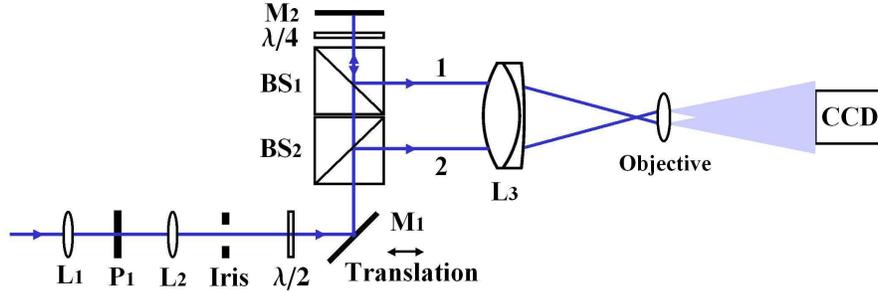


Fig. 2. Experimental set-up for creating and imaging the optical lattices with real-time control of periodicity. L1, L2 are singlet lenses; P1 is a pinhole; M1 and M2 are mirrors; BS1 and BS2 are polarizing cube beam splitters; and L3 is an achromatic doublet lens.

Our experimental setup for creating and imaging the optical lattices is shown in Fig. 2. A Gaussian beam with the desired waist is obtained by passing a laser beam ($\lambda = 532 \text{ nm}$) through two lenses (L1, L2), one pinhole (P1) and one iris. A $\lambda/2$ waveplate is used to change the orientation of the polarization of the beam, which controls the relative power of the two parallel

beams. The s-polarized component of the beam is reflected by BS2 and the p-polarized component passes through both beamsplitters. After passing through the $\lambda/4$ waveplate twice, the p-polarized component becomes s-polarized and is reflected by BS1. These two parallel beams are brought together by an achromatic doublet lens L3 to create the optical lattice. Then the optical lattice is magnified by an objective and imaged by a CCD camera. We tried two lenses with different focal lengths (30.0 and 80.0 mm) for L3. The optical lattice is formed at the focal plane of L3. Its periodicity can be changed in real time by moving M1 with a stepper motor, and its fringe contrast can be close to 100% by tuning the $\lambda/2$ waveplate.

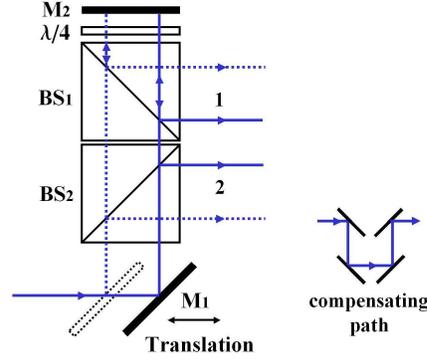


Fig. 3. The distance between the two parallel beams can be changed by moving M1.

As shown in Fig. 3, the distance between the two parallel beams can be changed by moving mirror M1 horizontally or vertically. The difference between the optical path lengths of the two beams does not change when M1 is moving. Thus in principle the center fringe of the optical lattice will not move when M1 is moving in any direction. A compensating path, as shown in the right part of Fig. 3, can be used to make the difference of the optical path lengths to be zero, if necessary, for lasers with small coherence length or divergent beams. The optical lattice is also not sensitive to the alignment of the beamsplitters. The objective lens is aligned by making sure that the image of beam 2 does not move when M1 does, ensuring that the focal plane of L3 is imaged at the CCD camera. Then we adjust M2 to let the image of beam 1 superpose with beam 2, which automatically makes two beams parallel.

3. Results and discussion

An image of the interference pattern created at the focus of the lens is shown in Fig. 4(a). The periodicity of this optical lattice is $0.81 \mu\text{m}$. It was created from two parallel beams separated by 19.25 mm, which interfered at the focal plane of a $f = 30.0 \text{ mm}$ lens. The waists of the two beams at the focus are $36 \mu\text{m}$ and $40 \mu\text{m}$, which were measured by a scanning knife edge. Although the beams were close to the edge of the lens and the angle was large ($\theta \approx 38^\circ$), the interference fringes were very straight even at the edge of the beams. This agrees with Eq. (5).

Figure 4(b) shows the lattice spacing as a function of the distance between the two parallel beams. The lattice spacings are determined by Fourier transforming the images. The imaging system can be calibrated by the waists of the beams, which gives $0.0853 \pm 0.0053 \mu\text{m}/\text{pixel}$, where the uncertainty comes from the measurements of beam waists. It can also be calibrated by fitting the data with Eq. (5), which gives $0.0855 \pm 0.0001 \mu\text{m}/\text{pixel}$. We use $0.0853 \mu\text{m}/\text{pixel}$ for the data shown in the figure. Equation (5) agrees with all data points, and clearly fits the data better than Eq. (1) when D is large.

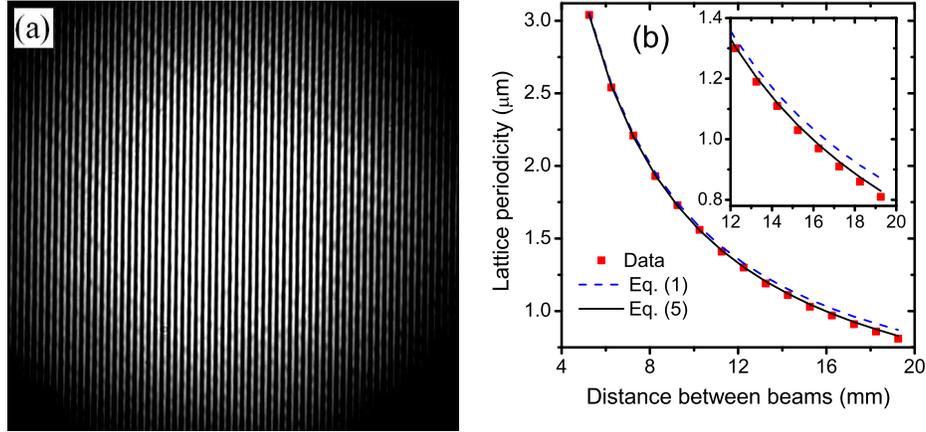


Fig. 4. (a): An optical lattice with spacing of $0.81 \mu\text{m}$, recorded by a CCD camera; (b): the lattice periodicity at the focus of a $f = 30 \text{ mm}$ lens as a function of the distance between the two parallel beams. The statistical error of the data is smaller than the size of the squares.

Figure 5 shows the optical lattices with spacing of $0.98 \mu\text{m}$ and $6.20 \mu\text{m}$. They are formed at the focal plane of a $f = 80.0 \text{ mm}$ lens. The change of spacing is achieved by moving M_1 .

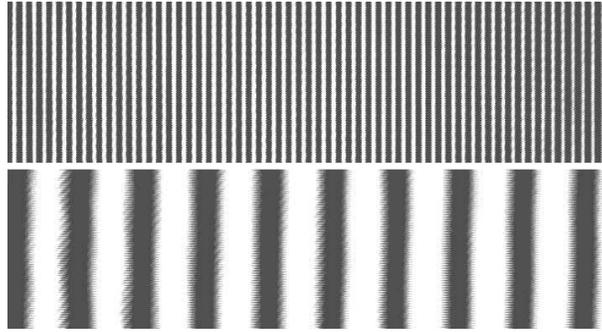


Fig. 5. Optical lattices with spacing of $0.98 \mu\text{m}$ and $6.20 \mu\text{m}$.

The continuous change of the lattice periodicity from $0.96 \mu\text{m}$ to $11.2 \mu\text{m}$, and back to $0.96 \mu\text{m}$ in real time is presented in Fig. 6. The optical lattice is formed at the focal plane of a $f = 80.0 \text{ mm}$ lens. Mirror M_1 is moved horizontally by 20.0 mm to change D from 43.81 mm to 3.79 mm . This figure is constructed from real-time images (30 frames/second) similar to Fig. 5. It shows that our optical lattice is very stable. The center fringe (marked by a solid line) moved less than $2.7 \mu\text{m}$ during the whole process, which is only quarter of the final lattice spacing. There is no apparent difference in the vibration of the lattice whether M_1 is moving or not. This means that the vibration due to translating M_1 does not transfer to the optical lattice. In Fig. 6(b), we change the lattice spacing from $0.96 \mu\text{m}$ to $11.2 \mu\text{m}$ in one second, wait for half a second, and change the spacing back to $0.96 \mu\text{m}$ in another one second. The life time of ultracold atoms in the optical lattices can be longer than 10 seconds [11], so this method enables one to change the lattice spacing in real time while keeping atoms trapped.

We also changed D by moving BS_1 and BS_2 together horizontally, which was similar to

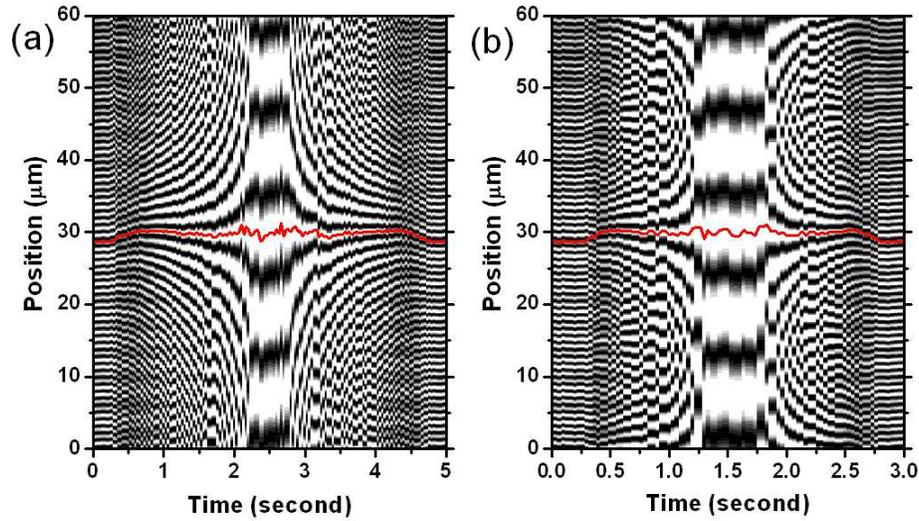


Fig. 6. Continuous change of the lattice periodicity from $0.96 \mu\text{m}$ to $11.2 \mu\text{m}$, and back to $0.96 \mu\text{m}$ by moving M1 at different speed: 10 mm/s (a) and 20 mm/s (b). The center fringe (marked by a solid line) moved less than $2.7 \mu\text{m}$ during the whole process.

Ref. [15]. In this case, the center fringe shifted much more and was extremely sensitive to the vibrations. If the motion is not exactly straight and parallel to the beams 1 and 2 (see Fig. 2), but deviates (or vibrates) by only $2.13 \mu\text{m}$ in the perpendicular direction, the difference between the optical path lengths of the two beams will change by $4.26 \mu\text{m}$. Thus the center fringe of the optical lattices will shift (or vibrate) by 8 fringes, which is $80 \mu\text{m}$ when the lattice spacing is $10 \mu\text{m}$.

4. Conclusion

In this paper we have presented an experimental method to create optical lattices with real time control of periodicity. The center fringe of the optical lattice shifts less than $2.7 \mu\text{m}$ while the lattice spacing is changed by one order of magnitude. Such accordion lattices can work as magnifiers or compressors for many applications.

Acknowledgments

The authors would like to acknowledge support from the Sid W. Richardson Foundation, the National Science Foundation, and the R. A. Welch Foundation.