Interferometric Modulation of an Atomic Beam by an Electric Field: A Phase Hologram for Atoms

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Electric-field-controlled atomic holography has been demonstrated. A binary hologram pattern was encoded in the gaps of regularly spaced parallel stripes of platinum electrodes formed on SiN_4 thin film. Each electrode was either grounded or connected to a terminal. The electrode connections were arranged so that an electric field appeared in approximately half the 512 gaps when a finite voltage was applied to the terminal. By controlling this voltage, we could shift, erase, or switch holographically reconstructed two-dimensional images of atoms on a screen.

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Holography is a technique for manipulating a wave into an arbitrary shape. It was invented by Gabor [1] and developed rapidly after the invention of lasers. Its principle is based on the Fresnel-Kirchhoff's diffraction theory of a wave [2]. In its basic form, a monochromatic wave is sent through a film, called a "hologram," that has a complex transmission function. Because the wave in the downstream direction of the hologram is uniquely determined by the complex amplitude of the wave immediately after the hologram, and the wave propagation is reciprocal, the amplitude of the wave on a surface can be manipulated to an arbitrary form. This technique is applicable not only to optical waves, but also to any monochromatic-matter wave.

We have demonstrated the holographic manipulation of an atomic wave by using a binary hologram [3–5]. Although the theoretical formulas for optical and atomic waves are identical, the image reconstruction of an atomic wave image is far behind that of an optical wave. A major reason for this is the difference in quality of presently available optical and atomic beams. An atom interacts with other atoms as well as with external fields, which is not the case for photons. As a result, the monochromatic flux of an atomic beam is many orders of magnitude smaller than that of a single-mode laser with a modest power. However, one can use this disturbance characteristic of atoms to achieve real-time phase-controlled holography, which is difficult to achieve in optics. We recently demonstrated one-dimensional interferometric manipulation of an atomic beam by an electric field [6].

In this paper, we report the manipulation of holographically generated atomic images by an electric field. By changing the electric potential applied to the electrodes deposited on hologram film, we shifted, erased, and switched atomic patterns on a screen.

The configuration of our experiment is shown in Fig. 1. The wave source was a pointlike source of laser-cooled neon atoms in the $1s_3[(2p)^5 3s{:}^1P_0]$ state. The atomic beam passed through the hologram, was diffracted by it, and formed an image on a screen, which was a microchannel plate detector. The distance from the source to the hologram was 28.5 cm, and the distance from the source to the detector was 112 cm. The resolution of the detector was approximately 50 μm, and the effective diameter of the source was 100 μm. The details of the source are described elsewhere [4]. The hologram had 513 regularly spaced stripes of platinum electrodes and holes that represented the transmission of a binary hologram. To form the electrodes, first, two layers of electron-beam resists (PMMA/MMA) were coated on 100-nm-thick SiN_4 film, and the pattern of the electrodes was delineated by electron-beam writer (JEOL 5FE). Then, the platinum film was evaporated to a thickness of 30 nm, and the electrode was formed by lifting off the platinum from the unnecessary areas. The width of each electrode was 0.5 μm, with a pitch of 1.0 μm.

Holes for the binary hologram were opened in the 0.5-μm gaps between electrodes. Each hole was 0.5 μm $\times$ 0.5 μm. Their pattern was delineated on ZEP resist (E-beam resist, NIPPON Zeon) by using an e-beam lithography system. CF4 dry etching was used to open the holes [7].

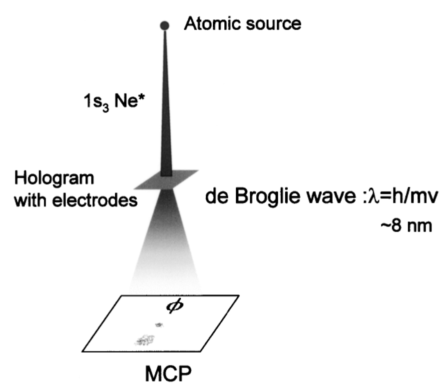

FIG. 1. Schematic diagram of experimental setup. The atomic source, the hologram, and the screen of microchannel plate (MCP) were placed vertically.

Figure 2 shows a scanning microscope photograph of a part of the hologram. Each electrode was connected to either one of two horizontally extended conductive ports which were formed above and below the figure. The electric potential of V was applied between the two ports. The electric field E generated by the potential V shifted the energy of the $1s_3$ atom downwards by $-\alpha E^2/2$, where α was the polarizability of the atom. When two adjacent electrodes had the same potential, the atoms in the gap were unaffected. If they had different potentials, the atoms accumulated an additional phase proportional to V^2 while passing through the hole.

The pattern of the binary hologram was calculated using a method previously described [4]. First, both the object and the hologram surface were divided into 1024×1024 cells. The complex transmission function of each cell, $f(i_x, i_y)$, of the hologram was calculated from the object pattern, $F(i_X, i_Y), i_X, i_Y = 1$ to 1024. The calculation was basically the Fourier transform of $F(i_X, i_Y)$ multiplied by a spherical phase function that produced the focusing of the image on the detector at a finite distance. Here, the suffices x and y denote the directions perpendicular and parallel to the length of the electrode, respectively. Then, the complex conjugate f^* of the complex function f was added to create a real transmission function.

$$f_{\rm real}(i_x, i_y) = f(i_x, i_y) + f^*(i_x, i_y) . \quad (1)$$

An electrode was formed on every second line along the x axis, $i_x = 0, 2, \ldots, 1024$. Finally, the position of the holes in the gaps between electrodes was determined by setting a threshold on the real function. The threshold conditions for the field-free gaps and for the gaps with an electric field were usually different, causing the image to be modulated by electric potential V.

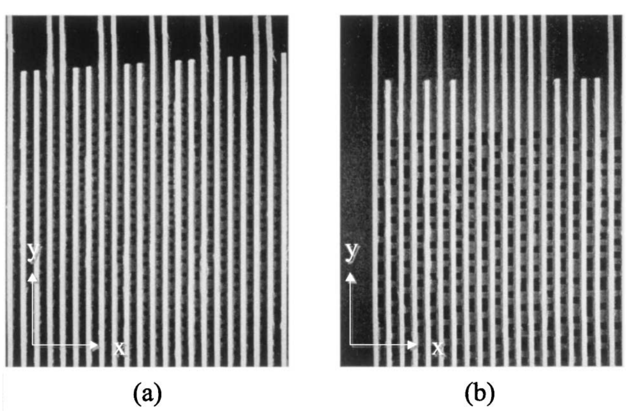

FIG. 2. Scanning electron microscope image of a part of the hologram. The white stripes are the platinum electrodes. The black rectangles in the gaps are holes. In the left figure (a), the electric field was applied regularly to every second gap. In the right figure (b), the gaps with the field were randomly distributed. Half the stripes were connected to the terminal from above, and half were connected from below.

Our experiments were carried out near the Fraunhofer diffraction limit, so the effect of the periodic electrode array can be separately discussed from the holographic reconstruction of the atomic pattern. The basic holographic pattern consisted of three kinds of images: the real image of the object, the nondiffracted pattern, and the conjugate image, which was the general characteristic of the pattern generated by an amplitude hologram. The nondiffracted pattern had a shape close to the projection of the hologram shape. In the following discussions, we call the nondiffracted pattern by the projection pattern. The focal plane of the conjugate image was in the upper stream of the hologram, and the image was usually out of focus on the screen. The electrodes dispersed the basic holographic pattern along the direction x perpendicular to the electrode array. When a voltage was not applied, the pattern that is nearly identical to the basic holographic pattern repeats along the x direction. This situation was the same as the diffraction pattern of a grating with a pitch of d. The successive pattern was separated by ht/md, where t is the transit time of the atom between the hologram and the detector, and m is the mass of the atom.

The intensity of the Nth diffraction pattern was proportional to

$$\frac{I(N)}{I(0)} = \frac{\sin^2(\pi N \beta)}{(\pi N \beta)^2} , \quad (2)$$

where β is the ratio between the gap width and the grating pitch. For the present case, $\beta = 0.5$, and the main pattern was accompanied by strong $N = \pm 1$ order diffraction patterns and much weaker higher-order terms.

In the present experiment, the cell length was half of the pitch of the grating d. Therefore, the unit length of the image area [5] extended to two diffraction orders: $2ht/md$. Two identical patterns appeared within this length along the x direction because the periodicity of the electrode was twice the cell length. The basic holographic pattern can repeat also along the y direction with an interval of $2ht/md$; they were weak, as evident from the envelope function of Eq. (2).

Figure 3 shows the reconstructed patterns when an electric field was applied regularly to every second gap using the hologram shown in Fig. 2(a). In the field-free gaps, the threshold for opening a cell was set so that $f_{\rm real} > 0$, whereas, in the gaps with a field, it was set so that $f_{\rm real} < 0$. This hologram produced a correct real image when the electric potential was applied to produce a π phase shift. When the potential was not applied, the amplitude of the partial wave coming from the gaps with a field had opposite sign in the direction of the zeroth-order diffraction pattern. Because the numbers of holes in the gaps with and without fields were nearly equal, the real image disappeared. However, along the direction halfway between two diffraction orders, the partial waves from gaps with a field aquired a π phase shift, which is needed to reconstruct the correct image. Therefore, the position of the

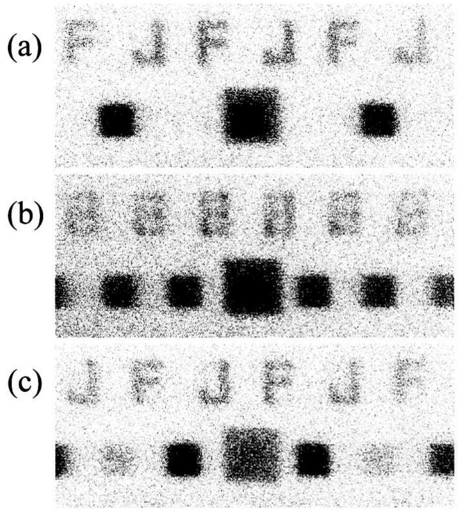

FIG. 3. Shifting of the atomic images "*F*" and "*J*" obtained by a hologram with a regular electric-field pattern. The voltage applied between two terminals was 0, 0.53, or 0.75 V corresponding approximately to 0, $\pi/2$, and π phase shift of the atomic wave: for (a), (b), and (c), respectively. The squares in the lower part of each figure are nondiffracted atomic patterns. The larger square in the center is the nondiffracted pattern of the 74-nm VUV photons emitted in the optical pumping process. Because VUV photons are not affected by the electric field, the pattern works as a fixed reference point on the screen. The conjugate images were below the nondiffracted pattern and are not shown in the figure.

real image shifted by half the diffraction order. The situation was the same for the projection pattern, except that the pattern appeared at the place of an integral diffraction order when the electric potential was not applied because the projection pattern is constructed from partial waves of the amplitude with the same sign. Figure 3(a) shows the pattern without a field, and Fig. 3(c) shows the pattern with a field that produced a π phase shift. The potential between two terminals was 0.75 V. In Fig. 3(b), the potential was reduced to 0.53 V to produce a $\pi/2$ phase shift. The squares in the figures are the projection pattern. The larger square in the middle of each figure was created by vacuum ultraviolet (VUV) photons emitted from the source in the optical pumping process. Because photons are not affected by the electric field, the square pattern serves as a reference point on the screen. The real image was composed of a series of two letters, "*F*" and "*J*," which were separated by half of the diffraction order [8]. Therefore, if one looks at a fixed point on the screen, the letter "*F*" is replaced by "*J*" when the potential of a π phase shift is applied. When the phase shift is $\pi/2$, the two letters overlap with equal intensity, as shown in Fig. 3(b). In each figure, the accumulation time was approximately 1.5 h. Figure 3(a) contains approximately 70 000 data points, including both atoms and VUV photons. Comparison of the intensities of the patterns in Figs. 3(a) and 3(c) gave the approximate number of VUV photons, the number of atoms in the zeroth-order projection pattern, and the number of atoms in the real signal. They were 13 000, 13 000, and 5000, respectively. The ratio between the number of atoms on the projection pattern and the real signal, 1:0.38, is in agreement with theory [5]. The intensity of real signals can be increased by reducing the width of the electrodes relative to the width of the gaps.

The image in the direction of the half diffraction order appeared in Fig. 3 because of the periodic structure of the field-free gaps. One may "erase" the image by choosing a different ordering. Figure 4 shows such a case. The threshold condition was the same as in Fig. 3, but the electric field was applied in a randomly distributed order using the hologram shown in Fig. 2(b). In this case, there was no special direction along which the missing π phase shift was compensated for in all gaps. As a result, the atoms were uniformly dispersed along the x direction when a field was not applied [Fig. 4(a)], while the image was correctly reconstructed when the phase was compensated for with the field [Fig. 4(b)]. For the nondiffracted pattern, the phase compensation functioned exactly in the opposite way, and the atoms were dispersed when the field was applied.

The result shown in Fig. 4 suggests that one can switch two different patterns by encoding them using different threshold conditions. If a single threshold condition, $f_{\mathrm{real}} > f_{\mathrm{th}}$, is used in all gaps, the image is reconstructed when a field is not applied. If a dual threshold is used, $f_{\mathrm{real}} > f_{\mathrm{th}}$ in the gaps without a field and $f_{\mathrm{real}} < -f_{\mathrm{th}}$ in those with a field, the image is reconstructed when the electric field compensates the π phase shift. A hologram that switches two images when an electric field is applied is obtained by opening holes for two patterns whose threshold conditions in the gaps with a field are opposite.

Figure 5 shows an example of an image reconstructed by using a hologram with a double exposure. The hologram

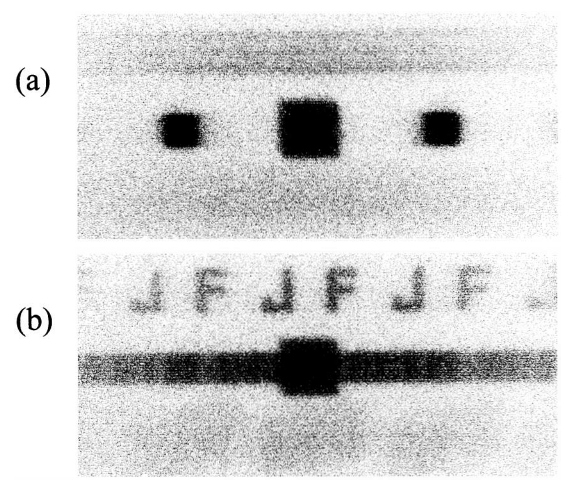

FIG. 4. Erasure of atomic images "*F*" and "*J*" obtained a hologram with a random electric-field pattern. In (a), a voltage was not applied. In (b), a voltage of 0.75 V was applied. The streaks below the nondiffracted patterns are the conjugate images, which were out of focus on the detector.

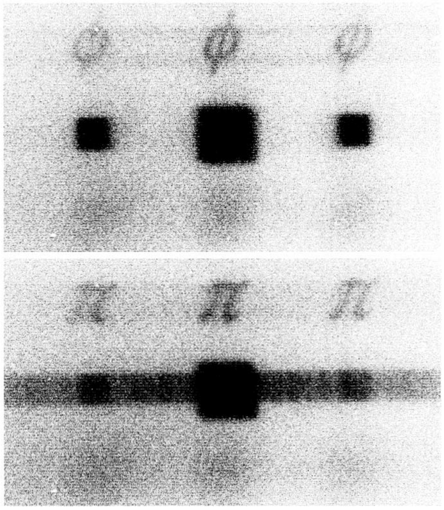

FIG. 5. Switching between atomic images "ϕ" and "π" obtained by a hologram with a random electric field pattern. The upper figure is without an electric-field, and the lower figure is with a field that produces a π phase shift.

pattern of the letter "ϕ" was calculated under the single threshold condition, while the letter "π" was calculated under the dual threshold condition. The threshold was set so that the overlap of the holes for the two letters was approximately 10%. The intensity of the image relative to the nondiffracted pattern was weaker (approximately 17%) compared to the cases of Figs. 3 and 4 because the number of holes contributing constructively to the real image was much smaller than in those cases.

In conclusion, we have demonstrated, for the first time, electrically phase controlled atom holography. By switching the phase shift of the atomic wave at the holes of the hologram between 0 and π, we have demonstrated the shift, the erasure, and the switching of reconstructed atomic images. One can extend this technique to the switching of N patterns, if the phase shift is controlled in steps of $2\pi/N$ instead of π, which can be done with $2(N - 1)$ wiring of the electrodes. Manipulation of atoms on a solid surface is an important technique in surface science for many technical applications. The real-time interferometric manipulation of atoms presented in this paper will open new possibilities in these scientific and technical research areas. It can also be used for real-time control of interferometric applications.

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[1] D. Gabor, Nature (London) **161**, 777 (1948); Proc. R. Soc. London A **197**, 454 (1949).
[2] M. Born and E. Wolf, *Principle of Optics* (Pergamon Press, Oxford, 1959).
[3] J. Fujita *et al.*, Nature (London) **380**, 691 (1996).
[4] M. Morinaga *et al.*, Phys. Rev. Lett. **77**, 802 (1996).
[5] T. Kishimoto, J. Fujita, S. Mitake, and F. Shimizu, Jpn. J. Appl. Phys. **38**, L683 (1999).
[6] F. Shimizu, J. Fujita, and S. Mitake (to be published).
[7] We believe that the dry etching process removed most of the resist over the platinum electrode. However, the resist could remain on some part of the electrode. For some holograms we fabricated, the sign of the voltage had to be switched at least every several minutes to maintain the field induced phase shift.
[8] The binary hologram pattern was calculated so that the real image was composed of two letters, the first "*F*" and the third "*J*" from the left in Fig. 3(c), if the holes were not blocked. However, the blocking of the holes on every second line by electrodes reproduced additional letters, the second "*F*" and the second "*J*" from the left in Fig. 3(c). Any combination of two letters, "*F*" and "*J*," will produce the same reconstructed pattern.