Nanometer definition of atomic beams with masks of light

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We build amplitude, i.e., absorptive masks, for neutral atoms using light, reversing the roles of light and atoms as compared to conventional optics. These masks can be used both to create and to probe spatially well-defined atomic distributions. The resolution of these masks can be significantly better than the optical wavelength. Applications range from atom lithography to fundamental atom optical experiments. [S1050-2947(97)50412-4]

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Efficient methods to prepare and to measure atomic distributions with nanometer resolution are of particular interest in atom optics and for possible applications in science and technology. For example, focusing of atoms by *near-resonant* standing light fields (acting as *refractive index* structures) has been already used to write well-defined periodic structures on substrates [1–7]. A more versatile and particularly useful tool in lithography experiments is *absorptive* masks. They can be used for both writing and probing fine structures. This has been demonstrated with nanofabricated material masks that were used to deposit nanometer-size atomic structures [8] and to read out atomic interference patterns [9,10].

In our experiment we combine the advantages of *absorptive* masks with the flexibility of *light structures*. We report the realization of well-defined absorptive masks with nanometer resolution for neutral atoms, which are entirely made of light.

In order to realize ''absorptive'' light we use the internal structure of our atom and its interaction with the light field. We tune the light frequency to an atomic transition where the *spontaneous* decay of the excited state proceeds mainly to a different internal state, which is not detected and which is inactive in a lithographic process. Atoms in this state can therefore be regarded as being effectively absorbed [11]. A thin standing light wave tuned *on* resonance acts as an absorption grating for the atoms. Only atoms passing near the intensity nodes survive in their original state (Fig. 1). Now, the spatial distribution of the atoms behind one absorptive mask can be detected by probing it with a second absorptive mask immediately behind the first one. This kind of detection scheme, probing one periodic structure with a second one, results in the well-known Moiré fringes.

The result of such an experiment is shown in Fig. 2. The total transmission is plotted as a function of the relative spatial phase between the two successive resonant standing light waves. The data show peaks with a separation of 401 nm. They are due to atoms passing the light grating at its intensity nodes. The periodicity corresponds to the grating constant of our standing light wave, which is half the optical wavelength ($\lambda = 801.7$ nm) in our experimental arrangement. The peak width (90 nm) is significantly smaller. This implies a spatial localization of the atoms behind each individual grating of better than 65 nm.

In the remainder of the paper we will first describe the absorption mechanism and then in more detail our experimental realization, using metastable Ar atoms. In the end we give an example of the versatility of these amplitude structures by presenting a measurement of the atomic wave field behind an amplitude grating.

The basic requirement for the generation of absorptive light masks is that the atoms change their internal state after being excited. For sufficiently long interaction times only atoms near the zeros of the light field will remain in their original state. In our experiments we use standing light waves realized by retroreflection of a laser beam at a plane mirror. Then the intensity distribution in the light field is

$$I(x) = I_0 \frac{1}{2}[1 - \cos(2kx)], \tag{1}$$

where I_0 is the amplitude of the standing wave, $k = 2\pi/\lambda$ is the wave vector of the incident laser radiation, and x is the transverse coordinate. The period of the light grating corresponds to half of the optical wavelength λ. In the case of low

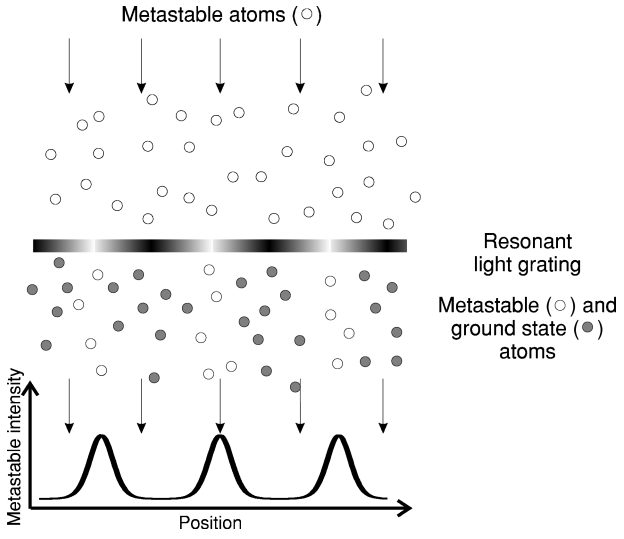

FIG. 1. ''Absorption'' grating for metastable atoms made by resonant light. Metastable atoms (open circles) are excited by the resonant light and consequently pumped to their ground state (filled circles), which is undetected. Only atoms near the nodes of the light field survive in their original metastable state.

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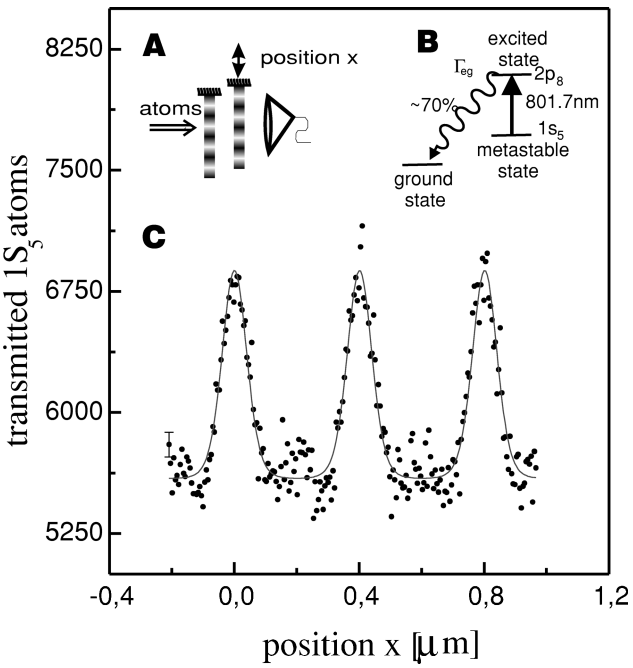

FIG. 2. Total intensity of metastable argon atoms after transmission through two absorptive light masks, i.e., two successive resonant standing light waves, as a function of their relative lateral position (see inset A). A sketch of the atomic levels used for the realization of ''absorptive'' light is drawn in (B). The solid line in graph (C) represents a fit with an exponential law of absorption. The measured full width at half maximum of the peaks is 90 nm and corresponds to an atomic localization of less than 65 nm behind each individual grating (see text).

light intensities [12] we can neglect saturation effects and hence the absorption is proportional to the local light intensity (electric field squared). The atomic transmission through a standing light wave is given by

$$T = e^{-\kappa(1/2)[1-\cos(2kx)]}. \tag{2}$$

The absorption κ is proportional to the intensity of the standing light wave [Eq. 1] [$\kappa \propto \int I_0(z)dz$], where the integration is along the direction of the atomic beam. Note that the transmission is a strongly nonlinear function of the light intensity. Therefore for sufficiently strong absorption ($\kappa \gg 1$) the transmission evolves into a comb of narrow peaks that is significantly smaller than the grating constant $\lambda/2$ (Fig. 2) (see also Ref. [13]). As shown in our experiment, this can be used to create atomic distributions with subwavelength resolution.

Figure 3 shows our experimental setup [14]. A thermal beam of excited (metastable) argon atoms (average velocity of 700 m/sec, corresponding to a de Broglie wavelength of $\lambda_{dB} = 14$ pm) emerges from an effusive argon source. The beam is collimated with a 10-μm and a 5-μm slit separated by 1.4 m, before entering the interaction region with our light gratings. One meter behind, the metastable atoms are registered by a ''channeltron'' detector (similar to a photomultiplier tube) with a typical count rate of 10 000 metastable atoms per second.

In the source the atoms are excited by a continuous gas discharge with an efficiency of 10^{-5} to two metastable states: a fraction of 85% to the $1s_5$ state ([4s[3/2]2) and a fraction of 15% to the $1s_3$ state (4s′[1/2]0). In our experiments we are only interested in $1s_5$ metastable atoms and thus optically pump the $1s_3$ atoms to their ground state by exciting the $1s_3 \rightarrow 2p_4$ (4s′[1/2]0 $\rightarrow$ 4p′[3/2]1) open transition with resonant laser light at 795.0 nm. The lifetime ($\sim$30 sec) of the remaining $1s_5$ state is much longer than the flight time in our beam line ($\sim$10 msec). The energy of the metastable argon atoms ($\sim$12.3 eV) is released in collisions with a surface. Therefore, the metastable atoms can be recorded by our ''channeltron'' detector, or can be used to expose a photoresist in lithographic applications [8,7,15], whereas the ground-state atoms are inactive in both processes.

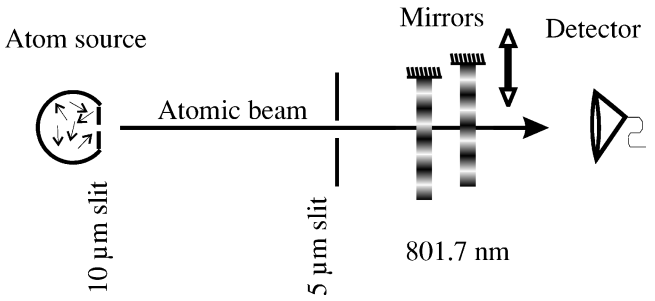

FIG. 3. Experimental setup (not to scale). A thermal beam of metastable argon atoms is collimated by a set of two slits (10 and 5 μm, separated by 1.4 m), and then crosses two standing light waves with an adjustable relative distance (4–15 mm). The relative spatial phase of the two light gratings can be scanned with nm resolution by shifting one of the mirrors with a piezoactuator. Transmitted atoms are registered by a ''channeltron'' detector (1.4 m behind the second grating). For recording far-field diffraction patterns, a third 10-μm slit can be scanned directly in front of the ''channeltron.''

For realizing ''absorption'' the most important feature of our metastable $1s_5$ atoms is their *open* transition $1s_5 \rightarrow 2p_8$ (4s[3/2]2 $\rightarrow$ 4p[5/2]2) at 801.7 nm (linewidth 5.8 MHz). If the atoms are excited at this wavelength they decay spontaneously with a branching ratio of 72% to the ground state. This is the optical transition we use to generate absorptive masks in the interaction region of our beamline. The light for the absorption gratings is produced using a single-mode diode laser with grating feedback in Littrow geometry, locked to the 801.7-nm transition using saturation spectroscopy. The linewidth of our laser light ($<$1 MHz) is much smaller than the atomic linewidth.

Our two light gratings are realized by retroreflection of the 801.7-nm laser beam (focused to a ribbon shape of approximately 3 cm height and 150 μm thickness) on two gold mirrors. The mirrors (flatness $\leq \lambda/8$) are mounted inside the vacuum chamber close to, and parallel to, the atomic beam (see Fig. 3). One of the mirrors is mounted on a flexure stage and can be translated in the direction orthogonal to the mirror surface with nm accuracy. The spacing between the two gratings is adjustable between 3 and 15 mm by shifting one of the laser beams along the direction of the atomic beam.

A crucial point in our experiment is that the two mirrors have to be aligned parallel to each other with better than 10 μrad accuracy. For this purpose the mirror angles are controlled with μrad resolution using piezoactuators and ''pico-

motors.'' In order to achieve parallel orientation of the mirror surfaces, we detect the interferometrically superposed diffraction patterns of the two *thick* far-off-resonant gratings (refractive Bragg crystals [16]) in the far field. There, atoms are only diffracted if their incidence angle at the light grating is near the Bragg angle (18 μrad) with an angular selectivity of better than 5 μrad [17]. In addition, this arrangement of *two* adjacent Bragg crystals forms an interferometer that is very sensitive to the parallel alignment of the two mirrors [18]. We then adjust the mirror angles by optimizing the contrast of the atomic interference fringes, obtained by translating one mirror in the direction of its surface normal. This measurement also provides an exact position gauge for the relative translation of the two mirrors with an accuracy better than ± 10 nm. When the mirrors are aligned we switch back to two *thin* absorptive light gratings as described above, and measure the total transmission through the two gratings, depending on their relative transverse position.

The data of Fig. 2 were taken with a relative grating distance of approximately 3 mm. The background of the data is mainly due to 20% of the $1s_5$ ($J=2$) atoms, which are originally in the $m=0$ magnetic sublevel, since their excitation (with linearly polarized light) to the $2p_8$ ($J=2$) decay channel is dipole forbidden. The light does not influence these atoms, whereas the remaining 80% of the atoms are strongly absorbed (transmission $<10\%$). The background might be removed by optically pumping the atoms into a defined magnetic sublevel. As already mentioned, the obtained transmission pattern with its peak width of 90 nm (full width at half maximum) results from a convolution of the transmission functions of the two gratings. A numerical deconvolution of the data shows that the localization behind each individual grating is at least better than 65 nm ($\lambda/12$). We can certainly conclude that the definition of the atomic beam is better than 65 nm directly behind each grating, considering that atoms passing through such narrow slits will experience diffraction, which broadens the atomic image at our separation of 3 mm.

As an example of the versatility of our absorptive light masks we investigated the *coherent* evolution of the atomic wave field behind such a narrow transmission grating as described by near-field Fresnel diffraction. A well-known phenomenon in near-field optics is self-imaging of an absorptive grating, the Talbot effect [19]. For gratings with very narrow slits, images with fractional periods can appear.

Figure 4 shows a series of measurements exploring the near-field atomic density distributions at various locations behind the first mask. We recorded the total transmission through the two masks as a function of their relative spatial phase at various relative distances between the two gratings. The data show clearly that an image with a doubled spatial frequency (period: $\lambda/4$) emerges at a distance of 5.8 mm, as predicted by Talbot theory. In contrast to the previous experiment, the high collimation (corresponding to a high spatial coherence) of our atomic beam is now essential in order to observe the Talbot fringes. Two effects explain the contrast reduction of the fringes observed at increasing distance from the light grating. First, the broad velocity distribution of the atomic beam limits the longitudinal coherence length. Second, 28% of the atoms fall back to the $1s_5$ state after spontaneous emission of a photon and contribute to an incoherent background. Nevertheless, our measurement demonstrates both the fact that our masks have a resolution better than light wavelength, and the possibility of producing higher-order atomic distributions using near-field imaging.

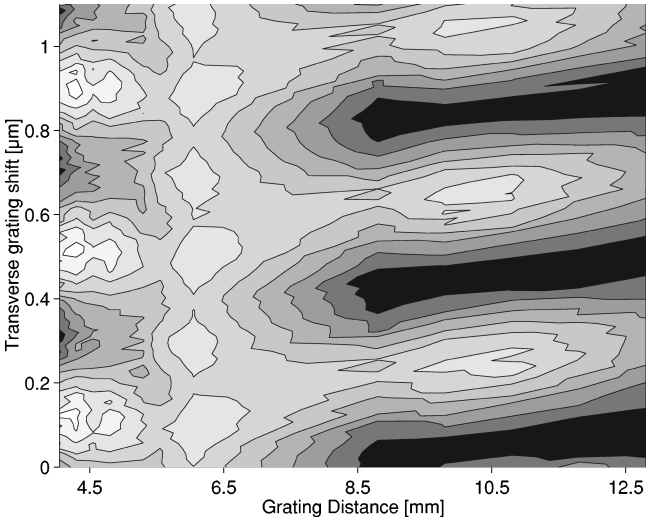

FIG. 4. Atomic wave field behind the first absorptive grating (brighter regions correspond to higher atomic densities). The data were measured, similar to Fig. 2, by scanning the relative spatial phase of the two gratings and recording the total number of transmitted atoms at several distances (from 4 to 13 mm) between the two gratings. A doubling of the spatial period, as expected for the Talbot near-field regime, is observed at a distance of 5.8 mm.

Simultaneously, we could measure the momentum distribution of the atoms passing through our masks (see Fig. 5). In this experiment we use only one of the resonant light gratings and record the far-field diffraction pattern by scanning a 10-μm slit in front of our ''channeltron'' detector. Observation of both the near-field interference and the far-field diffraction pattern demonstrates that the transmission of the atoms through the masks is a coherent process.

In conclusion, we have realized an optical mask for neutral atoms with nanometer spatial resolution by employing a resonant standing light field acting on a two-level atom with a strong leak channel to an undetected state. We used our

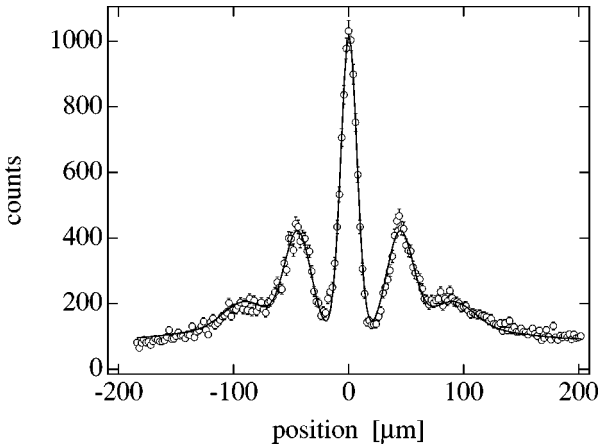

FIG. 5. Diffraction at a purely imaginary potential: far-field diffraction pattern for the scattering of metastable argon atoms at one of the resonant light gratings (801.7 nm). A 10-μm slit was scanned directly in front of the ''channeltron'' detector and the spatial atomic diffraction image was recorded as a function of the slit position.

masks to define a narrow atomic distribution and to measure its coherent evolution after the grating directly. Well-defined periodic atomic distributions with periods of $\lambda/2$ and $\lambda/4$, and linewidths of $\lambda/12$ have been demonstrated.

These masks made from *light* have many advantages as compared to material masks: Their spatial dimensions are given by the optical wavelength, which can be determined very accurately. Applications of light masks are advantageous in high-precision lithography, or as length standards. Optical masks can be easily manipulated; for example, translated, varied, or switched at short time scales. The shape of the masks can be designed using coherent (i.e., holography) or incoherent (i.e., superposition) methods. An interesting possibility arises because one can readily combine and superpose these masks with other atom optical elements made from light or even material structures. We expect that these absorptive light masks will have many applications in atom optics; e.g., for probing atomic wave fields, and for atomic lithography.

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[1] G. Timp, R. E. Behringer, D. M. Tennant, J. E. Cunningham, M. Prentiss, and K. K. Berggren, Phys. Rev. Lett. **69**, 1636 (1992).

[2] R. E. Behringer, V. Natarajan, and G. Timp, Appl. Phys. Lett. **68**, 1034 (1996).

[3] J. J. McClelland, R. E. Scholten, E. C. Palm, and R. J. Celotta, Science **262**, 877 (1993).

[4] R. Gupta, J. J. McClelland, Z. J. Jabbour, and R. J. Celotta, Appl. Phys. Lett. **67**, 1378 (1995).

[5] R. Gupta, J. J. McClelland, P. Marte, and R. J. Celotta, Phys. Rev. Lett. **76**, 4689 (1996).

[6] R. W. McGowan, D. M. Giltner, and S. A. Lee, Opt. Lett. **20**, 2535 (1995).

[7] M. Kreis, F. Lison, D. Haubrich, D. Meschede, S. Nowak, T. Pfau, and J. Mlynek, Appl. Phys. B: Lasers Opt. **63**, 649 (1996); U. Drodofsky, M. Drewsen, T. Pfau, S. Nowak, and J. Mlynek, Microelectron. Eng. **30**, 383 (1996).

[8] K. S. Johnson *et al.*, Appl. Phys. Lett. **69**, 2773 (1996).

[9] D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. E. Pritchard, Phys. Rev. Lett. **66**, 2693 (1991).

[10] A good overview on atom interferometry and atom optics is given in *Atom Interferometry*, edited by P.R. Berman (Academic, New York, 1997).

[11] This optical pumping to an undetected state is a dissipative process, equivalent to absorption. In that sense it is distinct from encoding position information by coherently shelving atoms to an undetected state, as described in the review by J. E. Thomas and L. J. Wang, Phys. Rep. **262**, 311 (1995); for a recent experiment, see also S. Kunze, K. Dieckmann, and G. Rempe, Phys. Rev. Lett. **78**, 2038 (1997); or in momentum space, M. Kasechich *et al.*, *ibid.* **66**, 2297 (1991).

[12] For high light intensities one has to take saturation of the atomic transition into account. Nevertheless, for structures where the interaction time is much longer than the natural lifetime of the excited state, setting κ proportional to the light intensity can still be justified: In the region where this approximation [Eq. 2] breaks down, the absorption is so strong that basically no atoms are transmitted anyway. An exact solution of this problem by integrating the full equation of motion in the light field confirms the above physical picture [13].

[13] A. P. Chu, K. K. Berggren, K. S. Johnson, and M. G. Prentiss, Quantum Semiclassic. Opt. **8**, 521 (1996).

[14] A detailed description of our experimental apparatus is given in H. Batelaan, S. Bernet, M. K. Oberthaler, E. Rasel, J. Schmiedmayer, and A. Zeilinger, in *Atom Interferometry* (Ref. [10]).

[15] K. K. Berggren, A. Brad, J. L. Wilbur, J. D. Gillaspy, A. G. Helg, J. J. McClelland, S. L. Rolston, W. D. Phillips, M. Prentiss, and G. M. Whitesides, Science **269**, 1255 (1995).

[16] P. J. Martin, B. G. Oldaker, A. K. Miklich, and D. E. Pritchard, Phys. Rev. Lett. **60**, 515 (1988).

[17] S. Bernet, M. K. Oberthaler, R. Abfalterer, J. Schmiedmayer, and A. Zeilinger, Phys. Rev. Lett. **77**, 5160 (1996).

[18] M. K. Oberthaler, R. Abfalterer, S. Bernet, J. Schmiedmayer, and A. Zeilinger, Phys. Rev. Lett. **77**, 4980 (1996).

[19] H. F. Talbot, Philos. Mag. **9**, 401 (1836); L. Rayleigh, *ibid.* **11**, 196 (1881); J. Cowley and A. Moodie, Proc. Phys. Soc. London, Sect. B **70**, 486 (1957); **70**, 497 (1957); **70**, 505 (1957). The Talbot effect was demonstrated for atoms by J. F. Clauser and S. Li, Phys. Rev. A **49**, R2213 (1994); M. S. Chapman *et al.*, *ibid.* **51**, R14 (1995).