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Complex Light-Mask Generation for Atom Guiding by Time and Frequency Domain Intensity Superposition

M. Mützel and D. Meschede*
Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, D-53115 Bonn, Germany
* e-mail: meschede@iap.uni-bonn.de
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Abstract—We propose to generate a complex light mask for atom nanofabrication by multiplexing light fields sequentially in the time domain or synchronously in the frequency domain. The method effectively superposes intensities rather than electric fields and may be useful for atomic beams at thermal velocity and also at very slow velocities.

1. INTRODUCTION

In atom optics, the center-of-mass trajectory of neutral atoms can be controlled by light forces [1]. Radiation pressure, for instance, serves to reduce atomic velocities as well as velocity spread; optical dipole forces have a conservative character, and atoms with resonance frequency ω_0 moving in a laser light field driven at frequency ω move in an effective potential U that has the form

$$U(\mathbf{r}) = \frac{\hbar\gamma^2}{8\Delta}\frac{I(\mathbf{r})}{I_{\text{sat}}}. \quad (1)$$

Here, Δ is the detuning $\Delta = \omega - \omega_0$ of the atom and the laser light field, $I(\mathbf{r})$ is the intensity distribution of the light field, and $I_{\text{sat}} = \pi hc/3\lambda^3\tau$ is the saturation intensity of the atomic dipole transition with wavelength λ and decay rate $\gamma = 1/\tau$.

In a standing wave, the light field is strongly modulated at the wavelength scale. It thus seems natural to translate the intensity distribution of such a light mask into a lateral density modulation of an atomic beam, which is then transferred into a corresponding lateral pattern on a suitable substrate.[1]

The method of atom nanofabrication, also called atom lithography, was introduced first by Timp *et al.* [3], who showed that a standing-wave light field acts as an array of lenses that focuses a beam of sodium atoms into an array of parallel lines. Then, McClelland *et al.* [4] showed that chromium atoms could be directly deposited onto a substrate by this method, and stable nanostructures could be taken from the vacuum chamber. Furthermore, it was shown that narrow lines down to a structural width of 30 nm could be obtained [5]. An attractive property of this direct-deposition method is the potential for one-step deposition of lateral nanostructures across a relatively large area.

In our laboratory, we have extended an alternative lithographic method that was first explored with metastable rare gas atoms [6]. In our case, a Cs atomic beam chemically modifies a thiole monolayer resist, which is subsequently prepared by chemical processes [7]. This method of neutral-atom lithography yields a convenient and reliable testing ground for atomic nanofabrication with light forces. A recent review of the method of atom nanofabrication is given in [8].

2. COMPLEX LIGHT FIELD PATTERNS

It is an interesting question how a light mask can be shaped such that patterns more complex than parallel straight lines appear. The light mask technique was straightforwardly extended to two dimensions (2D) by geometrically superposing several light waves [9, 10], where typically 2D periodic patterns with high symmetries were generated. It was also shown [11] that a holographic device ("holographic mirror") can be used to realize the simultaneous superposition of multiple waves. The complex interference pattern of the light mask was transferred to the substrate with good fidelity, including details, and was in good agreement with simulations.

In all these cases, the pattern of the light mask was generated by the superposition and interference of two or more waves of identical frequency. Each wave may have the form $E_i e^{-i(\omega_i t - \mathbf{k}_i \mathbf{r})}$ + c.c., $i = 1, 2, 3, \ldots$ with amplitude E_i, propagation vectors $\mathbf{k}_i$, and frequencies ω_i. It follows

$$I(\mathbf{r}) = \frac{1}{2}c\epsilon_0 |E_1 e^{-i(\omega_1 t - \mathbf{k}_1 \mathbf{r})} + E_2 e^{-i(\omega_2 t - \mathbf{k}_2 \mathbf{r})} + \ldots + \text{c.c.}|^2. \quad (2)$$

[1] Atomic beams have come a long way since they were invented during the days of O. Stern and W. Gerlach [2]. In the early 1980s, D.M. was taught in the laboratory of Herbert Walther, to whom this special issue is dedicated, that atomic beams are of continual interest in atomic and quantum physics. The ideas presented in this manuscript indicate that interest in atomic beams is still alive. Today, control of atomic properties rather than observation is a key issue of such experiments.

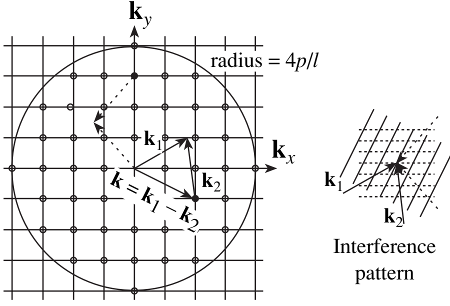

Fig. 1. Construction of reciprocal lattice vectors (dots) from interfering light fields (wave vectors given by arrows). In this example, a 2λ unit cell is assumed.

With $I_{ij} = c\epsilon_0 E_i E_j^*$, we find

$$I(\mathbf{r}) = (I_{11} + I_{22} + \dots + I_{12}\cos[(\omega_1 - \omega_2)t - (\mathbf{k}_1 - \mathbf{k}_2)\mathbf{r}] + \dots), \tag{3}$$

which, for a simple standing wave with $\omega_1 = \omega_2$ and $\boldsymbol{\kappa} = \mathbf{k}_1 - \mathbf{k}_2$, reproduces the well-known form

$$I(\mathbf{r}) = I_0(1 + \cos(\boldsymbol{\kappa}\mathbf{r}))/2 \tag{4}$$

for a standing wave. For our discussion, it is essential to note that this special intensity distribution also has the form of a harmonic wave.

Unfortunately, for a given $I(\mathbf{r})$, the so-called "inverse problem" of determining a sequence of waves such that their superposition according to Eq. (2) results in $I(\mathbf{r})$ is very difficult [12]. Since the origin of this difficulty is the mutual interference of all partial waves $I_{ij}\cos(\dots)$ in Eq. (3), we propose here to physically eliminate undesirable interference terms by either one of two methods:

(1) **Time multiplexing.** While atoms are transiting the light mask (typical breadth, 0.1–1 mm), the light field is varied on a fast time scale. At any given time, the atoms are subject to a simplified interference pattern only. The trajectories, however, are determined by an average and complex potential, which is effectively a result of the intensity superposition of all the individual interference patterns.

(2) **Frequency multiplexing.** If a light mask is composed from different frequencies $\omega_i \neq \omega_j$, the interference cross terms will not have a noticeable effect on the atomic motion if the difference frequency is large enough. Thus, only the interference patterns corresponding to waves of identical frequency affect atomic trajectories.

In both cases, the atomic trajectories are determined by an average potential

$$\bar{U}(\mathbf{r}) = \frac{\hbar\gamma^2}{8\Delta}\frac{\bar{I}(\mathbf{r})}{I_{\text{sat}}}. \tag{5}$$

Here, $\bar{I}$ is the sum of the intensities of each multiplexed interference field I_m:

$$\bar{I}(\mathbf{r}) = \sum I_m(\mathbf{r}). \tag{6}$$

This linear superposition of intensities prevents undesirable interference terms between multiplexed interference fields. Using intensity distributions of the type suggested by Eq. (4), it is clear that any given light-mask pattern can be constructed from a conventional Fourier analysis with $|\boldsymbol{\kappa}| \le \frac{4\pi}{\lambda}$ (see Fig. 1).

In Fig. 2, we show simulations in which periodic arrays of letters are reconstructed by complex light masks. Each light mask presented consists of 24 multiplexed interference fields with intensity distributions according to Eq. (4). They generate the necessary Fourier components of the desired pattern. The average intensity distribution of each light mask closely resembles its corresponding original pattern. The simulated flux distribution of a thermal atomic beam that passes

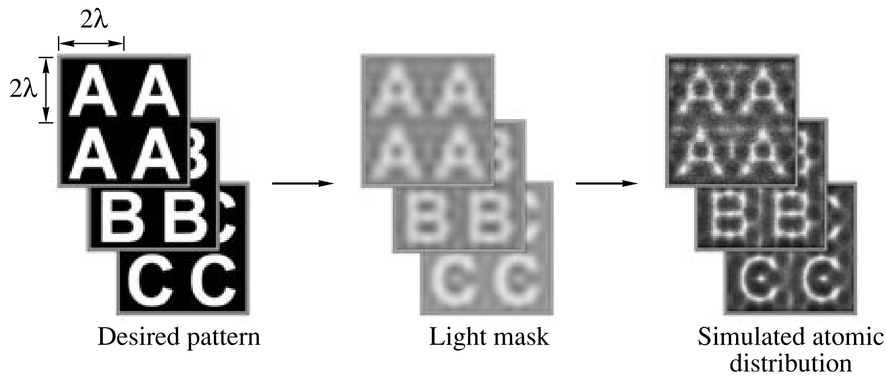

Fig. 2. Examples for periodic letter generation on a 2λ unit cell. Each calculated light mask consists of 24 multiplexed interference fields that generate the necessary Fourier components of the desired pattern. The simulation of the lateral atomic flux distribution after passing the red detuned light mask (Δ < 0) resembles the light mask, or the desired pattern, respectively.

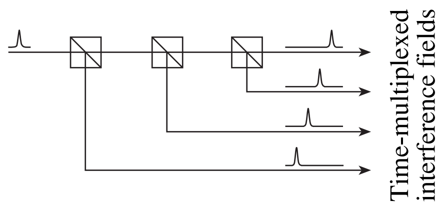

Fig. 3. Time multiplexing with a pulsed laser beam. The different lengths of the delay paths straightforwardly separate the individual interference fields in time. For 100-ps pulses, the lengths of the delay lines are of an order of several cm.

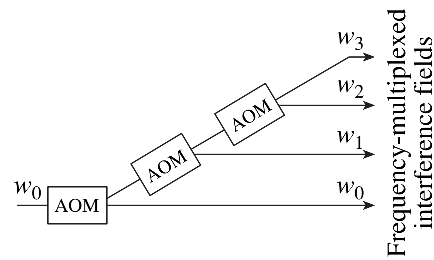

Fig. 4. Frequency multiplexing with a sequence of acousto-optical modulators (AOM).

through the light mask also shows very good agreement with the desired pattern.

2.1. Time-Multiplexed Light Mask

We demonstrated earlier [13] that a train of short light pulses with a typical pulse duration τ_P on the order 100 ps is capable of providing a light mask for atomic nanofabrication. In this method, the electronic atomic state adiabatically follows the driving light field, and the effective force can be derived from a time-averaged potential

$$\bar{U}(\mathbf{r}) = \frac{1}{T}\int_t^{t+T} U(\mathbf{r}, t')dt' \approx \frac{\hbar\gamma^2}{8\Delta}\frac{\bar{I}(\mathbf{r})}{I_{\text{sat}}}, \qquad (7)$$

where T is the duration of a pulse period and $\bar{I}$ is the time-averaged intensity. The average potential approximation holds if the adiabaticity condition ($|\tau_P\Delta| \gg 1.76$ for sech^2-pulses) is fulfilled.

Let us consider a typical atomic nanofabrication experiment carried out with a thermal atomic beam, where atoms travel at velocities of 300–600 m/s. With optical beam splitters, several laser beams are split off the pulsed laser beam, and each of them generates a pulsed interference field (see Fig. 3). By choosing suitable pulse delays, the superposed interference fields can mutually be separated in time. The light mask, with typical breadths of 0.1–1 mm, is then crossed by the atoms in about 1 μs. At a repetition rate of 80 MHz, corresponding to a pulse period of 12.5 ns, an atom is on average subject to about 100 light pulses from each of the multiplexed interference fields.

2.2. Frequency Multiplexed Light Mask

The superposition of light waves at different frequencies ω_1, ω_2, … causes a periodic modulation of the dipole potential. If the difference frequencies $\Delta\omega_{ij} = |\omega_i - \omega_j|$ are much larger than the characteristic center-of-mass oscillation frequencies of the atoms in the dipole potential, this periodic modulation will have negligible influence on atomic motion, since it will be averaged out. Thus, only interference patterns corresponding to waves of identical frequency effectively influence atomic trajectories. Each pattern of a given frequency contributes linearly to the average potential of the light mask.

Acousto-optical modulators are typically driven at a center frequency of several 10 MHz, which is much larger than atomic-oscillator frequencies in standing waves, which are usually much smaller than 1 MHz. They are thus ideal components for the generation of multiple-frequency light masks (see Fig. 4).

3. CONCLUSIONS

Undesirable interference terms impair the generation of arbitrary light-mask patterns from multiple monochromatic light waves. We suggest overcoming this limitation by superposing light fields in a noninterfering way, which amounts to a superposition of intensities rather than electric fields. Simplified interference light fields can be multiplexed either in a time or in a frequency domain. The harmonic intensity distribution of each multiplexed interference field contributes linearly to the average potential of the light mask. In particular, the necessary Fourier components of a desired pattern can be easily generated. The experimental realization of these concepts will lead to novel complex structures generated with atomic beams.

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