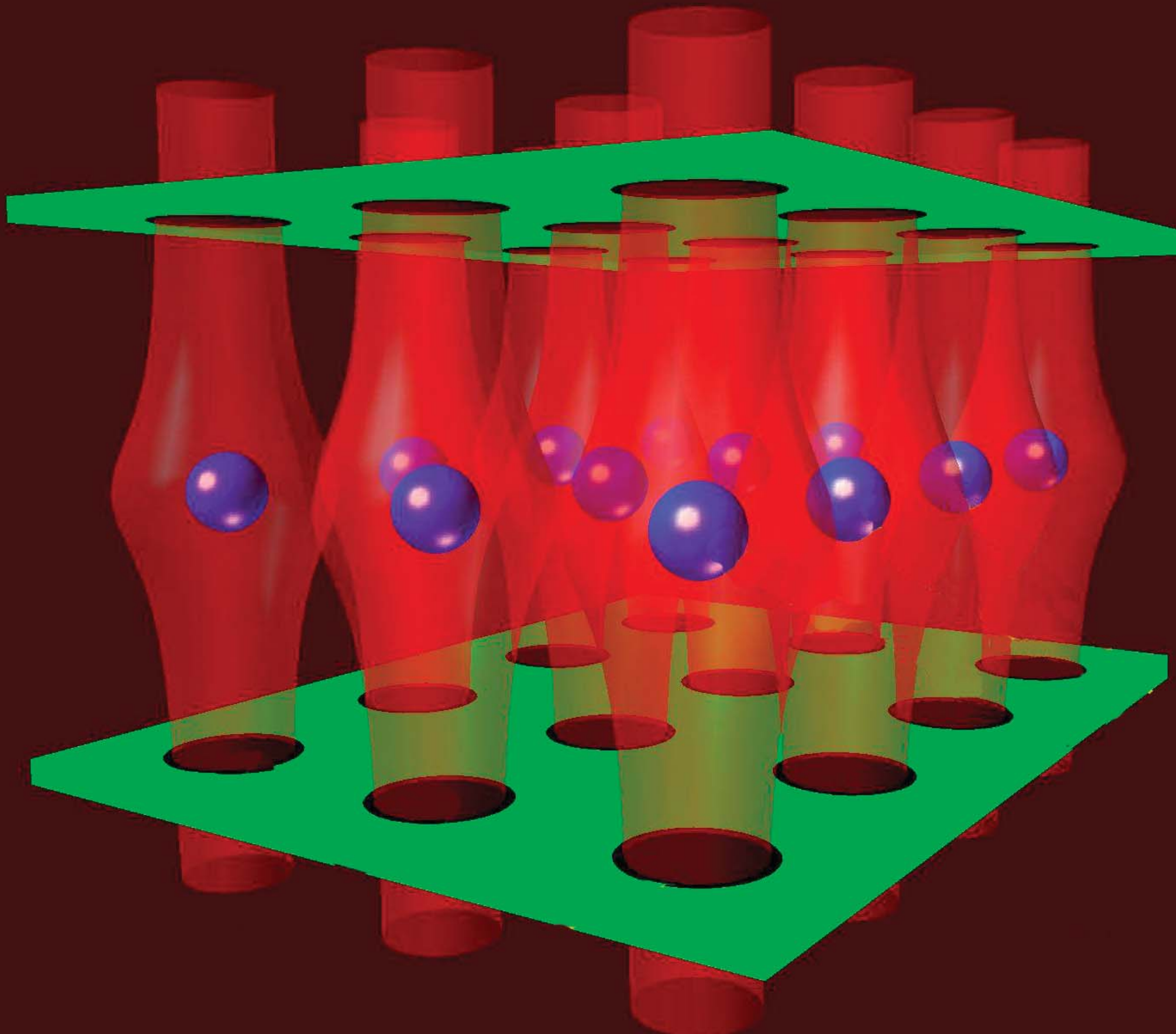

Atom Nano-Optics

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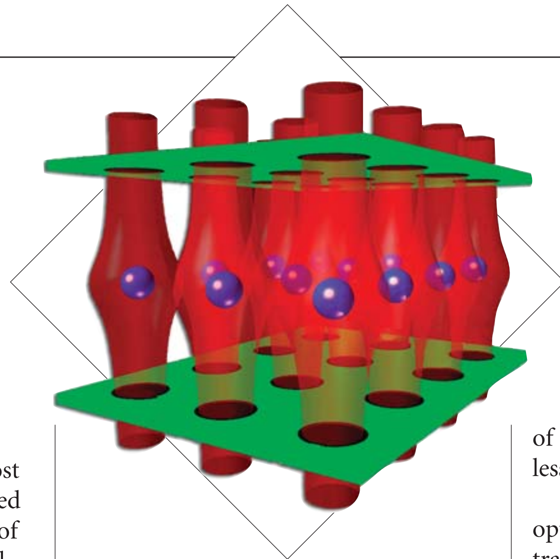
Nanolocalized light fields composed of photon dots and photon holes are being used to control the motion of atoms on a nanometer spatial scale.



In recent years the prefix "nano" has been applied to two of the most rapidly developing and best-funded avenues of investigation in the world of science: nanoscience and nanotechnology. The impact of nanoscience has extended into the field of optics and photonics, where it has found expression in the creation of entirely new research areas, such as near-field nano-optics. The development potential of the field of light nano-optics as a whole is, in itself, significant, especially as far as nanoscopy and optical imaging and diagnostics are concerned.

When laser light interacts with a substance, it becomes possible not only to investigate objects with nanometer-high spatial resolution, but also to modify matter on the nanoscale. Examples can be found in the fields of nanophotochemistry and nanophotoablation, to name only two. The manipulation of free atoms on the nanoscale, a branch of nano-optics termed "atom nano-optics," is part of an extensive research domain that embraces laser control of neutral atoms and molecules.

Like neutron optics and electron optics, the field of atom optics[1,2] is also concerned with the realization of traditional elements, such as lenses, mirrors, beam splitters and interferometers. It also involves the creation of dissipative elements not found in other branches of optics, such as equipment to slow and cool atoms. Neutral atoms can be manipulated through interaction with electrical, magnetic and optical fields.

The basic goals of researchers in atom optics are: 1) to use of various atomic species to explore wave-particle duality;[3] 2) to verify the fundamental laws of physics; and 3) to achieve collective quantum phenomena such as use of a combination of traditional atom optics elements and dissipative elements—extremely low temperature in the presence of high atom density—to create Bose–Einstein condensation and Fermi degenerate quantum gases of trapped atoms and molecules. On the practical side, researchers in atom optics are working to create a high resolution atom microprobe with short de Broglie wavelength, as well as to develop applications in the area of atom nanolithography.

From atom optics to atom nano-optics

The objective of workers in the field of atom nano-optics is to form nanometer-sized ensembles and beams of neutral atoms.[4,5] At the early stage of foundation of atom optics,[6] it was recognized that laser fields capable of forming such atomic ensembles must be well localized. For example, it was demonstrated in Ref. 6 that deep focusing of an atomic beam into an Ångstrom-sized spot could be achieved only by use of a laser beam focused onto a spot approximately the size of the laser wavelength.

Standing light waves—the best known laser fields—are finding widespread use in atom optics. The first application of standing light waves in atom nano-optics was the localization of atoms in a nanometer-sized space and their placement in channels.[7,8] The idea of channeling atoms in a standing light wave has led to the development of techniques of atom lithography that allow periodic one- and two-dimensional (2D) structures to be produced on a surface.[9,10] A three-dimensional standing light wave enables localization of atoms in volumes having dimensions less than a wavelength of light.[11]

Researchers in the field of atom optics, which includes the use of both traveling and standing light waves, work under a number of practical limitations that stem from the spatially nonlocalized characteristics of the laser light fields and which in turn create nonlocalized atom-optics elements. As a result, these elements are characterized by imperfections that include aberrations, low diffraction efficiency and, in the case of interferometers, limitations on the contrast of interference fields. On the basis of general physical considerations, it is evident that the use of spatially localized fields (and, accordingly, spatially localized atomic potentials) can offer new possibilities for the construction of atom-optical elements. To date, we have knowledge of only two types of laser field that are well enough localized in space to make this possible: surface (evanescent) light waves, which develop as a result of the total internal reflection of light, and light that arises in the vicinity of structures with a characteristic size of less than the wavelength.

Evanescent waves find widespread use in atom optics for the reflection, localization and cooling of atoms. A drawback of evanescent waves is that they are localized exclusively on a 2D surface. The field at the end of a thin waveguide (widely used in near-field microscopy) can serve as an example of diffraction-localized fields.

The best known example of the second type of localized light field is that which results after diffraction by an aperture the size of which is small in comparison to the wavelength of light. In this case, a local 3D maximum of field intensity is formed near the aperture. The magnitude of the maximum is governed mainly by the size of the aperture.

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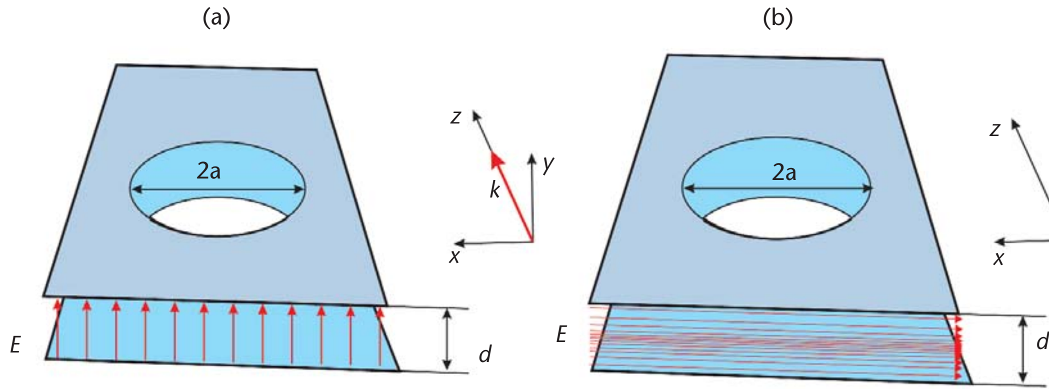

Figure 1. Plane waveguide and light field *E* orientation for (a) photon dots and (b) photon holes.

A number of proposals have been made to use such fields in atom optics, for example, to bring about sharp focusing of atoms.[12] Light fields reach their highest localization and concentration near sharp-pointed tips or nanoparticles,[13] but such fields cannot as yet be used to control atomic ensembles. A substantial drawback of these field structures is the accompanying standing or traveling light wave: When atoms move in a standing light wave they can undergo spontaneous decay processes that, from the standpoint of atom optics are, in many cases, undesirable.

Nanolocalized optical fields: photon dots and holes

In an earlier publication, we discussed optical nanofield configurations that are free from the above-mentioned shortcomings.[14] Figure 1(a) schematically illustrates realization of one version of an optical nanofield. Two plane conductive plates spaced a distance of the order of, or smaller than, the wavelength of light apart ($d \lesssim \lambda$) form a plane waveguide for the laser radiation coupled into it from one side. If the electric field strength vector of the laser radiation is normal to the plane of the waveguide, the radiation can propagate through the waveguide, no matter how thick it is. Now let two small coaxial apertures be made in the conductive screens that form the waveguide. If the diameters of these apertures are smaller than the wavelength of the radiation coupled into the waveguide, little radiation escapes from the waveguide through the apertures, but the light field near them is strongly modified.

The determination of the electromagnetic field distribution in the vicinity of the apertures in the waveguide walls is a complicated problem of electrodynamics. In the specific nanoaperture case under consideration (a, $d \ll \lambda$), the problem was solved by means of a quasi-stationary approximation.[14] Figure 2 shows the light field intensity distribution near the apertures inside and outside the waveguide when the thickness of the waveguide is equal to the radius of the apertures. As can be seen in Fig. 2, there is a light field intensity minimum in the direction normal to the plane of the waveguide. It is only natural to refer to such a field configuration as a photon hole. Its characteristic size is determined by the size of the apertures, the thickness of the waveguide and its volume $V{\sim}a^2\, d \ll \lambda^3$. The sharp field intensity peaks near the aperture edges are caused by the hypothetic infinite conductivity of the waveguide walls. In waveguides with walls of finite conductivity, the amplitude of the field intensity peaks is not manifested in such a pronounced manner.

Figure 1(b) schematically illustrates the realization of another nanofield. In this case, two conductive screens with coaxial apertures are spaced a distance of $d = \lambda/2$ apart and the electric field strength vector is parallel to the waveguide plane. The illustration is a generalization of the scheme for the localization of a light field in a conductive screen,[12] but is free of the disadvantages associated with the presence of a standing light wave. To calculate the light field in this geometry, as an initial approximation one can use the solution of the diffraction problem by a single aperture.

The intensity distribution in such a light field is presented in Fig. 4. As can be seen, the field drops off rapidly outside the waveguide in the direction normal to the waveguide and has its maximum at the center of the waveguide. This maximum is caused by the constructive interference of the fields scattered by the apertures. Such a light field configuration can be called a photon dot. Once again, the sharp intensity peaks near the aperture edges stem from the hypothetic infinite conductivity of the waveguide walls. In waveguides with walls of finite conductivity, the amplitude of the peaks will not be strongly manifested. The characteristic volume of such a photon dot is $V{\sim}(\lambda/2)a^2 \ll \lambda^3$. The maximum intensity at the photon dot is twice as high as the field intensity in the absence of apertures.

The characteristic size of a photon dot or a photon hole is in the nanometer region, which allows for nanometer-sized atomic ensembles to be formed. Let us consider as an example two possible uses for photon dots and photon holes: the focusing and localization of atoms.

Atom-optical lenses and traps

When an atom is exposed to laser light, electric field $\mathbf{E}(\mathbf{r},t)=\mathbf{e}E(\mathbf{r})\cos\omega t$ of the laser light induces in the atom an oscillating dipole moment, $\mathbf{P}(\mathbf{r},t)=\mathbf{e}P(\mathbf{r})\cos\omega t$, where $\mathbf{e}$ is the unit polarization vector and the dipole moment amplitude is related to the electric field amplitude of the light wave by the simple relation

$$\mathbf{P}(\mathbf{r})=\alpha(\omega)\mathbf{E}(\mathbf{r})\,. \qquad (1)$$

Polarizability α is a complex quantity that depends on the frequency of the light field. Its complexity results from the fact that the phase of the polarization oscillations fails to coincide with that of the light wave. The magnitude of polarizability is governed by the closeness of the field frequency to the resonance frequency ω_0 oscillations of the dipole. Far from resonance ($\omega \gg \omega_0$), the value of polarizability α is of the same order of magnitude as the volume of the electron cloud of the atom (~10^{-23} cm^3). Approaching resonance, the value of α increases significantly. An oscillating dipole in a light wave has a potential energy defined as

$$U_{\mathrm{dip}}=-\tfrac{1}{2}\langle \mathbf{pE}\rangle \quad \text{or}$$

$$=\frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I(\mathbf{r}) \text{ for } |\Delta|\gg\Gamma, \quad (2)$$

where $I(r)=\frac{c}{8\pi}|E(r)|^2$ is light intensity, Γ is the resonance width of the atomic dipole which is governed by radiative damping (spontaneous decay) of the excited state of the atom and $\Delta=\omega-\omega_0$ is detuning of field frequency ω from resonance frequency ω_0. Figure 3 shows the dependence of the potential energy U_{dip} of the dipole on radiation intensity I and detuning Δ. If the light field amplitude at the atom position is spatially nonuniform (as is the case for the Gaussian profile of a running light wave and the periodic amplitude variation of a standing light wave), a gradient force develops:

$$\mathbf{F}_{\mathrm{grad}}=-\mathrm{grad}\,U_{\mathrm{dip}}(\mathbf{r})\,. \qquad (3)$$

It is precisely the gradient force that is used to modify the trajectory of the atoms.

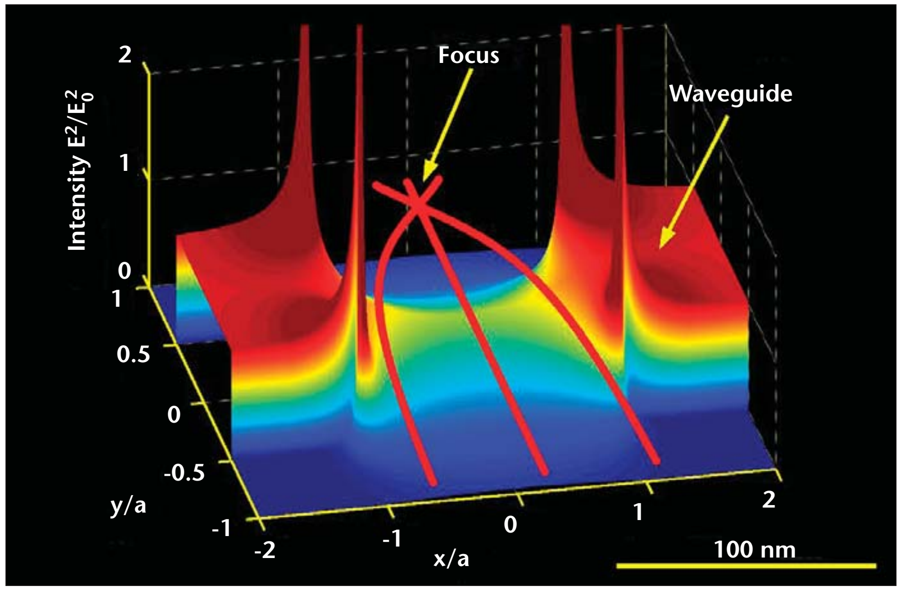

Figure 2. Focusing of atom waves. Light field intensity distribution near the apertures inside and outside the subwavelength-thickness waveguide and trajectories of slow atoms. The thickness of the waveguide is equal to the radius of the apertures.

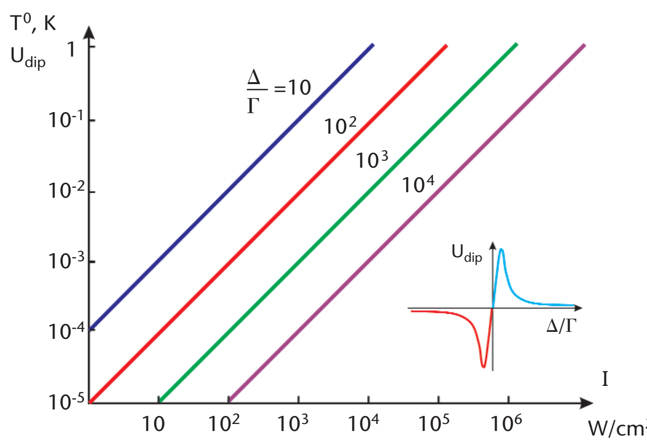

Figure 3. Dependence of potential energy U_{dip} of the dipole on radiation intensity $I=\frac{c}{8\pi}E^2$ and detuning Δ/Γ of field frequency ω relative to resonance frequency ω_0.

When the detuning Δ of the laser radiation frequency relative to the atomic transition (resonance) frequency is positive, an atom in the laser light configuration is drawn into the weak field region. In the case of a photon hole, the nanometer-sized weak field region is surrounded by the strong field inside the waveguide; if the light field frequency detuning is positive, the atoms that fly through the apertures in the waveguide walls will be attracted to the axis of the system—in other words, they will be focused.

A photon dot draws atoms in negative frequency detuning and also provides focusing for the atomic beam that passes through the apertures in the waveguide walls (Fig. 2). The theory of atomic beam focusing for both maximum and minimum light field intensity has been well developed. It has been shown[12] that, when spontaneous decay is disregarded, an atomic beam can be focused to a spot of the order of the de Broglie wavelength, which for a thermal beam amounts to a few Ångstroms.

The photon dot and photon hole light-field configurations have extreme points at which the gradient force is zero. Such light-field configurations are naturally considered atomic traps. The photon dot light-field configuration is stable

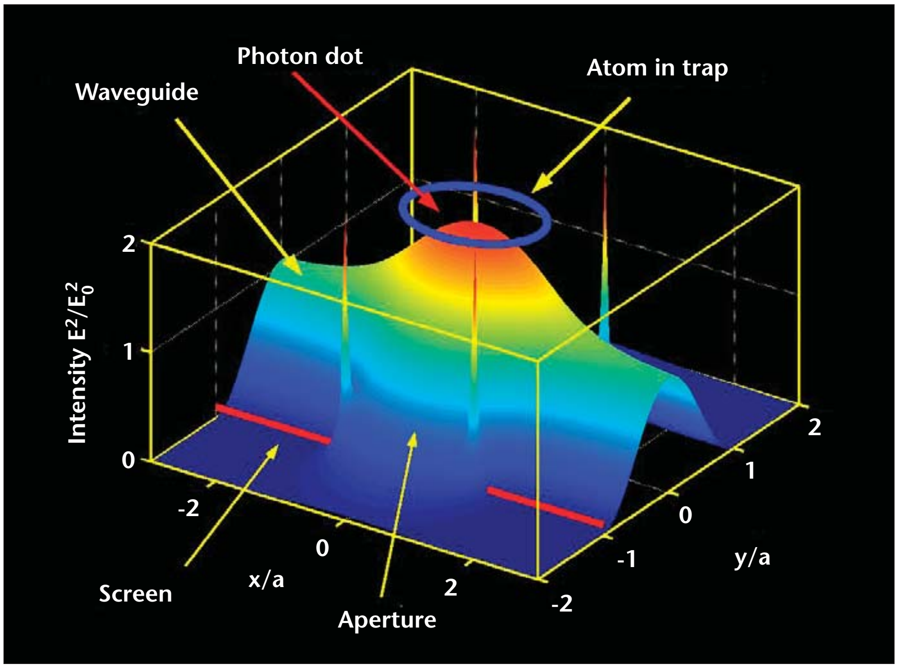

Figure 4. Light field intensity distribution near the apertures inside and outside the waveguide when the electrical strength vector is parallel to the waveguide-photon dot. The thickness of the waveguide is equal to the radius of the apertures. The photon dot forms a trap for an orbiting atom.

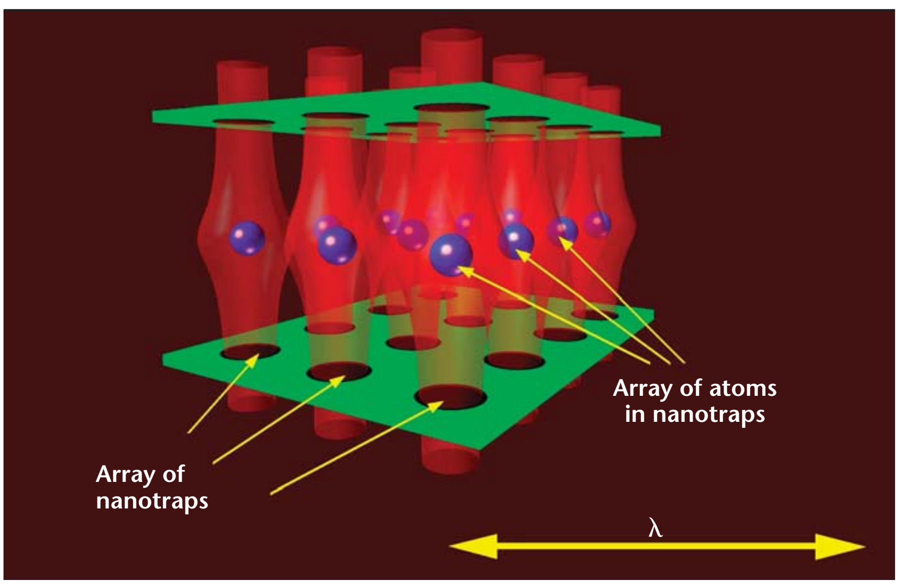

Figure 5. Array of atomic traps. Trapping of atoms in nanometer-sized regions spaced at distances much smaller than the wavelength of light.

and is truly three dimensional, while the characteristic size of the photon dot region is much smaller than the wavelength of light. Either the axial or the radial motion of the atom will be infinite since no matter what the sign of the frequency detuning, the extreme photon hole point is a saddle point. A number of schemes can be used to make the atomic motion in the photon hole region finite. One is based on the use of frequency detuning that varies in sign and over time, making it possible to localize atoms dynamically in a way similar to the localization of ions in high-frequency electromagnetic traps. For this reason, both the above light-field configurations provide for the 3D localization of atoms inside a nanometer-sized trap (Fig. 4).

An attractive feature of the light-field configurations in question is that they offer the possibility of creating a large number of pairs of apertures in a waveguide and, correspondingly, the same number of localized light fields. Such arrays allow for the simultaneous control of numerous beams of atoms. Figure 5 schematically illustrates atom trapping in nanometer-sized regions spaced at distances smaller than the wavelength of light. The localization of atoms by means of an array of nanotraps produces a lattice of atoms, the parameter of which depends neither on the wavelength of light nor on the characteristic dimensions of atom-atom interactions. Such periodic lattices can possess properties similar to those of planar photonic crystals.[15, 16]

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References

1. V. Balykin and V. Letokhov, Atom Optics with Laser Light, Vol. 18 of Laser Science and Technology (Harwood Academic, Chur, Switzerland, 1995).
2. P. Meystre, Atom Optics (Springer-Verlag, New York, 2001).
3. L. Hackermüller et al., Phys. Rev. Lett. **91**, 0904081 (2003).
4. V. Balykin and V. Letokhov, Physics Today **4**, 23 (1989).
5. Nanofabrication with Atom Optics, Special Issue of Appl. Phys., P. Meschede and J. Mlynek, eds., **B70**(5) (2000).
6. V. Balykin and V. Letokhov, Opt. Commun. **64**, 151 (1987).
7. C. Salomon et al., Phys. Rev. Lett. **59**, 1659 (1987).
8. V. I. Balykin et al., Opt. Lett. **13**, 958 (1988).
9. J. J. McClelland et al., Science **262**, 877 (1993).
10. R. J. Jackman et al., Science **280**, 2089 (1998).
11. M. Greiner et al., Nature **415**, 39 (2002).
12. V. I. Balykin et al., J. Phys. II. France **4**, 1981 (1994).
13. L. Kuiru et al., Phys. Rev. Lett. **91**, 227402 (2003).
14. V. I. Balykin et al., JETP Lett. **78**, 8 (2003).
15. E. Yablonovich, Phys. Rev. Lett. **58**, 2059 (1987).
16. S. John, Phys. Rev. Lett. **58**, 2485 (1987).