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Trapping of cold atoms for the hybrid system near a circular aperture with subwavelength size

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ABSTRACT

We propose and analyze a scheme to generate an optical trap for cold atoms using a thin circular aperture with a radius similar to or smaller than the wavelength diffracted by a plane light in the near field. The diffracted intensity in the near field is investigated by the vector theory as well as the optical potential and van der Waals potential for ^{87}Rb atoms are calculated in the trap. It shows that the total potential can form an attracting 3D localized trap for cold atoms with red-detuned light near the thin circular aperture below the diffraction limit. It shows that the spontaneous-emitting rate, Rayleigh and Raman scattering rates of trapped cold atoms are very small for the CO_2 laser. This scheme can provide an opportunity towards the generation of the hybrid system consisting of isolated atoms and solid devices.

1. Introduction

It is well-known that the laser trapping of neutral cold atoms has been widely applied in atomic optics and quantum optics as an important standard technique in recent years. Generally speaking, the laser trapping of cold atoms can be divided into two types, the red- and blue-detuned laser modes, in which neutral cold atoms have been successfully trapped in the attracting and repulsive optical potential with a micron region respectively [1–5]. However, till now, schemes of optical trapping of cold atoms have not been obtained easily and successfully below the diffraction limit of the light.

In addition, the research of hybrid systems consisting of isolated atoms and solid devices has become a hot research subject in atomic optics and nano-optics. The key character of hybrid systems is the ability to trap, manipulate cold atoms near the surface of the solid device in a nanoscale region. More recently, several schemes have been proposed to trap and manipulate cold atoms in a nanoscale region, for instance, one-dimensional light localization of the evanescent light wave [6,7], nanometer metallic plasmonic devices [8–13] and diffraction by structures with sub-wavelength characteristic sizes [14–17]. In 1995, Klimov et al. proposed a scheme of atomic trapping configuration by the total electromagnetic field of the incident, reflected waves and near field in the vicinity of a small aperture [14]. In 2003, Balykin et al. proposed a scheme of atom nanotrap based on photon dots and photon holes [15]. In 2006, Klimov et al. proposed a scheme of atom nanotrap in the vicinity of scanning near-field optical microscope tip [16]. In 2006, Gillen et al. proposed optical dipole traps for cold atoms using diffracted laser light far away from a circular aperture [17]. In this paper, we propose a scheme to generate an optical trap for cold atoms using a diffracted near field from a subwavelength thin circular aperture. The scheme can not only break the diffraction limit of the light and generate an optical trap for cold atoms, but also provide a hybrid system comprising isolated atoms and solid devices.

2. Diffracted intensity of the circular aperture in the near field

A proposed scheme to generate localized light to trap cold atoms in vacuum is shown in Fig. 1, in which the thin circular aperture is located in the x–y plane at $z=0$, and the central axis of the thin circular aperture is along the z direction. When the incident light propagates through the subwavelength thin circular aperture in the z direction, the localized diffraction will be generated in the near field of the aperture, in which cold atoms can be trapped in the red-detuned light and the atomic trap is sketched by the circle including points in Fig. 1.

As we know, the diffraction of the light at an aperture with a radius comparable as or smaller than the wavelength of light must be described by the vector theory, in which the light field is localized to about a wavelength region. Taking the plane wave with the unit electric field amplitude and the polarization in the x

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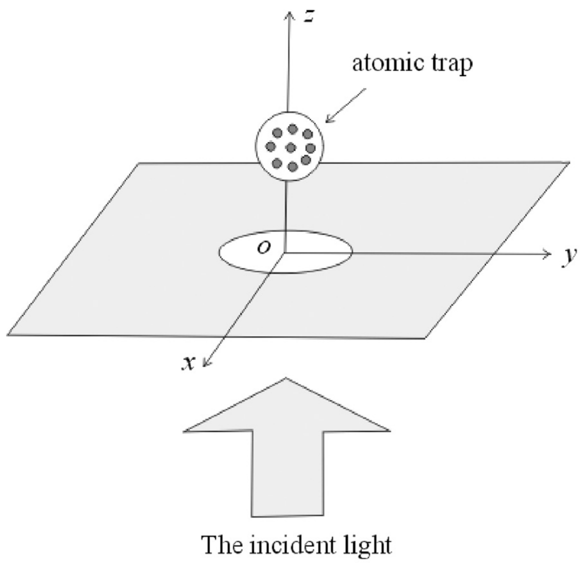

Fig. 1. Scheme diagram of the trapping of isolated cold atoms using the diffraction of a subwavelength thin circular aperture in the near field.

direction as the incident light, nonparaxial diffracted evanescent components of electric field amplitude in the x, y, and z directions can be given by the vector plane angular spectrum method respectively as follows [18]:

$$E_x^{ev}(x,y,z) = kR\int_1^{\infty} J_1(kRf)J_0(kf\sqrt{x^2+y^2})\exp(-kz\sqrt{f^2-1})\,df, \quad (1a)$$

$$E_y^{ev}(x,y,z) = 0, \quad (1b)$$

$$E_z^{ev}(x,y,z) = \frac{R}{\lambda}\int_1^{\infty}\frac{f}{\sqrt{f^2-1}}J_1(kRf)J_1(kf\sqrt{x^2+y^2}) \times \sin\left(\arctan\frac{x}{y}\right)\exp(-kz\sqrt{f^2-1})\,df \quad (1c)$$

Here f is the coordinate in the angular spectrum coordinate system, R is the radius of the thin circular aperture, $k=2\pi/\lambda$ is the wave number, and λ is the wavelength, $J_l(\cdot)$ is the first kind lth-order Bessel function.

And similarly, nonparaxial diffracted propagation components of electric field amplitude in the x, y, and z directions can be given respectively by

$$E_x^{pr}(x,y,z) = kR\int_0^{1} J_1(kRf)J_0(kf\sqrt{x^2+y^2})\exp(ikz\sqrt{1-f^2})\,df, \quad (2a)$$

$$E_y^{pr}(x,y,z) = 0, \quad (2b)$$

$$E_z^{pr}(x,y,z) = i\frac{R}{\lambda}\int_0^{1}\frac{f}{\sqrt{1-f^2}}J_1(kRf)J_1(kf\sqrt{x^2+y^2}) \times \sin\left(\arctan\frac{x}{y}\right)\exp(ikz\sqrt{1-f^2})df \quad (2c)$$

We can find from Eqs. (1) and (2) that the diffracted electric fields contain evanescent electric field component and propagation electric field component, and the whole electric field $E_x{}^{wh}$, $E_y{}^{wh}$ and $E_z{}^{wh}$ can be given respectively by

$$E_x^{wh}(x,y,z) = E_x^{ev}(x,y,z) + E_x^{pr}(x,y,z), \quad (3a)$$

$$E_y^{wh}(x,y,z) = 0, \quad (3b)$$

$$E_z^{wh}(x,y,z) = E_z^{ev}(x,y,z) + E_z^{pr}(x,y,z) \quad (3c)$$

According to Eqs. (3), the whole intensity can be given by

$$I(x,y,z) = I_x^{wh}(x,y,z) + I_y^{wh}(x,y,z) + I_z^{wh}(x,y,z), \quad (4)$$

where

$$I_x^{wh}(x,y,z) = I_0\left|E_x^{wh}(x,y,z)\right|^2, \quad I_y^{wh}(x,y,z) = 0, \quad I_z^{wh}(x,y,z) = I_0\left|E_z^{wh}(x,y,z)\right|^2 \quad (5)$$

where $I_0 = \left(\frac{1}{2}\right)\sqrt{\varepsilon_0/\mu_0}E_0^2$, I_0 and E_0 are the intensity and the electric field amplitude of the incident light respectively. In Eq. (5), the diffracted intensity in the z polarization is much smaller than one of the x polarization and can be neglected [18], and the transverse distribution in the x–y plane of intensity in the x polarization are the rotational symmetry, so we can think that the distribution of the whole intensity is the axial rotational symmetry.

According to Eqs. (1)–(5), the dependence of the whole intensity on z is calculated for different aperture radii R as $x=y=0$ and $I_0=1$ W/m^2, and results are shown in Fig. 2. We can find from Fig. 2 that $I(0,\ 0\ ,z)$will increase first to the maximum then decrease with the increasing of z as $R<0.8\lambda$. And $I(0,\ 0\ ,z)$ will decrease a little first to the minimum then increase to the maximum and then decrease with the increasing of z as $R>0.8\lambda$. That is to say, there is a maximal value of the on-axis intensity near the point o as the radius similar to or smaller than the wavelength λ. We can see from Fig. 2 that the maximal values are 1.53 W/m^2, 1.82 W/m^2, 2.09 W/m^2, 2.33 W/m^2, 2.54 W/m^2, and 2.72 W/m^2 for $R=0.5\lambda$, 0.6λ, 0.7λ, 0.8λ, 0.9λ, and 1.0λ respectively, and their corresponding positions are $z_{max}=0.22\lambda$, 0.32λ, 0.45λ, 0.59λ, 0.77λ, and 0.96λ respectively.

According to Eqs. (1)–(5), by taking $y=0$ and $I_0=1$ W/m^2, we can obtain the distribution of the whole intensity in the x–z plane as $R=0.5\lambda$ and 1.0λ respectively, and results are shown in Fig. 3 (a) and (b). We can find from Fig. 3(a) and (b) that there is a maximal value of the intensity at $x=0$ and $z=0.22\lambda$ for $R=0.5\lambda$, and $x=0$, $z=0.96\lambda$ for $R=1.0\lambda$.

According to Eqs. (1)–(5), the dependence of the whole intensity on x as $y=0$, $z=z_{max}$ and $I_0=1$ W/m^2 are calculated for different aperture radii R, and results are shown in Fig. 4. We can find from Fig. 4 that the maximal values of the whole intensity is on the z axis as $x=y=0$. We can find from Figs. 2–4 that the diffracted whole intensity can generate a 3D localized distribution above an aperture with a radius comparable as or smaller than the wavelength λ, and the trap for cold atoms will be generated with red-detuned light field in the vicinity of the maximal value of the whole intensity. And the full width at half maximum (FWHM) of the intensity distribution in the vicinity of the maximal value may be calculated by Eqs. (1)–(5). The transverse and longitude FWHM of the intensity are

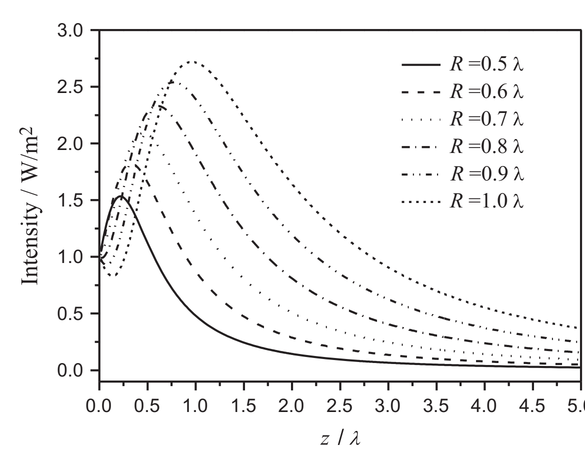

Fig. 2. The dependence of the whole intensity on z as $x=y=0$ and $I_0=1$ W/m^2 for different R.