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Design of atomic mirror for silicon atoms

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Abstract

Cook and Hill suggested that the gradient of an optical field can be used to reflect atoms. To reflect atoms, the repulsive dipole force is used, which comes from the interaction between the electric dipole moment of atoms and the evanescent field. The evanescent wave is generated when light is totally reflected internally at the interface of different refractive indices. Later, the way to enhance the evanescent wave with a thin dielectric waveguide has been reported. We designed the atomic mirror for silicon atoms, whose structure enhances the evanescent field that is used to repel silicon atoms. We also set up the equations of motion for silicon atoms and derive trajectories of the atoms reflected by the atomic mirror. Optical intensity, incident angle of the light, and effective detuning are described in terms of controlling the trajectory of the atom.

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Keywords: Atom optics; Atomic mirror; Evanescent wave; Silicon

1. Introduction

Atom optics dealing with atoms as conventional optics that deals with light, have attracted considerable attention. To manipulate atoms like light, an atomic mirror that repels the atom is often used. In 1982, the atomic mirror using evanescent wave was proposed by Cook and Hill [1]. In general, the evanescent wave that leaks into the low refractive index medium is generated, when light is totally reflected internally at the interface between two media of high and low refractive indices. The electric field of the evanescent wave decreases exponentially along the distance from the interface and the evanescent wave exists near the interface. An atom approaching the electric field experiences the dipole force caused by the interaction between the electric field and the electric dipole moment. The magnitude of this dipole force is in proportion to the gradient of the electric field. If effective detuning is blue-shifted from the atomic resonance, the dipole force guides atom to weak electric field region. Therefore, the evanescent wave can be used as an atomic mirror. Balykin performed the first

experimental demonstration [2]. After that, the reflection of atoms making use of both surface plasmons [3] and of a dielectric waveguide structure [4] had been demonstrated. We have developed a single-mode coherent light source for the resonant wavelength to the silicon atom [5], which is necessary to make the experiment of atomic mirror for silicon atoms.

2. Enhancement of the electric field

The waveguide structure of the atomic mirror is shown in Fig. 1. Two dielectric layers are deposited on a prism with the index of refraction n_1 . The waveguide structure works like a Fabry–Perot cavity. The light of frequency ω is incident from below the prism. The lower layer with a low index of refraction n_2 and a thickness d_2 , acts as a coupling mirror, and the higher layer (index of refraction n_3 , thickness d_3) confining the light enhances the electric field of light. Consequently, the evanescent wave generated in vacuum is also enhanced. The electric fields within the four regions are written as follows

$$E_1(z < -(d_2 + d_3)) = Ae^{ik_{z1}z} + Be^{-ik_{z1}z} \quad (1)$$

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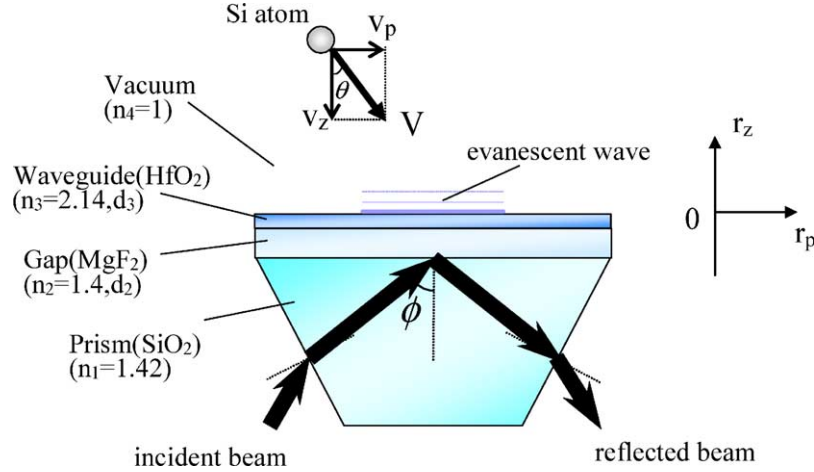


Fig. 1. Schematic arrangement of the atomic mirror. The atom (the electric dipole moment μ) is reflected from the evanescent wave enhanced by the waveguide structure.

$$E_2(-(d_2 + d_3) < z < -d_3) = Ce^{k_{z2}z} + De^{-k_{z2}z} \quad (2)$$

$$E_3(-d_3 < z < 0) = Ee^{ik_{z3}z} + Fe^{-ik_{z3}z} \quad (3)$$

$$E_4(0 < z) = Ge^{-k_{z4}z} \quad (4)$$

where k_{zj} (in medium j) are the components of the wave vector along the r_z direction. These components are defined involving the wave vector along the r_p direction k_p , which comes from the Snell's law given by $ck_p = \omega n_1 \sin \phi$ in all media:

$$k_p^2 + k_{zj}^2 = \frac{n_j^2 \omega^2}{c^2}, \quad j = 1, 3 \quad (5)$$

$$k_p^2 - k_{zj}^2 = \frac{n_j^2 \omega^2}{c^2}, \quad j = 2, 4 \quad (6)$$

We define the transmission factor T as Eq. (7), indicating how much the electric field is enhanced [6]. We choose promising materials for the atomic mirror that have refractive index causing above-mentioned enhancement of the electric field at the resonant wavelength to the silicon atom ($\lambda = 252.4$ nm). For the resonant frequency to the silicon atom, we fix these thickness of two layers ($d_2 = 1287.5$ nm, $d_3 = 15$ nm) and incident angle of the light ($\phi = 81.11^\circ$), so that maximum value of the transmission factor $T = 1189$ is given.

$$T = \frac{|E_4(z=0)|^2}{|E_1(z=-(d_2+d_3))|^2} \quad (7)$$

3. Atomic trajectories

A two-level atom (atomic transition frequency ω_0) moving at velocity \mathbf{V} experiences a dipole force \mathbf{F}_d and a spontaneous force \mathbf{F}_s by the evanescent wave. Here \mathbf{F}_d

and \mathbf{F}_s are given by

$$\mathbf{F}_s = \frac{2\hbar\Gamma\Omega_R^2 k_p}{\Delta^2 + 2\Omega_R^2 + \Gamma^2} \quad (8)$$

$$\mathbf{F}_d = -\frac{\hbar\Delta\nabla\Omega_R^2}{\Delta^2 + 2\Omega_R^2 + \Gamma^2} \quad (9)$$

where $\Omega_R^2 = \mu E_4/\hbar$ is the Rabi frequency and $\Delta = (\omega - \omega_0) - k_p \cdot v_p$ is the effective detuning [1]. Besides these forces, the van der Waals interaction between the atom and the dielectric layer needs to be considered. The van der Waals force \mathbf{F}_v is attractive, acting only at small distance ($z < \lambda$).

We derive trajectories of the atoms reflected from the designed atomic mirror by solving the following

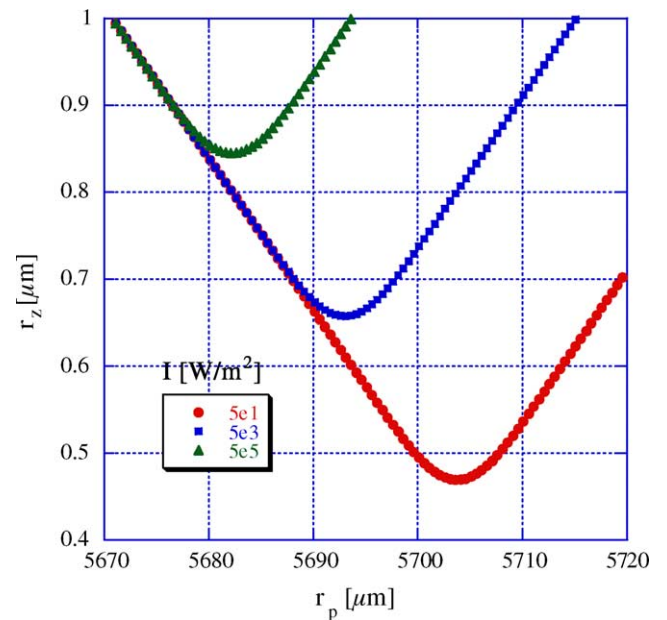


Fig. 2. Variation of the trajectories of a silicon atom with light intensity I . $\Delta = 1$ GHz, $\phi = 81.11^\circ$.

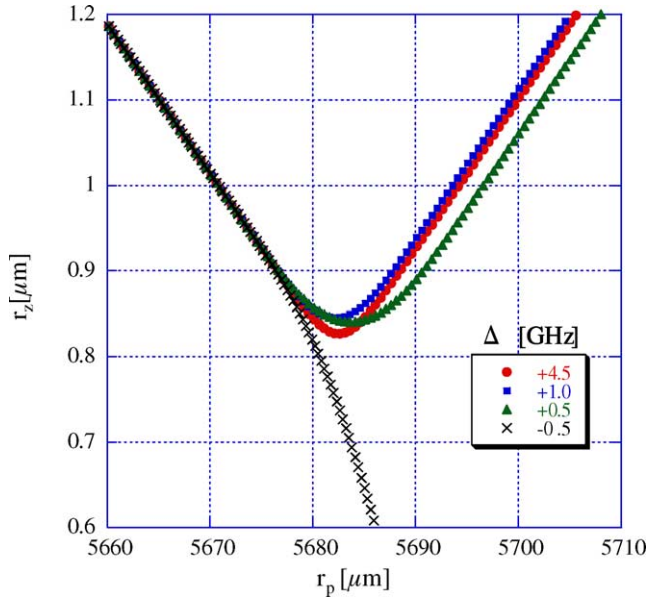


Fig. 3. Variation of the trajectories of a silicon atom with effective detuning Δ . $I = 5 \times 10^5 \text{ W/m}^2$, $\phi = 81.11^\circ$.

equation of motion

$$M \frac{d^2 \mathbf{r}}{dt^2} = \mathbf{F}_s + \mathbf{F}_d + \mathbf{F}_v - Mg\hat{\mathbf{z}} \quad (10)$$

where M is the mass of the atom and $\hat{\mathbf{z}}$ is a unit vector in the direction of z [7]. We do not take account of the atoms falling into the dark state. Figs. 2–4 display the variation of atomic trajectories with light intensity I , effective detuning Δ and incident angle of the light ϕ , respectively. In all cases the atom is initially at $(r_p, r_z) = (0, 100) \mu\text{m}$, the velocity is $V = 100 \text{ m/s}$, and the incident angle is $\theta = 89^\circ$.

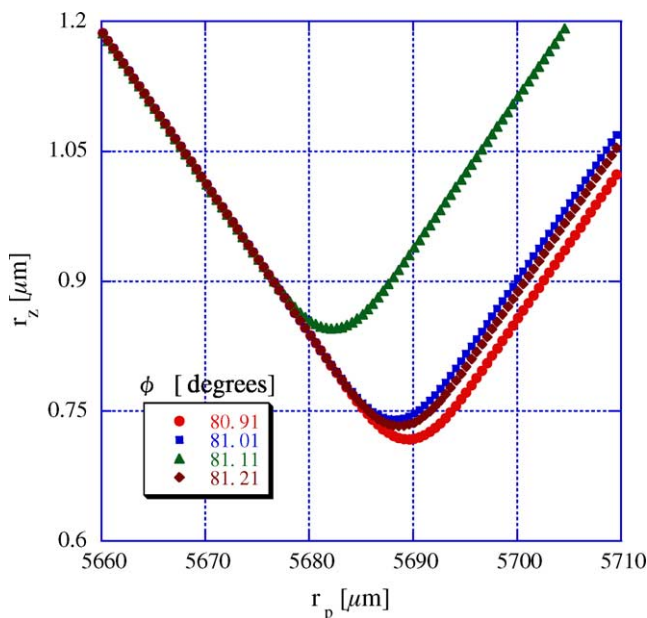


Fig. 4. Variation of the trajectories of a silicon atom with incidence of the light ϕ . $I = 5 \times 10^5 \text{ W/m}^2$, $\Delta = 1 \text{ GHz}$.

The high intensity of the light generates the intense evanescent field, and spreads the distribution of the evanescent field along the z direction. So the turning point at which the atom is repelled is high (Fig. 2). When the effective detuning is close to zero, \mathbf{F}_s acts on the atom greatly, this is accelerated to the right along the surface. \mathbf{F}_d increases as Δ decreases, but there is an optimum value of Δ which maximizes \mathbf{F}_d . Much smaller than the optimum value, \mathbf{F}_d decreases. However, for the negative detuning ($\Delta < 0$), the atom experiences an attractive dipole force (Fig. 3). The differences between the trajectories with ϕ depend on whether the electric field is enhanced in the waveguide layer, in other words, the magnitude of T . This enhancement is occurred when ϕ fills the resonance condition in the waveguide layer. Fig. 4 shows that the resonance occurs at $\phi = 81.11^\circ$, so the atom is repelled far from the surface of atomic mirror due to the enhanced ($T = 1189$) evanescent field.

4. Conclusion

We have designed the atomic mirror for silicon atoms, which consists of a prism and two layers. This structure like a Fabry–Perot cavity enhances the evanescent field in vacuum, so that the atom approaching the mirror at high velocity can be repelled. We have also derived trajectories of the atoms reflected from the atomic mirror. Optical intensity, incident angle of the light, and effective detuning are discussed in terms of controlling the trajectory of the atom. The magnitude of evanescent field depends on intensity and incident angle of the light. And the magnitude and the direction of dipole force depends on the evanescent field and effective detuning that determines the height at which atom is repelled. In an actual experiment, the atoms have velocity distribution. So the atoms need to be reflected far from the atomic mirror, not adhering to the atomic mirror.

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