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Optimal geometry of atom funnels with surface-plasmon enhanced evanescent light field

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ABSTRACT

We enhance the evanescent light field for funneling cold atoms by surface-plasmon resonance. When a 780.2-nm light beam is incident on a glass–gold interface from the glass side at an angle of 44.6°, the intensity rises 14.4-fold for *p*-polarization and 7.2-fold for circular polarization compared to the case with total-internal reflection. Then, we evaluate the flux intensity of a resultant Rb atomic beam for three funnel shapes of a cone, a quadrangular pyramid, and a triangular pyramid. Monte Carlo simulations show that the flux intensity exceeds 1 atom/nm^2 s when the outlet diameter is smaller than 10 μm. In particular, the conical funnel yields the highest flux intensity for circular polarization. Also, there is an optimal outside diameter of a hollow light beam generating evanescent light field for a given incident power. A prototype conical funnel is fabricated with a 3D printer.

1. Introduction

The self-organization that allows the precise control of shape and composition is considered a powerful technique to produce a large number of nanometric functional structures on a well-defined surface. A spin cluster composed of a small number of atoms is a most elemental sub-nanometer structure that is self-organized by spin exchange correlation interaction [1,2]. If it becomes possible to form the spin clusters on a substrate, they may be used as an ultrahigh density recording medium exceeding 1 Pb/in^2. In fact, we are planing to deposit dense spin-polarized cold alkali-metal atoms on a non-wetting substrate coated with rare-gas atoms [3,4].

To provide the ultrahigh density cold atoms, we are developing an atom-photonic element that concentrates laser-cooled atoms and outputs them as a cold atomic beam through a funnel-shaped evanescent light field (ELF) generated by the total-internal reflection (TIR) of a hollow light beam [5]. In our previous experiment with cold ^{87}Rb atoms whose resonant wavelength is 780.2 nm, we obtain a flux intensity of 6.2×10^8 atom/cm^2 s for a blue detuning of 1.2 GHz in the case with a 240 – μm – wide outlet [6]. On the other hand, according to Monte Carlo simulations we conducted, the flux intensity is expected to exceed 1×10^{10} atom/cm^2 s under our experimental conditions. The inefficient coupling of the hollow light beam to the funnel-shaped optics is a major part of the reason why the experimental value falls far short of the theoretical one. The ELF intensity becomes weak, so that the potential barrier to reflect atoms becomes lower. So, to decrease the loss of atoms by adsorption to the inner-wall surface of the funnel-shaped optics without reflection and increase the flux intensity, we try to enhance the ELF intensity by surface-plasmon resonance (SPR) [7].

Fig. 1 shows the cross section of the atom funnel, where the inner-wall surface is covered with metal. In this scheme, the intense ELF is excited on the inner-wall surface by SPR in place of TIR. Cold atoms produced inside the funnel-shaped optics by means of a magneto-optical trap (MOT) [8] fall with the force of gravity and are reflected by the repulsive dipole force from the ELF under blue-detuning conditions [9]. Moreover, the atoms lose their kinetic energy due to Sisyphus cooling in the process of reflection [10–12] and head down to a small outlet at the bottom. Then, the enriched cold atoms are guided downstream through the hollow light beam by the repulsive dipole force. The multiple loading from MOT makes a bunch of cold atoms into a beam.

The SPR usually takes place in the case of *p*-polarization (see Fig. 3b). However, it is impossible to be *p*-polarized in all directions in a 3D object such as the funnel. In that case, the use of circular polarization is effective for the increase in the atom flux intensity by SPR. In this paper, we describe experimental observations of the SP enhanced ELF for the circular polarization as well as the *p*-polarization with a scanning near-field optical

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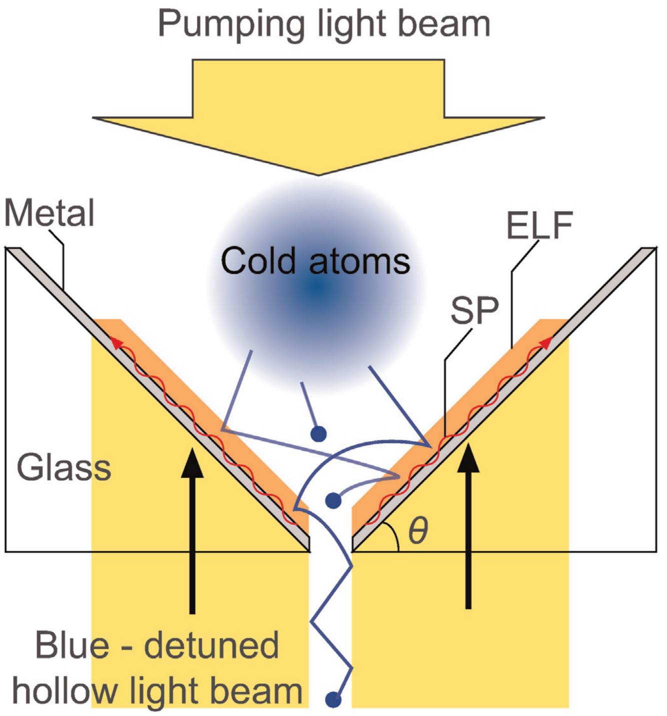

Fig. 1. Funneling of cold atoms for forming a dense atomic beam. Evanescent light field (ELF) is generated over the inner-wall surface of a funnel-shaped glass optics by irradiation of an upward hollow light beam under blue-detuning conditions. Laser-cooled atoms falling under gravity are reflected by a repulsive dipole force from the ELF and lose their kinetic energy due to Sisyphus cooling that is induced by applying a weak pumping light beam downward. Consequently, the re-cooled atoms gather at the bottom and flow from a narrow outlet. The output atoms are confined by the repulsive dipole force and go down through the hollow light beam. Metal coating over the inner-wall surface is made for surface-plasmon (SP) resonance.

microscope (SNOM) and numerical analyses on funnel operation under SPR for three shapes of a cone, a quadrangular pyramid, and a triangular pyramid with a Monte Carlo method. Then, we show that the atom flux intensity can increase to 10^{14} atom/cm^2 s = 1 atom/nm^2 s toward the efficient creation of spin clusters by self-organization.

2. Experiments

When a light beam with *p*-polarization is incident on a glass–metal interface from the glass side at an angle θ, SPR occurs in the case of

$$\sqrt{\varepsilon_g}\ \sin\ \theta = \mathrm{Re}\sqrt{\frac{\varepsilon_m}{\varepsilon_m + 1}}, \tag{1}$$

where Re means the real part, and ε_g and ε_m are the relative permittivity for air of glass and metal, respectively [13]. Considering a multireflection in the glass–metal–air layers, the reflectivity $R(\theta)$ for *p*-polarization is given by

$$R(\theta) = \left| \frac{r_1^p(\theta) + r_2^p(\theta)\ \exp\left(4\pi i d\sqrt{\varepsilon_m - \varepsilon_g\ \sin^2\ \theta}/\lambda\right)}{1 + r_1^p(\theta) r_2^p(\theta)\ \exp\left(4\pi i d\sqrt{\varepsilon_m - \varepsilon_g\ \sin^2\ \theta}/\lambda\right)} \right|^2, \tag{2}$$

where d is the thickness of the metal layer and λ is the wavelength in air [14–16]. The Fresnel reflection coefficients $r_1^p(\theta)$ at the glass–metal interface and $r_2^p(\theta)$ at the metal–air interface are written as

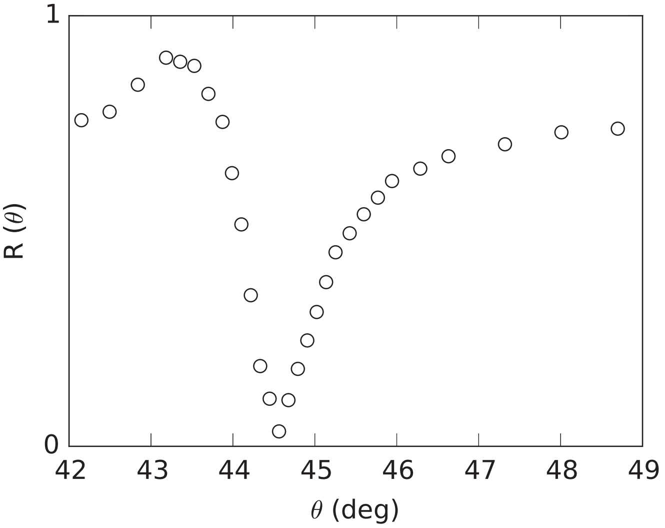

Fig. 2. Reflectivity $R(\theta)$ for a *p*-polarized 780.2-nm light beam incident on an interface between a silica glass prism and an Au thin film from the glass side plotted as a function of the incident angle θ.

$$r_1^p(\theta) = \frac{\varepsilon_m\ \cos\ \theta - \sqrt{\varepsilon_g(\varepsilon_m - \varepsilon_g\ \sin^2\ \theta)}}{\varepsilon_m\ \cos\ \theta + \sqrt{\varepsilon_g(\varepsilon_m - \varepsilon_g\ \sin^2\ \theta)}} \tag{3}$$

and

$$r_2^p(\theta) = \frac{\sqrt{\varepsilon_m - \varepsilon_g \sin^2\theta} - \varepsilon_m\sqrt{1 - \varepsilon_g\ \sin^2\ \theta}}{\sqrt{\varepsilon_m - \varepsilon_g\ \sin^2\ \theta} + \varepsilon_m\sqrt{1 - \varepsilon_g\ \sin^2\ \theta}}. \tag{4}$$

Now, we take Au with $\varepsilon_m = -22.48 + 1.40i$ for $\lambda = 780.2$ nm [17]. The permittivity of Au has a small imaginary part so that the light energy is efficiently converted into SP.

The reflectivity is supposed to be at a minimum around $\theta = 44.7°$ that satisfies Eq. (1) when Au is evaporated on the longest side of a silica glass prism with $\varepsilon_g = 2.12$. To know the resonance angle in our experimental conditions, we measure the reflectivity. Fig. 2 shows $R(\theta)$ obtained from a reflectometry as a function of θ. As you can see, the resonance angle is 44.6°. Meanwhile, the thickness of the Au thin film is estimated to be 48 nm at which the reflectivity vanishes when $\theta = 44.7°$ from Eq. (2). Indeed, we obtain $d = 45$ nm from the measurement with a step profiler. Note that the silicon oil compound for optical contact is put between the glass prism and the Au thin film to a negligible extent.

Next, we examine the intensity of ELF generated by a 780.2-nm laser diode (LD) beam incident at $\theta = 44.6°$. As shown in Fig. 3, let us consider three cases of (a) *p*-polarization illumination without the Au thin film, (b) *p*-polarization illumination with the Au thin film, and (c) circular-polarization illumination with the Au thin film. The ELF is excited by TIR in (a), whereas it is excited by SPR in (b) and (c). In the current TIR excitation, ELF is generated more intensely by *p*-polarization than by *s*-polarization [18]. In the SPR excitation, ELF that decays exponentially in the direction perpendicular to the surface is generated when SP propagates along the surface. The ELF intensity $I_{\mathrm{TIR}}(\theta)$ at the surface in (a) is given by [19]

$$I_{\mathrm{TIR}}(\theta) = \frac{4\varepsilon_g\ \cos^2\ \theta}{\cos^2\ \theta + \varepsilon_g^2\ \sin^2\ \theta - \varepsilon_g} I_0, \tag{5}$$

and the ELF intensity $I_{\mathrm{SPR}}(\theta)$ at the surface in (b) is given by [20]