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Optical surface devices for atomic and atom physics

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The applications in basic science of optical surface devices for atoms are reviewed, with the emphasis on the optical dipole mirrors. The example of experimental realization of such a mirror constructed in our group is shortly presented. Some methods used in its characterization are shown.

Keywords: atom cooling and trapping, optical dipole mirror.

1. Introduction

The interaction of an atom with a dielectric or metallic surface has been interesting for physicists for many years. However, it has recently attracted much attention and became a popular subject of investigation both in technological and fundamental research, because of new scientific tools, like traps for cold and ultracold atoms. Employing a surface allows one to obtain sophisticated magnetic or optical potentials which ensure precise manipulation of atoms movement, what is in turn the key issue for studying fundamental quantum phenomena. For neutral atoms such a control may be assured via the so-called dipole force [1] acting on an atom in an off-resonance electromagnetic field with a high intensity gradient. A good choice for such a field can be an evanescent wave (EW). It was suggested by Cook and Hill (1982) [2] to use the blue-detuned EW as a mirror for neutral atoms. The elastic optical dipole mirror was first demonstrated in 1987 with thermal atoms from an atomic beam at grazing incidence [3] and then in 1990 with cold atoms from a magneto-optical trap (MOT) at normal incidence [4].

Hereafter selected experiments in the field of optical surface physics are briefly presented. The small review is followed by the presentation of the optical dipole mirror for cold rubidium atoms, constructed in our group.

2. Principle of operation of a dipole mirror

An optical dipole mirror forms a basis of many optical surface devices for atoms. It is produced by total internal reflection of a blue-detuned laser beam from a dielectric–vacuum interface and allows elastic or inelastic reflections of atoms on a repulsive potential – see Fig. 1. The most popular elements used in the dipole mirrors are alkali atoms. In this case, an atom in the ground state $|Fm\rangle$ sees this repulsive dipole potential U_{Fm}:

$$U_{Fm}(\mathbf{r}, \theta) = \frac{3}{16} \frac{\Gamma \lambda_0^3}{\pi^2 c} I(\mathbf{r}, \theta) \frac{2J' + 1}{2J + 1} \sum_{F'} \frac{\left|C_{Fm,\, F'm}\right|^2}{\Delta_{FF'}}$$

where Γ is the spontaneous decay rate, λ_0 is the wavelength of the atomic transition, $C_{Fm,\, F'm}$ are Clebsch–Gordan coefficients for a given orbital momentum in the ground (J) and excited (J') state, and $\Delta_{FF'}$ is the EW detuning in relation to the F–F' transition. $I(\mathbf{r}, \theta)$ denotes the intensity of the EW, being a function of position in space, angle of incidence θ in total internal reflection, the index of refraction of the dielectric and also polarization state of the incident beam. The total potential in the dipole mirror includes also the van der Waals potential and the gravity – see, *e.g.*, Ref. [5].

An important feature of the mirror is a (usually unwanted) spontaneous photon scattering from the EW, which is, *e.g.*, responsible for radiation pressure exerted on bouncing atoms [6, 7].

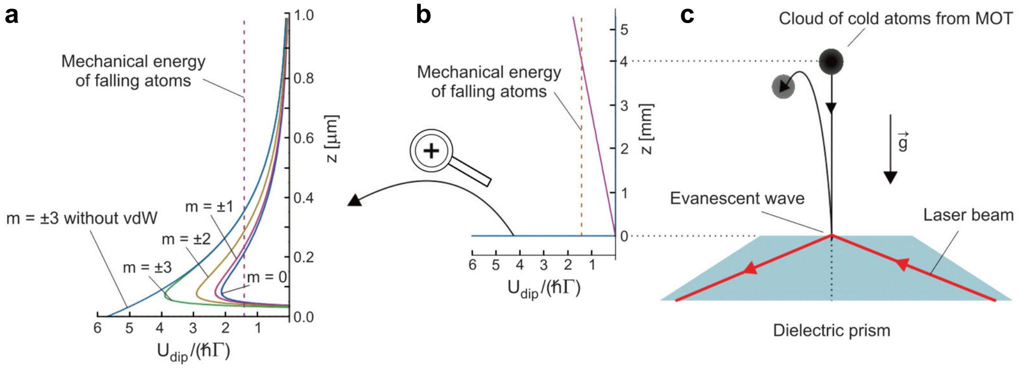

Fig. 1. Calculated potentials for different Zeeman sublevels of the ground state for the D1 line of ^{85}Rb atom (typical values in the dipole mirror experiments were used: the EW on-surface intensity – 37 kW/m^2, beam power – 17.4 mW, $\Delta_{F=3F'=3}$ – 2π×500 MHz, TM polarization of incident beam) (**a**); as in part **a** but for a greater range from a mirror surface – in this scale one obtains a hard-wall potential (**b**); cloud of cold atoms bouncing on the mirror, the displacement of the cloud after the reflection is due to the EW-induced radiation pressure force (**c**).

3. Applications of optical surface mirrors

Various interesting results were obtained in relatively simple cold atoms experiments in a dipole mirror setup. A direct observation of radiation pressure exerted by the EW on cold atoms from MOT [6] was performed by analyzing their horizontal motion after reflection. Measurements of the number of reflected atoms for various intensities and detunings of the EW led to determination of the van der Waals interaction between a ground state atom and a dielectric wall [8]. The specularity of the atom reflection from an EW mirror was studied in the context of the influence of the surface quality (theoretically – [9] and experimentally – [10]). The source of the diffuse reflection was identified and a method to minimize it was found [11].

Intense evanescent fields are usually required in atomic dipole mirrors. By increasing the intensity together with the laser detuning, the spontaneous emission rate may be reduced without lowering the repelling potential. Intense light fields permit also reflection of more energetic atoms. A reduction of fluctuation effects is, on the contrary, obtained at low intensities of the laser. A particular technique for achieving desired intensity enhancement is the addition of a metallic (*e.g.*, gold or silver) layer, several tens of nanometers thick, on the dielectric surface. It was demonstrated experimentally by ESSLINGER *et al.* [12] with thermal rubidium atomic beam, by FERON *et al.* [13] with metastable neon beam or by SEIFERT *et al.* [14] with metastable argon beam. The intensity enhancement of a factor of 60 is due to the surface plasmons, which are excited in a metallic film by TM polarized laser beam in the so-called Kretschmann configuration [15]. A theory of dipole mirrors with metallic layer was presented, *e.g.*, in [14, 16]. The use of atomic mirror with metallic coating allowed preparation of a quasi-2D gas of argon atoms confined in a planar matter waveguide in the close vicinity of a surface [17]. Later, the authors demonstrated an elementary, continuously operating circuit, involving an atom source, a switchable atomic waveguide at submicrometer distance from a metallic surface and an integrated atom detector, all produced by purely optical means [18]. An atom-trap, based on surface plasmons, being an analogy to the magnetic atom chips, was proposed [19]. It may be obtained by using a dipole mirror, coated with a structured thin metal film.

Combination of two counterpropagating EWs creates a mirror with a spatially periodic modulation, which acts as a reflection grating. In such mirrors diffraction of thermal atoms from an atomic beam or from MOT was observed (see references in [20]). Also theoretical analyses ([20] and references therein) for diffraction mechanisms for normal and grazing incidence were performed; authors reviewed approaches based on scalar diffraction, Raman couplings or in coupled-wave formalism for one-, two- or a multi-level atom.

A set of experiments with modified EW potential was demonstrated by the group of J. Dalibard. In the first experiment [21], the intensity of the evanescent light was modulated in time at a frequency from 0 to 2 MHz and the phase modulation of the de Broglie waves of reflected atoms was investigated. Changing the evanescent field intensity in time in a specified way led to creation of an analogy of vibrating mirror, which was used to manipulate atoms movement in the direction perpendicular to the mirror surface. Atom optics included acceleration, and trajectories focusing, also separately for different velocity classes by a "multiple lens" [22]. In the same experimental setup, a Young-slit-type interferometer was realized using temporally diffracted slow atoms. Atoms were prepared by a sequence of pulses of the mirror potential [23].

The Casimir–Polder and van der Waals forces [24, 25] are of great importance for fundamental reasons. They are also crucial for exploring non-Newtonian gravitational forces, *e.g.*, [26, 27] and have important technological applications, *e.g.*, in atomic force microscopy, mechanical systems in nanoscale and atom-optics surface devices. Direct methods of measuring the Casimir–Polder force include investigating perturbations in the frequency of center-of-mass oscillations of Bose–Einstein condensate perpendicular to a surface [28, 29] and surface temperature dependence of the Casimir–Polder force [30] and reflection of cold or ultracold atoms from an EW mirror. The latter was first performed by [8] when measuring the van der Waals potential but a relatively high uncertainty did not allow for a clear discrimination between the electrostatic and the QED model. Recently, a measurement of Casimir–Polder forces in the transition regime between the electrostatic short-distance and the retarded long-distance limit has been presented [31]. Contrary to [8], an ultracold cloud of rubidium atoms in a hybrid magnetic and optical surface trap [32] has been recently used. Similar method to resolve Casimir retardation effects, proposed in [33, 34], takes into account the quantum reflection's (classically forbidden above-barrier or attracting potential reflection) particular dependence on the details of the complete potential curve. The authors develop their idea and propose using a bichromatic EW mirror, created by red- and blue-detuned laser, to provide purely attractive potential for enhancement of the quantum reflection [35, 36].

With the use of EW spectroscopy, the first observation of atom modified radiative properties in vacuum near a dielectric surface was performed [37].

Another aspect of atomic dipole mirror setups is their ability to confine atom motion, *e.g.*, in gravito-optical cavities and traps. An important step for EW trapping was the experiment with atoms bouncing in a stable gravito-optical cavity [38]; the mirror was produced on a concave substrate and gave about 10 bounces. Then, a cooling mechanism by inelastic reflections (EW Sisyphus cooling) was introduced (suggested in [7, 39], realized experimentally [40–42]). It is a key mechanism in gravito-optical surface trap (GOST), which was first realized in Grimm's group [43]. In such a trap, the horizontal confinement is provided by the conservative optical dipole potential of a hollow far blue-detuned laser beam [44]. This led to formation of an optical microtrap, situated in the close vicinity of dielectric surface, by adding to the GOST a tightly focused red-detuned laser beam crossed with the horizontal dipole mirror [45]. After evaporative cooling of atoms in such a trap, a two-dimensional

Bose–Einstein condensate was created close to the dielectric surface [46]. Trapping and evaporative cooling was also demonstrated in a double EW trap (DEW trap), where a dense atomic sample was positioned as close as 1 micron from the surface. The DEW trap relies on the combination of a repulsive and an attractive EW field, produced by red- and blue-detuned laser beams with precisely defined intensities, decay lengths and wavelengths [47]. A different approach for reaching the 2D regime has recently been realized in a hybrid surface trap [48]. A combination of EW, standing wave (produced with broadband "white" light) and magnetic potentials was used to obtain a long-lived 2D quantum gas at a distance of a few microns from a glass surface. Also an all-optical atom dipole trap has recently been created [49]. Cold atoms from a mirror magneto-optical trap (MMOT) were loaded to a Fresnel far off-resonant dipole trap (FFORT), produced by a pattern of horizontal slits (Fresnel diffraction lens) on a gold mirror surface illuminated from behind with an intense red-detuned laser beam.

An alternative method of trapping and guiding atoms is the combination of micro- or nano-fibers and EW field. A theoretical analysis and experimental realization of coherent atomic motion through a hollow optical fiber were presented in [50] for attracting and in [51–53] for repelling potential; atoms were guided by EW potential at the internal glass–vacuum surface. For a U-shaped hollow optical fiber, a gravitational trap was proposed, which may confine atoms by gravity and evanescent field inside the fiber [54]. Spectroscopic measurements by two-step photoionization were performed in micron-sized hollow fibers together with an atomic-state filter for the two stable Rb isotopes [55]. It is also possible to trap and guide atoms outside a fiber, as suggested in [56], by using red-detuned EW field around a thin fiber. This idea was used, *e.g.*, to investigate the interaction of a small number of cold atoms from a MOT with the guided fiber mode and with the tapered fiber surface, to observe van der Waals interaction and an enhancement of the spontaneous emission rate of the atoms [57].

4. An example of the experimental realization

The experimental setup of a dipole mirror for cold rubidium atoms is described elsewhere [5]. Here we recall the basic parameters and new features. The heart of the system is a glass prism made of N-BK7 (see Fig. 2) situated in a vacuum chamber, a few millimeters below the place where the classical MOT is created. The flatness of the prism is $\lambda/20$ for the upper surface and $\lambda/10$ for the other surfaces ($\lambda = 800$ nm) and the roughness is 2 nm root mean square (RMS). The prism design allows creation of the EW on the upper surface, however two other total internal reflections are also used to guide the beam inside the prism. The vertical pair of MOT beams is going through the prism. Two resistively heated alkali metal dispensers are applied as a source of rubidium atoms.

Typical experimental sequence starts with 5 s of MOT loading. We trap typically 10^6–10^7 Rb^{85} atoms and subsequently increase their density with a temporal dark MOT technique [58] and cool them in optical molasses to 10 μK [59]. The last mentioned

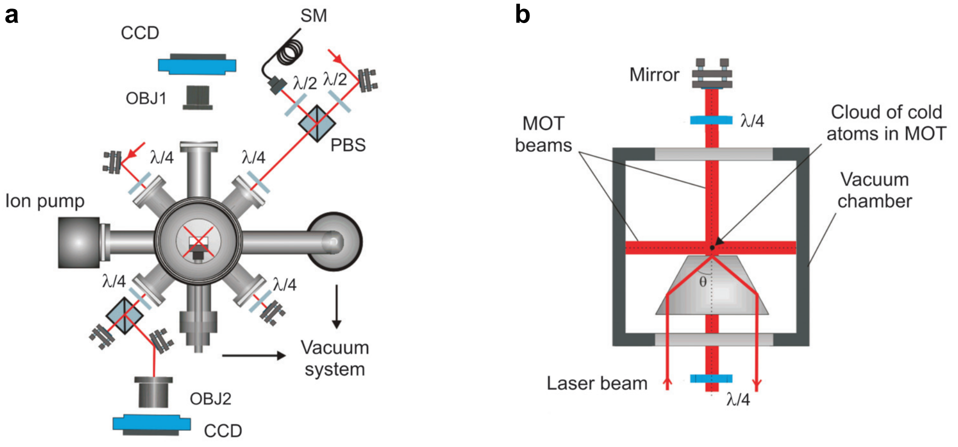

Fig. 2. Sketch of the experimental setup: top view – vacuum chamber and a part of the optical system (**a**), side view – inside the vacuum chamber and the vertical MOT beams pair (**b**). CCD – cooled CCD camera, $\lambda/4$, $\lambda/2$ – quarter-wave and half-wave plates, respectively, OBJ1, OBJ2 – common amateur camera objectives used here for fluorescent and absorption imaging, respectively, PBS – polarization beamsplitter, SM – single mode optical fiber (see text).

process requires cancellation of the laboratory magnetic field down to the milligauss range. This was achieved by installation of the three pairs of Helmholtz coils outside the vacuum chamber. In the next step all the MOT beams are turned off and atoms are falling under gravity towards the prism. The EW is turned on either permanently (for the detunings greater than 200 MHz) or for a few milliseconds of cloud reflection in the opposite case, in order to reduce stray light influence on the atom motion via radiation pressure force.

The typical experimental parameters are as follows: initial MOT height over the prism: 0.3 to 8 mm, EW detuning from a chosen transition: 0 to a few GHz, EW beam power: up to 30 mW, EW spot mean Gaussian radius (e^{-2}): 0.4 to 0.6 mm. The effective surface of the dipole mirror, defined as the area where the potential barrier is higher than the mechanical energy of falling atoms, is usually smaller than the surface of the EW spot (see Fig. 1).

Atoms that are bouncing on the dipole mirror are detected using either of two techniques: fluorescent or absorption imaging. In the first one, the atom fluorescence is induced by a pulse of MOT beams, resonant with cooling transition. The fluorescence is recorded with the cooled CCD (Alta Apogee U32) camera with the 2184×1472 pixels array. The optical resolution of the imaging system is 27 pixels/mm (with 2×2 hardware binning) and the integration time is 0.1 to 2 ms. In the second technique, additional resonant beam is mixed with one pair of MOT beams and then directed on CCD array (the same camera in different configuration). This technique allows the observation of a shadow of the cloud of atoms in the resonant beam. Both methods provide the number of atoms and their temperature with the help of time-of-flight (TOF) procedure. Both imaging techniques are destructive, so a new sample is always prepared for each picture. Additionally each image is usually averaged over 3 to 10 shots.

5. Results

High quality and efficiency of the dipole mirror were confirmed by the observation of two subsequent reflections of the same cloud of atoms. Fluorescent pictures were taken up to 100 ms after the beginning of the free fall – see Fig. 3. The final number of atoms after two reflections is about 1% of the number of atoms in MOT. The detuning of the evanescent field was 2.5 GHz, so the incoherent photon scattering (and thus the radiation pressure force) was greatly suppressed to the level of less than 0.5 photon per atom per bounce, allowing straight vertical reflection, in contrast to Fig. 1**c** and Fig. 5 later in the article.

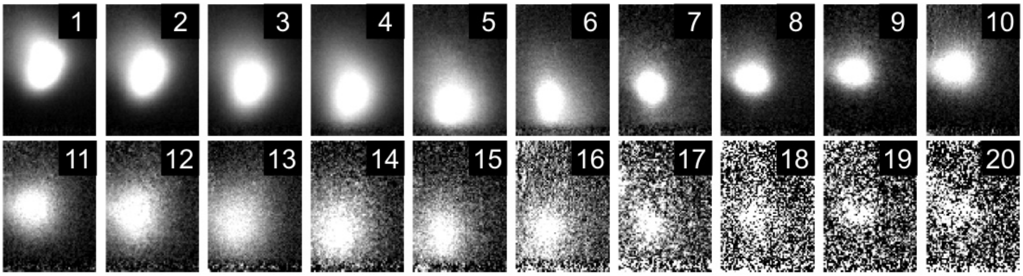

Fig. 3. Time sequence of the double reflection of atoms in the dipole mirror. The pictures were taken every 5 ms after releasing atoms from the molasses phase and are the result of averaging over three fluorescent pictures. In the images 5 and 15 the cloud is close to its lower turning point, whereas in the images 10 and 20 upper turning point is seen. Initial MOT height over the prism surface was 2.9 mm, MOT temperature was 12 μK, the EW laser beam power was 30 mW (TM polarization), the angle of incidence of the EW laser beam was 1.5° over the critical angle, and the EW spot Gaussian (e^{-2}) radii were 520×430 μm.

For the purpose of optimization of all the parameters of the optical dipole mirror for a given set of experiments, we have developed a computer simulation allowing the visualization of the falling and reflected cloud of atoms and giving predictions of the number and velocity of reflected atoms. The simulation takes into account the free fall of a cloud of atoms of a given temperature and initial size, the reflection from the hard-wall potential with a position-dependent barrier height and the van der Waals interaction (see Fig. 1), the intensity profile of the EW spot, the incoherent scattering and reemission of photons from the EW and stray light. An example of a reflection of some million of atoms (at a temperature of 12 μK) with the corresponding simulation is shown in Fig. 4. The EW detuning was 2.5 GHz again and the horizontal movement to the right of the center of mass of the cloud results solely from the initial 350 μm relative horizontal shift between centers of the MOT and the EW. Thus atoms with mainly the horizontal velocity to the right are reflected. The diffusive reflection is not

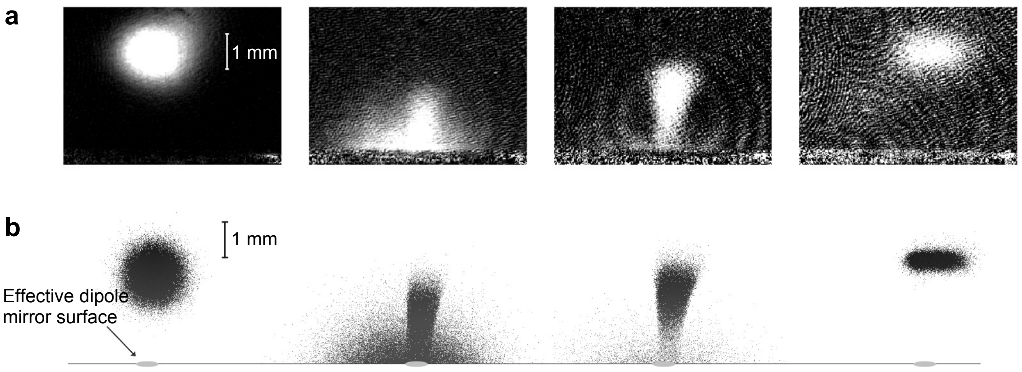

Fig. 4. Time sequence of a single reflection in the dipole mirror (**a**), along with a computer simulation (**b**). The pictures were taken 10, 30, 35 and 50 ms after releasing atoms from the molasses phase. The horizontal shift to the right of the reflected cloud is due to the on-purpose non-central reflection of the cloud on the dipole mirror. Each picture is an average of five shots of an absorption imaging. For the rest of the experimental parameters – see caption of Fig. 3.

taken into account in the simulation due to the lack of knowledge of the structure of the prism surface roughness. This is the reason why the simulated cloud has a smaller vertical cross section than its experimental counterpart.

We have also focused on the incoherent photon scattering by atoms being reflected in the field of moderately detuned EW. For the detunings on the order of tens of

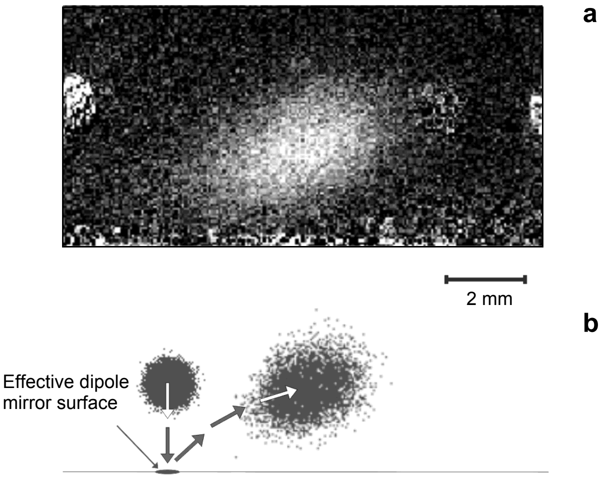

Fig. 5. Exemplary observation of the radiation pressure force induced by the EW detuned by 28.7 MHz from the $(F = 3)$–$(F' = 3)$ transition: fluorescence image (**a**), computer simulation including the initial position of the MOT (**b**). The picture was taken 40 ms after releasing atoms from the optical molasses. Initial MOT height over the prism surface was 2.0 mm, angle of incidence of the EW laser beam was 1.5° over the critical angle, MOT temperature was 12 μK, the EW laser beam power was 7 mW (TE polarization).

MHz, the horizontal displacement of the cloud after reflection is macroscopic and equals a few millimeters – see Fig. 5.

Although the cloud in Fig. 5**a** is in the upper turning point, there is the apparent tilt of the cloud in respect to the prism surface. It is caused by the stray light coming from the EW beam, scattered in the vacuum chamber. This light acts at the same time on both the falling and reflected part of the cloud, when EW is switched on for 6 ms. From the tilt of the cloud we have calculated that the average number of incoherently scattered photons from the stray light in the vacuum chamber was 4 per atom. It corresponds to the stray light intensity below $0.002 I_{\mathrm{sat}}$, where I_{sat} is the saturation intensity and equals 1.6 mW/cm^2 for rubidium atoms in two-level approximation. Note that the intensity of the laser beam forming the EW is even a few thousands times greater on the prism surface than I_{sat}. The deeper analysis will be published elsewhere.

6. Conclusions

We have listed the main experiments in which the optical dipole mirror or its derivatives were used. The optical surface devices have attracted much attention in the mid 1990s, after the techniques of cooling and trapping of atoms had been developed. Many basic science experiments were performed with the use of the dipole mirrors, but it seems that magnetic atom chips have become more promising for scientists. For example, the experiment with the 2D BEC in a surface optical trap (see [46]) has not been further developed any more. However, it has appeared recently that a new generation of hybrid optical-magnetic surface devices become popular, giving the possibility of sophisticated manipulation of atoms [31, 32, 48].

We have presented the dipole mirror for cold rubidium atoms constructed in our group, along with the method of its characterization. The setup will be used to test the possibility of construction of an optical atom chip, possibly with the use of surface plasmons in the thin metal film deposited on the prism surface.

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