

Features of atomic and molecular beams passage through capillary systems in the presence of evanescent light waves

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Summary. — A model of the transverse cooling of atoms in the field of a surface light wave inside a glass capillary is considered. The attenuation coefficient for transverse oscillations of atom in a microcapillary is estimated, and the length of effective atom cooling is calculated. A 3D model is constructed. The possibility for the practical application of this phenomenon both to develop the technology of atomic lithography and to fabricate the nanostructures is considered.

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The theory of atoms motion in the field of a plane light wave, a Gaussian beam, and a standing wave is currently well developed [1-3]; studies on atom focusing by Fresnel zone plates [4], magnetic lenses [5], single and hollow laser beams [6-9], and axially symmetric electric fields [10] have been performed. It is known that under the action of the gradient force of light pressure, atoms in the course of motion inside a laser beam can be focused in a spot of the Angstrom sizes [11-13]. In relation with the extensive development of nanotechnologies, the creation of elements of atomic and molecular optics based on these mechanisms is a topical problem.

Presently producing acceptable atomic optical elements based on the technologies of laser, electric, and magnetic fields is impossible because of a number of constraints of fundamental and technical characters, first of all, due to the spatial instability of electromagnetic fields. To overcome this problem, the methods of spatial localization of atom-field interaction potentials are required. These methods are mainly based on the application of the surface light wave, which is formed at total internal light reflection in the medium. The laser beam experiencing a total internal reflection from the dielectric-vacuum interface shapes a fine surface wave of the intensity equal to the original radiation intensity [14]. The surface wave intensity sharply decreases in vacuum at distances

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Fig. 1. – Transport of atoms in the field of the surface light wave inside the microcapillary.

comparable with the light wavelength, and in this case a large electric-field strength gradient is created; the force of this gradient is capable of turning trajectories of atoms approaching the surface. If there is a positive offset of the laser radiation frequency with respect to the atomic absorption frequency, the gradient force repulses atoms from the surface; in the case of a negative offset, it attracts atoms to the surface. The mirror reflection of atoms from the plane dielectric surface, to which laser radiation was supplied through the side surface, was first observed in [15]. The reflection efficiency for the laser-induced mirror depends on the atom incidence angle and, at small sliding angles, it reaches 100%.

1. – Motion of atoms in transparent capillary

Let us consider the specific features of the interaction between a flow of thermal atoms and a transparent capillary; laser radiation hits the wall of capillary in the regime of total internal reflection (fig. 1). In these conditions, a radial symmetric field of a surface wave of laser radiation is formed inside the capillary. The gradient force formed in this field, depending on the offset time $\delta = \omega - \omega_0$ of laser frequency ω with respect to the frequency of atomic transition ω_0 , attracts or repulses atoms from the capillary walls, inducing their motion along the modified trajectory.

The specular reflection from the capillary wall is satisfied only for those atoms whose transverse velocity v_r does not exceed some maximal value [16] $v_{\max} \approx \sqrt{\frac{2U_{\max}}{m}}$, where U_{\max} is the height of the potential barrier of the surface wave, and m is the atom mass. Thus, similarly to particle channeling in crystals [17], the motion of atoms in the capillary with a “specular” wall can be considered as “channeling” in the capillary structure. In this case atomic trajectories are determined by the capillary parameters and laser-radiation characteristics; varying these characteristics it becomes possible to control the atomic beam motion. Gradient fields of different configurations inside the channel can be formed choosing the capillary diameter, power, and frequency offset of laser radiation in a certain way. Such fields possess high spatial both localization and stability, thus providing conditions for the manipulation of atomic flows with high precision. For example, the spectrum of possible field configurations can be extended by means of conical nanocapillaries, and, thus, the interaction potential depends on the longitudinal coordinate along the capillary axis.

In this case it is fundamentally possible to focus atomic beams and create different batches for the precipitation of a required number of atoms on the surface. It is very important that these methods can be naturally applied for controlling molecular beams.

2. – Gradient field potential

The surface light wave propagates along the surface with the wave vector

$$(1) \quad k_x = \frac{2\pi}{\lambda} n \sin \theta$$

and exponentially decreases from the surface with the characteristic attenuation length $1/\alpha$, where

$$(2) \quad \alpha = \frac{2\pi}{\lambda} (n^2 \sin^2 \theta - 1)^{1/2},$$

θ is the laser beam incidence angle and n is the refractive index of the capillary wall.

The field potential of the surface light wave is represented as [18]

$$(3) \quad U(x) = \frac{1}{2} \hbar \delta \ln \left(1 + \frac{G_0 \exp[-2\alpha x]}{1 + \delta^2/\gamma^2} \right),$$

where \hbar is the Planck constant, x is the atom coordinate, 2γ is the natural absorption line width, $G_0 = I_0/I_s$, I_0 is the surface wave intensity on the capillary wall, and I_s is the transition saturation intensity.

Under the condition $|\delta| \gg \gamma$, ω_{R0} potential (3) can be represented in a simple exponential form,

$$(4) \quad U(x) = \frac{\hbar \omega_{R0}^2}{\delta} \exp[-2\alpha x],$$

where $\omega_{R0} = dE_0/2\hbar$ is the Rabi frequency, d is the matrix element of the dipole moment of the atom, and E_0 is the surface wave field amplitude.

Upon an examination of the interaction between atoms and the capillary wall, the wall curvature can be neglected and the motion of atoms can be considered the motion between two plane “mirrors”. Taking the capillary center as the point of origin, we obtain the potential

$$(5) \quad U_R(x) = U(x + R) + U(-x + R),$$

where R is the capillary radius; performing the corresponding transformation (5) for eqs. (3) and (4), we obtain the following equations of the surface wave field potential with respect to the capillary axis:

$$(6) \quad U_R(x) = \frac{1}{2} \hbar \delta \ln \left[1 + \left(\frac{G_0}{1 + \delta^2/\gamma^2} \right)^2 \exp[-4\alpha R] + \frac{2G_0 \exp[-2\alpha R]}{1 + \delta^2/\gamma^2} \cosh(2\alpha x) \right],$$

$$(7) \quad U_R(x) = \frac{2\hbar \omega_{R0}^2}{\delta} \exp[-2\alpha R] \cosh(2\alpha x).$$

Figure 2 shows the typical field potential inside the capillary.

To either focus or obtain a parallel atomic beam with a large transverse size, it is necessary to use the system of densely packed capillaries arranged in layers around a

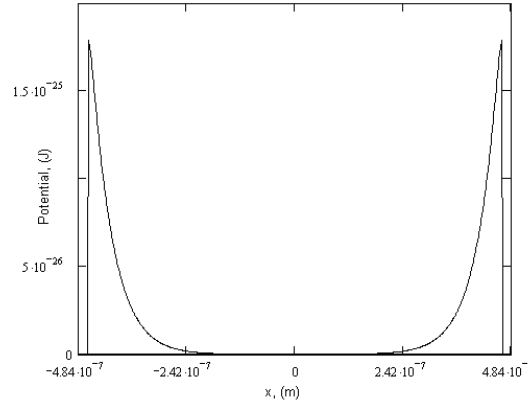


Fig. 2. – Typical field potential of the surface wave inside the capillary.

central capillary similar to the monocapillary lenses used in X-ray optics [19, 20]. The capillary curvature in this system varies from zero for the central capillary to a maximal value for peripheral capillaries in such a way that the acceptance of the capillary system is matched with the emittance of the atomic beam. In these conditions, the whole primary beam of thermal atoms is entrained in the channeling regime and efficiently transported without essential losses.

3. – Atom-cooling mechanism in the field of surface light wave

It is known that, upon the reflection of some atoms from the surface light wave, the process of their transverse cooling is possible; this process is connected with the optical pumping of the atom between sublevels of the hyperfine structure of its ground state [21-23].

In this case the atomic energy in the capillary in states 1 and 2 is determined as [22]

$$(8) \quad U_1(x) = \frac{1}{3} \frac{\hbar\omega_{R0}^2}{\delta} \exp[-2\alpha R] \cosh(2\alpha x),$$

$$U_2(x) = \frac{1}{3} \frac{\hbar\omega_{R0}^2}{\delta + \delta_{\text{hfs}}} \exp[-2\alpha R] \cosh(2\alpha x),$$

where δ_{hfs} is the frequency of hyperfine splitting of the ground level of the atom. In the presence of spontaneous decaying, the atom from the dressed state $|1, n\rangle$ can transfer to one of the states $|i, n-1\rangle$ with the decay rates of the following form in the case of low transition saturation $\omega_R^2(x)/2\delta^2 \ll 1$: $\Gamma_{11} \simeq q\Gamma s/3$, $\Gamma_{12} \simeq (1-q)\Gamma s/3$, and $\Gamma_{13} \simeq \Gamma(s/3)^2$, where $q = 0.72$ is the coupling coefficient of the excited state with the sublevel $|F=1\rangle$. The potential amplitudes of the states $|1, n\rangle$ and $|2, n-1\rangle$ essentially differ due to the different field offset with respect to the transitions $|F=1\rangle \rightarrow |e\rangle$ and $|F=2\rangle \rightarrow |e\rangle$. The spontaneous transition $|1, n\rangle \rightarrow |2, n-1\rangle$ from the deeper potential to the shallower potential is accompanied with the loss of kinetic energy $\Delta E_{\perp} = U_1(x) - U_2(x)$ by the atom.

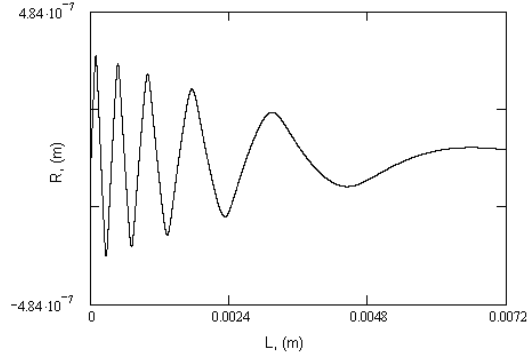


Fig. 3. – Sodium atom trajectory in the capillary with account for transverse cooling.

4. – Transverse atom cooling in the capillary

In the first approximation, the atom channeling in the field of the surface light wave inside the capillary can be considered as follows. Upon reflection from the capillary wall, the atom loses part of its transverse energy and the minimal energy to which atoms can be cooled in the radial plane is $E_{\min} = \hbar^2 k^2 / 2m$. In particular, for sodium atoms, the ratio of energy losses as a result of single scattering from the capillary wall is $\Delta E_{\perp} / E_{\perp} = 0.56$ [23]. Therefore, after $k = \log(E_{\min} / E_{\perp 0}) / \log(0.44)$ interactions with the capillary wall, the transverse energy of the atom reaches the minimum E_{\min} where $E_{\perp 0}$ is the initial value of transverse atomic energy.

Every time after it is reflected from the surface light wave, the atom loses part of transverse energy and, therefore, its flight time between the capillary walls increases; this time is calculated as

$$(10) \quad t_i = \sqrt{\frac{m}{2}} \int_{-R_i}^{R_i} \frac{dx}{\sqrt{E_{\perp i} - U(x)}},$$

where R_i is the root of the equation $U(x) - E_{\perp i} = 0$, $i = 0 \dots k$. The total time necessary for atom cooling to the minimal energy is $\tau = \sum_{i=0}^k t_i$. If the longitudinal velocity of the atom and the time required for transverse cooling are known, we find the optimal capillary length $L = v_z \times \tau$.

Using the formula $E(t) = E_0 \exp[-2\lambda t]$, we find

$$(11) \quad \lambda = -\frac{1}{2\tau} \ln \left(\frac{E_{\min}}{E_{\perp 0}} \right).$$

Taking into account energy losses, we obtain the equation

$$(12) \quad x'' + 2\lambda x' + \omega^2(x)x = 0,$$

where $\omega^2(x) = \frac{1}{m} \frac{\partial^2 U_R(x)}{\partial x^2}$. Solving eq. (12), we find the trajectory of sodium atom in the capillary (fig. 3).

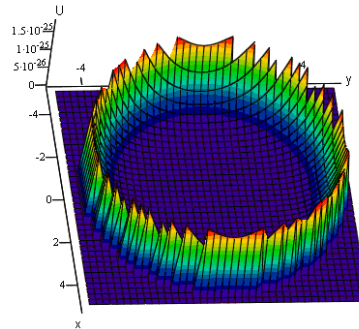


Fig. 4. – Field potential of the surface wave inside the capillary.

Transferring to the 3D coordinate system with account for $r = \sqrt{x^2 + y^2}$ for the field potential of the surface light wave (fig. 4), we obtain $U_R(x, y) = U_R(\sqrt{x^2 + y^2})$.

The equations of transverse motion for the atom in this case are written in the form of the system of two second-order differential equations,

$$(13) \quad \begin{cases} x + 2\lambda x' + \omega_x^2(x, y)x = 0, \\ y + 2\lambda y' + \omega_y^2(x, y)y = 0, \end{cases}$$

where $\omega_x^2(x, y) = \frac{1}{m} \frac{\partial^2 U_R(x, y)}{\partial x^2}$ and $\omega_y^2(x, y) = \frac{1}{m} \frac{\partial^2 U_R(x, y)}{\partial y^2}$. Solving system (13), we obtain the trajectory of the sodium atom in the capillary. The result of a simulation for the capillary with a diameter of $1 \mu\text{m}$ and a length of 10 mm is shown in fig. 5.

Obviously, by selecting the laser and capillary parameters in a certain way, the optimal conditions for the transverse cooling of a number of atomic elements can be created; this will yield the successful application of this method to parallel nanostructure fabrication. The application of assemblies with a large number of capillaries can make this method an efficient tool for parallel nanostructure fabrication.

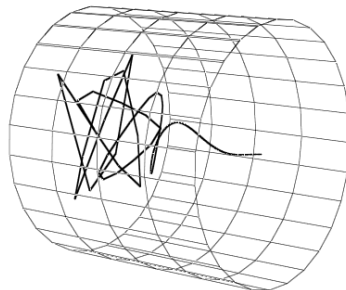


Fig. 5. – Result of a simulation of sodium atom motion in the capillary. The capillary diameter $1 \mu\text{m}$ is and the length is 10 mm .

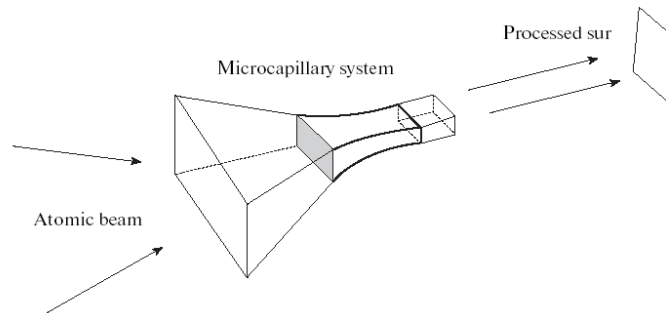


Fig. 6. – Schematic diagram of nanostructure fabrication.

5. – Lithography and nanostructure assembly

Standard technologies of optical, ultraviolet, and X-ray lithography currently in existence possess a diffraction resolution limit, and lithography methods using beams of charged particles are limited by the presence of Coulomb repulsion. In these conditions, methods for the structural organization or self-organization of matter on the surface or atomic lithography achieved according to the “bottom-top” principle become important.

Progress in this direction has been achieved in connection with the noticeable development of the technology of probe microscopy. A number of methods of probe microscopy, although they are laboratory conditions, offer surface observation and modification with atomic resolution. However, methods of probe microscopy possess low performance and are not very promising for this reason. In these conditions, atomic lithography and the structural assembly of nanoobjects based on the above principles of controlling technological processes can become efficient and competitive. Obviously, the standard lithography process using masks or atomic and molecular assembly by applying a picture directly on the substrate surface [24] can take place, for example, in the setup shown in fig. 6.

The results presented in this paper both indicate the promising character of the practical application of capillary structures for controlling atomic and molecular beams and reveal the capabilities for creating efficient technology for the fabrication of nanostructures.

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