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PAPER

Photon transport through a nanohole by a moving atom

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Abstract

We have proposed and investigated for the first time an efficient way of photon transport through a subwavelength hole by a moving atom. The transfer mechanism is based on the reduction of the wave packet of a single photon due to its absorption by an atom and, correspondingly, its localization in a volume is smaller than both the radiation wavelength and the nanohole size. The scheme realizes the transformation of a single-photon single-mode wave packet of the laser light into a single-photon multimode wave packet in free space.

1. Introduction

It follows from basic principles of wave physics that the passage of a wave through an aperture that is considerably smaller than the wavelength can be neglected. In the classical work by Bethe [1] on transmission of light by a *subwavelength* aperture in an infinitely thin and perfectly conducting screen, a simple expression for the transmission efficiency of light has been obtained, which is scaled in relation to the aperture size as $(r/\lambda)^4$, where r is the radius of the aperture, and λ is the wavelength. The Bethes theory describes the efficiency of the energy transfer of a wave as a continuously decreasing function of its wavelength. A remarkable discovery about the transmission of light through a subwavelength hole in a *metal* screen of a *finite* thickness and a *finite* conductivity that has been made by Ebbesen *et al* [2] has shown that the standard theory of diffraction by small holes is invalid, and, in this case, the transmission of light through the nanohole can be strongly enhanced. The majority of researchers [3–6] agree that the central role in this phenomenon is played by surface waves, such as *surface plasmons*.

In this work, we propose and investigate a fundamentally different mechanism by which a photon can be transferred through a *subwavelength hole*. It is based on photon transport that involves the participation of a particle other than a plasmon, namely, a *neutral atom*. In this scheme, a *single atom* transfers a *single photon* through a nanohole.

The proposed scheme is another mechanism of a photon's transport through a nanohole which supplements existing research [1, 2]. Besides the use of a new particle for photon transport it opens up a new possibilities for surface science. It is possible to use such scheme for investigation of van der Waals interaction because of atom–surface interaction [7, 8]. Another application of the described scheme it could be useful for atom–plasmon interaction investigation. Indeed the subwavelength hole is a highly nonlinear plasmonic element [9]. So the interaction of excited atom with such structure opens new way for tailoring the spectral properties of materials [10].

2. The basic idea

The basic idea of the single photon transport by a moving atom is presented in figure 1. An atom moving toward a metal screen with a hole absorbs a photon of laser radiation immediately in front of the hole. If the lifetime of the atom is substantially larger than the time of flight of the atom through the nanohole (in a real experiment, the nanochannel), the transition of the atom from the excited state to the ground state with emission of a photon can

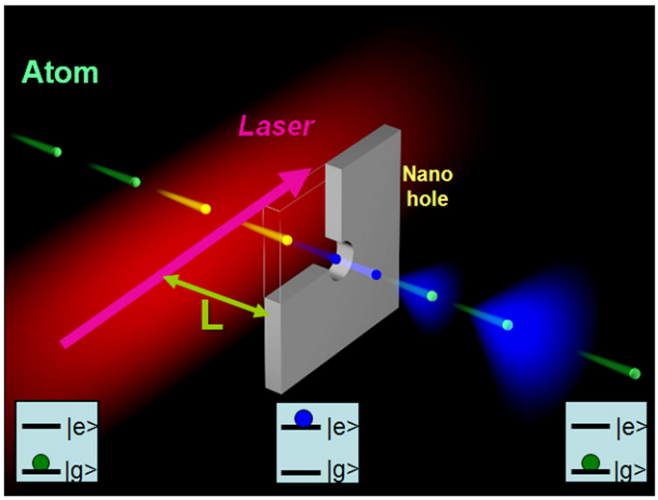

Figure 1. The basic idea of single photon transport by a moving atom. An atom that moves toward a screen with a nanohole is excited in front of the screen. The long lifetime of the excited atom enables this atom to transfer the excitation energy through the nanohole and reemit it as a photon on the other side of the screen.

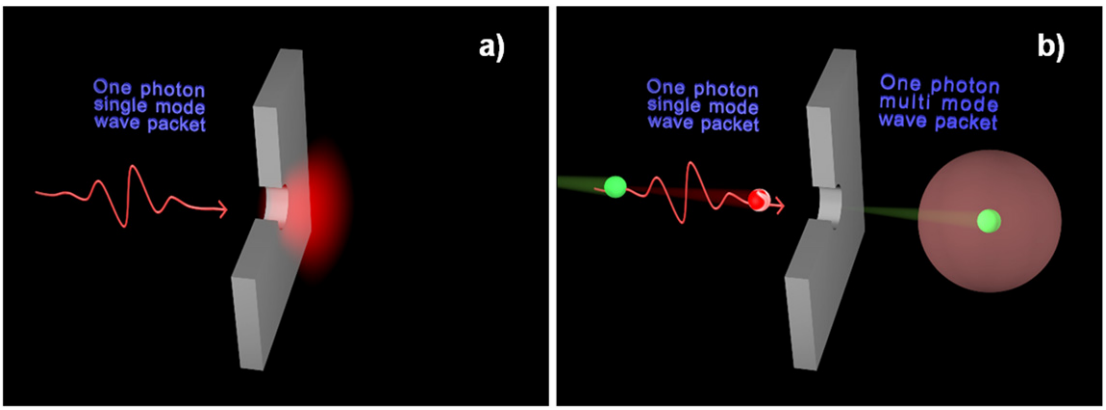

Figure 2. Two schemes of photon passage through nanoholes: (a) by means of photon tunneling and (b) via the reduction of the photon wave packet upon excitation of an atom and the transfer of photon energy by the atom through a nanohole.

occur on the other side of the screen, which means the transfer of the energy of the photon through the nanohole.

Classical particles can pass through a hole if their size is smaller than the hole. For atoms, being quantum particles, additional restrictions arise, which are related to their *wave nature*. The probability of passage of an atom through a nanohole that is considerably smaller than the de Broglie wavelength of the atom is negligibly small. For example, for cold atoms with a temperature of about μK and, correspondingly, with a de Broglie wavelength of about 1 μm, the transmission of an atom through a hole with a size of about a fraction of a micron is almost zero, even though the dimension of the atom (in the classical treatment) is significantly smaller than the hole size. For atoms with thermal velocities, the values of corresponding de Broglie wavelengths lie in the subnanometer range and, if the diameter of nanoholes is chosen to be a few tens of nanometers, the wave nature of the atom does no longer play a significant role. As will be shown below, this combination of (i) a screen with a nanohole, (ii) a thermal velocity of atom; (iii) a long lifetime in excited state can ensure an efficient photon transport by a moving atom through nanohole.

Let us evaluate the potential of an atom to be a photon carrier. If a photon is incident on a screen with a nanohole (figure 2(a)), the probability of photon passage through the nanohole is determined by the scattering cross section of the hole σ_{hole} and the cross section of a mode S occupied by the photon,

$$P_{\text{hole}} = \sigma_{\text{hole}}/S. \tag{1}$$

In the case of a subwavelength hole with $kr \ll 1$ ($k = 2\pi/\lambda$), its scattering cross section calculated in terms of Bethes theory [1] and is defined by the expression:

$$\sigma_{\text{hole}} = \sigma_{\text{Bethe}} = \frac{64k^4r^6}{27\pi}. \quad (2)$$

If an atom is now located immediately in front of the hole, the probability of transfer of a photon by the atom is determined by the following three parameters: (1) the absorption cross section of the atom σ_{atom}, (2) the photon mode cross section of S, and (3) the probability α_{atom} for the atom in the excited state to pass through the nanohole:

$$P_{\text{atom}} = \alpha_{\text{atom}}(\sigma_{\text{atom}}/S). \quad (3)$$

For a two-level atom with the absorption wavelength λ, the absorption cross section is $\sigma_{atom} = 3\lambda^2/2\pi$. From (1)–(3), it follows that the ratio of the probability of passage of a photon involving the participation of an atom to the probability of passage of a photon alone is

$$\zeta = \frac{P_{\text{atom}}}{P_{\text{hole}}} = \alpha_{\text{atom}}(\sigma_{\text{atom}}/\sigma_{\text{hole}}) \sim \alpha_{\text{atom}}(\lambda/r)^6. \quad (4)$$

At wavelength $\lambda = 800$ nm and nanohole radius $r = 50$ nm, the ratio ζ of the photon transfer probabilities is $\zeta \sim 2 \times 10^4$. Therefore, the probability of photon transport by the atom can be many orders of magnitude higher than the probability of the 'free photon' passage through the nanohole.

The physical reason for such high photon transfer efficiency is the reduction of the *single photon wave packet* due to its absorption by the atom and, as a result, its localization in a volume with the characteristic size much less than the wavelength and the nanohole size. In principle this scheme allows the transformation of 'single-photon in single-mode wave packet' of the laser radiation into a 'single-photon but multimode wave packet' in free space (figure 2).

3. Experimental scheme of atom-photon transport

The scheme of the photon transport by an atom considered above assumes that a *single atom* is excited by the electromagnetic field of a *single photon*. At present, the experimental implementation of this scheme of the photon transport seems to be a rather difficult task [11]. Several photons for the atom excitation are required in the case of the use of an ordinary laser field before the screen. So in the real experimental implementation the factor ζ decreases.

In this work, we show the possibility of transferring a photon by an atom involving the use of a continuous atomic beam (figure 1). The atomic beam is directed toward a screen with an array of nanoholes. In front of the screen, the atoms intersect a laser beam and are transferred to an excited state. The total area of nanoholes is only an insignificant fraction of the screen; therefore, when atoms of the beam collide with the screen, their main part is adsorbed on the screen or is diffusely scattered back. A small fraction of atoms (proportional to the total area of nanoholes) can pass through nanoholes. Precisely these atoms were used to characterize the photon transfer process by the atom.

Let us estimate the amount of photons that a beam of atoms can transfer through a single nanohole. Ideally, each atom can transfer no more than one photon. The total number of transferred photons is proportional to the number of atoms that pass through the nanohole,

$$N_{\text{photons}} = FS\eta, \quad (5)$$

where F is the flux of atoms, S is the area of the nanohole, and η is the atom-photon transport efficiency. The value η is determined by the following parameters: (1) the efficiency of atom excitation in front of the screen; (2) the probability of radiative relaxation of atom before screen; and (3) by the probability of nonradiative relaxation of atom via all possible decay channels. In the case of a two-level atom, the maximal value of the transfer efficiency is $\eta = 1$ (if the atom's population inversion before the screen and spontaneous emission after the screen is realized). A maximal flux of atoms in an effusive beam is F $\approx 10^{14}$ at s^{-1} cm^{-2}[12]. With such an atomic beam and nanohole radius of 130 nm ($S = 5.3 \times 10^{-10}$ cm^2), the photon flux is extremely small, $N_{\text{photons}} = 5.3 \times 10^4$ ph s^{-1}. The atomic flux decreases with the decrease in nanoholes diameter, making experimental difficulties with the detection of such a small flux of photons.

In the above atom-photon transport scheme, not only photons carried by the atom can pass through a nanohole in the screen, but also the background photons arising from: (i) laser light scattering and (ii) reemission of photons by atoms that failed to pass through the nanoholes. Under the assumption that the laser intensity equals the saturation intensity, the ratio of the number of photons transferred by atoms to the number of background photons is defined by the relation:

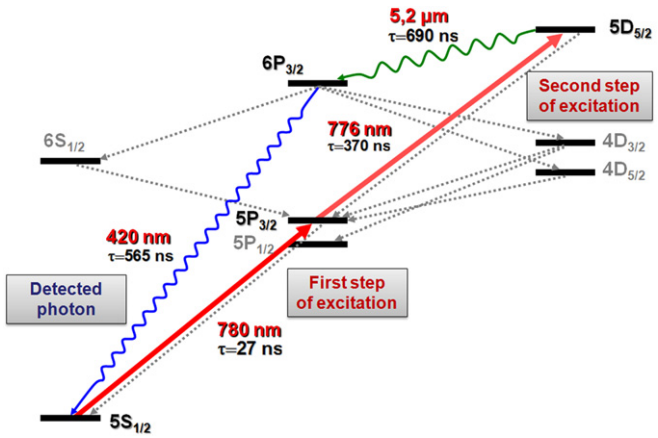

Figure 3. Scheme of energy levels of Rb atom. The red arrows show the excitation of atom to the $5D_{5/2}$ long-lived state; the green arrow shows the decay of the state $5D_{5/2}$ to the state $6P_{3/2}$, from which the atom returns to the ground state emitting a blue photon at a wavelength of 420 nm.

$$\kappa = \frac{27}{128\pi^3}\frac{\lambda^6}{r^4}\frac{1}{2\gamma}n_a v, \tag{6}$$

where n_a is the atomic beam density, 2γ is the linewidth. At the atomic beam density $n_a = 10^{10}$ at s^{-1} and the atomic velocity $v = 3 \times 10^4$ cm s^{-1}, the value κ is about $\kappa \sim 2$. Such a small value of the flux of photons transferred by atoms against the background of parasitic photons is a major challenge in the experimental realization of atom–photon transport.

One of the main parameters that determines both the efficiency of the atom–photon transport process and the possibility of its experimental realization is the lifetime of the atom in the excited state. Apart from the rather obvious physical requirements that were noted above, namely, the lifetime of the excited state of the atom should exceed its time of flight through a nanohole in the screen, there are two other physical reasons for the use of the long-lived state of the atom. The first of them is that the use of the long-lived state gives the possibility of increasing the distance over which the transfer of the photon energy occurs (a minimal value of this distance is the thickness of the screen with the nanohole). The second reason arises because of the probabilistic nature of the spontaneous emission of the atom: there is always a nonzero probability of reemission of a photon by the atom within a time interval that is considerably shorter than the average lifetime of the atom in the excited state. These photons reemitted in front of the screen can pass through nanoholes (without atom assistance), and they define the background signal which complicates the atom–photon transport investigation. At a long average lifetime of the atom in the excited state, the number of photons spontaneously reemitted in front of the screen decreases.

The number of these background photons N_{bg} depends on both the lifetime of the atom in the excited state and the size of the atom excitation region in front of the screen and is given by $N_{bg} \sim \frac{l}{v\tau}$, where l is the size of the excitation region, v is the average velocity of atoms, and $\tau = 1/2\gamma$ is the average lifetime of the atom in the excited state. It follows from this expression that, at a finite size of the atom excitation region (which is determined by the necessary condition of a high excitation efficiency of the atom), the long lifetime reduces the number of photons reemitted by the atom, which, in turn, reduces the background signal. It should be noted that the value of $v\tau$ is the mean the length of the photon transport with an atom.

3.1. Choice of an atom and the scheme of its excitation

The experiment was performed with Rb^{85} atoms. Let us consider the level scheme of Rb atom (figure 3) in terms of the optimal choice of atomic transitions for the experimental realization of the photon energy transfer across the screen with nanohole. If a thermal atomic beam is used and the resonant transition is $5S_{1/2} \rightarrow 5P_{3/2}$ (wavelength of 780 nm and the lifetime of 27 ns), then the photon transport length can be as long as 8 μm. It is very difficult to get experimental evidence of the photon transport through a nanohole with such a short transport length; therefore, it is necessary to use longer-lived atomic levels. Below we will show that excitation of Rb atom into the $5D_{5/2}$ state with a rather long lifetime (240 ns) is more appropriate choice of atomic state.

The state $5D_{5/2}$ has several decay channels. The deacy channel $5D_{5/2} \rightarrow 5P_{3/2} \rightarrow 5S_{1/2}$ is the most probable (about 65%), which leads to the emission of two photons: the first photon at 776 nm (370 ns decay time) and after that a second photon at 780 nm. The efficient atom photon transport can be realized by using this decay channel. There is another decay channel: atom can decay through $5D_{5/2} \rightarrow 6P_{3/2} \rightarrow 5S_{1/2}$ state with emission of a blue photon at 420 nm with probability of 8%. The excitation of an atom to the $5D_{5/2}$ state can be performed

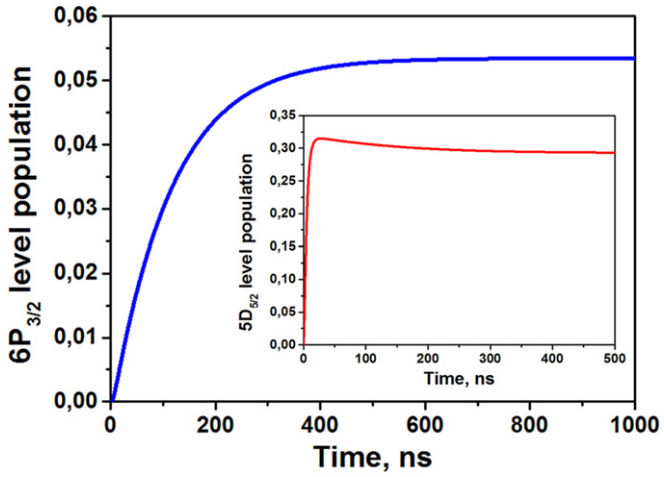

Figure 4. Dynamics of the populations of the $5D_{5/2}$ and $6P_{3/2}$ states of Rb atom.

using a two-step scheme [13]. At the first step, the transition $5S_{1/2} \rightarrow 5P_{3/2}$ is excited by laser radiation at 780 nm. At the second step, the transition $5P_{3/2} \rightarrow 5D_{5/2}$ is excited by the laser radiation at 776 nm.

In order to analyze the excitation process and the spontaneous transitions from the excited to the ground state of the atom, we calculated the temporal dynamics of the atomic state populations under the action of the double-frequency laser field. This calculation was performed in the framework of the quantum-mechanical approach, based on the density matrix, and also quasi-classically, using rate equations.

The two approaches yielded comparable results on the population dynamics of the $5S_{1/2}$, $5P_{3/2}$, $5D_{5/2}$, and $6P_{3/2}$ states. The calculations showed that one can achieve the atom excitation to the $5D_{5/2}$ state with a probability of about 50% at sufficiently large saturation parameters of the two transitions $5S_{1/2} \rightarrow 5P_{3/2}$ and $5P_{3/2} \rightarrow 5D_{5/2}$ [14].

Below, we present an analysis of the populations of levels of Rb atom that is based on solving rate equations. The rate equations have the following form:

$$\begin{aligned}
\dot{n}_{5S}(t) &= A_{6P5S} n_{6P}(t) + (A_{5P} + B_{5P5S} W_{780}) n_{5P}(t) \\
&\quad - B_{5S5P} W_{780} n_{5S}(t) \\
\dot{n}_{5P}(t) &= B_{5S5P} W_{780} n_{5S}(t) - B_{5P5D} W_{775} n_{5P}(t) \\
&\quad + (A_{5D5P} + B_{5D5P} W_{775}) n_{5D}(t) \\
&\quad - (A_{5P} + B_{5P5S} W_{780}) n_{5P}(t) \\
\dot{n}_{5D}(t) &= B_{5P5D} W_{775} n_{5P}(t) - (A_{5D} + B_{5D5P} W_{775}) n_{5D}(t) \\
\dot{n}_{6P}(t) &= A_{5D6P} n_{5D}(t) - A_{6P} n_{6P}(t) \\
\dot{n}_{4D}(t) &= A_{6P4D} n_{6P}(t) - A_{4D} n_{4D}(t) \\
\dot{n}_{6S}(t) &= A_{6P6S} n_{6P}(t) - A_{6S} n_{6S}(t)
\end{aligned} \tag{7}$$

where n_{5S}, n_{5P}, n_{5D}, n_{6P}, n_{4D}, and n_{6S} are the populations of the corresponding atomic levels and A and B are the Einstein coefficients of the rates of spontaneous and induced transitions between the corresponding levels [15] under the interaction with the field of energy density W_{780} and W_{775}.

Figure 4 presents the dynamics of the populations of the $6P_{3/2}$ and $5D_{5/2}$ atomic states that was obtained from numerical solution of the rate equations at the laser intensities that are used in experiments. As can be seen from the plots, an atom transfers from the $5D_{5/2}$ to the $6P_{3/2}$ state with a probability of 35%, and then it returns from this state to the ground $5S_{1/2}$ state with a probability of 31% and emits a photon at a wavelength of 420 nm [16].

The decay of the $5D_{5/2}$ state via the channel $5D_{5/2} \rightarrow 6P_{3/2} \rightarrow 5S_{1/2}$ with the emission of a photon at a wavelength of 420 nm takes place with a characteristic lifetime of 500 ns (figure 5). Such a long lifetime makes it possible for the atom to transfer the photon energy over a distance of about 150 μm. This value suffices to ensure the flight of the atom in the excited state through the nanohole and to realize an efficient scheme of the atom excitation to the $5D_{5/2}$ state in front of the screen. In this excitation scheme, the probability of emission of a blue photon by the atom is about 2%. The detection of blue photon gives an evidence of atom passage through the hole in the excited $5D$ state. As a consequence, this fact gives an evidence of photons transfer at 776 nm an 780 nm wavelengths (through the $5D_{5/2} \rightarrow 5P_{3/2} \rightarrow 5S_{1/2}$ decay channel). Our calculations show that for one detected blue photon there are about 20 photons at 776 nm and 780 nm wavelength.

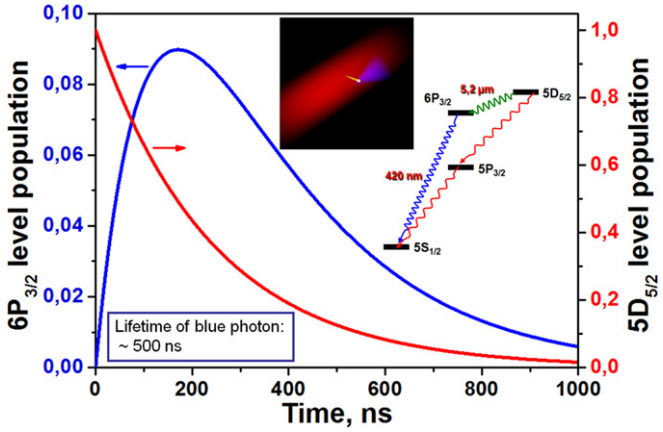

Figure 5. Decay of the excited state $5D_{5/2}$ of Rb atom via the channel $5D_{5/2} \rightarrow 6P_{3/2} \rightarrow 5S_{1/2}$ with emission of a photon at a wavelength of 420 nm. The fluorescence intensity at 420 nm is proportional to the population of atoms in the $6P_{3/2}$ state. As can be seen from the figure, the blue photon is emitted with a characteristic time of about 500 ns.

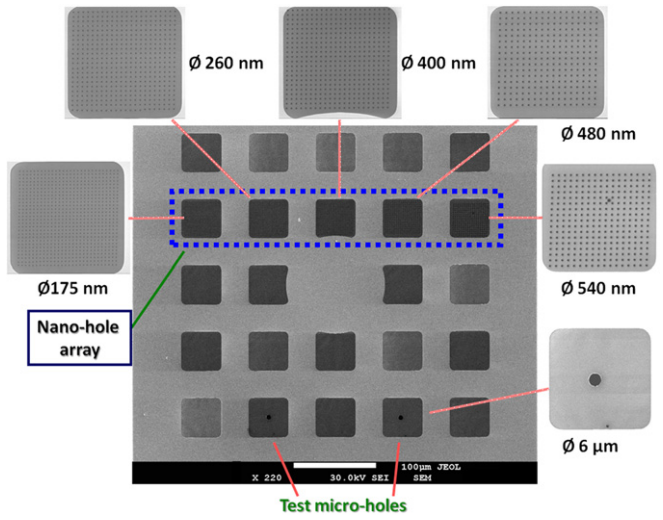

Figure 6. A screen with arrays of nanoholes. On top of the screen, fields with and without nanoholes are shown. The second row (indicated by a blue dotted rectangle) shows fields with nanohole arrays with the following diameters (d) and periods (T): (a) $d = 175$ nm, $T = 1$, 6 μm; (b) $d = 260$ nm, $T = 2$ μm; (c) $d = 400$ nm, $T = 2$ μm; (d) $d = 480$ nm, $T = 2$, 5 μm; and (e) $d = 540$ nm, $T = 2$, 5 μm. Fields in the middle part of the screen are also without holes. In the bottom part of the screen, there are two reference holes with a diameter of 6 μm.

3.2. Experimental setup

The atom–photon transport experiment was performed as follows. A beam of Rb atoms was directed toward a screen with nanoholes. The process of creation of the screen with nanoholes consisted of the following stages (figure 6): (i) onto a SiO_2 membrane, a thin silver layer (20 nm) was deposited, which is necessary for making nanoholes by an ion beam; (ii) nanoholes in the screen 'metal film + membrane' were made by a tightly focused beam of Ga^+ ions [17]; (iii) after the creation of an array of nanoholes, an additional silver layer with a thickness of 190 nm was evaporated onto the screen, to increase its optical density. The total thickness of the screen was 250 nm. The following arrays of the screens were created: (a) an array with a diameter of nanoholes $d = 175$ nm and their period $T = 1$, 6 μm; (b) $d = 260$ nm, $T = 2$ μm; (c) $d = 400$ nm, $T = 2$ μm; (d) $d = 480$ nm, $T = 2$, 5 μm; and (e) $d = 540$ nm, $T = 2$, 5 μm.

In addition to nanoholes, the test microholes with a diameter of 6 μm were made in the film. These microholes made it possible to measure values of the background radiation at 420 nm, which was emitted by a large number of atoms that collided with the screen and did not fly through nanoholes. The radiation created by these atoms can also pass through nanoholes, producing a parasitic signal.

A flux of rubidium atoms was formed by an atomic oven with a set of diaphragms. At a temperature of the atomic source of 140 ^{o}C, the intensity of the atomic beam was $F = 2 \times 10^{13}$ at s^{-1} cm^{-2} with a mean velocity

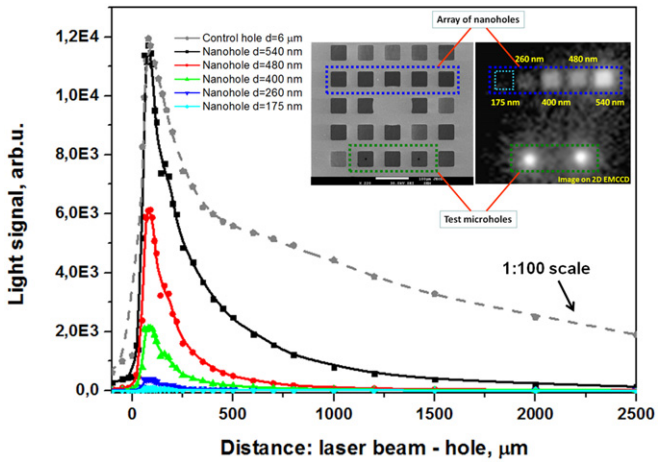

Figure 7. Fluorescence signal from atoms at a wavelength of 420 nm as a function of the distance L between the screen and the excitation region. The left inset is an electron image of the screen and the right inset is an optical image of luminous fields with nanoholes at a wavelength of 420 nm that was obtained with the CCD camera. The dashed curve is the dependence obtained from the reference holes (the signal was reduced 100-fold).

$v = 300$ m s^{-1}. Atoms were excited immediately in front of the screen using a two-stage excitation scheme (figure 3): an Rb atom was excited from the $5S_{1/2}$ ground state via an intermediate $5P_{3/2}$ excited state to the final $5D_{5/2}$ state ($5S_{1/2} \rightarrow 5P_{3/2} \rightarrow 5D_{5/2}$). To do this, two diode lasers were used. One laser ($\lambda = 780$ nm) was used to excite atoms via the transition $5S_{1/2} \rightarrow 5P_{3/2}$. This laser was stabilized in frequency using an external cell with a vapor of rubidium atoms. The other laser ($\lambda = 776$ nm) was used to excite atoms via the transition $5P_{3/2} \rightarrow 5D_{5/2}$. The frequency stabilization of this laser was implemented using a high-Q FabryPerot etalon. Measurement and testing of the radiation wavelengths of the lasers, as well as tuning of their frequencies, were performed using a λ-meter.

The interaction region of atoms with laser field was 50 μm in size. The intensities of the laser radiation were chosen such that to ensure only a single excitation of rubidium atoms to the $5D_{5/2}$ state as they flew through the laser beams. The Rabi frequencies were as follows: $\Omega_{780} = 2\pi 100$ MHz and $\Omega_{776} = 2\pi 2$ MHz.

The atom fluorescence at the wavelength of 420 nm (from atoms that passed through the nanohole) was filtered and detected with a high-sensitivity two-dimensional EMCCD camera (Princeton Instruments). To do this, an image of the screen with nanoholes was formed on the EMCCD matrix using a lens with a high numerical aperture ($NA = 0.54$). The photon collection angle was 0.48 sr. The use of the two-dimensional camera made it possible to *simultaneously* register the fluorescence signals from atoms that passed through all nanoholes and microholes in the screen, as well as to detect the background signal. The optical image of luminous fields with nanoholes that was obtained with the EMCCD camera is shown in the right inset of figure 7.

The detection of the fluorescence signal from microhole fields made it possible to estimate the fluorescence signal of atoms in front of the screen and to determine the photon transfer efficiency through the nanohole. The detection of the fluorescence signal from fields without holes made it possible to take into account the contribution of the background fluorescence signal generated by excited Rb atoms in front of the screen.

4. Results

The experimental verification of atom–photon transport was performed by a measurement of the fluorescence (at a wavelength of 420 nm) of atoms that passed through a nanohole in a screen (figure 1). In order to determine the efficiency of the atom-photon transport, we measured the fluorescence signal from atoms passed through nanoholes as a function of the distance L between the screen and the excitation zone (figure 1). Figure 7 presents the results of these measurements for the arrays of nanoholes with different diameters. The right inset shows an optical image of luminous fields with nanoholes at a wavelength of 420 nm. As can be seen from the plot in the figure 7, for all diameters of nanoholes, the signal increases with increasing distance L and reaches a maximum at $L = 100$ μm. Upon a further increase in the distance between the excitation zone and the screen, the fluorescence signal sharply falls. This is due to fact that at large distances between the atom and the screen, deexcitation of atoms in front of the screen takes place, and, as a result, there are no atoms that flew through nanoholes in the excited state. As should be expected, this fall in signal occurs at distances that are equal to the distance that an atom can travel during its time of flight in the excited state and it is of the order of 150 μm. A decrease in the

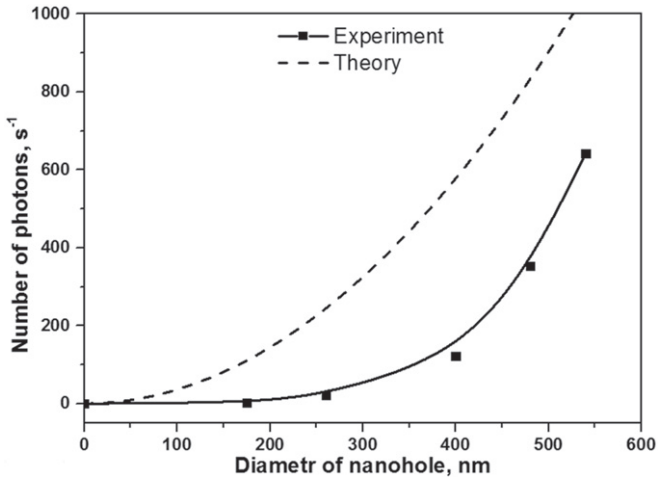

Figure 8. Number of photons transferred by atoms as a function of the hole diameter: experimentally measured (squares) and theoretically expected (dashed curve) dependences.

signal at distances shorter than 100 μm is explained by a decrease in the excitation region of atoms in front of the screen.

The signal that was obtained from fields with nanoholes (figure 7) was compared with the signals from fields without nanoholes and fields with microscopic holes (with a diameter of 6 μm). Comparison of the signals from fields with nanoholes of different diameters (figure 7) shows that the fall in the fluorescence signal upon an increase in the distance is sharper for fields with nanoholes of a smaller diameter. This is explained by the fact that larger nanoholes transmit background radiation generated by atoms that emitted photons at a wavelength of 420 nm in front of the screen. This background signal is higher for nanoholes of a greater diameter, since, apart from photons transferred by atoms through the screen, the detector also receives photons emitted by atoms that were in front of the screen (and that passed through it already in the ground state). This is the reason for which the rate of the signal decrease in figure 7 is different depending on the diameter of nanoholes. The parasitic effect is most pronounced for holes with a greater diameter (540 nm), where a nonzero background signal is observed at large distances between the excitation region and the screen.

Figure 7 also presents the plot of the dependence of the signal on the distance L between the screen and the excitation zone for test *microscopic* holes (the signal is presented on a scale of 1 : 100). As can be seen from the plot for these holes, the dependence of the signal on the distance is not so sharply pronounced compared to the case with nanoholes. This is explained by the fact that, in this case, the signal contains the fluorescence from all atoms, i.e., those that passed through the screen with holes in the excited state and those that emitted photons in front of the screen. Comparison of the behavior of the signal from microholes with the signal from nanoholes convincingly proves the occurrence of the effect of radiation transfer through nanoholes in an opaque screen.

5. Discussion of a results

A minimal value of the nanoholes diameter that was used in our experiment was $d = 60$ nm. However, only for nanoholes with a diameter of $d = 175$ nm or greater, was a measurable signal observed. An image of the field with nanoholes with $d = 175$ nm is shown on the right insert of figure 7 in the cyan dotted rectangle. As can be seen from this figure, at this value of the diameter of nanoholes, the fluorescence of atoms is hardly observed at all.

In the excitation scheme of the Rb atom that was used in our experiments, the fluorescence efficiency parameter η (equation (5)) is determined by the atom energy levels scheme and is equal to $\eta = 0.02$. At this value of the fluorescence efficiency and for the used atomic flux of $F = 2 \times 10^{13}$ at s^{-1} cm^{-2}, the number of blue photons transferred by the atom through a nanohole with a diameter $d = 260$ nm is $N_{\text{photons}} = 212$ photons s^{-1}. The calculated photon flux at wavelengths of 776 nm and 780 nm is 20 times higher (about 4 000 photons s^{-1}). Figure 8 presents an experimental dependence of the number of blue photons transferred by the atom N_{photons} on the diameter of the nanohole (squares) and a similar dependence that was obtained through equation (5). It can be seen from the figure that the number of transferred photons that was measured in the experiment is considerably smaller than the calculated number. At a nanohole diameter of 175 nm, the signal is small. At a nanohole diameter of 540 nm, atom–photon transport efficiency is about 61%. The calculated dependence is described by an expected quadratic function of the holes diameter, by virtue of the linear dependence of the

atomic flux on the holes area. The measured dependence differs from the calculated one. The possible reason of such discrepancy is an efficient deexcitation of atom flying through the nanohole. Our calculations show that in the framework of the theory [18] for the interaction of excited atom with the flat surface the significant deexcitation appears for the holes with a diameter smaller than 400 nm.

6. Conclusion

In this work, we have proposed and investigated for the first time an efficient way of transfer of energy of a photon through a subwavelength hole by a moving atom. The transfer mechanism is based on the reduction of the wave packet of a single photon due to its absorption by the atom and, correspondingly, its localization in a volume the characteristic size of which is much smaller than both the radiation wavelength and the size of the nanohole. The scheme realizes the transformation of a single-photon *single-mode* wave packet of the laser light into a single-photon *multimode* wave packet in free space.

The photon transfer efficiency depends on the geometrical dimensions of the nanohole, the material of the screen with nanoholes, and the velocity and the scheme of energy levels of the atom. At small sizes of the nanohole, the photon transfer efficiency decreases substantially because of the interaction of the excited atom with the surface, as a result of which the surface of the nanohole in the screen causes deexcitation of the atomic state. The described scheme of the atom interaction with the surface offers opportunities to study quantum friction [19, 20] and strength of atom-surface interaction [21–23]. Also the interaction of atoms with plasmons opens new way for tailoring the spectral properties of materials [10].

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References

[1] Bethe H A 1944 *Phys. Rev.* **66** 163–82
[2] Ebbesen T W, Lezec H J, Ghaemi H F, Thio T and Wolff P A 1998 *Nature* **391** 667–9
[3] Garcia-Vidal F J, Martin-Moreno L, Ebbesen T W and Kuipers L 2010 *Rev. Mod. Phys.* **82** 729–87
[4] García de Abajo F J 2007 *Rev. Mod. Phys.* **79** 1267–90
[5] Vengurlekar A S 2010 *Curr. Sci.* **98** 1020–32
[6] Martín-Moreno L, García-Vidal F J, Lezec H J, Pellerin K M, Thio T, Pendry J B and Ebbesen T W 2001 *Phys. Rev. Lett.* **86** 1114–7
[7] Lennard-Jones J E 1932 *Trans. Faraday Soc.* **28** 333–59
[8] Bloch D and Ducloy M 2005 *Advances In Atomic, Molecular, and Optical Physics* **50** 91–154
[9] Melentiev P N, Konstantinova T V, Afanasiev A E, Kuzin A A, Baturin A S, Tausenev A V, Konyaschenko A V and Balykin V I 2013 *Laser Phys. Lett.* **10** 075901
[10] Stern L, Grajower M and Levy U 2014 *Nat. Commun.* **5** 4865
[11] Stobińska M, Alber G and Leuchs G 2009 *Europhys. Lett.* **86** 14007
[12] Melentiev P N, Borisov P A and Balykin V I 2004 *JETP* **98** 667–77
[13] Grove T T, Sanchez-Villicana V, Duncan B C, Maleki S and Gould P L 1995 *Phys. Scr.* **52** 271–6
[14] Wielandy S and Gaeta A L 1998 *Phys. Rev.* A **58** 2500–5
[15] Heavens O 1961 *J. Opt. Soc. Am.* **51** 1058
[16] Akulshin A, McLean R, Sidorov A and Hannaford P 2009 arXiv:0910.2292
[17] Melentiev P N, Zablotskiy A V, Lapshin D A, Sheshin E P, Baturin A S and Balykin V I 2009 *Nanotechnology* **20** 235301–7
[18] Persson B N J and Andersson S 1984 *Phys. Rev.* B **29** 4382–94
[19] Scheel S and Buhmann S Y 2009 *Phys. Rev.* A **80** 042902
[20] Intravaia F, Behunin R O and Dalvit D A R 2014 *Phys. Rev.* A **89** 050101
[21] Persson B N J and Lang N D 1982 *Phys. Rev.* B **26** 5409–15
[22] Barnes W L 1998 *J. Mod. Opt.* **45** 661–99
[23] Afanasiev A and Minogin V 2010 *Phys. Rev.* A **82** 052903