

Single photon transport by a moving atom

A E Afanasiev¹, P N Melentiev¹, A A Kuzin^{1,2}, A Yu Kalatskiy^{1,2}
and V I Balykin¹

¹ Institute for Spectroscopy, Russian Academy of Sciences, 5 Phizicheskaya str.,
Troitsk 108840, Moscow, Russia

² Moscow Institute of Physics and Technology, 9 Institutskiy per., Dolgoprudny 141700,
Moscow region, Russia

E-mail: afanasiev@isan.troitsk.ru

Abstract. The results of investigation of photon transport through the subwavelength hole in the opaque screen by using single neutral atom are represented. The basis of the proposed and implemented method is the absorption of a photon by a neutral atom immediately before the subwavelength aperture, traveling of the atoms through the hole and emission of a photon on the other side of the screen. Realized method is the alternative approach to existing for photon transport through a subwavelength aperture: 1) self-sustained transmittance of a photon through the aperture according to the Bethe's model; 2) extra ordinary transmission because of surface-plasmon excitation.

It follows from basic principles of wave physics that the passage of a wave through a hole that is considerably smaller than the wavelength can be neglected. In the classical work by Bethe [1] on transmission of light by a nanohole 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 hole size as $(r/\lambda)^4$, where r is the radius of the hole, and λ is the wavelength. Under assumptions made on the screen, the transmission efficiency falls rapidly when the wavelength becomes greater than the hole radius. Ebbesen and collaborators [2] discovered the Extraordinary Optical Transmission (EOT) through sub-periodic hole array. The EOT is mediated by the aid of electromagnetic surface modes supported by the holey surfaces [3]. The majority of researchers agree that the central role in this phenomenon is played by surface waves, such as *surface plasmons*.

Here we demonstrate a new physical approach for an effective light transmission through nanohole. It is based on the 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 an another mechanism of photon's transport through the nanohole which supplement existing [1, 2]. Besides the using 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 [4]. Another application is for atom-plasmon interaction investigation. Indeed the subwavelength hole is a highly nonlinear plasmonic element. So, the interaction of excited atom with such structure opens a new way for tailoring the spectral properties of materials [5].

The basic idea of the photon transport by a moving atom is presented in figure 1 [6]. 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 excited atom is substantially larger than the time of



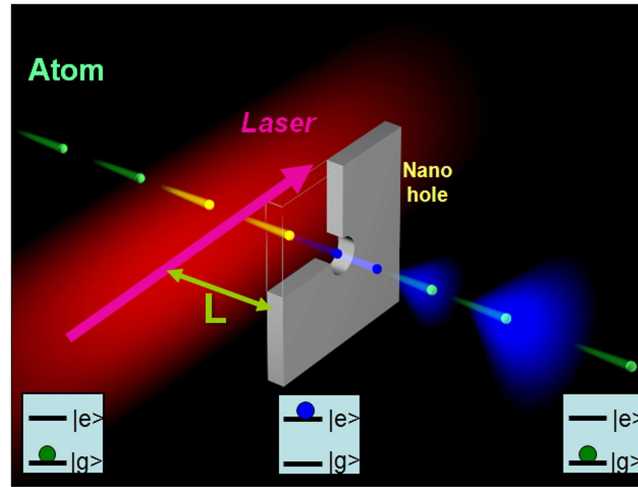


Figure 1. Scheme of a photon transport by atom through nanohole.

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

At the wavelength $\lambda = 800$ nm and the nanohole radius $r = 50$ nm, 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 $\eta \sim 2 \times 10^4$. 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 less than the wavelength and the nanohole size. In principle this scheme allows to transform “single-photon in single-mode wave packet” of the laser light into a “single-photon but multimode wave packet” in free space.

The experiment was performed with *Rb* atoms. A beam of *Rb* atoms is directed to the sample with nanoholes. Atoms were excited into a long-lived excited state $5D_{5/2}$ at the transitions $5S_{1/2} \rightarrow 5P_{3/2}$ and $5P_{3/2} \rightarrow 5D_{5/2}$. 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. Such a long lifetime makes it possible for the atom to transfer the photon energy over a distance of about $150 \mu\text{m}$. This value suffices to ensure the flight of the atom in the excited state through the nanohole. 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 and 780 nm wavelengths (through the $5D_{5/2} \rightarrow 6P_{3/2} \rightarrow 5S_{1/2}$ decay channel). Our calculations show that for one detected blue photon there are about 20 photons at 776 nm and 780 nm.

The photon transfer efficiency depends on the nanohole size, the material of the screen, 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 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 [7] and strength of atom-surface interaction [8].

This work was supported by the Russian Science Foundation (project no. 14-12-00729).

References

- [1] Bethe H A 1944 Theory of diffraction by small holes *Phys. Rev.* **66** 163
- [2] Ebbesen T W, Lezec H J, Ghaemi H F, Thio T and Wolff P A 1998 Extraordinary optical transmission through sub-wavelength hole arrays *Nature* **391** 667
- [3] GarcaVidal F J, Martn-Moreno L, Ebbesen T W and Kuipers L 2010 Light passing through subwavelength apertures *Rev. Mod. Phys.* **82** 729
- [4] Bloch D and Ducloy M 2005 Atom-wall interaction *Advances In Atomic, Molecular, and Optical Physics* **50** 91–154
- [5] Aljunid S A, Chan E A, Adamo G, Ducloy M, Wilkowski D and Zheludev N I 2016 Atomic response in the near-field of nanostructured plasmonic metamaterial *Nano Lett.* **16** 3137
- [6] Afanasiev A E, Melentiev P N, Kuzin A A, Kalatskiy A Yu and Balykin V I 2016 Photon transport through a nanohole by a moving atom *New J. Phys.* **18** 053015
- [7] Scheel S and Buhmann S Y 2009 Casimir-Polder forces on moving atoms *Phys. Rev. A* **80** 042902
- [8] Persson B N J and Lang N D 1982 Electron-hole-pair quenching of excited states near a metal *Phys. Rev. B* **26** 5409–15