Control transmission of light through a single nanohole with the use of photon crystal microcavity

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Abstract

We demonstrate an approach to control transmission of light through a single nanohole with the use of photon crystal microcavity. By using this approach the enhancement in transmission of light, photo induced luminescence and third harmonics generation for a single nanohole in Au film has been investigated for the first time. By use of the approach we demonstrate nanometer-scale, broadband or narrowband tunable light and background-free light source with a narrow directivity of the radiation.

1. Introduction

Propagation of electromagnetic waves through holes in a screen has always been of a great fundamental and practical interest. One of the important characteristics of light propagation through a hole is transmission. When holes diameter is smaller than the corresponding wavelengths, the diffraction impose restrictions on their use and, accordingly, limits possible applications. Therefore, the discovery of extraordinary optical transmission (EOT) phenomenon [1] has attracted considerable interest among scientists.

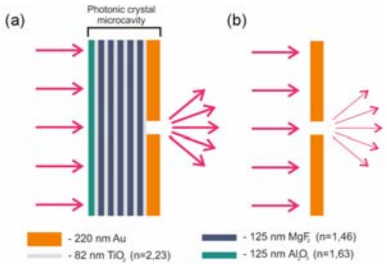

Fig. 1: Schematic of the experiment: (a) a nanohole of 60 nm diameter in 220 nm thick Au film, comprising the last layer of photonic crystal microcavity, (b) a nanohole of 60 nm diameter in 220 nm thick Au film.

In the implementation of the EOT conditions, the ratio of the energy transmitted through the screen with a hole to the energy incident on the hole may exceed one and several orders of magnitude higher than the value predicted by the Bethe's diffraction theory for the subwavelength holes. The increased transmission of radiation is based on multiple factors, the major of them are excitation of surface (plasmon) waves and proper arrangement of the holes in the screen, and for single holes – excitation of surface waves and periodic corrugations around apertures. Due to mechanism of its occurrence the EOT can be effectively used only for: (1) relatively large holes; (2) holes in a screen made of highly-conductive materials; (3) periodical structures; and (4) limited number of applications, as the frequency resonances of the transmitted radiation are wide.

In this paper, another approach to realize the EOT is considered. It is based on placing a nanohole into radiation field of a 1D photonic crystal. Quantum-mechanical system placed into a photonic crystal manifests physical properties different from those of the system in a free space [2]. Propagation of light through a nanohole can be simulated to a good accuracy with the use of the Babine principle, which allows one to replace the nanohole by a nanodisc, characterized by the corresponding (magnetic and electric) dipole moments [3]. As is well known, radiation of a dipole placed into a resonator is different from those in a free space.

The main idea of this paper is to realize conditions, at which nanohole (effective dipole) is placed into region with maximum electro-magnetic field of light in a 1D photonic crystal. The realized conditions can increase the emission rate of the effective dipole, and let to increase the total power of light emitted into free-space radiative modes on the exit side of the nanohole. With use of the approach we demonstrate increase of effectiveness of photo induced luminescence and third harmonic generation processes for a single nanohole in Au film.

2. Light transmission by single nanohole embedded in photonic crystal microcavity

In the experimental realization the PCM is formed on a quartz substrate by 12-layer stack of alternating high-index and low-index dielectric layers of thickness $\lambda/4n$, coated on one side with optically thick Au layer (Fig. 1a). The 12-layer stack of dielectric layers forms 1D type photonic crystal, realizing low, about 2%, transmission of light in spectral range of 650 to 800 nm. Coating of the 1D photonic crystal by the 220 nm thick Au film realizes a photonic crystal microcavity with resonance frequency λ_{res} = 781.7 nm, and the width $\Delta\lambda_{res} \approx 8.4$ nm, which corresponds to a cavity with the Q-factor of 93. PCM preparation was carried out under the conditions of Class 100 cleanroom.

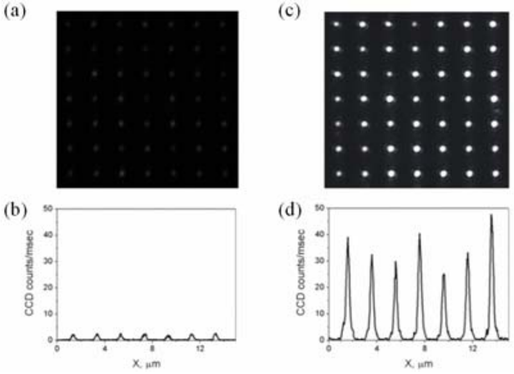

Fig. 2: Transmissions of nanoholes at a wavelength nearby the PCM's resonance mode: (a) 2D image of nanoholes in the reference Au film, (b) cross-section of the images of Fig. 2a; (c) 2D image of nanoholes in the PCM, (d) cross-section of the images of Fig 2c (the figure is taken from [4]).

We prepared two samples to investigate the PCM's influence on optical properties of nanoholes: (1) nanoholes in an Au layer of the PCM, (2) nanoholes in a reference Au film deposited on a 2 mm thick SiO_2 substrate. We used focused ion beam machine FEI Quanta 3D to mill an array of circular apertures of about 60 nm diameter in the reference Au film and in an Au layer of the PCM. Microscopy of nanoholes was conducted by electron microscope JEOL JSM-7001F with spatial resolution about 5 nm.

The experiment is performed as follows: the samples with nanoholes were illuminated at normal incidence with: (1) collimated light for measurements of transmission of a single nanohole, (2) 406 nm 10 mW laser for a photoluminescence measurements, (3) 780 nm 100 fs laser light for THG measurements. Light transmitted through the nanohole was collected with a 100x Nikon microscope objective (NA=1.49), and analysed through: (1) a 2D cooled CCD camera with avalanche gain, or (2) a monochromator with a high optical efficiency, coupled to another cooled CCD camera. The experimental setup was allowed to obtain 2D optical image of single nanohole with spatial resolution of about 300 nm as well as transmission spectrum of a single nanohole.

Fig. 2 shows images of nanoholes in both samples at a light wavelength nearby the PCM's resonance mode. 2D images of nanoholes (Fig. 2a, 2c) indicate that the image signal amplitude for nanoholes in the reference Au film is so small that they are practically invisible, while the image signal amplitude for nanoholes in the microcavity is so high that it exceeds the dynamic range of signal representation in 2D. This means that at identical parameters of incident radiation the flux of photons emitted into free-space radiative modes on the exit side of nanoholes produced in the PCM is significantly higher than that for nanoholes in the reference Au film. The fact is a direct proof of influence of the photonic crystal microcavity on the nanoholes transmission enhance.

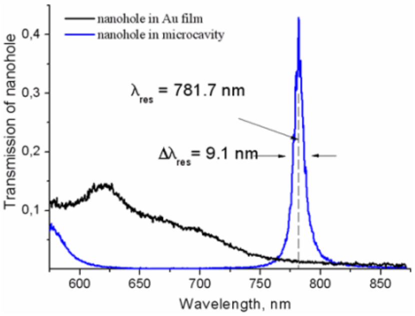

Fig. 3: Transmission spectra for a single nanohole in the reference Au film and in the PCM (the figure is taken from [4]).

Fig. 3 shows transmission spectra of a single nanohole. The figure distinctly depicts the transmission resonance of nanohole in the PCM at the wavelength of the microcavity's resonance mode. The resonance width is roughly 9 nm corresponding to the spectral width of the microcavity's resonance mode.

3. Results and Conclusion

The demonstrated experiments show that utilization of the photonic crystal microcavity allows one considerably enhances the photon flux at the exit of the nanohole. By use of the approach 28-fold enhanced transmission of light through a single nanohole of λ/13 diameter in Au film has been experimentally demonstrated. By using this approach the 30-fold enhancement of photo induced luminescence of nanoholes in Au film was demonstrated. Finally we demonstrate enhancement of a third harmonics generation for a single nanohole in Au film. Let us note the potentialities of the system «nanohole + photonic crystal microcavity». While in this work a microcavity with a fairly moderate Q-factor of ~ 100 was used, the utilization of high-Q cavities with Q-factor of $\sim 10^6$ is a promising prospect for further investigations in the area.

References

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