Optical Tamm state and extraordinary light transmission through a nanoaperture

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We investigate the light transmission through a nanoaperture in a metal film deposited on a planar metamaterial. An effect of an anomalously high light transmission (up to 800%) through the nanoaperture is revealed, which we associate with the enhancement of the field at the interface of the planar structure "metamaterial–metal-film" due to the appearance of an optical Tamm state. Our numerical results are in qualitative agreement with experimental data.

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I. INTRODUCTION

The effect of an extraordinary transmission of light through an array of nanoapertures in a metal film has been observed for the first time by Ebbesen *et al.* [1]. The effect describes the light transmission through a nanoaperture array, which is considerably higher in magnitude than predicted according to the Bethe-Bouwkamp theory [2,3]. At present an extraordinary light transmission has been observed both for a periodic nanoaperture array in a metal film [4] and for single nanoapertures in it [5,6]. In the latter case, various techniques are used to increase the light transmission. For example, in [5], a method of structuring of the surface near the aperture is applied in order to match the wave vectors of the incident electromagnetic field and plasmons on the film surface. In general, there exists a large variety of physical mechanisms and methods of their realization that lead to similar effects. It seems that, in all these cases, the field intensity in the region of the aperture is enhanced due to the excitation of propagating plasmons, and precisely this enhancement of the field causes the intensity of the passing light to increase [7]. At the same time, the field enhancement can also occur in ideally conducting geometries, where there are no plasmons but an anomalously high transmission also arises [8,9].

Recently, an extraordinary increase in the light transmission through nanoapertures in a gold film on the surface of a multilayer periodic dielectric structure, a planar metamaterial [10,11], has been experimentally detected. In view of the importance of the observed effect, the question of its theoretical explanation arises, to which this work is devoted. From our point of view this effect is related to optical Tamm states [12–17] in which the intensity of the magnetic field from the side of the metamaterial on the surface of the metal film has a maximum [13]. (In what follows, we will term the light frequency at which the optical Tamm state arises as the resonance frequency). As a result the light transmission through nanoapertures increases by several orders of magnitude compared to the case in which there is no metamaterial.

The plan of the remaining part of the paper is as follows. Section II presents the descriptions of the geometry and model of the numerical experiment. Results of the numerical simulation of a gold film on the surface of a metamaterial with and without apertures are presented in Secs. III and IV, respectively. Section V is devoted to a discussion of the results.

II. THE MODEL OF THE NUMERICAL EXPERIMENT

The theoretical calculation of this work is based on the geometry of experiment of [10]. The values of the geometric parameters and the optical properties of materials were taken from that paper, unless otherwise specified.

The experiment of [10] is extremely subtle, because it is very difficult to control the manufacturing process (the shape of apertures, the thicknesses of layers) with a nanometer accuracy. Figure 1(a) shows the images of the array and one of nanoapertures used in the experiment of [10]. We can assume from this figure that the nanoaperture does not have an ideal cylindrical shape. Therefore, in the numerical model, the aperture was approximated by a generalized truncated cone.

A cross section of one period of the structure "metamaterial–metal-film" that was used in the numerical experiment is shown in Fig. 1(b).

A 12-layer periodic dielectric structure (metamaterial) is deposited on a quartz substrate [which is shown at the top in Fig. 1(b)]. The dielectric structure consists of an Al_2O_3 layer (with a thickness of 125 nm) and alternating TiO_2 and MgF_2 layers (with their thicknesses being 82 and 125 nm, respectively). A gold film with a thickness of 220 nm is deposited on the surface of the metamaterial [at the "bottom" in Fig. 1(b)]. Since the thickness of this film considerably exceeds the thickness of the skin layer (~20 nm), the film is opaque in the considered wavelength range of the incident light (from 575 to 875 nm). Nanoapertures in the metal film form a square lattice with a period of 2 μm. In the numerical model, the aperture is approximated by a truncated cone, with the diameters of its bases being d_1 (on the TiO_2 layer) and d_2 (on the opposite side). The whole space inside the aperture and behind the gold film is filled with an immersion oil. In [10], the thickness of the SiO_2 substrate was 2 mm, and the immersion oil was used to reduce the reflection. In our

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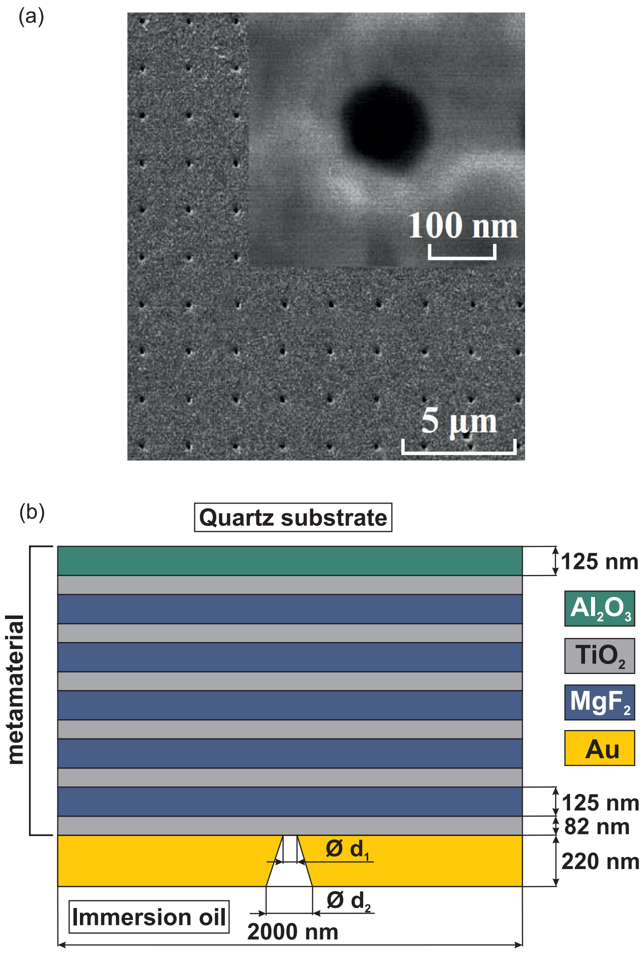

FIG. 1. (Color online) (a) Images of the array and one of the nanoapertures in the experiment of [10] obtained by the scanning electron microscopy method; (b) schematic image of the cross section of one period of the nanoaperture array in the gold film on the metamaterial used in the numerical experiment.

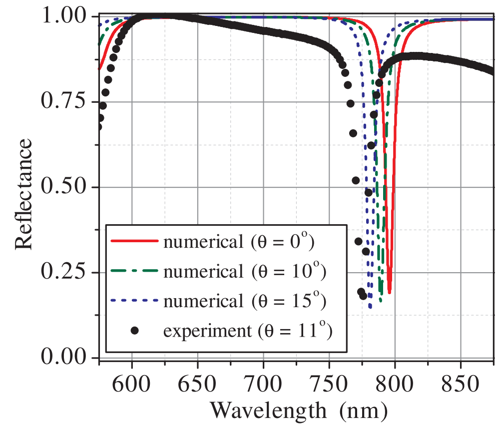

FIG. 2. (Color online) Dependencies of the reflection coefficient on the wavelength and on the angle of incidence of light for the optical structure metamaterial–metal-film.

numerical experiment, the quartz layer and immersion oil are assumed to be infinitely thick. The refractive indices n of all the used dielectric materials were taken from the experimental data of [10]: SiO_2 ($n_q = 1.443$), Al_2O_3 ($n = 1.63$), TiO_2 ($n = 2.23$), MgF_2 ($n = 1.38$), and immersion oil ($n_{io} = 1.51$). In calculations, the dispersion of the dielectrics was neglected. The dispersion dependence of the dielectric permittivity of gold was taken from [18].

The light transmission through nanoapertures was simulated for the normal incidence of light on the structure. In this case, the wave that was incident on the structure from the side of the quartz substrate (from the top) was expressed as $\mathbf{E}_{up} = \mathbf{E}_0 \exp(ik_0 n_q z)$.

III. OPTICAL PROPERTIES OF A STRUCTURE METAMATERIAL–METAL-FILM

Initially, we will consider the optical properties of a structure metamaterial–metal-film with no apertures. To do this, we will use the analytical method of [19–21]. In each separate layer, the solution is represented as a sum of the "incident" and "reflected" waves. The amplitudes of these waves can be found from the condition of continuity for the tangential components of the electric and magnetic fields at the boundary between the layers. As a result, we obtain a system of linear algebraic equations, the numerical solution of which was found using MATLAB. Let us consider the case in which the light is incident on the structure metamaterial–metal-film with no apertures from the side of the quartz [from the top; see Fig. 1(b)].

Figure 2 shows the calculated and experimental [10] dependencies of the energy reflection coefficient on the wavelength and on the angle of incidence of light for the metamaterial with the gold film on it. The experimental curves are shown in black. It can be seen from Fig. 2 that there is a qualitative agreement between the theory and experiment. In the numerical experiments, we have also slightly varied the thicknesses of the layers, as a result of which the agreement became much better. This is indicative of possible errors in specifying the optical constants of the materials or of the imperfect preparation of experimental specimens.

A characteristic feature of the dependence of the reflection coefficient of the optical structure metamaterial–metal-film is the occurrence of a narrow resonance dip. This phenomenon is well known and corresponds to excitation of the optical Tamm states [12–17]. The corresponding resonant wavelength can be estimated from the condition [13]

$$r_M r_{MM} = 1, \quad (1)$$

where r_M is the amplitude reflection coefficient at the Au-TiO_2 interface, while r_{MM} is the amplitude reflection coefficient of the wave incident from TiO_2 half-space on the metamaterial starting with a TiO_2 layer.

The spectrum of the light transmission coefficient for this system is shown in Fig. 3. From this picture one can see that instead of the dip in reflection coefficient (see Fig. 2) in this case we have the peak at the corresponding wavelength. Investigations of the properties of the structure metamaterial–metal-film upon variation of the film thickness from 100 to 220 nm showed that the shape of the reflection curve (see Fig. 2) changes insignificantly, whereas the transmission coefficient [see Fig. 3(b)] changes by more than three orders of magnitude. This behavior can explain some differences

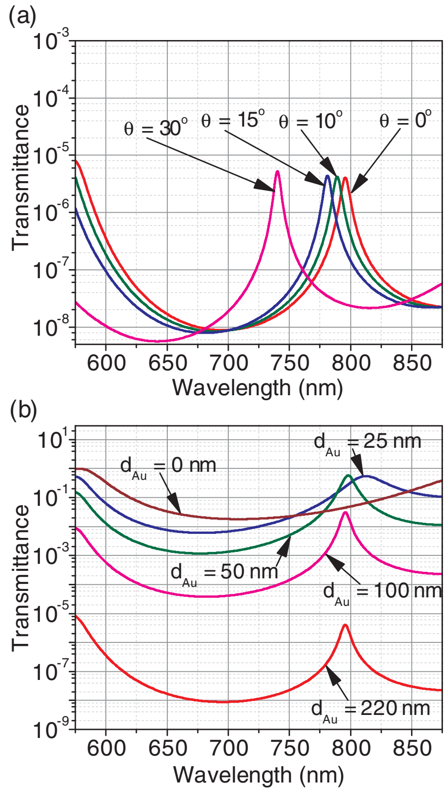

FIG. 3. (Color online) Dependencies of the light transmission coefficients through the optical structure metamaterial–metal-film: (a) on the wavelength and on the angle of incidence of light; (b) on the wavelength and on the thickness of Au film (d_{Au}) for normal incidence of light.

between experimental data (where some deviation from design can occur) and numerical simulations.

IV. OPTICAL PROPERTIES OF AN OPTICAL STRUCTURE "METAMATERIAL–METAL-FILM WITH NANOAPERTURES"

Having clarified the behavior of the optical structure metamaterial–metal-film with no apertures, we consider now how apertures in the gold layer affect the light transmission through the structure. To do this, we have used the finite element method, implemented in the program COMSOL (with a relative calculation accuracy of no worse than 10^{-3} at resonance). Further, under the transmission coefficient of light now we will understand the energy flux through the area of one period of the optical lattice structure normalized to the flux incident onto the same area. The light transmission coefficient defined in this way is always smaller than unity. Figure 4 shows the light transmission coefficient through a gold film with different apertures but without metamaterial.

It can be seen from this figure that there is qualitative coincidence between the experiment of [10] and the numerical calculation for cylindrical apertures with a diameter of 100 nm, though the calculated light transmissions are still smaller than experimental ones. It is very important to note that there is no resonance transmission related to the periodicity of the lattice, as that observed in the experiments by Ebbesen [7].

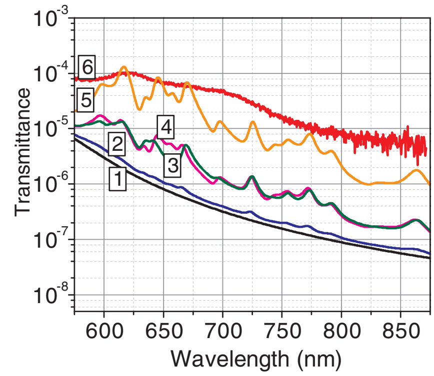

FIG. 4. (Color online) Dependencies of the transmission coefficient through the gold film with apertures but with no metamaterial on the wavelength of the incident light for different geometries of nanoapertures. The light is incident from the side of the SiO_2 layer. Curves: (1) the case with no apertures ($d_1 = d_2 = 0$ nm); (2) apertures in the shape of a cylinder ($d_1 = d_2 = 60$ nm); (3) apertures in the shape of a truncated cone ($d_1 = 60$ nm, $d_2 = 100$ nm); (4) apertures in the shape of a truncated cone ($d_1 = 100$ nm, $d_2 = 60$ nm); (5) apertures in the shape of a cylinder ($d_1 = d_2 = 100$ nm); (6) experimental data from [10].

In the case of the optical structure metamaterial–metal-film with nanoapertures, the situation radically changes. Figure 5 shows the coefficient of the light transmission through this structure [see Fig. 1(b)]. It can be seen from Fig. 5 that, in this structure, there arises an anomalously high light transmission at the resonance frequency ($\lambda = 796$ nm). It is also seen that the shape of the obtained transmission curve coincides well with the measurement data from [10]. The difference between the resonance positions in the numerical simulations and the experiment can evidently be a consequence of factors such as (i) the use of the oblique incidence in the experiment, (ii) deviations in the values of the optical constants that were

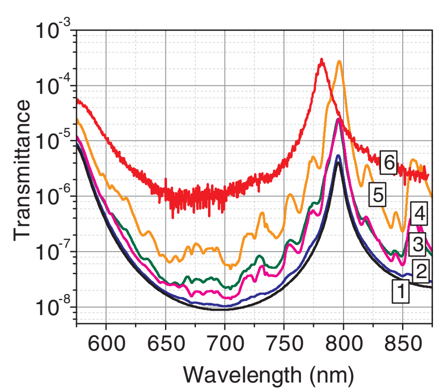

FIG. 5. (Color online) Dependencies of the transmission coefficient through the optical structure metamaterial–metal-film with apertures on the wavelength of the incident light for different geometries of apertures (the light is incident from the side of the metamaterial): (1) the case with no apertures ($d_1 = d_2 = 0$ nm); (2) apertures in the shape of a cylinder ($d_1 = d_2 = 60$ nm); (3) apertures in the shape of a truncated cone ($d_1 = 60$ nm, $d_2 = 100$ nm); (4) apertures in the shape of a truncated cone ($d_1 = 100$ nm, $d_2 = 60$ nm); (5) apertures in the shape of a cylinder ($d_1 = d_2 = 100$ nm); (6) experimental data from [10].

used for the description of gold, and (iii) errors of preparation of experimental specimens. In addition, possible reasons can also be the distinction of the shape of the real aperture from the shape of the aperture used in our model, and the occurrence of a shell from gallium atoms on the aperture walls, which appears because apertures were formed with the gallium ion beam. The real thickness of the gold film also strongly affects the transmission coefficient.

It is interesting to note that the transmission curves for the two types of apertures in the shape of a truncated cone, which differ only in the orientation, almost coincide (see Fig. 5). We can conclude from this that the transmission is mainly determined by the effective volume of the aperture rather than by its shape.

Also, we note that the numerically simulated curves of the transmission coefficient in Fig. 5 have multiple maxima and minima, whereas the experimentally determined curves do not show such features [10,11]. This difference is caused by interference effects in the lattice of nanoapertures, since we have considered illumination of the whole structure [see Fig. 1(a)] by plane wave. At the same time, the transmission measurements [10,11] were performed with focused beam on a single nanoaperture, and no interference phenomena were observed in this case. Results of investigation of these interference effects and their possible applications will be considered elsewhere [22].

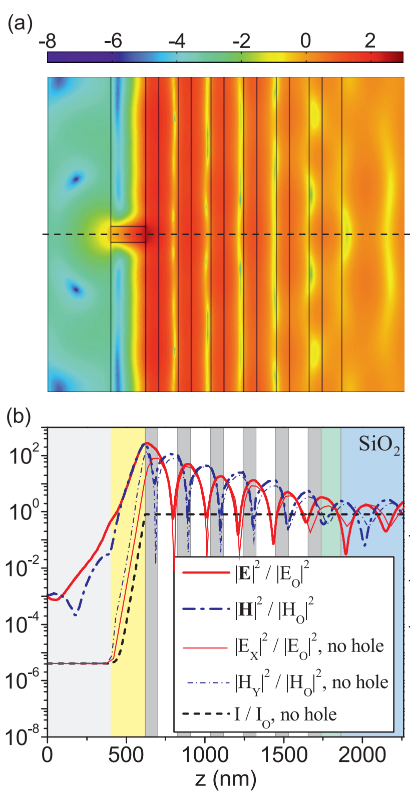

FIG. 6. (Color online) (a) Distribution of the electromagnetic field ($|\mathbf{E}|^2/|\mathbf{E}_0|^2$) of a plane light wave propagating through the optical structure metamaterial–metal-film with apertures in the case where the light wave is incident on the structure from the side of the metamaterial at resonance ($\lambda = 796$ nm). (b) The section of the two-dimensional distribution (a) along the dashed line. A logarithmic scale is used.

The picture of the light transmission through the aperture in the structure under study becomes more clear from the consideration of Fig. 6, which shows the distributions of the electromagnetic field ($|\mathbf{E}|^2/|\mathbf{E}_0|^2$) in the cases of the normal incidence from the top of the structure at resonance ($\lambda = 796$ nm).

As can be seen from Fig. 6(a), when the light is incident from the side of the metamaterial, the amplitude of the field behind the aperture is comparable with the amplitude of the incident wave.

Far away from the aperture, the field decreases as a spherical wave according to a law $\sim 1/r$. In addition, the formation of a dipole directivity pattern of the transmitted wave is clearly seen in Fig. 6(a). Figure 6(b) shows the section of the two-dimensional distribution along the dashed line. The black dashed line shows the intensity distribution along the structure for the case with no aperture. The thin solid red and thin dash-dotted blue lines show the dependencies of the squared electric and magnetic field components along the structure for the case with no aperture. The corresponding distributions for the case with the aperture are shown by the red solid and blue dash-dotted lines. Figure 6(b) shows how the magnitude of the electromagnetic field increases in the direction toward the gold film and an optical Tamm state is formed on the surface of this film due to the constructive interference of the light propagating in the metamaterial. It is also seen that the magnitude of the field on the inner surface of gold at the center of the aperture is higher than in the absence of the aperture.

Although the above presented results explain the experiment and are in reasonable agreement with it we have also investigated the behavior of light transmission for a wider range of aperture diameters. The results of our simulations are shown in Fig. 7.

From Fig. 7 it follows that the maximal transmission for considered geometry is about 800% for an aperture of 200 nm in diameter if one uses the normalization to

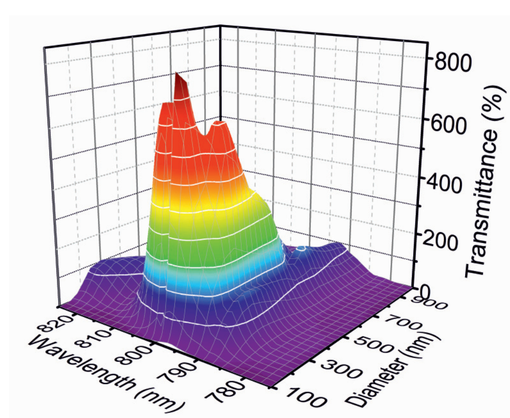

FIG. 7. (Color online) Dependencies of the transmission coefficient through the optical structure metamaterial–metal-film with apertures on the wavelength of the incident light for different sizes of apertures (the light is incident from the side of the metamaterial and we use the normalization to the light flux incident on the aperture cross section). Experimental data (100 nm) correspond to left side of the plot.

the light flux incident on the aperture cross section. This value is almost by two orders of magnitude greater than the value measured in our nonoptimized experiment and exceeds the record values known from literature on plasmonic extraordinary transmission ([6], 690%). Moreover we expect that further optimization of geometry will result in even greate transmission values.

V. DISCUSSION OF RESULTS

In this work, using the finite element method, we have numerically simulated the light transmission through a periodic lattice of nanoapertures in a gold film deposited on the surface of a metamaterial. An effect of an anomalously high light transmission has been revealed, which we associate with the enhancement of the field at the interface metamaterial–metal-film due to the appearance of an optical Tamm state.

Qualitatively, an increase in the light transmission through the nanoaperture can be estimated in the case of interest by applying the Bethe-Bouwkamp theory simultaneously with considering the enhancement of the local magnetic field due to the occurrence of an optical Tamm state. Indeed, according to the Bethe-Bouwkamp theory, the transmission coefficient of light at a wavelength of $\lambda = 796$ nm through a cylindrical nanoaperture with a diameter of $d = 100$ nm is $T_{\text{Bethe}} = (64\pi^2/27)(d/\lambda)^4 \approx 5.8 \times 10^{-3}$ (here, we use the normalization to the light flux incident on the aperture cross section). The coefficient of transmission through the film with apertures alone at a wavelength of $\lambda = 796$ nm found by numerical simulations is 1.7×10^{-3} (see Fig. 4; with the normalization to the flux incident on the aperture cross section). Qualitatively, these quantities coincide. The smaller value obtained upon the simulation is seemingly related to a greater thickness of the gold film (220 nm).

In the case of the film with apertures on the metamaterial, the transmission coefficient at a wavelength of $\lambda = 796$ nm is 1.4×10^{-1} (see Fig. 5; here, the normalization to the flux incident on the aperture cross section is also used). That is, the use of the metamaterial leads to a 90-fold increase in the transmission coefficient. At the same time, the intensity of the magnetic field in the metamaterial, which excites the magnetic dipole moment of the nanoaperture (which, in turn, forms the transmitted field), is 50 times higher than the intensity of the magnetic field on the surface of the gold film. That is, there is a qualitative coincidence between these quantities, which allows us to state that the extraordinary light transmission in the case under consideration is related to an increase in the intensity of the magnetic (as well as, electric) field. Thus, the transmission coefficient of our structure can be estimated with the following simple formula indeed:

$$T = T_{\text{Bethe}} G, \tag{2}$$

where $T_{\text{Bethe}} = (64\pi^2/27)(d/\lambda)^4$ is the Bethe-Bouwkamp transmission coefficient, and $G = |\mathbf{H}|^2/|\mathbf{H}_0|^2$ is the enhancement of the magnetic field intensity at metal surface due to the appearance of the Tamm state.

Therefore, in this work, it has been theoretically shown that the enhancement of the field related to the occurrence of the optical Tamm state of the electromagnetic field leads to a corresponding increase in the light transmission through the nanoaperture. Moreover we have shown that this enhancement can be as large as 800% if one uses the normalization to the light flux incident on the aperture cross section. We are sure that further optimization of our system can result in even greater extraordinary transmission.

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