Optical Tamm state and giant asymmetry of light transmission through an array of nanoholes

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We have predicted theoretically and verified experimentally the occurrence of a giant asymmetry of the transmission of arbitrarily polarized light propagating through a linear nonmagnetic optical system that consists of a metal film with a two-dimensional array of nanoholes in it and that is deposited on the surface of a planar dielectric photonic crystal. The asymmetry of the light transmission is caused by two factors: (i) the excitation of an optical Tamm state in the system, and (ii) the existence of many secondary lobes in the diffraction pattern. Our results are of interest for the development of efficient planar optical diodelike systems and related nanophotonic devices.

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I. INTRODUCTION

At present, optical systems and devices for controlling the propagation of light at a nanoscale level (nano-optics) are being studied and developing intensively [1–4]. This is motivated by the possibility of using such devices to create high-speed optical computers [5], high-density data storage systems [3], optical biosensors for DNA sequencing technology [6], etc. The development of optical diodelike systems is also an important field of the research [7]. In such a device, the light transmission coefficient through it considerably depends on from which side the optical system is irradiated. In order to create optical diodelike systems, various geometrical and physical mechanisms are used to obtain the effect of asymmetry of the light transmission. Most frequently, elements that are used in the composition of devices for this purpose are such that their dielectric permittivity either is an asymmetric tensor (because of the Faraday effect) [8] or depends nonlinearly on the intensity of the excitation field [9], or depends explicitly on time. The class of systems listed above is nonreciprocal, since the Lorentz reciprocity lemma is violated [10–12].

The asymmetry of the light transmission coefficient can be obtained in Lorentz reciprocal systems also [12]. In particular, if light with specific polarization is used, the transmission asymmetry may be obtained on the base planar structures that efficiently convert one polarization into the other [7,13,14]. In these diffraction-free systems, the light transmission coefficient for one of the polarizations depends strongly on the direction of irradiation of the optical system; i.e., transmission asymmetry for the polarized light takes place. There are more complicated reciprocal systems where the asymmetry of the light transmission with specific polarization can be obtained by making use of multilobe diffraction patterns (i.e., they contain a diffraction grating) [15,16].

This work is devoted to the investigation of a class of optical diodelike systems in which giant light transmission asymmetry is realized for an arbitrary polarization of light incident on a two-dimensional array of nanoholes in a metal nanofilm that is deposited on a photonic crystal formed by quarter-wave dielectric layers. Schematically, the device under consideration is shown in Fig. 1.

The photonic crystal possesses a band gap for the transmission of light propagating along the normal to its layers. Deposition of a metal film without holes on the surface of the photonic crystal gives rise to the appearance of a singularity in the light transmission spectrum: in the region of the spectrum that corresponds to the band gap of the photonic crystal, a narrow transmission peak appears. The appearance of the transmission peak is related to the localization of the field at the interface between the photonic crystal and a metal film without holes. In the literature, this effect is referred to as the optical Tamm state [17–22]. Adding an array of holes on the metal film results in a different mechanism of giant extraordinary transmission [23–25]. This mechanism is different in principle from the original one of Ebbesen *et al.* [26].

In the present work, we will show that the combination of optical Tamm states with an array of nanoholes in a metal film has giant asymmetry in light transmission without a magnetic field. This fact is not obvious, and it was not analyzed in [25], where only extraordinary transmission in similar systems was described and explained.

We define the light transmission coefficient as the ratio of the energy flux of the transmitted light (along the normal to the structure surface) and the total flux of the incident light. For optical diodelike systems, at the same intensity

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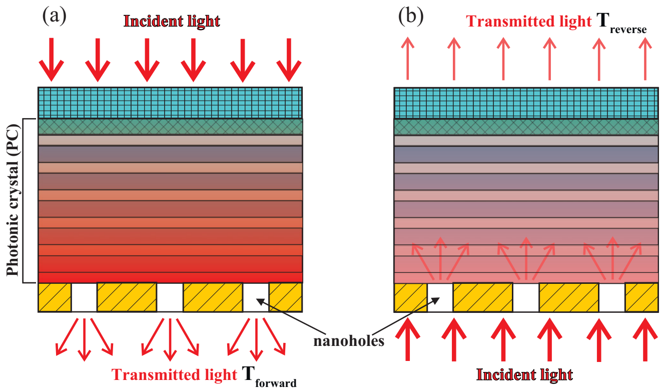

FIG. 1. (Color online) Schematic image of a planar device with an asymmetric light transmission coefficient: (a) Light is incident on the structure from the side of the photonic crystal and the light transmission coefficient T_{forward} is measured; (b) light is incident on the structure from the side of the metal film and the light transmission coefficient T_{reverse} is measured. For optical diodelike systems, when the intensity and wavelength of the incident light are the same in the two cases, we obtain different values of the transmission coefficients T_{forward} and T_{reverse}. The light transmission coefficients T_{forward} and T_{reverse} are defined as the energy flux in the normal (to the structure surface) direction from the side of the transmitted light normalized to the total flux of the incident light.

and wavelength of the incident light, the values of the light transmission coefficients in the forward, T_{forward}, and reverse, T_{reverse}, directions are different. That is, the main feature of this device is that its light transmission coefficients strongly differ from each other if the direction of irradiation of the system is reversed.

The remaining part of the paper is organized as follows. Section II describes the numerical simulation of the structure under study and analyzes reasons for the light transmission asymmetry. In Sec. III, we consider the experimental verification of the effect found in Sec. II.

II. NUMERICAL SIMULATION AND ANALYSIS OF REASONS FOR THE TRANSMISSION ASYMMETRY

The light transmission through the planar optical system under consideration was numerically simulated in terms of a model, the geometry of which is shown in Fig. 2. This model is based on the geometry of a sample in which an extraordinary light transmission through a lattice of nanoholes on the surface of a planar photonic crystal was previously observed experimentally [23,24] and was explained theoretically [25] for the light incident on the system from the side of the one-dimensional photonic crystal. This system consists of an infinite quartz substrate (the refractive index is $n_{\text{SiO}_2} = 1.443$) onto the surface of which a dielectric one-dimensional photonic crystal is deposited. The photonic crystal consists of an Al_2O_3 layer with a thickness of $d_{\text{Al}_2\text{O}_3} = 125$ nm ($n_{\text{Al}_2\text{O}_3} = 1.63$) and alternating TiO_2 and MgF_2 layers ($n_{\text{TiO}_2} = 2.23$ and $d_{\text{TiO}_2} = 82$ nm; $n_{\text{MgF}_2} = 1.38$ and $d_{\text{MgF}_2} = 125$ nm). The values of the refractive indices for the dielectric layers were taken from experimental data of [23]. Onto the surface of the photonic crystal, a gold film with a thickness of 220 nm

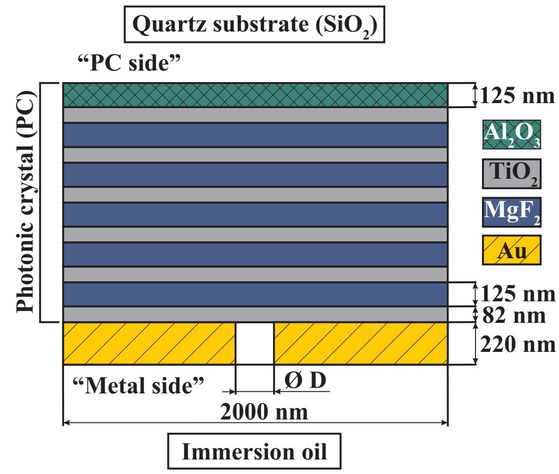

FIG. 2. (Color online) Schematic image of one period of a square lattice of circular nanoholes with a period of 2000 nm.

was deposited. The dispersion dependence of the dielectric permittivity for gold was taken from [27]. In the metal film, a square array of circular holes was made. The hole diameter D was varied in the range from 100 to 1000 nm. The lattice period was 2000 nm. Holes in the metal film and the infinite layer behind the metal film were filled with immersion oil ($n_{\text{IO}} = 1.51$). The immersion oil was used to relate results of this work with previously obtained results [23–25]. In fact, a larger period of the lattice compared to the considered wavelength makes our system a diffraction grating with a principal (zero-order) maximum and side lobes.

In the model under consideration, light (a plane electromagnetic wave) is normally incident on the sample from the side of either the photonic crystal (forward direction) or the metal film (reverse direction). The light wavelength in vacuum λ_0 is varied from 700 to 875 nm. Upon numerical simulation, a system of Maxwell's equations is solved in the frequency domain by the finite-element method. We used the version of this method that is realized in a COMSOL MULTIPHYSICS commercially available software package. The asymmetry of the light transmission through our system can be characterized by the *asymmetry coefficient*, which is defined as $\xi = T_{\text{forward}}/T_{\text{reverse}}$, where T_{forward} is the transmission coefficient of light that is incident on the system from the photonic crystal side, and T_{reverse} is the transmission coefficient of light that is incident from the metal side. Results of this simulation are presented in Fig. 3.

It can be seen from Fig. 3 that there is a maximum in the asymmetry coefficient at a hole diameter of 150 nm. In the resonance region (where the wavelength range of the incident light is around 800 nm) at small and large (in comparison with 150 nm) hole diameters, the ratio between the transmission coefficients (or the asymmetry) decreases. The decrease is explained by the fact that, when the hole diameter equals zero, the system is transformed into a planar structure without holes (a gold layer on the surface of a photonic crystal) and the asymmetry is equal to 1. In this case, the occurrence of the symmetry in the light transmission can be rigorously proven [28]. A similar situation occurs upon an increase in the hole diameter. In this case, the gold layer gradually vanishes,

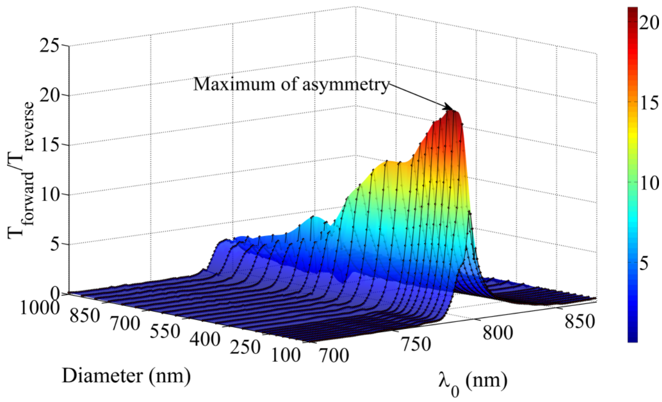

FIG. 3. (Color online) Ratio between the transmission coefficients upon incidence of light from the side of the photonic crystal (T_{forward}) and from the side of the metal film (T_{reverse}) in relation to the wavelength of the incident light and the hole diameter. The period of the structure is 2000 nm.

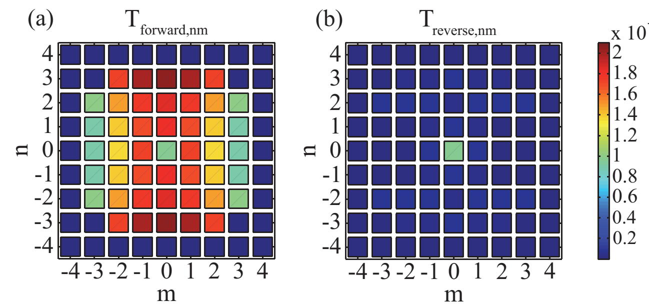

FIG. 5. (Color online) Distribution of light transmission coefficients over different spatial channels, which are defined by the Bragg angle θ_{nm}: (a) $T_{\mathrm{forward},nm}$, the light is incident from the side of the photonic crystal (forward direction); (b) $T_{\mathrm{reverse},nm}$, the light is incident from the side of the metal film (reverse direction). The hole diameter is 150 nm. The wavelength of the incident light λ_0 is 796 nm. [Polarization of the incident light is along the x axis (n axis)].

and only a planar photonic crystal remains, and the asymmetry is equal to 1 again.

To understand the origin of the maximum in the light transmission asymmetry coefficient we have plotted the asymmetry coefficient ($T_{\mathrm{forward}}/T_{\mathrm{reverse}}$) and the transmittance of the sample without holes (the latter does not depend on the direction of the incident light) as functions of the wavelength of the incident light (see Fig. 4). Also on Fig. 4 we show the spectra of the transmittances T_{forward} and T_{reverse}.

It can be seen from Fig. 4 that the main maxima near the wavelength 800 nm on the curves of asymmetry coefficient and the transmittance in the case without holes coincide. The occurrence of the maximum of the transmittance in the case without holes upon variation of the wavelength is caused by the excitation of the optical Tamm state in the band gap of the structure [25]. So it can be concluded that the

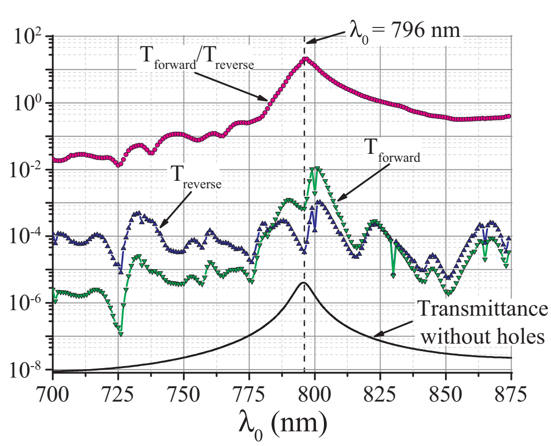

FIG. 4. (Color online) The light asymmetry coefficient ($\xi = T_{\mathrm{forward}}/T_{\mathrm{reverse}}$), the transmittance without holes, and the transmission coefficients (T_{forward} and T_{reverse}) as functions of the incident radiation wavelength. The hole diameter is 150 nm. In the forward case, the light is incident from the side of the photonic crystal. In the reverse case, the light is incident from the side of the metal film. Normalization to the total incident flux is done.

optical Tamm state plays an important role in the occurrence of the asymmetry of light transmission. In the case with holes, the transmittances additionally have other resonances, which are related to scattering the incident light by holes and the excitation of eigenmodes of the structure different from the optical Tamm state. However, these additional peaks have the same appearance in transmission coefficients in both the forward and reverse directions and cancel each other when the asymmetry coefficient is calculated.

To provide more insight into the nature of the asymmetry effect, the distributions of the transmitted energy over diffraction lobes $T_{\mathrm{forward},nm}$ and $T_{\mathrm{reverse},nm}$ are shown in Fig. 5, where $\sum_{nm} T_{\mathrm{forward},nm} = T_{\mathrm{forward}}$ and $\sum_{nm} T_{\mathrm{reverse},nm} = T_{\mathrm{reverse}}$, and n and m are integers (diffraction orders; n corresponds to the direction along the x coordinate axis, while m corresponds to the direction along the y coordinate axis; the x and y axes lie in the plane which is parallel to the surface of the structure). Let us also recall that the Bragg angle of the diffraction lobe θ_{nm} (the angle between the normal to the surface and the vector $\mathbf{k}_{nm}$ of the corresponding diffraction order) is defined by Bragg's law [29]:

$$\sin\theta_{nm} = \frac{\lambda_0}{n_{\mathrm{medium}} P}\sqrt{n^2 + m^2}, \tag{1}$$

where n_{medium} is the refractive index of the medium where the diffracted field propagates ($n_{\mathrm{medium}} = n_{\mathrm{IO}}$ if light is incident from the side of the photonic crystal; $n_{\mathrm{medium}} = n_{\mathrm{SiO_2}}$ if light is incident from the side of the metal film); P is the period of the square lattice.

Figure 5(a) shows that the light transmitted through the structure in the forward direction is distributed over 45 diffraction lobes. Due to the small size of the holes, all these energies are approximately equal to 2% of the total energy. We note that the energy that passes through the principal lobe ($T_{\mathrm{forward},00} = 9.6 \times 10^{-6}$) is smaller than the energy that is diffracted into side lobes.

If the light is incident from the side of the metal film (reverse direction) [see Fig. 5(b)], the light energy is also distributed over 45 diffraction lobes; however, in this case, the principal lobe ($T_{\mathrm{reverse},00} = 9.6 \times 10^{-6}$) predominates: about 30% of the total energy passes through it [see Fig. 5(b)]. Through the

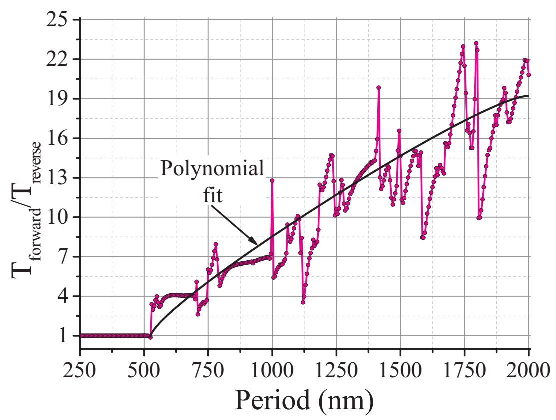

FIG. 6. (Color online) The light asymmetry coefficient ($\xi = T_{\text{forward}}/T_{\text{reverse}}$) as a function of the period of the square lattice of nanoholes in the metal film. The diameter of the nanohole is 150 nm. The wavelength of the incident light is 796 nm.

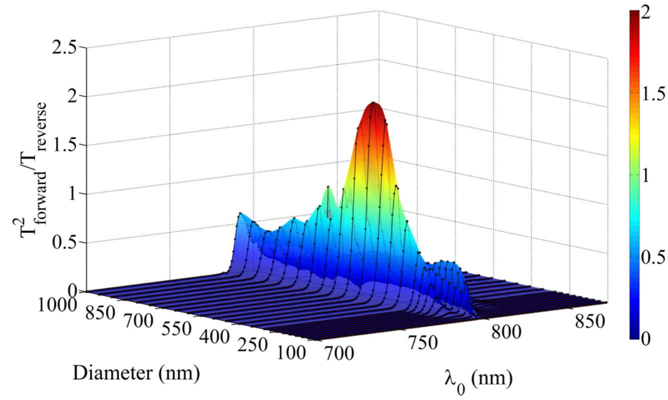

FIG. 7. (Color online) Figures of merit of our optical diodelike system, $\eta = (T_{\text{forward}}/T_{\text{reverse}})T_{\text{forward}}$. The period of the system is 2000 nm.

remaining lobes, little of the energy passes, since the light propagation in these directions is forbidden by the band gap structure of the photonic crystal. Note that the diffraction patterns in Figs. 5(a) and 5(b) are slightly distorted due to linear polarization of the incident light (x polarization).

The importance of the number of the diffraction lobes can be clearly seen in Fig. 6, which shows the dependence of the asymmetry coefficient on the period of the square lattice of nanoholes. Figure 6 shows that if the period of the system is less than 525 nm, all the side lobes disappear and the asymmetry completely vanishes. This fact confirms the correctness of our description once again.

On the whole, our analysis shows that the giant asymmetry of the light transmission is caused by two factors: (i) the excitation of an optical Tamm state in the system, and (ii) the existence of many secondary lobes in the diffraction pattern. It is important that both factors make a key contribution to the asymmetry of light transmission.

Also one should point out an important feature of the considered system: the value of the energy that passed through the principal lobe remains unchanged if the direction of irradiation of the system is reversed. This follows from comparison of Figs. 5(a) and 5(b): the fraction of the incident energy in the principal lobe [the green (light gray) square in the center of Figs. 5(a) and 5(b)] is the same for the forward direction and for the reverse direction, $T_{\text{forward},00} = T_{\text{reverse},00} = 9.6 \times 10^{-6}$. The latter circumstance indicates that the Lorentz reciprocity lemma is satisfied for the considered system; i.e., the system is reciprocal. This fact is not trivial, since it appears that a rigorous proof of the Lorentz reciprocity lemma for arbitrary infinite objects is unavailable [10,11].

From the practical point of view, the asymmetry itself is not particularly interesting. An important point is that not only would a giant asymmetry take place, but also the magnitude of the transmission coefficient in the forward direction would be high. In order to take this fact into account, it is convenient to use the figure of merit (FOM), which we will define as a product of the light transmission asymmetry coefficient and the light transmission coefficient, i.e., $\eta = \xi T_{\text{forward}} = (T_{\text{forward}}/T_{\text{reverse}})T_{\text{forward}}$. The dependence of our FOM on the diameter of the holes and the wavelength of the incident light is presented in Fig. 7.

It is seen from Fig. 7 that η has a maximum $\eta \approx 2$ at $D \sim 500$ nm and $\lambda_0 = 796$ nm. Such a maximal value of the FOM means that both the transmission ($T_{\text{forward}} \approx 0.17$) and the asymmetry ($\xi \approx 11.5$) are rather high at this point and our device is useful. For the latter case Fig. 8 shows the light transmission asymmetry coefficient ($T_{\text{forward}}/T_{\text{reverse}}$), the transmittances T_{forward} and T_{reverse}, and the transmittance of the sample without holes.

Note that the FOM of our system is significantly better than the FOM of the structure investigated in [15] despite the fact that in our geometry the relative area of the nanoholes is substantially less than the relative area of the slots. It is clear that, by further optimizing of the system (changing the number of layers of the photonic crystal, their thickness, and spacing between nanoholes), even more efficient optical diodelike systems may be developed.

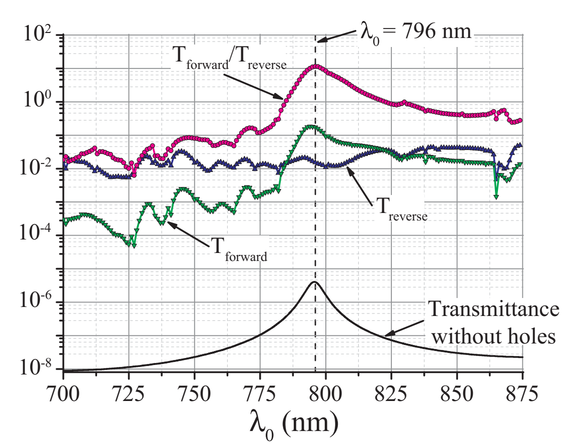

FIG. 8. (Color online) The light asymmetry coefficient ($\xi = T_{\text{forward}}/T_{\text{reverse}}$), the transmittance without holes, and the transmission coefficients (T_{forward} and T_{reverse}) as functions of the incident radiation wavelength. The hole diameter is 500 nm. In the forward case, the light is incident from the side of the photonic crystal. In the reverse case, the light is incident from the side of the metal film. Normalization to the total incident flux is done.

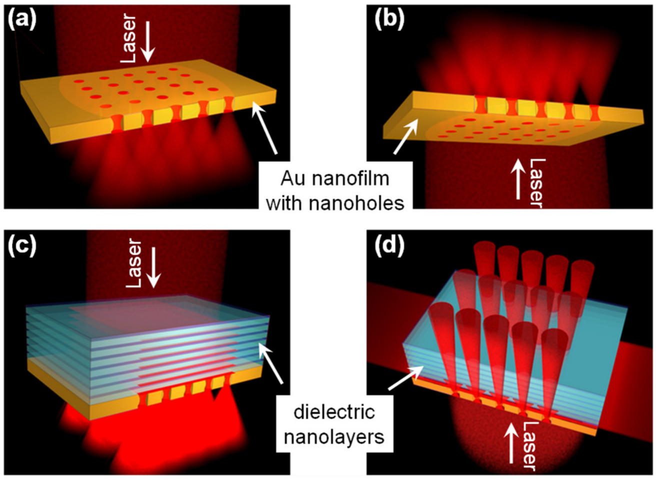

FIG. 9. (Color online) Scheme of experiments on measuring the asymmetry of light transmission with a perforated metal film: (a),(b) Light transmission through the perforated metal without the photonic crystal; (c),(d) light transmission through the perforated metal film on the photonic crystal where asymmetry of the light transmission is expected.

III. EXPERIMENT

In order to verify the theoretical predictions of the light transmission asymmetry, we performed corresponding experiments. Figure 9 illustrates the principle of measuring the transmission asymmetry of our structure. Measurements were made for samples of two types: (i) perforated gold nanofilms without a photonic crystal [Figs. 9(a) and 9(b)] and (ii) perforated gold nanofilms on the photonic crystal [Figs. 9(c) and 9(d)]. The metal films and arrays of nanoholes in the samples of the two types were the same. For the samples of both types, we measured the radiation passed through the sample and compared the intensities of the radiation that was transmitted through the sample in the forward and reverse directions. Perforated gold nanofilms without a photonic crystal were not expected to violate the symmetry visibly, and they were used as reference samples. In structures based on the photonic crystal with excitation of the optical Tamm state, there was an asymmetry of light transmission and the degree of asymmetry was determined from the ratio between the propagation of light in the forward [Fig. 9(c)] and reverse [Fig. 9(d)] directions.

Figure 10(a) shows the scheme of the experimental setup for the investigation of the asymmetry of light transmission of our structure. The light transmission was measured using a Nikon inverted optical microscope. The magnitudes of the light transmission in the forward and reverse directions were measured. Two radiation sources were used: (i) a spectrally broad incoherent radiation source and (ii) a narrowband laser source with the spectrum width smaller than the characteristic width of the resonant peak of transmission of the sample. The radiation was focused onto the structure into a spot with a diameter of about 50 μm. The size of the spot was large enough to cover the matrix of 10 × 10 nanoholes completely, ensuring an almost normal incidence. The light transmitted through the sample was collected with a 40× Nikon objective (numerical aperture 0.6). The experimental setup ensured obtaining a two-dimensional (2D) optical image of a single nanohole with a spatial resolution of about 1 μm. The spectral characteristics of the transmitted light were examined using a high-sensitivity spectrometer equipped with an incorporated cooled CCD linear array (Princeton Instruments).

Nanoholes in the gold layer [Figs. 10(b)–10(e)] were made with a tightly focused ion beam. The parameters of the ion-beam setup (FEI Quanta 3D) were as follows: operation ions were Ga^{+} ions; the accelerating voltage was 30 keV; the beam diameter on the surface was about 10 nm. With this ion beam, it was possible to prepare nanoholes with a diameter in the range between 50 and 500 nm. Microscopic examinations of nanoholes were performed with a spatial resolution of about

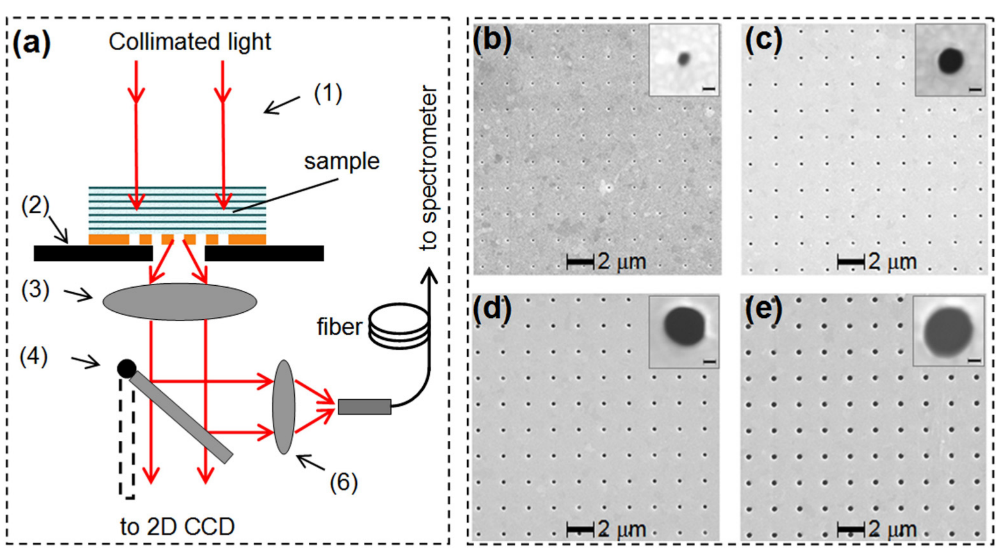

FIG. 10. (Color online) (a) The experimental setup to investigate the asymmetry of light transmission; (b)—(e) electron-microscope images of the samples under investigation with nanohole diameters of 100 (b), 200 (c), 300 (d), and 400 (e) nm. The insets of panels (b)—(e) show enlarged electron-microscope images of the individual nanoholes that form the corresponding perforated gold nanofilms (the length of the bar in the inset corresponds to 100 nm).

5 nm using a JEOL JSM-7001F electron microscope. To reduce the effect of deposition of carbon onto the surface of the gold film, which is induced by the tightly focused electron beam, the microscopy of nanoholes was performed at a rather moderate value of the accelerating voltage, equal to 5 keV.

The spacing between nanoholes was 2 μm just as in theoretical investigations. The insets of Fig. 10 show enlarged electron images of individual nanoholes. There is an insignificant dispersion in the size and geometrical shape of the created nanoholes. The spread in the size and geometry of nanoholes is related to the surface inhomogeneity of the gold film, which was made by the method of thermal evaporation onto the dielectric surface. Under this method of formation of the gold film, nanosized gold crystals are formed in it due to a high surface energy of the gold atoms [30].

Figure 11 demonstrates the asymmetry of the light transmission coefficient of the structure under investigation. Figures 11(a), 11(b) and 11(c), 11(d) show, respectively, the optical images of the reference perforated gold nanofilm and the perforated film placed on the photonic crystal. The images were obtained with an optical microscope and a two-dimensional CCD array. The perforated gold nanofilms with and without the photonic crystal were illuminated with laser radiation ($\lambda_0 = 795$ nm, $\Delta\lambda_0 < 0.1$ nm). The insets of the figure show the directions of incidence of the light with respect to the sample surface. As can be seen from Fig. 11, in the case of the sample with the gold film without the photonic crystal, that is, without the optical Tamm state [Figs. 11(a) and 11(b)], the change in the direction of propagation of the radiation does not alter the pattern of the transmitted light.

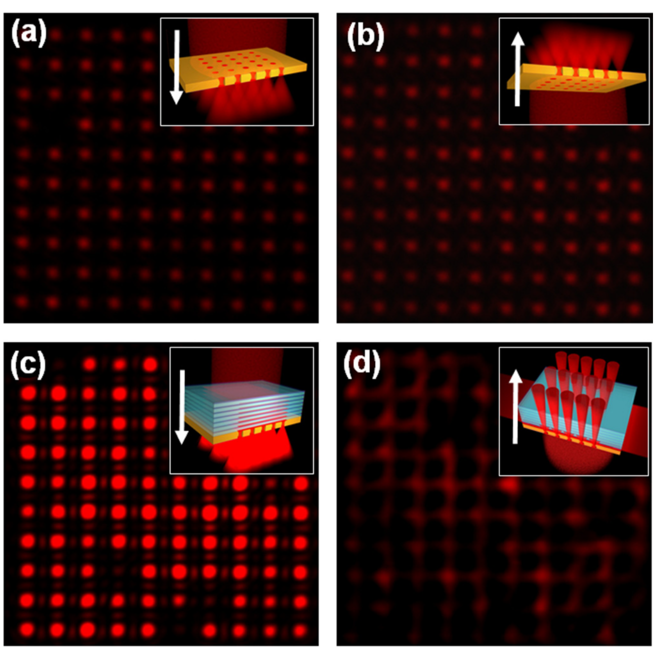

FIG. 11. (Color online) Experimental demonstration of the asymmetry of light transmission in our structure under illumination with laser light. (a),(b) show the optical images of the reference perforated gold nanofilm for different directions of laser illumination on the sample surface: the change in the direction of illumination does not alter the pattern of the transmitted light. (c),(d) show the optical images of the perforated gold nanofilm on the photonic crystal: the dramatic difference between the transmission patterns under illumination from opposite directions can be seen. (Laser radiation: $\lambda_0 = 795$ nm, $\Delta\lambda_0 < 0.1$ nm.)

In contrast, for the gold nanofilm on the photonic crystal, a dramatic difference between the propagation of the light in the opposite directions is observed. If the light is incident from the side of the photonic crystal [Fig. 11(c)], each nanohole is a bright glowing source! If the laser radiation is incident from the side of the gold nanofilm, only a weak emission from individual nanoholes and scattered diffuse radiation of the entire surface are observed. Nonuniformity of the emission from different holes is explained by slight differences between the parameters of the nanoholes (imperfection of the creation of nanoholes with the ion beam). Fluctuations in the nanohole diameter were about 10% of its value. There is also an insignificant ellipticity in the nanohole shape: the ratio between the ellipse axes for nanoholes with a diameter of 150 nm was 1.35. As is well known, even these insignificant variations in the parameters of nanoholes lead to substantial variations in their optical properties [25]. Figures 11(c) and 11(d) convincingly demonstrate the asymmetry of light transmission of this structure.

The asymmetry of light transmission of the perforated gold nanofilm on the photonic crystal also clearly manifests itself upon the use of a broadband radiation source (radiation from an incandescent lamp). Figure 12 illustrates such measurements. The measurement scheme is similar to that used in the laser experiment (Fig. 10). Upon propagation of white light through the perforated gold nanofilm on the photonic crystal, we observed the following particular features. In the forward direction [Fig. 12(a)], the magnitude of the transmission considerably exceeds the transmission in the reverse direction [Fig. 12(b)]. This coincides with results of similar measurements with the use of the laser light. We also observed the trapping of the radiation into the waveguide mode, which manifested itself in the appearance of an intensive halo that was emitted from the region occupied by the matrix of nanoholes.

We also performed quantitative measurements of the transmission spectra of the perforated gold nanofilm on the photonic crystal in the forward and reverse directions [see Fig. 13(a)]. The transmission spectrum of the structure was measured using as a radiation source an incandescent lamp

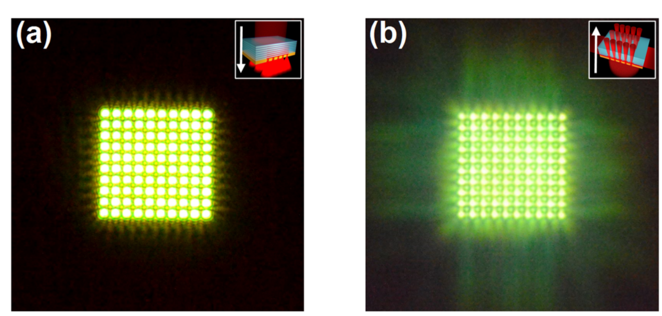

FIG. 12. (Color online) Manifestation of the asymmetry of light transmission of the perforated gold nanofilm on the photonic crystal under illumination with white light. The figure shows the optical images of the surface upon its irradiation from (a) the photonic crystal and (b) the metal film. In the insets the white arrows show the light beam direction.

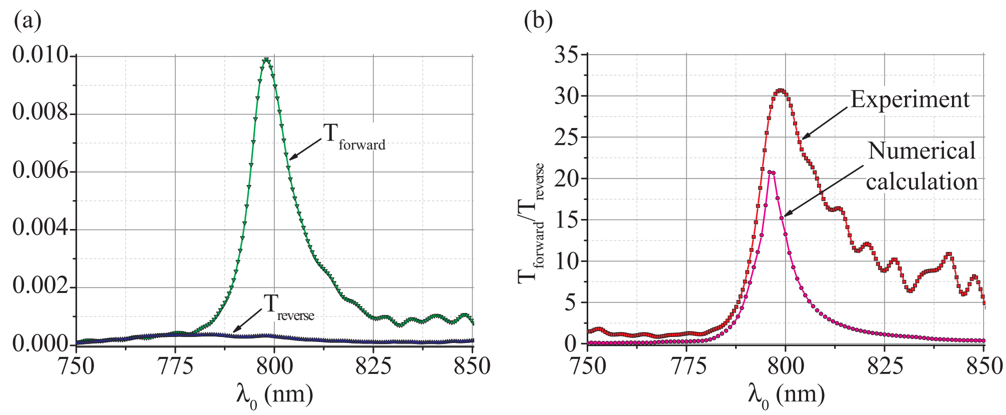

FIG. 13. (Color online) (a) Experimental transmission coefficients of the perforated gold nanofilm on the photonic crystal (T_{forward} and T_{reverse}) as functions of the incident radiation wavelength. (b) Spectrum of coefficient of asymmetry of light transmission, $\xi = T_{\text{forward}}/T_{\text{reverse}}$. The nanohole diameter is 150 nm. The period of the square lattice is 2000 nm. In the forward case, the light is incident from the side of the photonic crystal. In the reverse case, the light is incident from the side of the metal film. Normalization to the total incident flux is done.

with a broad and smooth spectrum. From the results of these measurements, we determined the spectrum of the coefficient of asymmetry $\xi = T_{\text{forward}}/T_{\text{reverse}}$ which is shown in Fig. 13(b). Figure 13(b) also shows the calculated spectrum of the asymmetry coefficient.

The theory predicts that the asymmetry of light transmission of a perforated gold nanofilm on a photonic crystal should have a resonant character. As can be seen from Fig. 13(b), the experimental plot also exhibits a resonance. The resonance is observed near the wavelength that corresponds to the excitation of the optical Tamm state in our sample. A maximal magnitude of the asymmetry of the light transmission coefficient is achieved at the resonance, and its theoretical value for this specific structure is 21. The maximal asymmetry value obtained in our experiment was 31. Therefore, we can state that there is a rather good agreement between the theory and experiment.

IV. CONCLUSION

In this work, we predicted theoretically and verified experimentally the occurrence of a giant asymmetry of the transmission coefficient of arbitrarily polarized light upon its propagation through a linear nonmagnetic optical system that is composed of a metal film with a lattice of nanoholes in it that is deposited on the surface of a planar dielectric photonic crystal. Such asymmetry of the light transmission coefficient is caused by two factors: (i) the excitation of an optical Tamm state in the system and (ii) the existence of many secondary lobes in the diffraction pattern. If the light is incident from the side of the photonic crystal, diffraction lobes of the transmitted light are formed behind the metal film, and the light propagation in them is unrestricted; however, if the light is incident from the side of the metal film, diffraction lobes of the transmitted light are formed in the space between the photonic crystal and the metal film, and the band gap structure of the optical system allows propagation of the light through only one (principal) diffraction lobe. The energy that does not propagate in the principal lobe is reflected, absorbed, or can propagate in the form of waveguide modes of the considered structure, when eventually it is still absorbed.

Upon reversal of the direction of irradiation of the system, the amount of transmitted light can differ by a factor of 31 (the experimental result). We are not aware of any restrictions on this value, and we believe that further optimization of the geometry may yield even stronger asymmetry, with the transmission coefficient being rather large. Another important result of our work is that we have shown that, if there is an asymmetry in the light transmission coefficient, the reciprocity principle still holds in this case, and the partial transmission coefficients $T_{\text{forward},00}$ and $T_{\text{reverse},00}$ (principal lobe) coincide with each other, despite the fact that the Lorentz reciprocity lemma cannot be rigorously proven for an arbitrary infinite object [10,11].

Technologically, the proposed optical system has a simple structure and consists of only optically linear materials with a single-side square lattice of nanoholes in the metal film. This system appears to be much simpler and more effective than developed before [15]. The simplification of our highly efficient system is due to the application of fundamental mechanisms such as the optical Tamm state in our system.

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