Hybrid States Formed by the Optical Tamm and Defect Modes in a One-dimensional Photonic Crystal

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Abstract— We investigate the spectral properties of a one-dimensional photonic crystal with the structural defect conjugated to the nanocomposite layer. The nanocomposite consists of spherical silver particles dispersed in the matrix. We demonstrate the possibility of implementing the hybrid state formed by the interaction between the optical Tamm and defect modes. It is shown that the hybrid state resonance splitting can be changes by varying the structure parameters.

In recent years, a new type of localized electromagnetic states called the optical Tamm states (OTSs) has been intensively studied [1]. These states are analogous to the Tamm surface states in physics of condensed matter. The OTSs manifest themselves in experiments in the form of a narrow peak in the transmission spectrum of a sample. In addition, the OTS-based hybrid states have attracted much attention. In [2, 3], the coupled Tamm plasmon polaritons in a photonic crystal (PC) bounded by metal or nanocomposite (NC) layers on its both sides were considered. Afinogenov et al. [4] theoretically and experimentally investigated the hybrid states of the surface and Tamm plasmon polaritons. The authors of [5, 6] theoretically and experimentally studied the hybrid states formed by the Tamm and defect modes (DM) in a one-dimensional PC.

The OTSs are promising for application in sensors, optical switches, multichannel filters, Faraday- and Kerr-effect amplifiers, and organic solar cells and absorbers.

In this work, we investigate the spectral properties of a one-dimensional PC with the structural defect conjugated to the resonant NC layer. We discuss the hybrid states formed by the optical Tamm and defect modes.

The structure under study consists of a PC with a defect at the symmetry center, which is conjugated to the NC layer (Fig. 1). The alternating layers that form the PC unit cell are silicon dioxide SiO_2 with a permittivity of $\varepsilon_a = 2.10$ and zirconium dioxide ZrO_2 with a permittivity of $\varepsilon_b = 4.16$. The respective layer thicknesses are $W_a = 74\,\text{nm}$ and $W_b = 50\,\text{nm}$. The defect layer is introduced by broadening of the central ZrO_2 layer to a thickness of $W_d = 82\,\text{nm}$. The PC structure is placed in a medium with a unit permittivity (air). The number of structural layers is $N = 20$, including the defect and NC layers.

The NC layer with a thickness of $W_c = 100\,\text{nm}$ consists of spherical nanoparticles uniformly distributed in a dielectric matrix made of transparent optical glass with a permittivity of $\varepsilon_c = 2.56$. The effective permittivity of the NC is determined by the Maxwell-Garnett formula widely used in studying composite media [7, 8]

$$\varepsilon = \varepsilon_c \left(1 + \frac{f}{(1-f)/3 + \varepsilon_c/(\varepsilon_m - \varepsilon_c)}\right), \tag{1}$$

where f is the filling factor, i.e., volume fraction of nanoparticles in the matrix, ε_c is the matrix permittivity, and $\varepsilon_m(\omega)$ is the permittivity of the nanoparticle material. The investigated structure contains silver nanoparticles with the permittivity expressed by the Drude-Sommerfeld formula

$$\varepsilon_m(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \tag{2}$$

where ε_0 is the constant that takes into account the contributions of interband transitions of bound electrons, ω_p is the plasma frequency, γ is the damping coefficient, and ω is the frequency of the incident light. The material parameters of silver are $\varepsilon_0 = 5$, $\hbar\omega_p = 9\,\text{eV}$, and $\hbar\gamma = 0.02\,\text{eV}$ [9].

Figure 2 shows the dependence of the effective NC permittivity calculated using formula (1) on the wavelength of the incident light for the chosen NC parameters. The permittivity exhibits resonant features, while the matrix material and silver do not reveal such features in the optical range. The resonant optical response exceeds the maximum value for the forming media. This is explained by the Clausius-Mossotti relation and electromechanical vibrations of the surface charge on spatial boundaries between the materials forming the composite [9, 10].

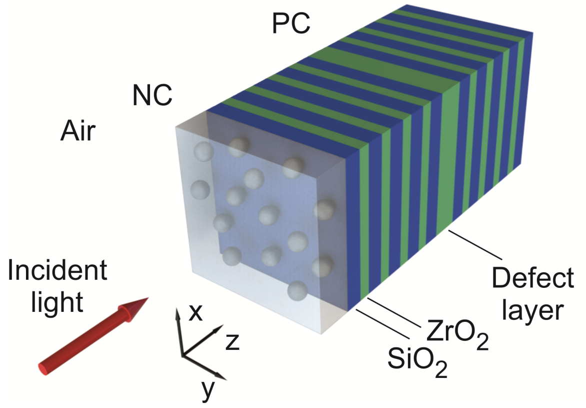


Figure 1: One-dimensional PC with the structural defect conjugated to the NC layer.

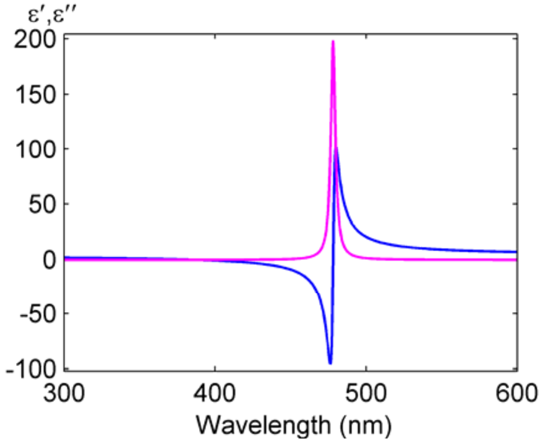
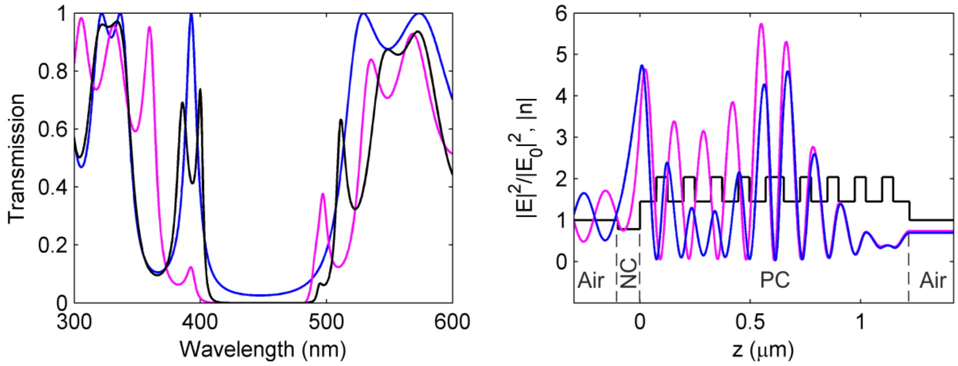


Figure 2: Real (blue) and imaginary (purple) parts of the NC permittivity at $f = 0.2$; $\varepsilon_c = 2.56$.



(a)

(b)

Figure 3: (a) Transmission spectrum of the PC with a defect (blue), PC conjugated to the NC layer (purple), and PC with a defect conjugated to the NC layer (black). (b) Spatial distribution of the light field local intensity and refractive index (black) at split peak wavelengths of 385.9 (blue) and 399.7 nm (purple).

Transmission spectra of the layered structure were calculated by the transfer matrix method at the normal incidence of a planar light wave onto the structure. In addition, this method allows the light field distribution in the structure to be calculated.

The blue line in Fig. 3(a) shows the transmission spectrum of the PC with a defect at the center. In the PC band gap, one can see a peak corresponding to the PC DM. The DM light field is localized on the structural defect. The purple line shows the transmission spectrum of the PC conjugated to the NC layer. Near the band gap, there is a peak corresponding to the OTS. The OTS light field is localized at the PC/NC interface. The field appears enclosed between the multilayer dielectric and metal mirrors, since at this wavelength the real part of the NC permittivity is negative (Fig. 2); i.e., the NC appears similar to a metal.

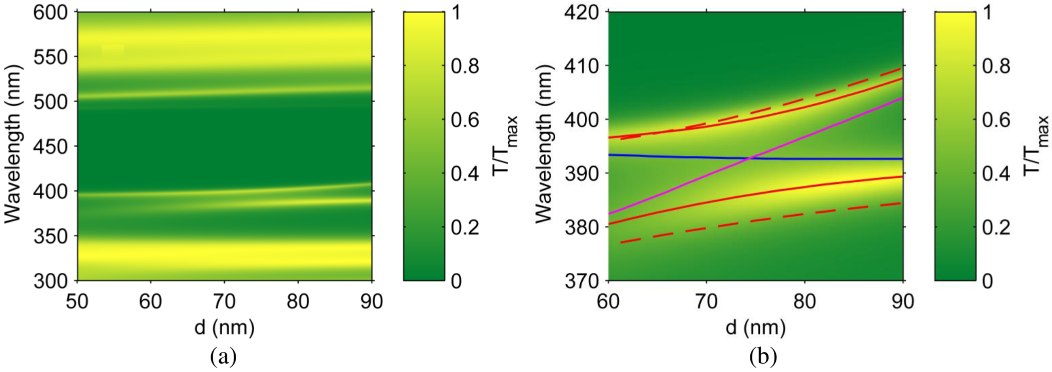
When the structure contains both inhomogeneities and the DM and optical Tamm mode are jointly excited, the spectrum contains a split peak shown with black in Fig. 3(a). The splitting results from elimination of the degeneracy caused by the correlation between the DM and optical Tamm mode, which separately have the same wavelength. In this case, the splitting is 13.8 nm. The correlation between the DM and OTS leads to the formation of bound hybride modes. The transmittance for each peak is intermadiate between the transmittances at the DM and OTS wavelengths in the first two cases. The field energy in the hybrid modes has the localization maxima both at the PC/NC interface and on the defect layer (Fig. 3(b)).

Figure 4(a) shows the transmission spectrum of the structure in dependence on thickness d of the SiO_2 layer adjacent to the NC layer. Near the short-wavelength boundary of the PC band gap, there are two transmission peaks corresponding to the hybrid modes. Fig. 4(b) shows the enlarged repulsion of the peaks corresponding to the hybrid modes by the wavelength.

It can be seen in Fig. 4(b) that the positions of the peaks and distance between them significantly change upon variation in thickness d of the first layer. As was mentioned in [6], with an increase in the thickness of the first PC layer adjacent to the plasma-like medium (in our case, this is the NC with the negative real part of the permittivity in the investigated wavelength range), the OTS wavelength increases (shown with purple in the figure). Thus, the wavelength of the OTS localized at the interface between the NC and the layer of variable thickness changes, while the DM wavelength remains nearly invariable (shown with blue in the figure). Upon detuning of wavelengths of the bound modes, the distance between the peaks increases and attains its maximum at $d = 74\,\text{nm}$; i.e., when the PC structure becomes symmetric and the wavelengths of the bound modes coincide (Fig. 3(a)), their dispersion curves intersect.

The significant dependence of the transmission peak positions on the first PC layer thickness makes it possible to create a tunable filter on the basis of the proposed structure. For this purpose, the first layer should have a variable thickness, e.g., be wedge-like.

As the number of PC layers is decreased, the distance between the peaks of the bound modes along the wavelength grows. This is due to the fact that the distance between the NC and defect layers decreases and the spatial region of overlap of the interacting modes increases, which leads to their stronger coupling and repulsion of the peaks (Fig. 4(b)).



(a)

(b)

Figure 4: (a) Transmission spectrum of the system in dependence on thickness d of the first SiO_2 layer ($T_{\max} = 0.9821$). (b) Enlarged displacement of the peaks corresponding to the hybrid states ($T_{\max} = 0.8524$). Red solid lines show transmission peak maxima for the number of PC layers of $N = 20$ and red dashed line, for $N = 16$. Blue line shows the DM position in the PC structure with a defect. Purple line shows the OTS position in the PC structure conjugated to the nanocomposite.

Note that the split peak position significantly depends on the filling factor, thickness and position of the defect layer, permittivity of the NC matrix, and angle of light incidence onto the structure. The sensitivity of the split peak position in the transmission spectrum to the structural parameters can be used to create a new type of tunable optical filters and sensors.

ACKNOWLEDGMENT

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