Coupled Optical Tamm States at Edges of a Photonic Crystal Enclosed by a Composite of Core-Shell Nanoparticles

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Abstract—Coupled optical Tamm states localized at the edges of a photonic crystal enclosed with a nanocomposite are theoretically studied. The nanocomposite consists of nanoparticles with a dielectric core and a metal shell, which are dispersed in a transparent matrix. It is shown that the positions of the spectral peaks are sensitive to the thickness of the outermost photonic crystal layer.

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1. INTRODUCTION

Recently, extensive investigation has been given to a special type of localized electromagnetic states (optical Tamm states (OTSs)) that can be excited by light normally incident on the sample [1, 2]. These states are an analogue of the Tamm surface state in solid state physics. The OTS can be excited between two different photonic crystals (PCs) that have overlapping bandgaps (BGs) [3] or between a PC and a medium with negative permittivity $\varepsilon$ (plasma-like medium) [4, 5]. The surface electromagnetic wave at the interface of the PC and the medium with $\varepsilon < 0$ is an inseparable whole with the surface plasmon—oscillations of free electrons near the conductor surface. This coupled mode of the radiation field and the surface plasmon excitation is termed the Tamm plasmon polariton (TPP). The OTS experimentally manifests itself as a narrow peak in the sample transmission spectrum [6, 7].

Potential applications of surface modes and OTSs are sensors and optical switches [8], multichannel filters [9], Faraday rotation amplifiers, Kerr effect amplifiers [10], organic solar cells [11], and absorbers [12].

When the PC is bounded on both sides by a plasma-like medium, coupled TPPs can be obtained [13]. In [5] it was shown that coupled TPP could be obtained using a metal–dielectric nanocomposite (NC) as a plasma-like medium. The position of the frequency interval in which the NC is similar to metal, i.e., where $\text{Re}(\varepsilon(\omega)) < 0$, depends on the permittivity of the NC materials and the concentration and shape of its filling nanoparticles. This opens up wide possibilities of controlling optical properties of OTSs by varying NC parameters.

In this work we investigate the effect of the structure parameters on the spectral manifestation of the coupled TPPs occurring in a PC bounded on both sides by an NC consisting of core-shell particles. The spectral properties of the PC are calculated using the transfer matrix method.

2. MODEL

The PC used consisted of alternating silicon dioxide ($\text{SiO}_2$) and zirconium dioxide ($\text{ZiO}_2$) layers with the respective permittivities and thicknesses $\varepsilon_a = 2.10$, $W_a = 74$ nm and $\varepsilon_b = 4.16$, $W_b = 50$ nm. The PC was bounded on two sides by an NC layer with the thickness $W_d = 150$ nm, which consisted of core-shell layered spherical nanoparticles uniformly distributed in a dielectric matrix of transparent optical glass with the permittivity $\varepsilon_m = 2.56$. The structure consisted of $N = 17$ layers, including NC layers, and was placed in a medium (air) with the permittivity of unity (Fig. 1(a)).
where $\varepsilon_0$ is the constant to allow for contributions from interband transitions of bound electrons, $\omega_p$ is the plasma frequency, $\gamma$ is the damping factor (the inverse of the electron relaxation time), and $\omega$ is the incident light frequency. For silver, $\varepsilon_0 = 5$, $\hbar\omega_p = 9$ eV, and $\hbar\gamma = 0.02$ eV.

Figure 1(c) shows calculated dependence of the effective NC permittivity on the incident light wavelength for our chosen parameters of the nanocomposite. It is evident from the figure that there arise two, shortwave and longwave, resonant parts of the permittivity, which are related in nature to the plasmon resonance of the nanoparticles. An increase in the core permittivity results in increasing shortwave resonant part of the permittivity, while its longwave part decreases. As the matrix permittivity increases, the situation is reverse. In addition, both resonances redshift. A decrease in the shell thickness results in enhanced coupling of plasmons localized at the shell boundaries, and the shortwave resonant part of the permittivity is seen to blueshift while the longwave part redshifts. When the real part of the NC permittivity becomes negative, the NC becomes similar to a metal mirror.

3. RESULTS OF CALCULATIONS

Figure 2(a) shows the dependence of the structure transmission spectrum on the thickness $d$ of the first SiO$_2$ layer immediately adjacent to the NC layer. Two transmission peaks are seen near the shortwave boundary of the PC BG. As was shown in [16], these peaks correspond to coupled TPPs. The light field at the wavelength of these peaks is localized at the interface between the PC and NC layers and exponentially decays through the depth of the superlattice and the composite. In fact, the light turns out to be between two mirrors, the Bragg and the metal ones, because the OTS wavelength falls within the bandgap of the photonic crystal and is also in the region of negative values of the real part of the NC permittivity. Figure 2(b) shows wavelength repulsion of the peaks corresponding to the coupled TPPs.

It is evident from Fig. 2 that the positions of the peaks and distances between them appreciably vary with the first-layer thickness $d$. The peak splitting is due to removal of degeneracy that arises from the coupling of the optical Tamm modes localized at the interface. As was pointed out in [17], the increase in the thickness of the first PC layer immediately adjacent to the plasma-like medium (in our case it is the NC with the negative real part of its permittivity in this wavelength range) entails an increase in the OTS wavelength (shown by dots in the figure) and thus a change in the wavelength of the OTS localized at the interface of the NC and the layer of variable thickness.