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Optical generation in an amplifying photonic crystal with an embedded nanocomposite polarizer

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ABSTRACT

We show the possibility of selective polarization generation in an amplifying photonic crystal structure via the use of an embedded film of a sub-wavelength thickness with uniformly oriented metallic elongated nanoparticles chaotically distributed in the volume of a semiconductor. Such nanocomposite polarizer presents a uniaxial crystal with different values of dielectric permittivity components along and perpendicular to the polar axis of the nanoparticles. Dispersion of the dielectric permittivity of the nanocomposite is defined by the concentration and shape factor of the nanoparticles. Wavelength dependence of imaginary part of the nanocomposite permittivity possesses a resonance behavior resulting from plasmon resonance in nanoparticles. We show that this allows, depending on the relative orientation of the nanocomposite anisotropy axis and the polarization direction of the light, to achieve the mode discrimination of the photonic structure in the vicinity of a resonance of one of the permittivity components, where the absorption of the nanocomposite layer is maximal. Also we vary the parameters of the nanocomposite polarizer to obtain the optimal conditions of optical generation at the given wavelength.

1. Introduction

During the last decades photonic crystals (PCs) are intensively investigated because of their promising applications in modern photonics [1,2]. The PCs are artificial structures composed of materials with different refractive indices which are periodic in one-, two-, or three-dimensions, with periods comparable to the length of an electromagnetic wave passing through the photonic structure. The differences in the refractive indices of the PC's constituents lead to the appearance of prohibited regimes in transmittivity spectra of the PC, the so-called photonic band gaps, where the electromagnetic waves cannot propagate through the structure.

The use of PC structures with amplifying fibers opens the possibility of creating a compact semiconductor lasers with a vertical cavity resonator working in optical and near-infrared regimes, or vertical cavity surface-emitting lasers [3,4]. At the same time one of the main obstacles to obtain a stable generation in such a resonator can be simultaneous amplification of waves with different polarizations, which leads to the rise of extremely undesirable polarization and amplitude instabilities [5,6] which break a stable operation of the laser. The solution of this problem can be using a thin-film subwavelength polarizer, integrated directly into the structure of the resonator PC. This assumes the use of plasmonic technology, which has recently been widely used in integrated optics and laser technology [7,8]. Using these techniques will allow to embed a polarizer directly into the structure of the semiconductor vertical-cavity surface-emitting laser ensuring its compactness and minimizing the possible optical losses.

This paper is devoted to studying the possibility of the use of a composite film with the inclusion of metallic aspherical shape nanoparticles as an integrated polarizer for amplifying PC system. As was shown in [9,10], in the region of the plasmon resonance of inclusions, such nanocomposite film of subwavelength thickness may exhibit a high polarization selectivity in both reflection and transmission with moderate absorption. Resonance properties of the nanocomposite layers with metal inclusions can be used to suppress the resonance modes of the PC structures, which makes the spectra of such structures polarization-sensitive [11–14]. Thus it would expect to obtain selective polarization generation in the similar PC with amplification.

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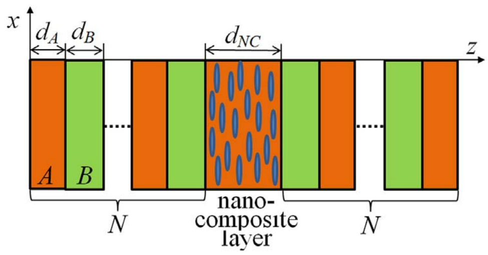

Fig. 1. Schematic of the system: two distributed Bragg reflectors of structure $(AB)^N$ and $(BA)^N$ and a nanocomposite layer placed between them. Layers A and B of thicknesses d_A and d_B are isotropic materials. The nanocomposite layer of thickness d_{NC} contains evenly distributed metallic nanoparticles of ellipsoidal shape.

2. Description of the system

Let us consider a symmetric PC microcavity system composed of two distributed Bragg reflectors of structure $(AB)^N$ and $(BA)^N$ and a nanocomposite layer placed between them (Fig. 1). Layers A and B with thicknesses d_A and d_B are made from isotropic amplifying materials with complex dielectric permittivities $\varepsilon_{A,B} = \varepsilon'_{A,B} + i\varepsilon''_{A,B}$. For simplicity we neglect the frequency dispersion of $\varepsilon_{A,B}$, and the magnetic permeabilities of all the layers in the structure are taken to be unity.

Light is incident from vacuum along the z-axis which is perpendicular to the interfaces of the PC, and (xz) is plane of incidence. Time and coordinate dependence of the electric and magnetic fields of light propagating along the z-axis is described by $\exp[i(kz - \omega\ t)]$, where k is the wavevector, and ω is the angular frequency of the electromagnetic wave. Note that in this case the amplification of an electromagnetic wave in layers A and B is described by negative values of the imaginary part of dielectric permittivities ($\varepsilon''_{A,B} < 0$).

The nanocomposite layer of thickness d_{NC} contains uniformly oriented metallic nanoparticles of ellipsoidal shape evenly distributed on the volume of the nanocomposite matrix. The maximal size of these particles is much less than the wavelength. We use the effective medium approximation in order to describe the optical properties of the nanocomposite. The essence of this approximation is in the assumption that the heterogeneous mixture of different materials that has macroscopic optical homogeneity can be characterized by a certain effective (averaged) relative permittivity. For composite materials of different topologies the Bruggeman, Maxwell Garnett, Landau–Lifshitz effective medium models, etc., were proposed [15,16]. In this work we consider the case where the nanocomposite layer is an isotropic medium with metal inclusions and the volume fraction of inclusions does not exceed 0.1. The effective optical characteristics of such composites, including those in the range of plasmon resonance frequencies of metal inclusions, can be adequately described by the formula of the Maxwell Garnett model [17,18].

Let the polar axes of the nanoparticles are aligned parallel to the x-axis. In this case the nanocomposite presents a uniaxial crystal, and its effective permittivity is represented in the major axes by a diagonal tensor with components $\varepsilon_x = \varepsilon_\parallel$ and $\varepsilon_y = \varepsilon_z = \varepsilon_\perp$ (the subscripts ∥ and ⊥ refer to two orientations of the electric field vector of the electromagnetic wave: parallel and perpendicular to the optic axis of the metallic nanoparticles, respectively). In the frame of Maxwell Garnett model these components can be calculated using the following expression [15]:

$$\varepsilon_{\perp,\parallel} = \varepsilon_m\left(1 + \frac{\eta(\varepsilon_p - \varepsilon_m)}{\varepsilon_m + (1-\eta)(\varepsilon_p - \varepsilon_m)g_{\perp,\parallel}}\right), \quad (1)$$

where ε_m and ε_p are the permittivities of the matrix and inclusions, η is the volume fraction of the inclusions, $g_{\perp,\parallel}$ are geometric factors which take into account the effect of the nanoparticles shape on the induced dipole momentum of the nanoparticles. Factors $g_{\perp,\parallel}$ can be expressed through the ratio $\xi = b/a$ of the semi-polar axis b to the semi-equatorial axis a of the ellipsoidal inclusions:

$$g_\parallel = \frac{1}{1-\xi^2}\left(1 - \xi\frac{\arcsin\sqrt{1-\xi^2}}{\sqrt{1-\xi^2}}\right),\ \ g_\perp = \frac{1}{2}(1 - g_\parallel). \quad (2)$$

Difference in geometrical factors results in different behavior of the permittivity components $\varepsilon_{\perp,\parallel}$ of the nanocomposite layer, which, in turn, would affect the polarization states of the reflected and transmitted electromagnetic waves.

We assume the matrix material of the nanocomposite is the same as that of layer A of the PC, so that $\varepsilon_m = \varepsilon_A$. To describe the optical properties of metal nanoparticles, we use the expression of the Drude model:

$$\varepsilon_p(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}, \quad (3)$$

where ω_p is the plasmon frequency, ε_0 is the lattice contribution, and γ is the relaxation parameter.

As far as in the effective medium approximation the optical properties of the nanocomposite layer are defined by the coordinate-independent effective permittivity, to calculate the transmittivity and the reflectivity, one can use transfer matrix method [11–13,19,20].

3. Results of the numerical calculations

For the numerical calculations, we assume layer A to be GaAs with ε'_A=12.25, layer B to be $GaAl_{0.3}As_{0.7}$ with ε'_B=11.56. The imaginary parts of the dielectric permittivities are $\varepsilon''_A = \varepsilon''_B = -0.007$. Such values are reliable in semiconductors in near-infrared regime and do not exceed the maximal values of the amplification [21].

Thicknesses of the layers of the PC are d_A=108.5 nm and d_B=111.6 nm, and thickness of the nanocomposite layer is d_{NC}=2d_A. This choice is made to provide a photonic band gap with low-wavelength edge at λ_0=1.5 µm. The number of periods of the PC on each side of the nanocomposite layer is N=100. Such a number of periods is taken to provide a pronounced photonic band gap in the transmittivity spectra of the PC, whose layers possess small difference in the dielectric permittivities. Thus, the thickness of the whole PC structure is approximately 44.24 µm.

Metallic inclusions material in the nanocomposite layer is Ag with the following parameters: ω_p=1.36×10^{16} s^{-1}, ε_0=5, γ=3.04×10^{16} s^{-1}[22]. The volume fraction of the inclusions is η=10^{-3}, and the size of nanoparticles does not exceed 50 nm. For parameter ξ=3.2 one of surface plasmon resonance frequencies of nanoparticles is at λ_0=1.5 µm.

3.1. Dispersion of the nanocomposite permittivity

The dependences of real $\varepsilon'_{\perp,\parallel}$ and imaginary $\varepsilon''_{\perp,\parallel}$ parts of the nanocomposite effective permittivity components on wavelength λ are illustrated in Fig. 2(a) and (b), respectively, in the case of the nanocomposite matrix (GaAs) without amplification (*i.e.,* for $\varepsilon''_A = 0$) in order to focus on the effect of the metallic inclusions only. One can see that the permittivities exhibit resonant behavior with different resonance wavelengths $\lambda_\perp$=0.63 µm for $\varepsilon_\perp$ and $\lambda_\parallel$=1.5 µm for $\varepsilon_\parallel$, which eventually leads to a significant dependence of the optical properties of the nanocomposite on the polarization of propagating waves. The observed resonances are associated with the plasmon resonances of the nanoparticles, and their resonance wavelengths depend on the orientation of the optic axes of the nanoparticles with respect to the electric field vector of the electromagnetic wave [9,10]. It should be noted that positive values of imaginary parts $\varepsilon''_{\perp,\parallel}$ correspond to damping of light.

The width and maximal values of resonance peaks of $\varepsilon''_{\perp,\parallel}$ depend on the volume fraction η of the metallic inclusions, as shown in the insets in Fig. 2 for η=0.5·10^{-3} (dotted lines), 1.0·10^{-3} (solid lines), and 1.5·10^{-3} (dash-dotted lines). One can see that the peak values of $\varepsilon''_{\perp,\parallel}$