Optical generation in an amplifying photonic crystal with metal nanoparticles

I. Glukhov[1], S. Moiseev[1,2,3]

[1]Ulyanovsk State University, Ulyanovsk, Russia, 432017
[2]Kotelnikov Institute of Radio Engineering and Electronics of Russian Academy of Sciences, Ulyanovsk Branch, Ulyanovsk, Russia, 432011
[3]Ulyanovsk State Technical University, Ulyanovsk, Russia, 432027

Abstract. We show the possibility of selective polarization generation in photonic crystal structure with the monolayer of metal nanoparticles. Optical properties of the monolayer are defined by the surface concentration and shape factor of the nanoparticles. Wavelength dependence of the monolayer reflectance and transmittance possesses a resonance behavior resulting from plasmon resonance in nanoparticles. We show that this allows, depending on the relative orientation of the monolayer anisotropy axis and the polarization direction of the light, to achieve the mode discrimination of the photonic structure.

1. Introduction

The use of photonic crystal (PC) structures with amplifying component 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 [1, 2]. 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 [3, 4] 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 [5]. This assumes the use of plasmonic technology, which has recently been widely used in integrated optics and laser technology [6]. 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 thin semiconductor layer with the inclusion of metallic aspherical shape nanoparticles as an integrated polarizer for amplifying PC system. In the region of the plasmon resonance of inclusions, such monolayer may exhibit a high polarization selectivity in both reflection and transmission with moderate absorption [7]. Resonance properties of the metal inclusions can be used to suppress the resonance modes of the PC structures,

which makes the spectra of such structures polarization-sensitive [8-11]. Thus it would expect to obtain selective polarization generation in the 1D PC with amplification.

2. Description of the system under consideration

Let us consider a symmetric PC microcavity system composed of two distributed Bragg reflectors of structure $(AB)^N$ and $(BA)^N$ and an additional layer with metal nanoparticles placed between them (Fig. 1). Layers A and B with thicknesses d_A and d_B are made from isotropic amplifying materials with dielectric permittivities $\varepsilon_{A,B} = \varepsilon'_{A,B} + i\varepsilon''_{A,B}$. For simplicity we neglect the frequency dispersion of dielectric permittivities $\varepsilon_{A,B}$, 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. Time and coordinate dependence of the electric and magnetic fields of light propagating along the z-axis is described by $\exp\left[i\left(kz - \omega t\right)\right]$, where k is the wavevector, and ω is the angular frequency of the electromagnetic wave. In this case amplification of electromagnetic wave in layers A and B is described by negative values of the imaginary part of dielectric permittivities $\left(\varepsilon''_{A,B} < 0\right)$.
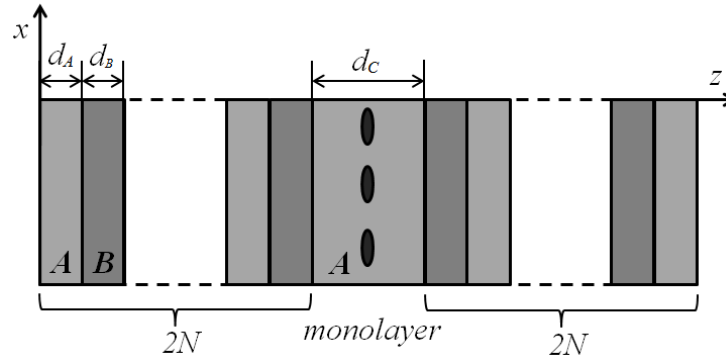
Figure 1. Schematic of the system: two distributed Bragg reflectors of structure $(AB)^N$ and $(BA)^N$ and a monolayer of nanoparticles placed between them. Layers A and B of thicknesses d_A and d_B, respectively, are isotropic materials. The isotropic layer of thickness d_c contains a 2D array of metallic nanoparticles of ellipsoidal shape.

The layer of thickness d_c contains monolayer of uniformly oriented metallic nanoparticles of ellipsoidal shape. The maximal size of these particles is much less than the wavelength. For simplicity we consider the case of the ordered monolayer film in which nanoparticles are located at the sites of square lattice lying in the plane (xy). The polar axes of the nanoparticles are aligned parallel to the x-axis.

In order to calculate reflectivity and transmission of plane-layered structure with embedded 2D array of nanoparticles we employ T-matrix technique. A special case is interface, optical qualities of which are determined by Fresnel reflection and transmission coefficients [12]. Since array of nanoparticles situated in the same plane interacts with electromagnetic wave like plane interface, it can be also treated as an interface with its own reflection and transmission coefficients.

According to the introduced notation, complex amplitudes of counter-propagating waves on m interface in the layer with reflection index n_{m-1} are equal to $E_f(z_m^-)$ and $E_b(z_m^-)$. At the same interface but in the layer with reflection index n_m they are equal to $E_f(z_m^+)$ and $E_b(z_m^+)$. Relationship of these fields on m-interface (to the left and to the right of it) can be expressed as matrix equation:

$$\begin{pmatrix} E_f(z_m^-) \\ E_b(z_m^-) \end{pmatrix} = I_{m-1,m} \begin{pmatrix} E_f(z_m^+) \\ E_b(z_m^+) \end{pmatrix}, \tag{1}$$

$$I_{m-1,m} = \frac{1}{t_{m-1,m}} \begin{pmatrix} 1 & -r_{m,m-1} \\ r_{m-1,m} & t_{m-1,m}t_{m,m-1} - r_{m-1,m}r_{m,m-1} \end{pmatrix}, \tag{2}$$

where $r_{i,j}$, $t_{i,j}$ are complex reflection and transmission coefficients of the interface deviding media with refraction indexes n_i and n_j when the lightwave is incident from the medium with refraction index n_i. Relationship of the fields on two interfaces of m and $m+1$ numbers confining homogeneous layer of m number is via transfer matrix $\hat{F}_m$:

$$\begin{pmatrix} E_f(z_m^-) \\ E_b(z_m^-) \end{pmatrix} = \hat{F}_m \begin{pmatrix} E_f(z_m^+) \\ E_b(z_m^+) \end{pmatrix}, \tag{3}$$

$$\hat{F}_m = \begin{pmatrix} exp(-i\delta_m) & 0 \\ 0 & exp(i\delta_m) \end{pmatrix}, \tag{4}$$

where $\delta_m = k_0 n_m L_m$ is phase thickness of the layer; $k_0 = \omega/c$ is the wave number.

Applying expressions (1) – (4) to the entire PCs we obtain relation for the amplitudes to the left of the first interface and to the right of the last (with number N) interface:

$$\begin{pmatrix} E_f(z_1^-) \\ E_b(z_1^-) \end{pmatrix} = \hat{G} \begin{pmatrix} E_f(z_N^+) \\ E_b(z_N^+) \end{pmatrix}, \tag{5}$$

$$\hat{G} = I_{0,1}F_1 I_{1,2} F_2 \cdots F_{N-1} I_{N-1,N}. \tag{6}$$

Note that in semi-infinite medium with refraction index n_N there exists only transmitted wave, therefore we shall assume $E_b(z_N^+) = 0$ in (5).

Reflectance and transmittance of PCs are calculated from the formulas

$$T = \left| \frac{1}{\hat{G}_{11}} \right|^2, \qquad R = \left| \frac{\hat{G}_{21}}{\hat{G}_{11}} \right|^2. \tag{7}$$

To calculate coefficients of monolayer reflection and refraction we use expressions

$$r_p = t_p - 1 \approx -i \frac{k_0 \sqrt{\varepsilon_A} \tilde{\alpha}}{2} \tag{8}$$

where

$$\tilde{\alpha} = \frac{\alpha_p}{1 - f n_s \alpha_p / 2\varepsilon_A}, \tag{9}$$

$$\alpha_p = V \frac{\varepsilon_p - \varepsilon_A}{g(\varepsilon_p - \varepsilon_A) + \varepsilon_A} \tag{10}$$

are the effective electric polarizability density per unit area and the polarizability of a single particle with the shape of a spheroid (ellipsoid of revolution) in an external field applied along one of the principal axes of the particle. Here, V is the volume of the particle, g is geometric factor which take into account the effect of the nanoparticles shape on the induced dipole momentum of the nanoparticles, and for a square array of period d structure factor $f \approx 0.72/d$ [13], $n_s = d^{-2}$ is the number of scatterers per unit area. Factors $g_{x,y}$ 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:

$$g_x = \frac{1}{1 - \xi^2} \left(1 - \xi \frac{\arcsin \sqrt{1 - \xi^2}}{\sqrt{1 - \xi^2}} \right), \quad g_y = \frac{1}{2}(1 - g_x). \tag{11}$$

Difference in geometrical factors results in different behavior of the effective polarizability components $\tilde{\alpha}_{x,y}$ of the monolayer, which, in turn, would affect the polarization states of the reflected and transmitted electromagnetic waves.

3. Results of calculations

For the numerical calculations, we assume layer A to be GaAs with $\varepsilon'_A = 12.25$, layer B to be GaAl$_{0.3}$As$_{0.7}$ with $\varepsilon'_B = 11.56$. 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 does not exceed the maximal values of the amplification [14].

Thicknesses of the layers of the PC structure under consideration are $d_A = 108.5$ nm and $d_B = 111.6$ nm, and thickness of the layer with nanoparticles is $dc = 2d_A$. This choice is made to provide a photonic band gap with low-wavelength edge at $\lambda_0 = 1.5$ 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.

To describe the optical properties of metal nanoparticles, we use the expression of the Drude model:

$$\varepsilon_p(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}, \tag{12}$$

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

Metallic inclusions material in the nanocomposite layer is Ag with the following parameters: $\omega_p = 1.36\times10^{16}$ s^{-1}, $\varepsilon_0 = 5$, $\gamma = 3.04\times10^{16}$ s^{-1} [15]. The interparticle distance is $d = 10$ nm, and the size of nanoparticles does not exceed 6.4 nm. For parameter $\xi = 3.2$ the frequency of surface plasmon resonance of nanoparticles is at $\lambda_0 = 1.5$ μm.

Calculated refraction coefficient of silver nanoparticle monolayer in the semiconductor GaAs without amplification is shown in Fig. 2 for the longitudinal (R_{px}) and transverse (R_{py}) polarizations. One can see that for the longitudinal polarization monolayer reflection spectrum is subject to strong changes. The observed resonance is associated with the longitudinal plasmon resonances of the nanoparticles [16, 17]. Thus, spectral characteristics of the monolayer of metal nanoparticles depend on internal geometrical parameters which make it possible to control to a certain extent its influence on spectrum of PC.
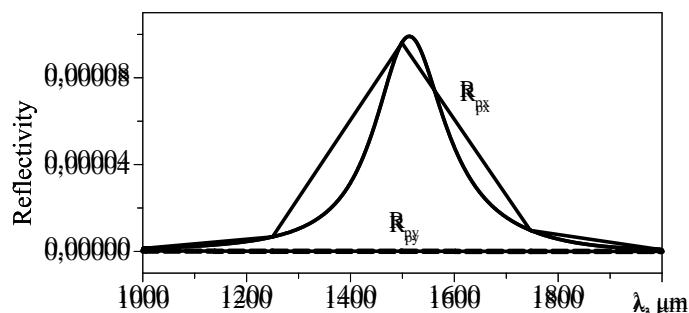
Figure 2. Reflection spectra for monolayer of silver nanoparticles for the longitudinal and transverse polarizations. Period of structure is d=10 nm.

The transmittivity spectra of the PC without metallic nanoparticles are shown in Fig. 3. The presented results correspond to both transmittivities $T_x(\lambda)$ and $T_y(\lambda)$ of the waves polarized along the x- and y-axes, as at normal incidence $T_x = T_y$ for isotropic layers. The total width of the photonic band gap is approximately 0.035 μm. In the case when A and B layers of the PC are non-amplifying

(solid line), i.e., when $\varepsilon''_{A,B} = 0$, a high-intensity defect mode is present in the center of the photonic band gap. When amplification is present in the PC (dashed line), i.e., when $\varepsilon''_{A,B} < 0$, the photonic band gap edges become more sharp and the transmittivity demonstrates an abrupt increase, which corresponds to optical generation [1]. On the other hand, in the presence of amplification the defect mode becomes almost negligible, as one can see from the inset in Fig. 3. Further we focus on study of the spectra in the vicinity of low-frequency photonic band gap edge.
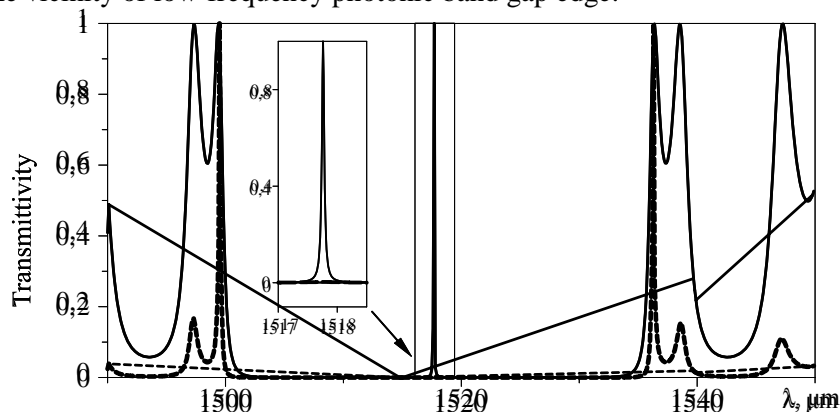
Figure 3. Transmittivity spectra $T_x(\lambda) = T_y(\lambda)$ in the vicinity of the photonic band gap of the PC without metallic nanoparticles ($n_s = 0$) in the case of amplification absence in layers A and B (solid line) and with amplification (dashed line). Inset shows the transmittivity in the vicinity of the defect mode.

Fig. 4(a) shows the transmittivity spectra of the PC structure without nanoparticles (in this case $T_x(\lambda) = T_y(\lambda)$) in the vicinity of the low-wavelength photonic band gap edge ($\lambda_0 \approx 1.5$ μm). One can see that at λ_0 both T_x and T_y exhibit abrupt increase, i.e., as was mentioned above, generation of electromagnetic wave with both components (along the x- and y-axes) takes place. Thus, the outcoming signal contains mixed polarization state.

In the case when metallic ellipsoids are present in the PC structure, the situation drastically changes for T_x component, as shown by solid line in Fig. 4(b). The damping of the field component parallel to polar axis of nanoparticles (*i.e.* along the x-axis) is strong in the vicinity of λ_0 due to resonance of R_{px} (see Fig. 2) and cancels the amplification of the PC layers and thus prevents generation of this component of the electromagnetic wave. On the other hand, $\tilde{\alpha}_{py}$ which is responsible for damping of the wave component perpendicular to the polar axis of nanoparticles (the y-axis) is small around λ_0, so that T_y almost doesn't change and generation takes place (dashed line in Fig. 4(b)).

4. Conclusion
To conclude, we considered an amplifying photonic crystal structure with embedded plasmon polarizer which represents a semiconductor film of sub-wavelength thickness with uniformly oriented 2D array of metallic elongated nanoparticles. Spectral characteristics of nanopolarizer are defined by the ratio of the geometric parameters of the nanoparticles. We have shown that in a considered resonance structure the generation of the electromagnetic waves at the photonic band gap edge is very sensitive to the polarization state of light. The mode discrimination of the photonic crystal can be achieved through the absorption of the monolayer which depends on the relative orientation of its anisotropy axis and the polarization direction of the light wave.

5. Acknowledgment
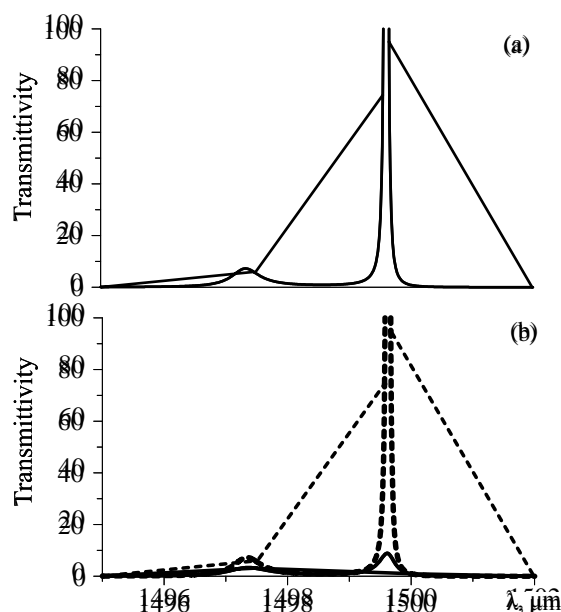
Figure 4. Transmittivity spectra in the vicinity of the low-wavelength photonic band gap edge ($\lambda_0 \approx 1.5$ μm) in the cases when central layer of PC is (a) without nanoparticles; (b) with nanoparticles ($d = 10$ nm). Solid and dashed lines show the transmittivities $T_x(\lambda)$ and $T_y(\lambda)$ of the waves polarized parallel and perpendicular to the polar axis of the nanoparticles, respectively. Results are obtained accounting for the amplification in the PC layers.

6. References

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