Optical generation in an amplifying photonic crystal with metal nanoparticles

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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.

In recent times, the attention of researchers has been attracted by metal-dielectric nanocomposite media, i.e., dielectric matrices containing metal nanoparticles evenly distributed throughout the matrix volume [7-10]. It was shown that resonance properties of the metal inclusions can be used to suppress the resonance modes of the PC structures [11-17].

This paper is devoted to studying the possibility of the use of a thin semiconductor layer with 2D array (monolayer) 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 [13]. 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 reflectorsof 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 $\exp(ikz - \omega t)$, where $k$ is the wavevector, and $\omega$ 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 $\varepsilon_{A,B}'' < 0$.

![Figure 1. Schematic of the system: two distributed Bragg reflectorsof 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.](image)

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 [18]. 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 refractive index $n_m$ are equal to $E_f(z_m^{-})$ and $E_b(z_m^{+})$. At the same interface but in the layer with refractive 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:

$$
\begin{pmatrix}
E_f(z_m^{-}) \\
E_b(z_m^{-})
\end{pmatrix}
= \hat{f}_{m-1,m}
\begin{pmatrix}
E_f(z_m^{+}) \\
E_b(z_m^{+})
\end{pmatrix},
$$

(1)

$$
\hat{f}_{m-1,m} = \frac{1}{t_{m-1,m}} \begin{pmatrix}
1 & -r_{m,m-1} \\
-r_{m,m-1} & t_{m,m-1} - t_{m-1,m} r_{m,m-1}
\end{pmatrix},
$$

(2)

where $r_{i,j}$, $t_{i,j}$ are complex reflection and transmission coefficients of the interface dividing media with refractive 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 $\hat{F}_m$:

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

(3)

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

(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:

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

(5)

$$
\hat{G} = \hat{I}_{0,1} \hat{F}_1 \hat{I}_{1,2} \hat{F}_2 \cdots \hat{F}_{N-1,N} \hat{I}_{N-1,N}.
$$

(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

$$
T = \frac{1}{|\hat{G}_{12}|^2}, \quad R = \frac{|\hat{G}_{22}|^2}{|\hat{G}_{11}|^2}.
$$

(7)

To calculate coefficients of monolayer reflection and refraction we use expression

$$
r_p = t_p - 1 \approx -i \frac{k_0 \sqrt{e_A} \alpha}{2},
$$

(8)

where

$$
\alpha = \frac{\alpha_p}{1 - fn \alpha_p / 2e_A},
$$

(9)

$$
\alpha_p = \frac{e_p - e_A}{g(e_p - e_A) + e_A}
$$

(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 $f \approx 0.72/d$ [19], $n_s = d^{-2}$ is the number of scatterers per unit area. Factor $g$ for $x$- and $y$-components of field ($g_x$ and $g_y$) 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:

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

(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 [20].

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 $d_C = 2d_A$. 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:

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

(12)

where $\omega_p$ is the plasmon frequency, $\varepsilon_0$ is the lattice contribution, and $\gamma$ is the relaxation parameter.

Metallic inclusions material in the nanocomposite layer is Ag with the following parameters: $\omega_p = 1.36 \times 10^{16}$ s$^{-1}$, $\varepsilon_0 = 5$, $\gamma = 3.04 \times 10^{16}$ s$^{-1}$ [21]. 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 $\lambda_0 \approx 1.5$ µm.

Calculated reflection coefficient of silver nanoparticle monolayer in the semiconductor GaAs without amplification is shown in Fig. 2 for the longitudinal ($R_p$) and transverse ($R_m$) polarizations. One can see that for the longitudinal polarization monolayer reflection spectrum subject to strong changes. The observed resonance is associated with the longitudinal plasmon resonances of the nanoparticles [7, 8]. 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.](image-url)
The transmittivity spectra of the PC without metallic nanoparticles \((n_s = 0)\) 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 35 nm. 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. 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.** Transmittivities spectra \(T_x(\lambda) = T_y(\lambda)\) in the vicinity of the photonic band gap of the PC without metallic nanoparticles 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.

**Figure 4.** Transmittivity spectra in the vicinity of the low-wavelength photonic band gap edge \((\lambda_0 \approx 1.5 \mu\text{m})\) in the cases when central layer of PC is (a) without nanoparticles; (b) with nanoparticles \((d = 10 \text{ nm})\). 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.
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 ($\lambda_0 \approx 1.5 \mu m$). One can see that at $\lambda_0$ 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 outgoing 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 $\lambda_0$ 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, $\tilde{a}_{py}$ which is responsible for damping of the wave component perpendicular to the polar axis of nanoparticles (the $y$-axis) is small around $\lambda_0$, 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 such 2D 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. References

[1] Yu S F 2003 Analysis and Design of Vertical Cavity Surface Emitting Lasers (Wiley: Hoboken)
[2] Wilmsen C W, Temkin H and Coldren L A 1999 Vertical-Cavity Surface-Emitting Lasers: Design, Fabrication, Characterization, and Applications (Cambridge: Cambridge University Press)
[3] Winful H G 1986 Opt. Lett 11 33
[4] Zheludev N I 1989 Sov. Phys. Uspekhi 32 357
[5] Dadoenkova Y, Glukhov I, Moiseev S, Svetukhin V, Zhukov A and Zolotovskii I 2017 Optics Communications 389 1
[6] He X Y, Wang Q J and Yu S F 2012 IEEE J. Quantum Electron 48 1554
[7] Moiseev S G 2011 Opt. Spectrosc. 111(2) 233
[8] Moiseev S G 2011 App. Phys. A 103(3) 775
[9] Kalenskii A V, Zvekov A A, Galkina E V, Nurmuhametov D R 2018 Computer Optics 42(2) 254-262 DOI: 10.18287/2412-6179-2018-42-2-254-256
[10] Karamaliyev R A, Qajar Ch O 2012 J. Appl. Spectr. 79 404
[11] Moiseev S G, Ostatochnikov V A and Sementsov D I 2012 Quantum Electronics 42(6) 557
[12] Moiseev S G, Ostatochnikov V A and Sementsov D I 2014 JETP Lett 100(6) 371
[13] Glukhov I A and Moiseev S G 2017 CEUR Workshop Proceedings 1900 43
[14] Vetrov S Ya, Pankin P S and Timofeev I V 2014 Quantum Electronics 44 841
[15] Lozovski V and Razumova M 2016 J. Opt. Soc. Am. B 33 8
[16] Elsayed H A 2018 Materials Research Express 5(3) 036209
[17] Aly A H, Elsayed H A and Malek C 2017 Journal of Nonlinear Optical Physics and Materials 26(1) 1750007
[18] Born M and Wolf E 1999 Principles of Optics (Cambridge: Cambridge University Press)
[19] Kuester E F, Mohamed M A, Piket-May M and Holloway C L 2003 *IEEE Transactions on Antennas and Propagation* 51 2641

[20] Vasil'ev P P 1999 *Quantum Electronics* 29 842

[21] Johnson P B and Christy R W 1972 *Phys. Rev.* 6 4370

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