*Regular paper*

# Optical gain in one-dimensional photonic band gap structures with *n-i-p-i* crystal layers

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**Abstract — The gain enhancement in a layered periodic photonic band gap structure containing active medium based on GaAs *n-i-p-i* superlattices separated by AlGaAs layers is analyzed. The dependences of extinction coefficient and refractive index on excitation level and wavelength are presented. Transmission characteristics of a probe light versus excitation level are calculated. It is shown that the threshold of generation can be essentially reduced if the wavelength of probe light falls to the band gap edge.**

***Keywords — photonic crystal, doping superlattice, optical gain, tunable source.***

## 1. Introduction

The interest in multilayer periodic structures forming a photonic band gap (PBG) is increasing because of their attractive application for controllable optical switches and other various nonlinear optical devices [1, 2]. All nonlinear phenomena are enhanced at the PBG edge due to strong delay of the energy velocity and electric field concentration within certain areas of PBG structures. Besides, the optical gain can be enhanced at the band edge in one-dimensional (1D) PBG structures due to the same reasons [3].

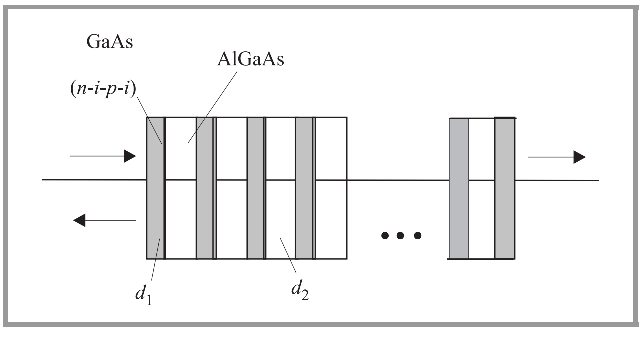

***Fig. 1.*** 1D PBG structure with the GaAs *n-i-p-i* crystal layers.

In the present work, the possibilities to use of *n-i-p-i* superlattices as optically controllable active layers in PBG structures are investigated. We consider such a photonic structure in the GaAs-AlGaAs system where the absorption layers with optical controllable parameters are the GaAs *n-i-p-i* crystal layers (see Fig. 1). In certain spectral range the absorption in *n-i-p-i* layers disappears and the light amplification occurs. The gain coefficient in *n-i-p-i* layers depends on the wavelength and the difference in the quasi-Fermi levels $\Delta F$. The model, where a pump, which can be electrical or optical, excites uniformly all active layers, is considered. Light transmission characteristics versus $\Delta F$, which is assumed to be the same all over the active layers, are calculated. As shown, the described photonic structures with the *n-i-p-i* layers are attractive to make narrow-band tunable radiation sources.

## 2. Dispersion characteristics of *n-i-p-i* layers

We consider the optical properties of the GaAs-AlGaAs photonic structures where the absorption layers are the GaAs *n-i-p-i* crystal layers (Fig. 1). In particular, the active *n-i-p-i* layers can be in the form of $\delta$-doped semiconductor superlattices. In this case, the donor and acceptor concentrations are assumed to be $N_a = N_d = 10^{20}$ cm$^{-3}$, width of doped *n*- and *p*-type regions $d_n = d_p = 1$ nm, thickness of *i*-layers $d_i = 8$ nm. Under optical excitation, the concentration of charge carriers in the *n-i-p-i* layers increases. Therewith, the difference in the quasi-Fermi levels $\Delta F$ grows and conditions of radiation absorption and refraction change as well.

Dispersion characteristics of the *n-i-p-i* layers are shown in Fig. 2. Dependencies of the extinction coefficient $\kappa$ and change in the refractive index $\Delta n$ at different wavelengths $\lambda$ on the excitation level $\Delta F$ have been calculated according to the Kramers-Krönig relation taking into account the transformation of the potential relief of the doping superlattice under optical or electric excitation. Effects of the density state tails, screening of the impurity electrostatic potential, and shrinkage of the energy band gap are included too [4, 5]. The quantizied change in the refractive index $\Delta n$ is related to the filling of the subband levels by current carriers at the excitation of the layers. At definite values of $\Delta F$, the extinction coefficient $\kappa$ becomes negative, i.e., light amplification occurs in the certain interval of wavelengths. Here, the normalized parameter $\kappa_0(\lambda)$ is the initial extinction coefficient at the thermodynamic equilibrium ($\Delta F = 0$). The index of refraction of the *n-i-p-i* layers is estimated as a sum of the quantity $\Delta n$ and the value of the refractive index for the GaAs host material.

To find connection between $\Delta F$ and the exciting radiation power $P$ in the layers under uniform optical excitation of the structure, the following approach is used. It is assumed

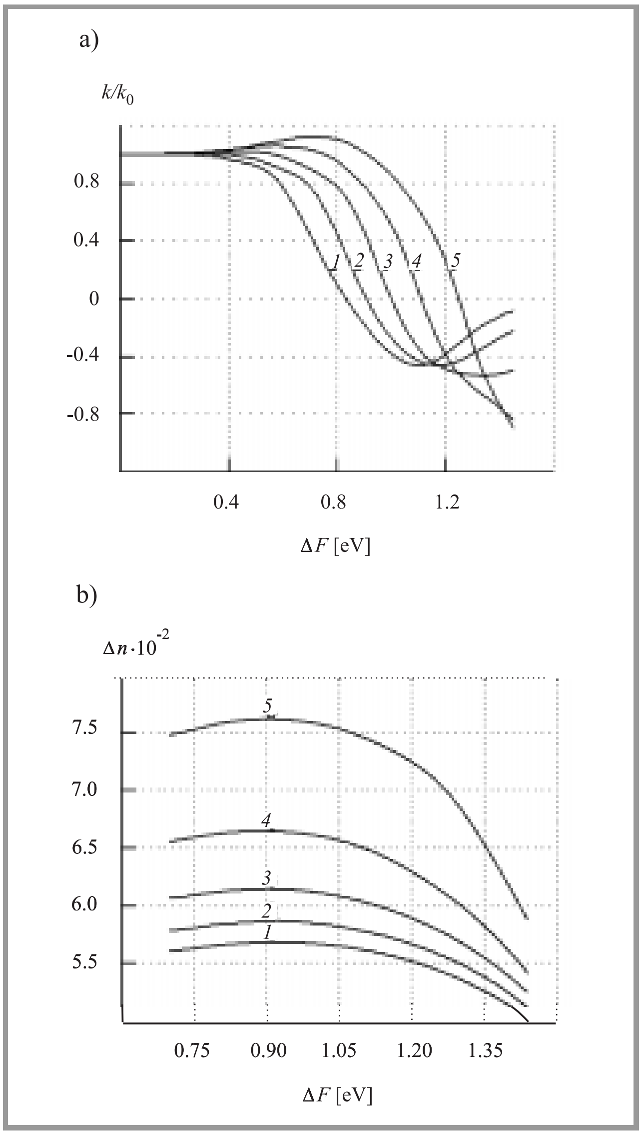

***Fig. 2.*** Dependencies (a) of the extinction coefficient $\kappa$ and (b) quantizied refractive index $\Delta n$ at different wavelengths $\lambda$ on the excitation level $\Delta F$. 1 – $\kappa_0 = 9.50 \cdot 10^{-6}$, $\lambda = 1500$ nm, 2 – $\kappa_0 = 3.70 \cdot 10^{-5}$, $\lambda = 1375$ nm, 3 – $\kappa_0 = 1.68 \cdot 10^{-4}$, $\lambda = 1250$ nm, 4 – $\kappa_0 = 8.71 \cdot 10^{-4}$, $\lambda = 1125$ nm, 5 – $\kappa_0 = 4.60 \cdot 10^{-3}$, $\lambda = 1000$ nm.

that the quantum yield at the excitation of the controllable layers in the 1D PBG structure equals 1, i.e., every absorbed quantum produces one electron-hole pair. Concentrations of non-equilibrium carriers are found from the stationary continuity equation that determines the simple relation between the excitation level $\Delta F$ and the generation rate at the absorption of excitation quantum. The rate of the carrier generation per unit volume in a definite *n-i-p-i* layer is equal to $kP/h\nu_{\mathrm{exc}}$, where $k$ is the absorption coefficient and $h\nu_{\mathrm{exc}}$ is the energy of excitation quantum. The spectrum of absorption $k(\lambda)$ is connected with the spectrum of the extinction coefficient as $k = 4\pi\kappa/\lambda$.

The increase of the two-dimensional concentration of electrons $n$ versus the difference in the quasi-Fermi levels $\Delta F$ is shown in Fig. 3a. Using the dependence $n(\Delta F)$, from the relation between $kP/h\nu_{\mathrm{exc}}$ and $\Delta F$, which is given in Fig. 3b, one can evaluate the effective life-time of carriers at the radiative recombination. For the *n-i-p-i* structure examined, values of the effective life-time of carriers cover a wide range from 1 ms at a low-intensity excitation to10 ns at the high excitation levels.

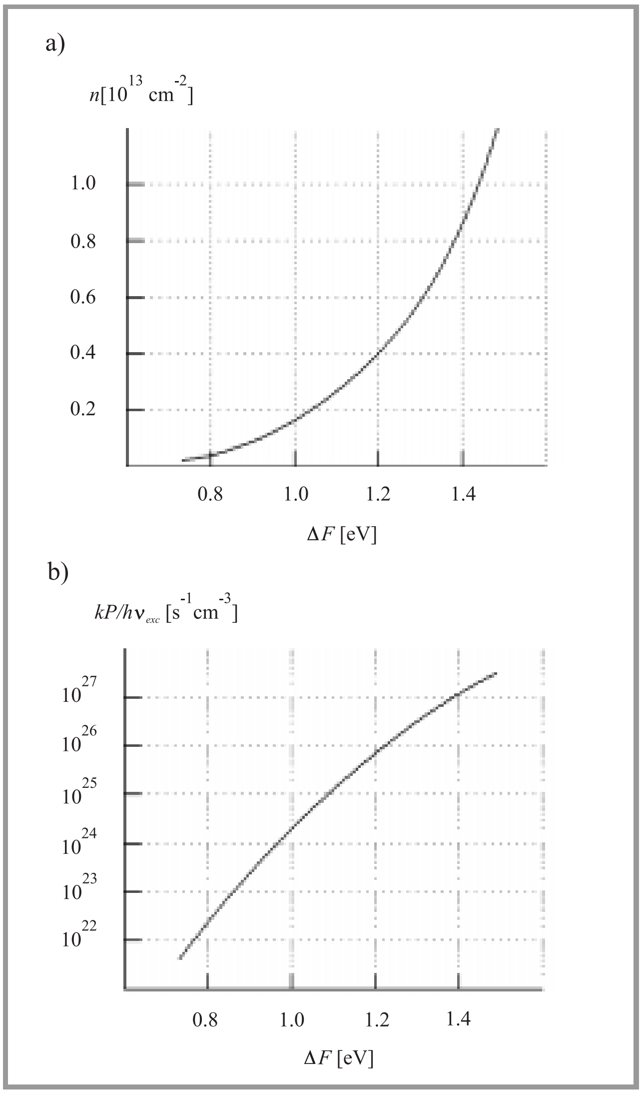

***Fig. 3.*** Dependencies (a) of the electron concentration $n$ and (b) rate of excitation $kP/h\nu_{\mathrm{exc}}$ on the quasi-Fermi level difference $\Delta F$ in the *n-i-p-i* layers of the photonic structure.

## 3. Gain in the PBG structure

The spectral range where the absorption coefficient in *n-i-p-i* layers is negative at the high excitation levels can be seen in Fig. 2a. The 40-period structure, whose parameters are taken in such a way as the PBG edge falls within the region of maximal gain, was considered. Thicknesses of GaAs and $Al_{0.3}Ga_{0.7}As$ layers are $d_1 = 64.5$ nm and $d_2 = 72.9$ nm, respectively.

The transmission characteristics in a suitable spectral range are presented in Fig. 4, where $T$ is the amplitude transmission coefficient. The maxima of transmission peaks correspond to the band edges, both of them are within the region of negative absorption coefficients. Thus, the PBG structure with the active *n-i-p-i* layers allows considerably to enhance the light amplification and to reduce the necessary level of excitation.

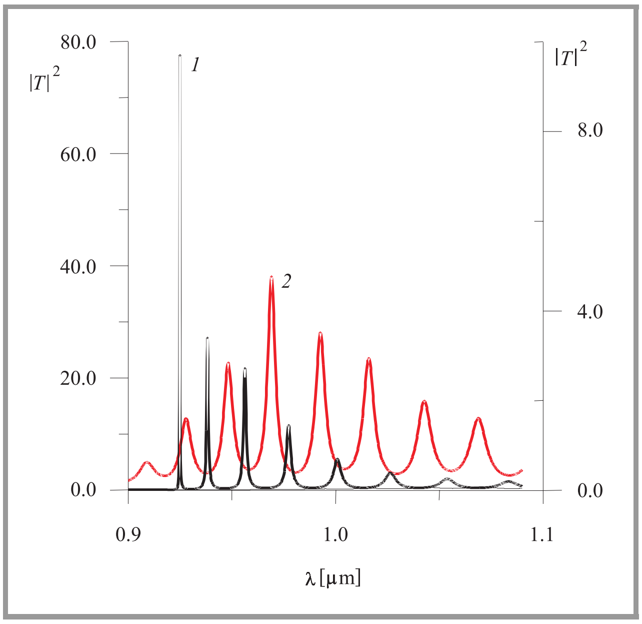

***Fig. 4.*** Transmission coefficient $|T|^2$ versus the wavelength $\lambda$ for the 40-period structure (curve 1, left $Y$-axis) and for the 1-period structure (curve 2, right $Y$-axis), having the same optical thickness, at $\Delta F = 1.348$ eV.

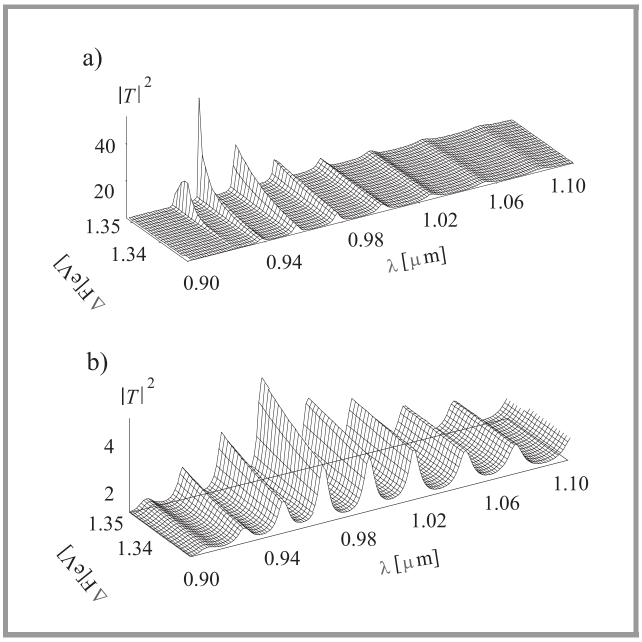

***Fig. 5.*** Surfaces of the transmission coefficient $|T|^2$ versus the wavelength $\lambda$ in microns and difference in the quasi-Fermi levels $\Delta F$ for (a) the 40-period and (b) 1-period structures of the same optical thickness.

Next two-dimensional surfaces of the transmission $|T|^2$ versus the difference in the quasi-Fermi levels $\Delta F$ and the wavelength $\lambda$ are presented for the 40-period (Fig. 5a) and for the 1-period (Fig. 5b) structures. (One-period structure has the 2582 nm GaAs *n-i-p-i* layer and the 2916 nm $Al_{0.3}Ga_{0.7}As$ layer). One can see that the gain is achieved for the 40-period structure exceeds in an order the gain in 1-period structure having the same optical length of active medium. If the excitation level $\Delta F = 1.348$ eV, that corresponds to the peak of transmission $|T|^2 = 5$ for the 1-period structure (Fig. 4), we obtain $|T|^2 \approx 80$ for the 40-period structure at the wavelengths corresponding to the band edges. The gain starts to rise markedly from some a threshold level of excitation. This threshold level for the 1-period structure significantly exceeds the respective values for the 40-period structure.

## 4. Discussion

Thus, the results obtained show that 1D PBG structure with the active *n-i-p-i* layers can be promising for creating miniaturized light sources. The main advantage of the resonator with active medium embedded into periodic multilayer is caused by strong delay of the energy velocity in comparison with the energy velocity in a bulk material or in DFB structure with a slight index modulation [6]. Comparison with one-period structure shows that application of the multiperiod structure allows to reduce the resonator length where threshold of generation can be achieved at the same parameters of active medium and the excitation level. Thus, a laser used the resonator considered can be alternative to the DFB laser whose fabrication is too complicated, quite expensive and low-reproducible.

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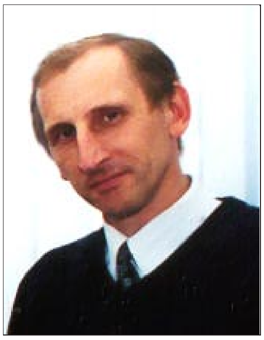

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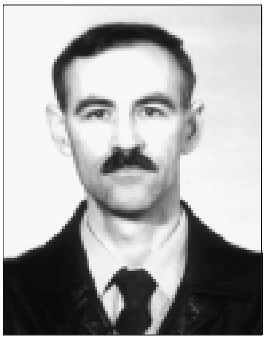

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