Numerical modeling of functionally integrated injection lasers-modulators

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ABSTRACT

Physical-topological model of injection lasers with a functionally integrated optical radiation modulators, allowing to carry out the numerical analysis of transient processes in lasers-modulators taking into account the additional cross-control field and the irregular electrons, holes and photons spatial distributions was proposed. The results of numerical modeling of conventional double heterostructure lasers and functionally-integrated lasers-modulators was presented. The results of numerical modeling and the limits of applicability of the proposed model was analyzed.

Keywords: injection laser-modulator, model, numerical modeling

1. INTRODUCTION

Not high enough efficiency of applying the inter-cores metal interconnections that no longer satisfies the growing demands for speed, energy consumption and noise immunity is one of the problems of increasing the integration degree of modern very large integrated circuits (VLSI) and, in particular, increasing the number of cores on a chip. Leading specialists agree that this problem could be solved by using optical switching integrated systems. One of the major challenges of optical switching integrated systems building is the high-speed optical radiation sources and modulators realization, and its integration on a chip using conventional semiconductor technology [1], [2].

The amplitude modulation is widely used in modern integrated optical switching systems: external - by using modulators, or internal - by controlling the current density of the pump laser. The controlling the current density of the pump modulation dynamics is determined by transients processes in the laser power supply circuit, which limits the maximum modulation frequency. External modulators are also not always meet the requirements for speed and usually implemented on the basis of materials that do not allow to produce them a single technological cycle with integrated semiconductor structures [3].

2. FUNCTIONALLY INTEGRATED INJECTION LASERS-MODULATORS STRUCTURE

In [4] proposed the concept of VLSI building which uniting of silicon-based technologies cores, and optical switching system on the basis of the group $A^{III}B^{V}$ materials as one of the possible approaches to solving this problem, and the implementation of this system is possible in a single technological cycle. To increase the maximum frequency of laser radiation modulation in such optical switching integrated systems in [5], [6], [7] proposed design methods and structures of injection lasers-modulators, which suggesting the functionally integration of the actual laser and modulator (amplitude or frequency) in single nanoheterostructure. The structure of these devices schematically represented in general form in Figure 1.

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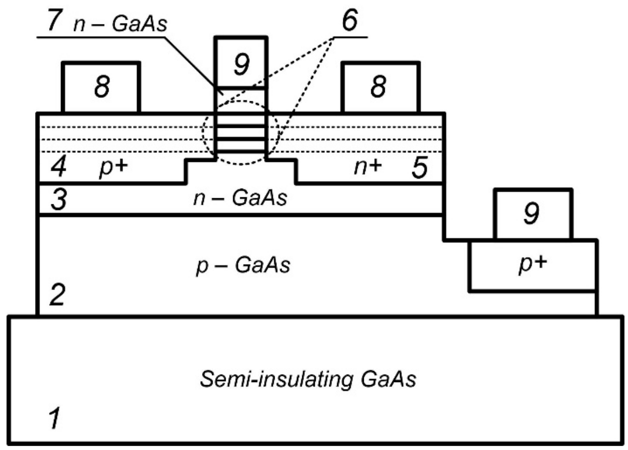


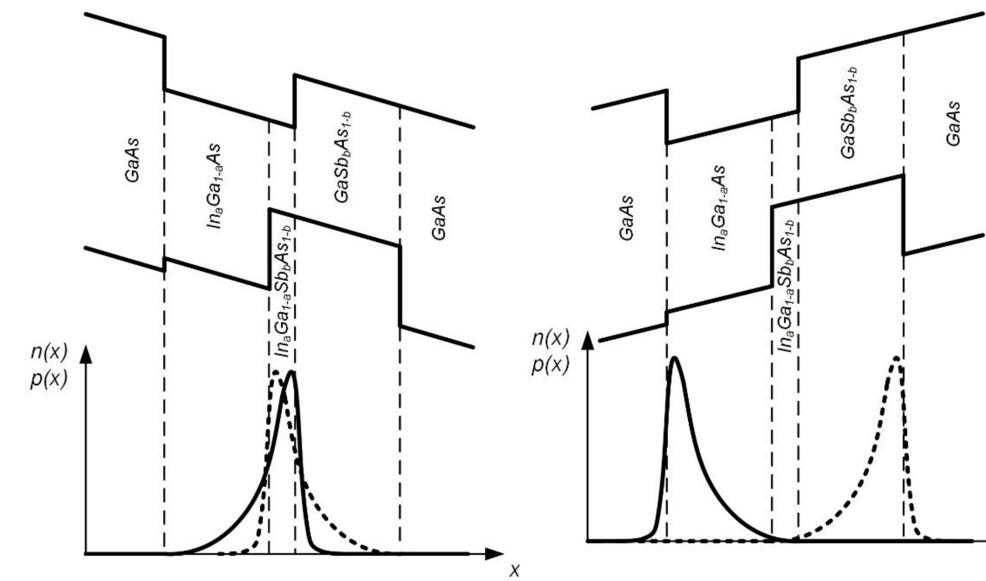
Figure 1. The structure of functionally integrated injection laser-modulator: 1 – semi-insulating GaAs; 2 – p-GaAs; 3, 7 – n-GaAs; 4, 5 – high-alloy p+ и n+-areas; 6 – optical radiation modulator nanoheterostructure (amplitude or frequency); 8 – power contacts; 9 – control contacts [5], [6]

Unlike conventional laser diodes in this injection laser-modulator high-alloy p+ and n+ type regions (Pos. 4, 5) with the appropriate laser power contacts (Pos. 8), the amplitude or frequency modulator heterostructure (pos. 6) with additional control contacts (Pos. 9) and the control junctions (Schottky junction - Pos. 7, 9, and p-n-junction - Pos. 2, 3) are functionally integrated in accordance with Figure 1. That provides the ability to change laser radiation intensity or wavelength depending on the modulation type at a constant laser's pump current by changing the transverse field of additional control contacts (Pos. 9) [5], [6] and [7].

Integrated amplitude modulator band diagram is presented in Figure 2. It comprises two spatially offset potential wells (one in the conduction band and other in the valence band) formed by second type heterojunction. Changing the direction of the transverse field control contacts (Pos. 9 in Figure 1) leads to spatial relocation of electrons and holes maximum densities in potential wells. The potential wells are spatial displaced. Thus maximums of electrons and holes densities are aligned under the direction of the control field corresponding to Figure 2,a, that increases the generated laser radiation intensity, while the opposite direction of the control field corresponding to Figure 2,b, maximums of electrons and holes densities become spatially separated, that reduces the laser beam intensity.

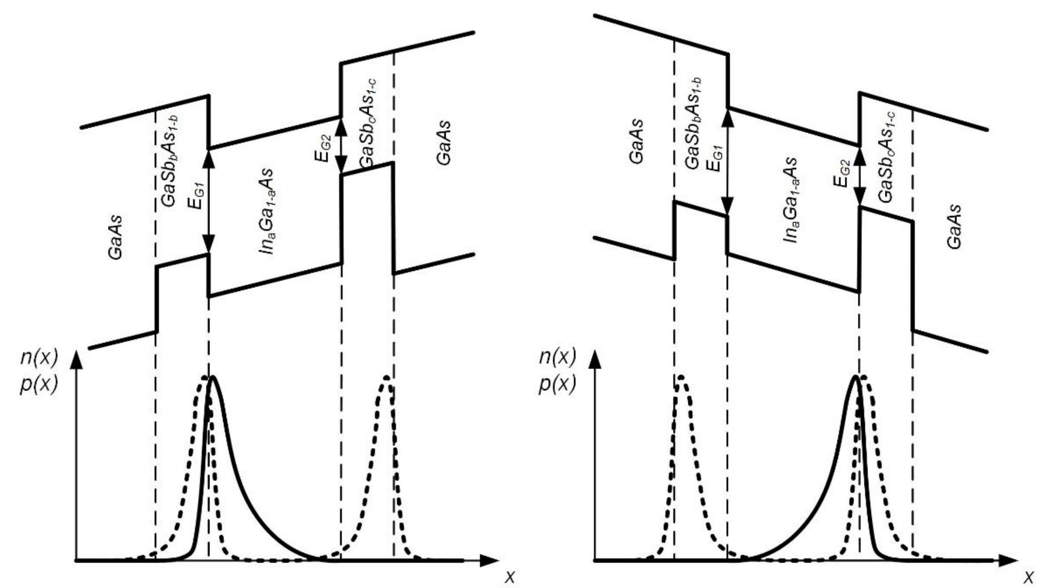
The integrated frequency modulator band diagram represented in Figure 3. It comprises a potential well in the conduction band and two narrower potential wells of varying depth in the valence band formed by the second type heterojunctions. In this case, when control field directed like it shown in Figure 3,a, spatial coincidence of the electrons and the holes densities maximums is happens in potential wells separated by a band gap width E_{G1}, and generation of laser radiation with a wavelength λ_1 in active region is occurs. The opposite directed control field corresponding to Figure 3,b, leads to spatial alignment of the electrons and holes densities maximums in potential wells separated by a band gap width E_{G2}, and thus generation of laser radiation with a wavelength λ_2. Given that the optical radiation spectrum of the functionally integrated laser-modulator comprises emission maximums at wavelengths λ_1 and λ_2, the laser's resonator length must be a multiple of both $\lambda_1/2$, and $\lambda_2/2$ in the case of frequency modulation [7].

Since both the amplitude and the frequency modulation of the optical radiation carried out at constant in time current pump in these lasers-modulators, maximum frequency of modulation is not limited by duration of transient processes in the laser power supply circuit, and determined by the inertia of electrons and holes densities maximums controlled relocation processes in modulator's heterostructure potential wells under the action of transverse field. This allows to predict the possibility of increasing the maximum modulation frequency to terahertz band, which is very important for modern optical switching integrated system in multi-core VLSI.



a b

Figure 2. Band diagrams of the amplitude modulator heterostructure and the electrons n(x) (solid lines) and holes p(x) (dashed lines) density distributions with opposite directions of the control electric field corresponding to a high (a) and low (b) laser radiation intensities



a b

Figure 3. Band diagrams of the frequency modulator heterostructure and the electrons n(x) (solid lines) and holes p(x) (dashed lines) density distributions with opposite directions of the control electric field corresponding to the λ_1 (a) and λ_2 (b) laser wavelengths ($\lambda_1 < \lambda_2$)

3. THE FUNCTIONALLY INTEGRATED LASERS-MODULATORS MODELING

Modeling is one of the main stages of the lasers-modulators development and investigation.

Traditionally, the injection lasers processes dynamics is described by kinetics equations which binding the photons density with the charge carriers concentration in the active region and the current pump density [8], [9]:

$$\frac{dn}{dt} = \frac{j}{eD} - \frac{n}{\tau_S} - v_g g\left(n, n_{ph}\right) n_{ph}; \tag{1}$$

$$\frac{dn_{ph}}{dt} = -\frac{n_{ph}}{\tau_f} + \beta \frac{n}{\tau_S} + v_g g\left(n, n_{ph}\right) n_{ph}, \tag{2}$$

where n is the mobile charge carriers concentration in the laser active region; n_{ph} is the photon density; j is the laser current pump density; t is the time; e is the elementary charge; D is the characteristic size of the laser active region; $g\left(n, n_{ph}\right)$ is the optical gain; β is the spontaneous emission to the laser mode; τ_S is the spontaneous radiative recombination time; τ_f is the photon lifetime in the laser active region; v_g is the photon speed in the laser active region.

The equations (1) and (2) are a system of ordinary differential equations, so it do not take into account a number of factors, which may be important in many cases (and in these lasers-modulators design particularly) to analyze the laser structures characteristics: the difference of electrons and holes concentrations distributions in the laser active region over the coordinates (kinetic equations obtained on the assumption that within the laser active region, the electrons and the holes concentrations are equal), the irregular spatial distribution of electrons, holes and photons concentrations in the active region, characteristics of the current density spatial distribution, the influence of the laser peripheral regions on its characteristics.

There are many different structures of injection lasers, which mathematical modeling requires consideration of their structural and topological features. In the kinetic equations (1) and (2) are usually introduced additional terms and equations for description of individual structural areas of injection lasers, which significantly narrows the range of models applicability [9]. It should also be noted that all of the models obtained on the basis of the kinetic equations describe the transient processes in the laser structures for a given change in time of the pump current and not allow to investigate a predetermined voltage change mode at the contacts.

To solve these problems in this paper we propose a mathematical model derived from the kinetic equations analysis (1), (2) and the fundamental system of equations of semiconductors in a diffusion-drift approximation [10].

In general, the proposed drift-diffusion model of the charge carriers and photons transport in injection lasers can be written as follows:

$$\nabla(\varepsilon \nabla \varphi) = \frac{e}{\varepsilon_0}(n - p - N); \tag{3}$$

$$\frac{dn}{dt} = \nabla\left[\mu_n\left(-n \nabla(\varphi + V_n) + \varphi_T \nabla n\right)\right] - \frac{\sqrt{np - n_i^2}}{\tau_S} - v_g g\left(\sqrt{np - n_i^2}, n_{ph}\right) n_{ph}; \tag{4}$$

$$\frac{dp}{dt} = \nabla\left[\mu_p\left(p \nabla\left(\varphi - V_p\right) + \varphi_T \nabla p\right)\right] - \frac{\sqrt{np - n_i^2}}{\tau_S} - v_g g\left(\sqrt{np - n_i^2}, n_{ph}\right) n_{ph}; \tag{5}$$

$$\frac{dn_{ph}}{dt} = -\frac{n_{ph}}{\tau_f} + \beta \frac{\sqrt{np - n_i^2}}{\tau_S} + v_g g\left(\sqrt{np - n_i^2}, n_{ph}\right) n_{ph}; \tag{6}$$

$$g = \begin{cases} g\left(\sqrt{np - n_i^2}, n_{ph}\right) > 0, \text{при } E_{Fn} - E_{Fp} \geq E_C - E_V; \\ 0, \text{при } E_{Fn} - E_{Fp} < E_C - E_V, \end{cases} \tag{7}$$

where n is the electrons density; p is the holes density; N is the effective concentration of the impurities; n_i is the intrinsic concentration; φ is the electric potential; φ_T is the temperature potential; V_n is the heterostructure potential in the conduction band; V_p is the heterostructure potential in the valence band; ε is the semiconductor permittivity; ε_0 is the vacuum permittivity; E_{Fn}, E_{Fp} are quasi-Fermi levels for electrons and holes; E_C, E_V are "bottom" level of the conduction band and the "top" level of the valence band.

In the proposed model (3) - (7) the kinetic equation (1) for the charge carriers generalized concentration, which assumed that concentrations of electrons and holes in the laser active region are equal is replaced by the continuity equations for electrons (4) and holes (5) of diffusion-drift model, supplemented by the Poisson equation (3) and the equation describing the photon density spatial distribution change in time dynamics (6). In this case we use specified terms describing the spontaneous and stimulated radiative recombination processes taking into account electrons, holes and photons concentrations spatial distribution in the continuity equations for electrons and holes (4), (5) and the kinetic equation for the density of photons (6).

One of the key parameters of injection lasers is the optical gain coefficient g. The dependence of the optical gain on the charge carriers and photons concentration in the laser active region is traditionally determined by the model given in [11]. In the proposed system of equations (3) - (7), the optical gain coefficient is defined similarly to proposed in [11] analytical expressions in which generalized charge carriers concentration (assuming equality $n = p$ in the laser active region) is replaced by the expression $\sqrt{np - n_i^2}$, which determine the degree of electrons and holes concentrations deviations from the equilibrium values the more accurately to account for the influence of the electrons, holes and photons concentrations.

In addition, to study charge carriers and photons transport processes in the entire laser structure, but not only in its active region, the proposed system of equations is supplemented by the expression (7), to determine the optical gain coefficient values spatial distribution depending on the energy levels population inversion condition in various areas of the injection laser.

4. THE RESULTS OF NUMERICAL MODELING DISCUSSION

It is important to determine the applicability limits of the proposed model. Investigation of this problem is made on the basis of the comparative analysis of the conventional injection double heterostructure lasers numerical modeling results obtained using the kinetic equations (1), (2) and the proposed model equations (3) - (7).

The numerical solution of the system (3) - (7) is performed using the finite difference method. The initial condition was obtained by numerical solution of the stationary problem (3) - (7) (for $\frac{\partial n}{\partial t} = \frac{\partial p}{\partial t} = \frac{\partial n_{ph}}{\partial t} = 0$) using the Newton method.

The results of numerical modeling of the transition process in a laser with double heterostructure n+-$Al_{0.3}Ga_{0.7}As$/i-GaAs/p+-$Al_{0.3}Ga_{0.7}As$ with the active region width 50 nm, the photon lifetime in the resonator τ_f = 3 ps, spontaneous radiative recombination time τ_S = 4 ns, spontaneous emission share to the laser mode, $\beta = 10^{-4}$, and duration of the current pump pulse τ_P = 100 ps shows on Figure 4.

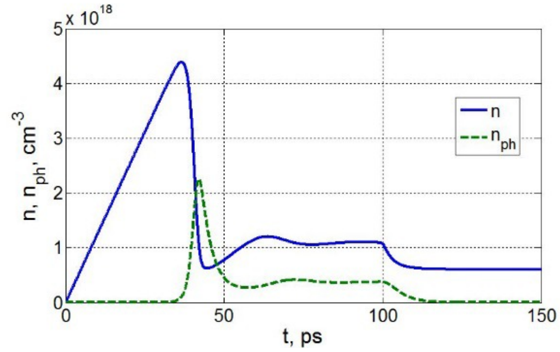
The results shown in Figure 4,a obtained by solving the kinetic equations (1), (2).

Similar results which were obtained by using the proposed model (3) - (7) for different sections of the laser active region, are shown in Figure 4,b,c,d.

It can be seen the almost total correspondence of kinetic equations solving results (Figure 4,a) and the results obtained with the model (3) - (7) for the central section of the laser active region (Figure 4,c), in which the electron and holes equality condition is fulfilled. It is corresponds to the approximation of the kinetic equations (1) and (2). However, for the peripheral sections of the laser active region (Figures 4,b,d) disparity of numerical modeling results exceeds 50%, which caused by significant irregularity of spatial distribution of the electrons, holes and photons concentrations. This is confirmed by the electrons, holes and photons concentration spatial distributions, given on Figures 5 and 6 obtained by numerical solution of the system (3) - (7).

The lasers kinetic equations formulated assuming that then the current pumping density exceeding a threshold value, optical gain g while the transition process flowing changes periodically only in time. Given the irregular electrons, holes and photons spatial distribution, it can be assumed that the optical gain coefficient values in the coordinate within the laser active region can also be distributed irregularly.

The results of numerical modeling obtained using the proposed model (3) - (7), confirm the possibility of the laser optical gain coefficient values periodic changes not only in time but also in the coordinate that allows to analyze the transient processes in laser structures, taking into account this aspect.



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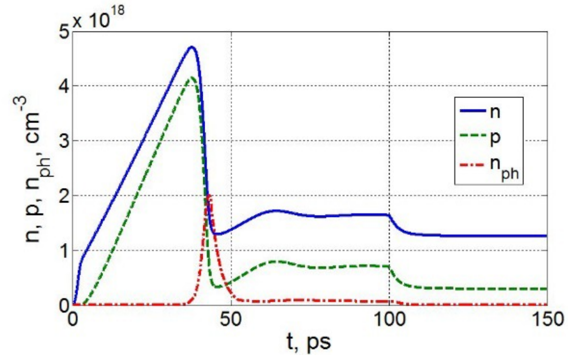

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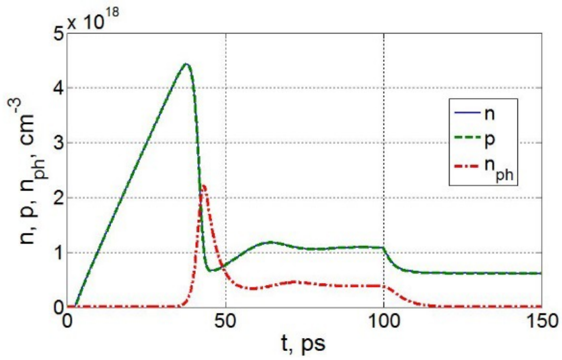

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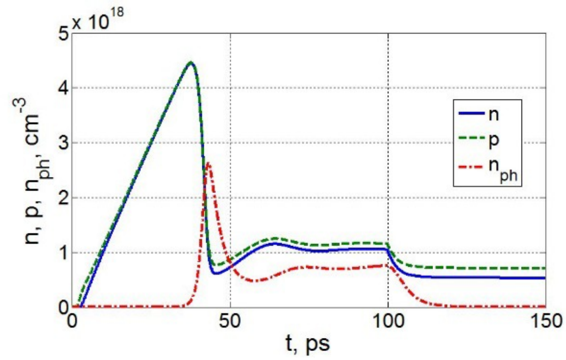


d

Figure 4. The results of the double heterostructure laser transition process numerical modeling obtained by solving the kinetic equations (a) and the equations of the proposed model for the central (c) and peripheral (b, d) cross sections of the active region

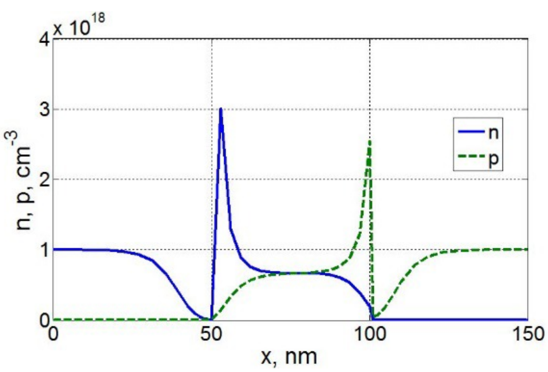


Figure 5. The electron and hole concentrations spatial distribution in the double heterostructure laser 50 ps after the pump current applying

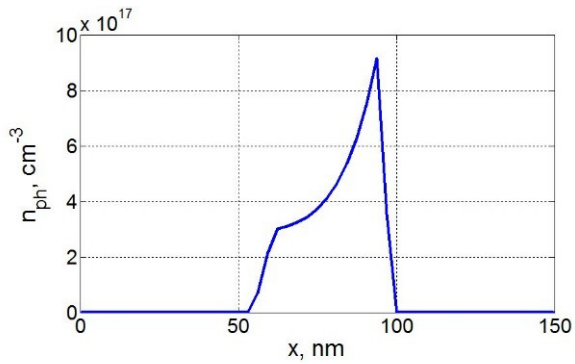
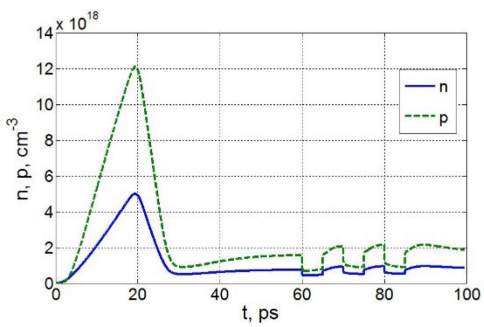


Figure 6. The photons density spatial distribution in the double heterostructure laser 50 ps after the pump current applying

Unlike the kinetic equations (1), (2), equations (3) - (7) allows to study the electrons, holes and photons concentrations spatial distributions change in time dynamics not only in active, but also in the peripheral laser regions. Moreover, depending on the boundary conditions transient processes can be investigated for a given change in time both the pump current and the voltage on contacts. Taking into account the wide range of laser diodes structures, it is important that in the equations (3) - (7) heterostructure potential spatial distributions and dopant profiles are used as input data, which allows to obtain the lasers numerical modeling results considering various structural and topological features, thereby extending the applicability limits of the proposed model.

The results of numerical modeling of the injection laser with a functionally integrated amplitude modulator obtained by solving the system (3) - (7) are shown in Figures 7 - 10. The structure and band diagram of this laser-modulator are shown in Figures 1 and 2.



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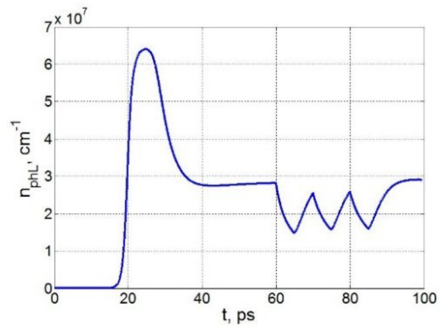

b

Figure 7. The time dependences of the charge carriers concentration in the central section of the active region (a) and the linear density of photons (b) in a laser with a functionally integrated amplitude modulator

Figure 7 shows the transient process in the laser-modulator numerical modeling results obtained for the constant pump current which applied in the initial time, and a series of the 5 ps control pulses, applied to the control contacts of the laser modulator, beginning at the time of 60 ps.

Figure 7,a shows the electrons and holes time dependence in the central section of the functionally integrated laser-modulator active region. Figure 7,b shows the corresponding linear photons density time dependence obtained by the photons volume density spatial distributions integrating on the laser-modulator active region area.

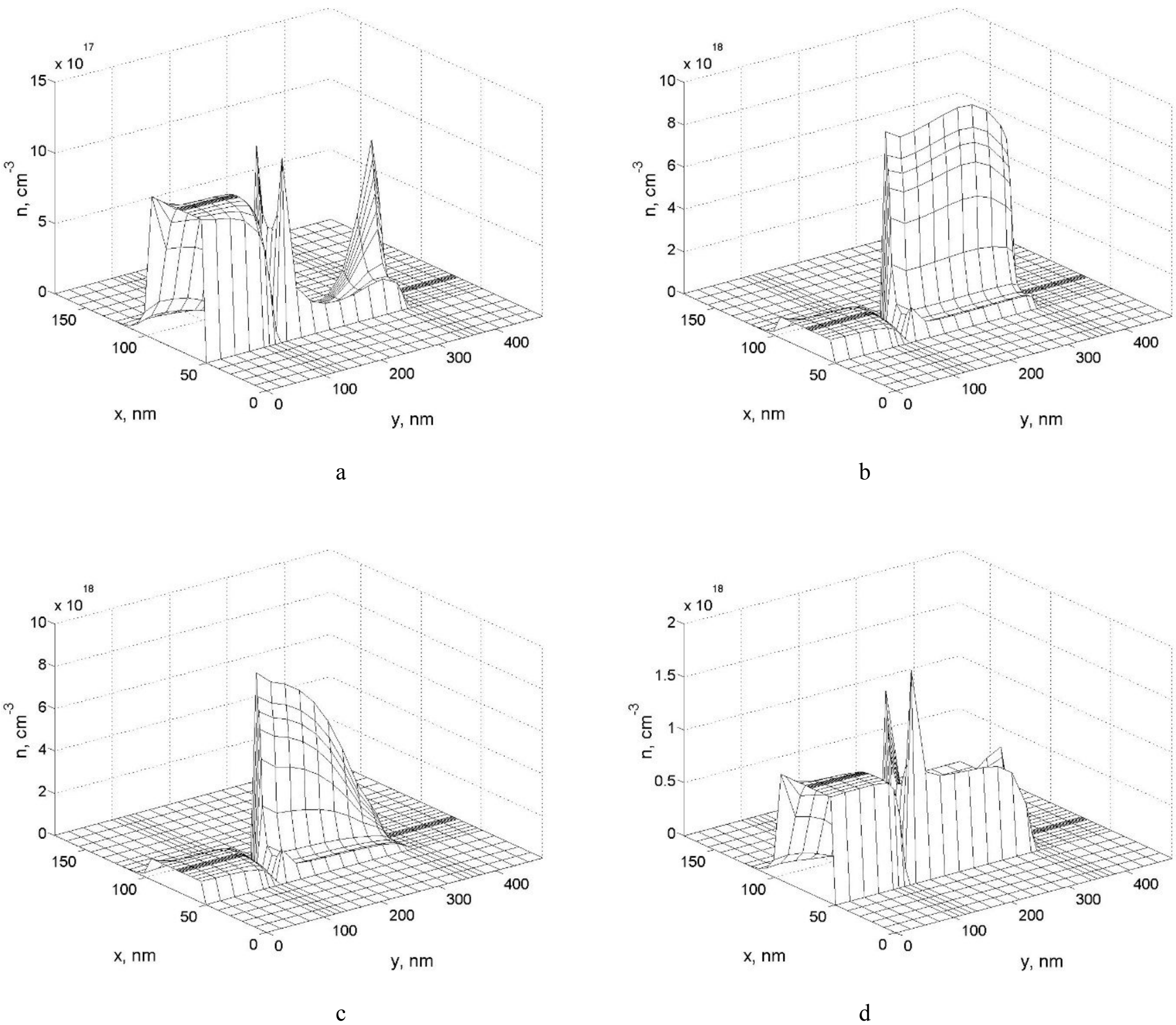

Figure 8. The electrons density spatial distribution in a laser with a functionally integrated amplitude modulator at time points 1.5 ps (a), 19.3 ps (b), 21.3 ps (c), 60.4 ps (d)

In accordance with Figures 7,a,b, by applying the pump current at initial time the transient process in the power circuit of the laser-modulator occurs at the final stage of which (at time 60 ps, when the concentrations of charge carriers and photons change in time are minor) 5 ps pulses are applied on control contacts at constant pump current, leading to the electrons and holes density maximums controlled relocation within the potential wells in amplitude modulator heterostructure (Figure 7, a) and the corresponding changes of the photons linear density (Figure 7, b).

The electrons, holes and photons densities spatial distribution in a functionally integrated laser-modulator at different times of the transition process are shown in Figures 8, 9, 10, respectively. Analysis of the results shows that the additional control contacts and the transverse control field not only significantly increase the irregularity of electrons, holes and photons densities spatial distribution in the laser-modulator active region in comparison with conventional injection lasers, but also changes the nature of this irregularity in coordinate and time.

Time dependences of the charge carriers concentrations shown on Figure 7,a, suggest that the duration of both electrons and holes maximums concentrations redeployment which controlled by transverse electric field in the amplitude modulator heterostructure potential wells is extremely small and does not exceed 0.1 ps. It is allows to increase the control voltage modulating maximum frequency to a 1 – 3 terahertz. However, in accordance with Figure 7,b, photons density variations inertia time in the active region of the laser-modulator is more than 50 times more than the inertia of the charge carriers controlled relocation in the potential wells. It is greatly limits the optical radiation maximum modulation frequency and can be explained by the photons long lifetime in the laser cavity (τ_f = 3 ps).

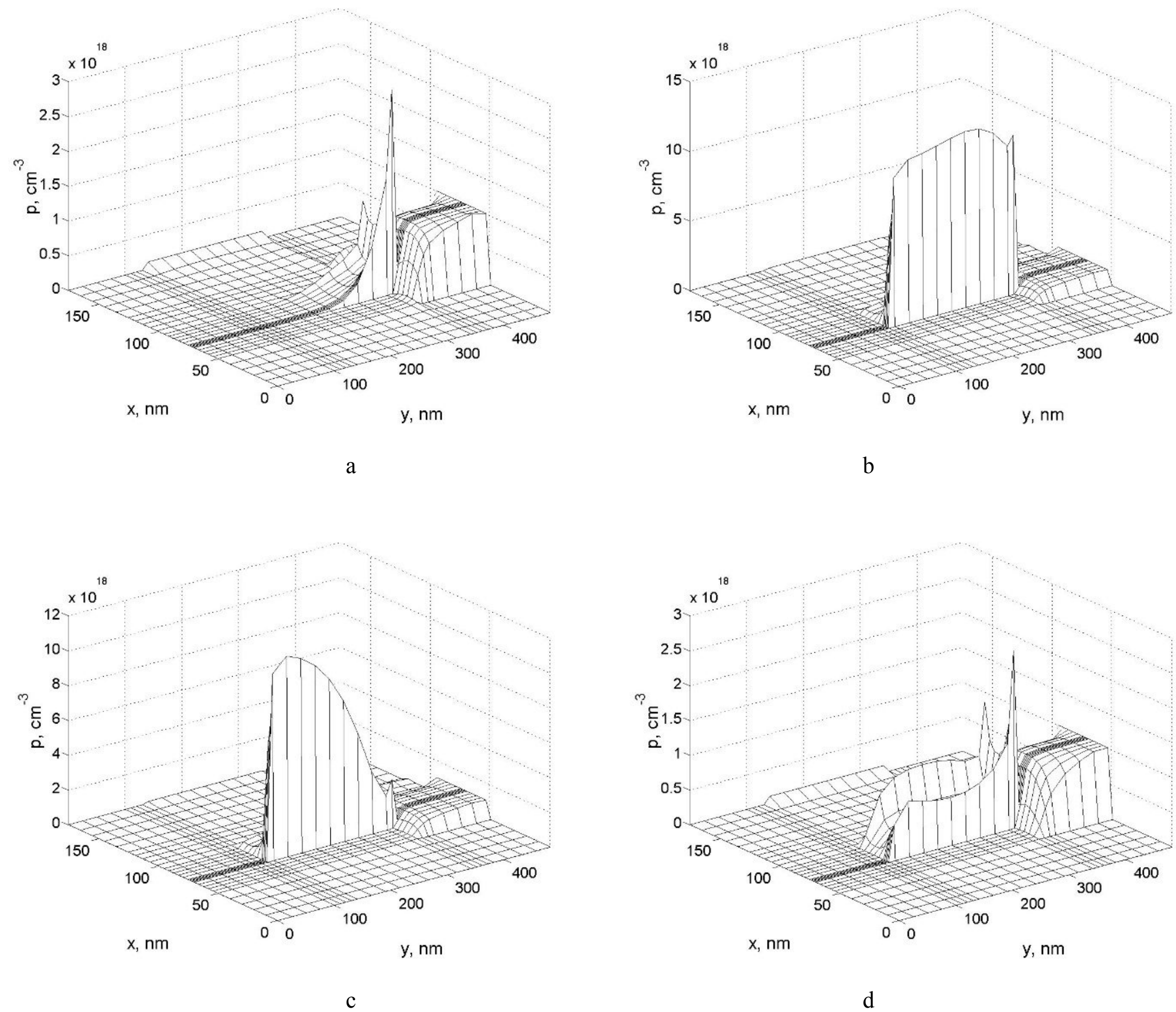

Figure 9. The holes concentration spatial distributions in a laser with a functionally integrated amplitude modulator at time points 1.5 ps (a), 19.3 ps (b), 21.3 ps (c), 60.4 ps (d)

To solve this problem it is necessary to reduce the photons lifetime in the laser-modulator active region. It can be achieved by changing the parameters of the resonator mirrors, but this would lead to an undesirable increase of the threshold current density and power dissipation, which is especially critical for integrated optical switching systems VLSI lasers-modulators. Thus, the functionally integrated laser-modulators parameters optimization allowing to achieve the specified performance of speed and power is an actual challenge that can be solved using the model proposed in this paper (3) - (7).

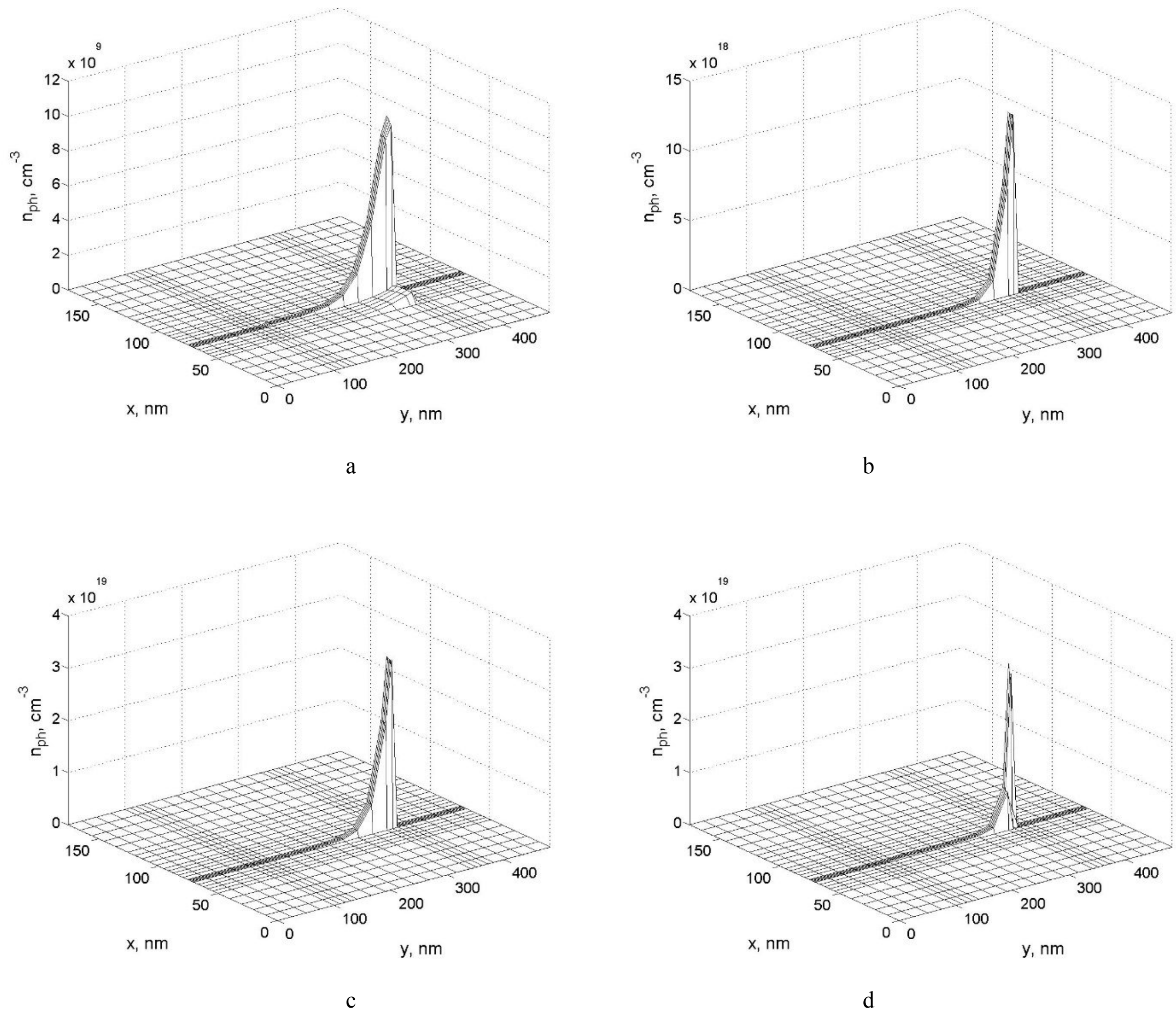

Figure 10. The photons density spatial distribution in the laser with a functionally integrated amplitude modulator at time points 1.5 ps (a), 19.3 ps (b), 21.3 ps (c), 60.4 ps (d)

5. CONCLUSION

Designed injection lasers with a functionally integrated optical radiation modulators represent a new class of semiconductor integrated optoelectronics devises. The principles of functioning and features of the lasers-modulators structures do not allow use kinetic equations (1) and (2) for occurring processes modeling due to their inherent limitations.

The proposed physical-topological model (3) - (7) of injection lasers with a functionally integrated optical radiation modulators, allows to perform the numerical analysis of transient processes in lasers-modulators with the additional transverse control field and the irregular electrons, holes and photons spatial distributions in the laser active and peripheral regions, as well as with the structure characteristics and the laser-modulator band diagram and the irregular current density spatial distribution.

The comparative analysis of the injection lasers with double heterostructure numerical modeling results suggest that in some cases the equations (3) - (7) should be used for the modeling of transient processes in conventional injection lasers, particularly in cases, when the conditions of the modeling problem require consideration of the above factors (or some of them).

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