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EFFECT OF PULSED HEATING OF THE ACTIVE REGION OF AN INJECTION LASER ON THE DYNAMICS OF STORAGE OF A PULSE INFORMATION SEQUENCE IN AN ELECTROOPTICAL RECIRCULATION CIRCUIT

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With account for the effect of a residual charge, a theoretical analysis is carried out of the effect of pulsed heating of the active region of an injection laser on the dynamics of storage of a pulse information sequence in a closed electrooptical circuit consisting of an injection laser, a fiber-optic light guide, and a regenerator based on a threshold shaper. Results on the time of storage of information in the circuit for different kinds of storage devices are obtained.

In a large number of practical applications (analysis of fast processes, monitoring of the environment, etc.) storage of small collections of information contained in a sequence of closely spaced pulses can be effected using fiber-optic storage devices that consist of an injection laser, a fiber-optic light guide, an avalanche photodiode, and a regenerator – all set up to complete a ring. The information in this kind of fiber-optic storage device is contained in the time intervals between the pulses of the sequence, and its storage is effected due to the recirculation of the pulse sequence in a closed circuit. Systems of this kind can be used for storing not only digital but also analog information (analog fiber-optic memory [1], digital bit-serial memory [2]). The drawback of these devices is the loss (decay) of information due to the deformation of the pulse sequence in the process of storage. The deformation is caused by distortions of the pulse sequence during conversion of "current–light" signals in the injection laser and during inverse conversion in the avalanche photodiode and also during propagation of the sequence in the fiber-optic light guide. The distortions are, in turn, associated with dynamic effects occurring in the injection laser during high-rate modulation of the injection current and also with the dispersion of the propagation of pulsed radition in the fiber-optic light guide. The effect of these factors on the dynamics of storage of pulse information sequences was already investigated in a number of works (see, e.g., [3, 4]). However, up to the present time the literature lacks mathematical models for investigating the dynamics of storage of pulse information sequences for both analog and digital fiber-optic storage devices with account for the simultaneous influence of temperature and dynamic effects in an injection laser. The present work is devoted to the study of the effect of heating of the active region of an injection laser on the dynamics of recirculation of a pulse sequence in a fiber-optic storage device with account for the accumulation of charge from the previous pulse of injection.

The dynamics of the interaction of temperature and dynamic effects in an injection laser consists of the following. During the pumping current pulse a laser crystal is heated, and after the termination of the pulse, the temperature of the active region of the laser is decreased. By the time of the arrival of the next pulse, the temperature of the active region has no time to regain the initial value. As a result, the increase in the temperature entails an increase in the threshold current of the injection laser for the given pumping pulse,

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and this leads to an increase in the delay between the pumping current pulse and the radiation pulse and, consequently, to an increase in the time interval between circulating pulses. On the other hand, when a fiber-optic storage device stores pulses with the time intervals between them $T < [(2-5)\tau_{sp} + \tau_p]$, the dynamics of lasing in the injection laser is influenced by the residual charge from the previous excitation pulse, which leads to a shortening of the time interval between circulating pulses [3]. Because of the residual charge left from the previous pumping pulse, the threshold current for the subsequent pulse turns out to be smaller. The delay in laser generation for this pulse is decreased, and the amplitude of the stimulated radiation pulse is increased. In regenerative storage of a pulse sequence, the time interval between closely spaced pulses will shorten at each cycle of recirculation because of the effect of the residual charge, and this can lead to the merging of pulses.

Thus, when closely spaced pulses are stored in a fiber-optic storage device, effects are observed in an injection laser that exert the opposite influence on the time interval between pulses.

To analyze the dynamics of the change in the time interval, the interval $T^N_{j,\,j+1}$ between the jth and the $(j+1)$th pulses on the Nth cycle of recirculation is determined, as in [4], in the following way:

$$T^N_{j,j+1} = T^{N-1}_{j,j+1} - \tau^N_j + \tau^N_{j+1}\,, \quad j = 1, \ldots, m-1\,. \tag{1}$$

Expression (1) is a recurrent equation. In solving this equation for each recirculation cycle, it is possible to follow the dynamics of change in the time interval in the process of storage. We assume that in the initial time instant all the intervals $T_{j,\,j+1}$ are equal to some initial values $T^{\mathrm{in}}_{j,\,j+1}$.

Using [5], we write the dependence of the delay for the jth pulse in the Nth recirculation cycle τ^N_j on the pumping regime of the injection laser, the avalanche photodiode parameters, the fiber-optic light guide, and the threshold of the regenerator response in the form

$$\tau^N_j = \tau^N_{\mathrm{sp}j} \ln \frac{I}{I - (I^{N\Sigma}_{\mathrm{thr},j} - I_0)} + \frac{U_{\mathrm{thr}}\tau_{\mathrm{fr}}}{[I - (I^{N\Sigma}_{\mathrm{thr},j} - I_0)]\, \eta_{\mathrm{las}}\, \eta_{\mathrm{phr}} R_{\mathrm{load}} KM}\,. \tag{2}$$

In Eq. (2), the first term describes the delay of stimulated radiation in the injection laser and the second the delay in the response of the threshold shaper of the regenerator if it is assumed that the front of increase of the pulse from the avalanche photodiode is linear. The period of one cycle of recirculation T_{rec} for each pulse is determined by the length of the fiber light guide L, the magnitude of the delay determined from (2), and the delay in the propagation of electric signals in the elements of the fiber-optic storage device.

According to [5], for the temperature range 240–340 K the time dependences of the generation threshold and spontaneous lifetime of nonequilibrium charge carriers in the injection laser are represented in the form

$$I_{\mathrm{thr}}(\Theta) = I_{\mathrm{thr}0} \exp[\Theta(t)/\Theta_0]\,, \tag{3}$$

$$\tau_{\mathrm{sp}}(\Theta) = \tau_{\mathrm{in}} - k_{\mathrm{las}}[\Theta(t) - \Theta_{\mathrm{in}}]\,. \tag{4}$$

From the experimental data of [4], we have $I_{\mathrm{thr}0}$ = 2.8 mA, Θ_0 = 120 K, τ_{in} = 2 nsec, $k_{\mathrm{las}} = 3.6 \cdot 10^{-11}$ sec/K, and Θ_{in} = 293 K.

To solve problem (1)–(4), it is necessary to find the time dependence of the change in the temperature of the active region of the injection laser by solving the heat-conduction equation. For this purpose, we use a one-dimensional nonstationary thermal model of an injection laser ignoring the nonuniformity of pumping in the plane of the p–n transition. This model allows one to calculate temperature profiles in a laser crystal and during heat removal under boundary conditions that approximate the experimental ones.

We considered a GaAs/AlGaAs injection laser based on a double heterostructure with a lateral optical restriction [6] and a radiation wavelength of 825 nm. The calculation was performed for the case where the structure was mounted on a heat sink by the method of soldering. It is shown in [6] that the influence of the solder material and its thickness (1–10 μm) on the temperature of the active region is insignificant; therefore, this layer in the structure of the injection laser was not considered.

Since the density of heat sources in the active region is, at a minimum, one and a half or two orders of magnitude in excess of the density of heat sources in other layers [7], the distribution of temperature in the layers can be described by nonstationary heat-conduction equations of the following form (for the active layer and for the remaining layers, respectively):

$$C_i\,\rho_i \frac{\partial \Theta_i}{\partial t} = k_i \frac{\partial^2 \Theta_i}{\partial x^2} + P\,, \quad C_i\,\rho_i \frac{\partial \Theta_i}{\partial t} = k_i \frac{\partial^2 \Theta_i}{\partial x^2}\,. \tag{5}$$

We assume that the coordinate x is directed normally to the heterostructure layers and that it changes from zero to l. In solving this equation, an assumption is made that in the plane of the p–n transition the structure is not bounded, the parameters C_i, ρ_i, and k_i are independent of the time, coordinate, and temperature, and that P is independent of the coordinates y and z. It is assumed that heat sources are uniformly distributed in the active region of the crystal. In Eqs. (5), the subscripts i denote the following layers of the laser crystal: heat sinks (1 and 7), contact layer (2), bounding layers (3 and 5), active layer (4), and backing (6).

Equations (5) were solved under the initial condition $\Theta_i(x, 0) = \Theta_{in} = 293$ K. As boundary conditions, it was assumed that the outer surfaces of the heat sinks were maintained at a constant temperature of $\Theta_{in} = 293$ K.

The condition of continuity of the functions $\Theta(x, t)$ and $\frac{\partial \Theta}{dx}(x, t)$ yields the following conditions of conjugation on the boundaries of the layer:

$$\Theta_i\,(x, t)\big|_{x=x_i-0} = \Theta_{i+1}\,(x, t)\big|_{x=x_i+0}\,, \quad k_i \frac{\partial \Theta_i}{\partial x}\,(x, t)\Bigg|_{x=x_i-0} = k_{i+1} \frac{\partial \Theta_{i+1}}{\partial x}\,(x, t)\Bigg|_{x=x_i+0}\,.$$

The main heat sources in the active region of the injection laser are related to the nonradiative recombination and absorption of radiation; using [7], we can write their density as

$$P = \frac{U}{V_{las}} \left\{ I_{thr}\,(1 - f_{sp}\eta_{sp}) + (I + I_0 - I_{thr})\,[1 - \eta_{las} - (1 - \eta_{int})\,\eta_{sp} f_{sp}] \right\}. \tag{6}$$

The coefficient f_{sp} describes that part of spontaneous radiation which penetrates into the passive layers of the laser. It can be evaluated from the formula

$$f_{sp} \approx 2 \sin^2 \left[\frac{1}{2} \arcsin \left(1 - 0.62 \frac{\Delta x_{Al}}{n_{las}} \right) \right].$$

The calculations were carried out at $U = 1.7$ V, $V_{las} = 7.5 \cdot 10^{-16}$ m^3, $\eta_{sp} = 0.5$, $\eta_{las} = 0.25$, and $\eta_{int} = 1$. The refractive index of the material in the active region was calculated from the expression $n_{las} = 3.59 – 0.62 x_{Al}$.

The parameters of the layers used in the calculations were obtained from the data of [6]. The system of equations (5) was solved numerically using the standard procedure of the grid method.

The threshold current of the injection laser for the first pulse in the information sequence (denoted as I_{thr1}) can be determined from the relation [8]

$$I_{thr1} = I_{thr}^{st} / [1 - \exp\,(-\tau_p / \tau_{sp})]\,. \tag{7}$$

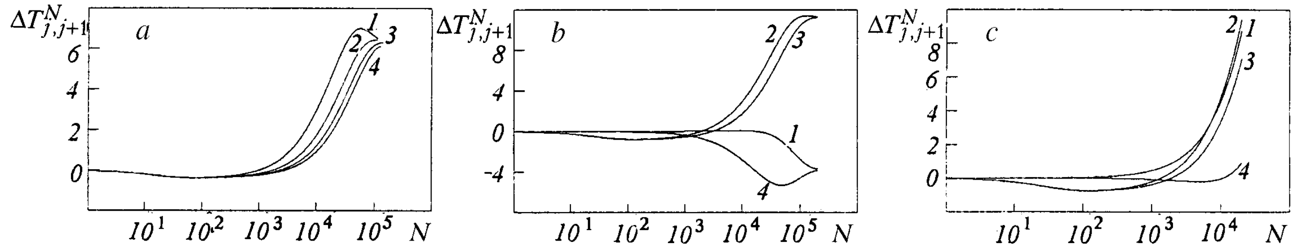


Fig. 1. Calculated dependences of the increment of the value of time intervals $\Delta T^N_{j,j+1}$, relative to the initial values of $T^{\text{in}}_{j,j+1}$, on the number of the recirculation cycle N: 1) ΔT^N_{1-2}; 2) ΔT^N_{2-3}; 3) ΔT^N_{3-4}; 4) ΔT^N_{4-5}; $\Delta T^N_{j,j+1}$ nsec.

For the pumping current pulse that immediately follows the previous one ($T < [(2-5)\tau_{\text{sp}} + \tau_{\text{p}}]$), the threshold current I_{thr2} turns out to be smaller due to the accumulation of the charge from the previous excitation pulse and can be determined from the expression [9]

$$I_{\text{thr2}} = \frac{I^{\text{st}}_{\text{thr}}}{[1 - \exp(-\tau_{\text{p}}/\tau_{\text{sp}})]\,[1 + \exp(-(T - \tau_{\text{p}})/\tau_{\text{sp}})]}\,. \tag{8}$$

For the Nth cycle of recirculation, Eqs. (7) and (8) yield the expression for the magnitude of the threshold current of the $(j+1)$th pulse caused by the residual charge of the jth pulse $I^N_{\text{thr},\,j+1}(q)$ in the form

$$I^N_{\text{thr},j+1}(q) = \frac{I^N_{\text{thr},j}}{1 + \exp(-(T_{j,j+1} - \tau_{\text{p}})/\tau_{\text{sp}})}\,. \tag{9}$$

The resultant threshold current caused by the joint influence of temperature and dynamic effects in the injection laser was calculated as the mean of the values $I^N_{\text{thr},\,j+1}(\Theta)$ and $I^N_{\text{thr},\,j+1}(q)$. The resulting value of $I^{N\Sigma}_{\text{thr},\,j+1}$ was substituted into expression (2), and then the time interval between the jth and $(j+1)$th pulses at each cycle of recirculation was determined from formula (1).

The following parameters for the elements of the fiber-optic storage device were used in the calculations: $I^{\text{st}}_{\text{thr}} = 31$ mA at $\Theta_{\text{in}} = 293$ K, $I = 17$ mA, $I_0 = 0.9I_{\text{thr}}$, $\eta_{\text{phr}} = 0.6$, $R_{\text{load}} = 50\ \Omega$, $U_{\text{thr}} = 8$ mV, $M = 10$, $\tau_{\text{p}} = 5$ nsec, and $\tau_{\text{fr}} = 2$ nsec; the losses in the fiber-optic light guide at a wavelength of 0.82 μm were equal to 4.5 dB/km; the losses on joining by means of adapters were 5 dB per connection.

Figure 1 presents the calculated results for the dynamics of the change in the time intervals between five pulses of length 5 nsec for the analog case (when the magnitude of the time interval may take a continuous series of values). First, the changes in the time interval were calculated for identical initial periods $T^{\text{in}}_{1-2} = T^{\text{in}}_{2-3} = T^{\text{in}}_{3-4} = T^{\text{in}}_{4-5} = 15$ nsec for a fiber-optic light guide of length 20 m (Fig. 1a). During the first 1000 circulations, the time intervals between pulses changed (were decreased) mainly due to dynamic effects in the injection laser; thereafter the heating of the active region of the injection laser became predominant, and the time intervals between pulses began to increase. After 10^5–10^8 circulations, the deformation of the pulse sequence stopped and stationary oscillations were observed in the circuit, with the period between pulses increasing by 6 nsec in comparison with the initial one.

At the next stage of the investigations, simulation of the change in the duration of the time intervals depending on the number of circulations was carried out, provided that at the initial instant of time the pulse sequence had the form $T^{\text{in}}_{1-2} = 30$ nsec, $T^{\text{in}}_{2-3} = 15$ nsec, $T^{\text{in}}_{3-4} = 15$ nsec, and $T^{\text{in}}_{4-5} = 30$ nsec. The simulation of the dynamics of storage of such a sequence was performed for fiber-optic light guides of lengths 20 m (Fig. 1b) and 300 m (Fig. 1c). From the analysis of the curves in Fig. 1b obtained for the case where the

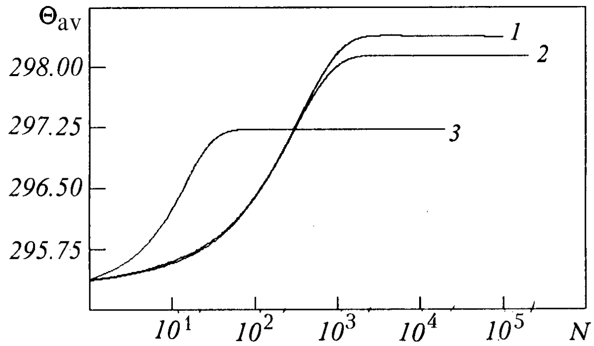
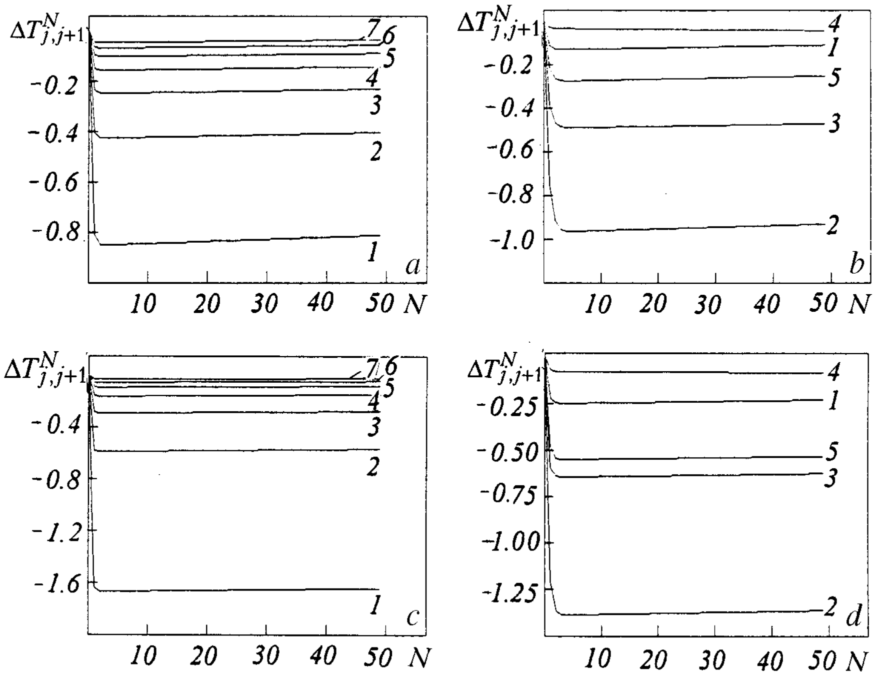


Fig. 2. Dynamics of the change in the average (for the period of recirculation) temperature of the active region of the injection laser Θ_{av} with the number of the recirculation cycle for different information sequences. Θ_{av}, K.

initial state of the injection laser at the $(j+1)$th cycle of recirculation depended on the regime of its excitation at the jth cycle (i.e., by the beginning of the pulse sequence at each subsequent cycle of recirculation the initial state is not recovered), it is seen that the information in such a fiber-optic storage device during a period of $2 \cdot 10^3$ recirculation cycles is preserved. Thereafter, the time intervals between pulses are compared during nearly the same number of cycles, and the information turns out to be lost. Figure 1c presents the results on simulation of the dynamics of storage of pulse sequence when the time interval between circulating pulse sequences is commensurable with the characteristic time of system relaxation to the initial state. In this case, just as in the previous one, the information is stored during approximately $2 \cdot 10^3$ circulations, and thereafter a nonuniform increase in all of the time intervals is observed. Comparison of the results presented in Fig. 1b and c shows that storage of analog signals in such fiber-optic storage devices is possible, with an accuracy not worse than 1%, during $\sim 10^3$ circulations; moreover, the time of storage of the pulse sequence t_{stor} can be changed by selecting the length of the fiber-optic light guide (e.g., t_{stor} = 135 μsec for L = 20 m (Fig. 1b) and t_{stor} = 1.5 msec for L = 300 m (Fig. 1c)).

The dynamics of the change in the circulation-period mean temperature of the active region of a laser crystal is presented in Fig. 2. Curve 1 corresponds to the case of equal intervals between pulses (Fig. 1a); curve 2 is for the sequence with variable initial time intervals and for the fiber-optic light guide of length 20 m (Fig. 1b), and curve 3 is for the same sequence in a light guide 300 m in length (corresponds to Fig. 1c). It is seen that in 300 μsec a stable temperature is established in the active region of the injection laser. However, approximately for the same time the information in the fiber-optic storage device has been virtually completely destroyed. Consequently, to be able to store a new collection of information during $2 \cdot 10^3$ cycles it is necessary to have a time interval of about 300 μsec for the establishment of the initial temperature state in the fiber-optic storage device or organization of recirculation with the same interval between the sequences at the expense of the fiber-optic light-guide length. In both cases, this factor limits the frequency of recording/reading information in such a fiber-optic storage device.

Let us consider the case of a digital fiber-optic storage device (when the information is coded in the following way: the presence of a pulse in a prescribed clockwise time interval T_{clock} is taken to be 1 and its absence to be "0"). Of greatest interest is the case where the information parameters of the fiber-optic storage device are limited by noises in the circuit [10]. Consider a fiber-optic storage device with the following parameters: time of storage of information with a probability of error not worse than 10^{-9} for 10 sec, speed of information arrival S_{inf} = 240 Mbits/sec for pulses of length τ_0 = 3 nsec and S_{inf} = 310 Mbits/sec for τ_0 = 2 nsec (for both cases the initial ratio of the informational time interval to the duration of circulating pulses is 1.5). A fiber-optic storage device with such parameters is capable of solving the problem of dynamic storage of information, for example, in a high-speed lidar used for diagnosing the environment. For a fiber-optic stor-



Fig, 3. Calculated dependences of the increments of time intervals between information pulses $\Delta T^N_{j,j+1}$ in storing 8 bits of digital information on the number of the recirculation cycle: a and c) 11111111; b and d) 10111011. Curves 1–7 correspond to the change of the time intervals $T_{j,j+1}$ between the jth and $(j+1)$th pulses, where j = 1, ..., 8; a and b) τ_0 = 3 nsec, S_{inf} = 220 Mbits/sec (T_{clock} = 4.5 nsec); c and d) τ_0 = 2 nsec; S_{inf} = 330 Mbits/sec (T_{clock} = 3 nsec). $\Delta T^N_{j,j+1}$, nsec.

age device with the above characteristics, Fig. 3 demonstrates the change in the time intervals between information pulses due to dynamic and temperature effects in an injection laser when two different 8-bit words are stored. Calculation with the use of model (1)–(4) showed that the smallest spacing between pulses in the first case (S_{inf} = 240 Mbits/sec, τ_0 = 3 nsec) is 0.9 nsec and in the second case is 1.6 nsec. Thus, to provide the above-indicated information parameters of a fiber-optic storage device in the case of simultaneous influence of temperature and dynamic effects in an injection laser it is necessary to enlarge the clockwise interval by 0.9 and 1.6 nsec, respectively. Then, for τ_0 = 3 nsec the maximum speed of arrival of information will be equal to 185 Mbits/sec, and for τ_0 = 2 nsec $S_{\text{inf}} \le 220$ Mbits/sec. The simultaneous influence of the heating of the active region and of dynamic effects in the injection laser leads to a decrease in the volume of memory of the fiber-optic storage device by 25%. With decrease in the duration of circulating pulses the dynamic effects (cf. Fig. 3a and c) are stronger, since the compensating effect of the heating of the active region of the injection laser is lessened.

Thus, account for the simultaneous influence of heating of the active region and of dynamic effects in an injection laser gives new characteristics in the change in time intervals in an information pulse sequence in the process of recirculation. In this case, in recirculation of adjacent pulses, instead of monotonically approaching each other in the fiber-optic storage-device circuit (as is the case where only dynamic effects are taken into account), they cease to approach each other with increase in the temperature of the crystal, and, thereafter, the increase in the time interval between pulses is also ceased. This fact must be taken into account in optimization of the fiber-optic storage device by the time of storage and amount of information stored. The results considered can be obtained in designing different-purpose fiber-optic storage devices and evaluation of their operational parameters.

NOTATION

τ_{sp}, spontaneous lifetime of nonequilibrium charge carriers in a laser; τ_p, duration of pumping current pulses of an injection laser; N, the number of cycles (the number of the cycle) of recirculation; m, number of recorded pulses; τ_j^N, delay of the jth pulse in the Nth cycle of recirculation depending on the conditions of injection laser generation and parameters of the threshold device; $\tau_{sp,j}^N$, spontaneous lifetime of charge carriers for the jth pulse in the Nth cycle of recirculation; T, the magnitude of the time interval; I, amplitude of the pumping current pulse of the injection laser; I_0, constant bias current; I_{thr}, threshold current of the injection laser; $I_{thr,j}^{N\Sigma}$, resultant threshold current of the injection laser for the jth pulse in the Nth cycle of recirculation; U_{thr}, threshold of response of the regenerator; τ_{fr}, duration of the pulse front at the exit of the photoreceiver; η_{phr}, quantum efficiencies of the photoreceiver; R_{load}, the magnitude of the loading resistance of the avalanche photodiode; M, coefficient of avalanche multiplication of avalanche photodiode; K, coefficient of transmission of radiation from an injection laser to the receiving area of the avalanche photodiode; it takes into account the losses on joining also in propagation of it along the fiber-optic light guide; $K = 10^{-0.1(k_1+k_2+k_3L)}$; k_1, k_2, and k_3, coefficients of laser radiation attenuation in input–output and in the fiber-optic light guide itself; L, length of the fiber-optic light guide; Θ, absolute temperature; t, time; I_{thr0}, Θ_0, k_{las}, parameters of the approximation of the functions $I_{thr}(\Theta)$ and $\tau_{sp}(\Theta)$; τ_{in}, spontaneous lifetime of nonequilibrium charge carriers at $\Theta = \Theta_{in}$; Θ_{in}, the value of the temperature of the active region at the initial time instant; C_i, heat capacity; ρ_i, density of the layer material; k_i, thermal conductivity of the layer; P, density of heat sources; V_{las}, volume of the active region; l, length of the laser crystal; U, voltage drop at the p–n transition; η_{sp}, η_{las}, and η_{int}, internal quantum efficiency of spontaneous emission, external differential quantum efficiency, and internal quantum efficiency of the injection laser radiation, respectively; n_{las}, refractive index of the material of the active region; Δx_{Al}, difference in the content of Al in a limiting layer and in the active region; x_{Al}, fraction of Al in the active region; I_{thr}^{st}, threshold current of the laser for the stationary regime of operation; τ_0, duration at half-height of the optical pulse generated by the injection laser; $T_{j,j+1}$, time interval between the jth and $(j+1)$th pulses; $\Delta T_{j,j+1}^N$, increment of the value of the time interval between the jth and $(j+1)$th pulses in the Nth cycle of recirculation relative to the initial value; t_{stor}, time of storage of information; S_{inf}, speed of entry of the information flux; T_{clock}, value of clockwise time interval. Subscripts: sp, spontaneous; thr, threshold; rec, recirculation; load, loading; las, lasing; fr, front; p, pulse; inf, information; int, internal; clock, clockwise; i, number of layers of the laser crystal. Superscript: in, initial.

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