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REVIEW

METHODS OF THERMOSTABILIZATION OF THE RADIATION POWER OF PULSED INJECTION LASERS

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Operating and thermal characteristics of the most popular types of pulsed injection lasers (ILs) are presented; reasons for and mechanisms of the temperature dependence of their radiation power are briefly considered. The simplest methods of stabilization of the injection-laser power, based on control of the laser pumping depending on the ambient temperature, compensation for the temperature change in laser parameters, and maintenance of the laser-crystal temperature at a constant level are analyzed. As the most perfect, methods of thermostabilization of injection lasers based on the use of photoelectric feedback and methods based on the principle of discrimination of pulsed signals by the criterion of priority of their arrival are investigated in greater detail. Methods of protection of the laser crystal against thermal overloads and injection-current surges are considered briefly.

Injection lasers are finding increasing use in range-finder and location systems [1, 2]. Considerable study is being given to the problem of application of injection lasers as sources of optical pumping of solid-state lasers as well as of atoms of alkaline metals (Na, Rb, Cs) and alkaline-like ions (Be^+, Ba^+) for the development of a new generation of quantum frequency standards with improved characteristics [3, 4]. The use of injection lasers in optoelectronic systems of transmission and processing of data [5, 6] has become traditional. In the indicated cases of application of injection lasers, the stability of the radiation power of the source is determined significantly by the accuracy and operating characteristics of a laser information-measuring system (LIMS) based on an injection laser.

The expediency of the wide use of injection lasers in laser information-measuring systems is attributed to a number of their positive properties. Injection lasers can compete with many lasers in the level of output power. The radiation power of commercial injection lasers operating in the continuous mode is higher than, for example, the power of He–Ne lasers, and it is capable of reaching tens and thousands of watts in the pulsed mode [2, 3, 7]. Injection lasers have a high efficiency, a low lasing threshold, and a service life sufficient for practical applications (about 10^5 h) [8, 9]. Different types of injection lasers operate in spectral ranges from the infrared range to the visible one and possess good modulation properties. Their radiation spectrum can be tuned by changing the injection current, the temperature, the magnetic field, and the pressure [10]. In longevity, they approach the best products of semiconductor technology [1, 2].

Injection lasers based on the heterostructures of the systems GaAlAs/GaAs and InGaAsP/InP (Table 1) are used most frequently at present owing to a number of their characteristics (radiation power, spectral properties, threshold current, efficiency). In the case of direct modulation of the injection current, these lasers can generate radiation pulses with a duration from less than 0.1 nsec to the continuous mode.

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TABLE 1. Characteristics of the Most Popular Types of Injection Lasers

Type of laser	Threshold current, mA	Radiation wavelength, μm	Width of the radia-tion spectrum, nm	External differential quantum efficiency, W/A	Maximum pulse power, mW	Excitation threshold of multi-mode lasing (excess over the lasing threshold in %)	Radiation-beam divergence, deg (at 20% excess over the threshold	Reference
GaAlAs/GaAs system								
Planar stripe laser	60–80	0.83–0.87	–	0.3–0.4	10	10–30	10	[11]
Channel laser	30–60	0.87–0.89	–	0.3–0.5	50	50	5	[12]
Zigzag-mesa-stripe laser	30–80	0.85–0.87	–	0.2–0.4	50	100	8	[13]
InGaAsP/InP system								
Overgrown mesastripe laser	30–75	1.28–1.32	–	0.5–0.8	100	200	12	[14]
Lasers with an emitting surface	18–40	1.25	0.6	0.1	0.5	Single-mode operation is easily attained; these lasers are most suitable for production of two-dimensional matrices of emitters		[15]
Lasers with an emitting surface	0.5	1.205	0.6	0.1	0.5	The same		[15]
Distributed-feedback hetero-structure lasers	23	2.54	0.5	0.18	10	Good predictability of λ; these lasers are used in communication systems with frequency multiplexing of channels. There are strips of five lasers operating at 1298.5, 1303.2, 1308.4, 1313.8, and 1318.3 nm [7]		[7] [15]-[17]
Quantum-well distri-buted-feed-back hete-rostructurelasers	15–20	1.5	0.15	–	20	–	–	[18]
Externally mode-locked heterostructure lasers	25	1.55	0.3	0.1	Shapers of ultrashort radiation pulse sequences. Light pulses of duration 8 psec with a peak power of 39 mW are obtained in modulation by a sine-current with an effective value of 70 mA and a constant bias of 40 mA			[19], [20]
Externally mode-locked heterostructure lasers	32	1.55	0.1	0.1	15	80	High thermal stability of λ without a mode jump in the range 288–313 K	[15]

At the same time, in practice, laser information-measuring systems should be designed with allowance for the fact that the energy characteristics of radiation of injection lasers are temperature dependent [21], their parameters are characterized by a large spread from device to device, and they can fail in the case of short-duration optical or thermal overloads [1]. Because of this, it is necessary that special provisions be made for thermostabilization of injection lasers and protection of them against damage in the case of high densities of the optical power in the laser cavity at an increased temperature.

1. Temperature Dependence of the Radiation Power of Pulsed Injection Lasers. The pulse-radiation power of an injection laser can be described by the expression [22]

$$P = \frac{h\nu}{e} \eta_g (I - I_{thr} + I_0) F . \quad (1)$$

In (1), the main temperature-dependent parameter is the threshold current I_{thr} of the injection laser. The dependence $I_{thr}(\theta)$ is attributed to the influence of the temperature on the parameters determining the conditions of occurrence of lasing in the injection laser [21]:

$$I_{thr}(\theta) = e \int [R(\theta) + Q(\theta) + R_{s.lum}(\theta)] \, dV + I_{leak}(\theta) . \quad (2)$$

Evaluating the contribution of the dependences $R(\theta)$, $Q(\theta)$, $R_{s.lum}(\theta)$, and $I_{leak}(\theta)$ to the resultant dependence $I_{thr}(\theta)$, one can determine the actual reason for the temperature dependence $I_{thr}(\theta)$ and, consequently, for $P(\theta)$.

Rates R and $R_{s.lum}$ in (2) are described by the expressions [23]

$$R = \int_{\nu_1}^{\nu_2} W_{lum}(\nu)/(hc) \, d\nu , \quad (3)$$

$$R_{s.lum} = \int_{\nu_1}^{\nu_2} k(\nu) \, W_{lum}(\nu) / \left\{ h\nu \, [k_{loss}(\nu) - k(\nu)] \right\} d\nu . \quad (4)$$

The leakage current of the injection laser is determined by the structural features of its active region, and since $I_{leak} << I_{thr}$ the influence of $I_{leak}(\theta)$ on $P(\theta)$ is most often disregarded when $P(\theta)$ is analyzed [24].

Analysis of (2)–(4) for a GaAs-based injection laser [25] shows that at temperatures lower than 80 K, there is a region where the value of $I_{thr}(\theta)$ is constant, which, in view of the band $W_{lum}(\nu)$ and the distribution of states in the impurity bands is attributed to the recombination of nonequilibrium charge carriers (NCCs). For temperatures higher than 80 K, the luminescence spectrum and, consequently, the gain factor $k(\nu)$ are broadened because of the filling of the states beyond the quasi-Fermi levels with carriers, which causes a rapid increase in I_{thr} with temperature.

However, in the region of high temperatures the dependence $I_{thr}(\theta)$ is completely determined by the broadening of $W_{lum}(\nu)$ only for an injection laser with an effective restriction of nonequilibrium charge carriers and at small values of the rates $R_{s.lum}$ and Q [26]. This condition is fulfilled for a GaAs/GaAlAs injection laser with a double heterostructure (DHS) and a stripe geometry of the active region.

Long-wavelength lasers are characterized by high rates of nonradiative recombination [27, 28] and high rates of transitions stimulated by luminescence [23]. Thus, the mechanism of the temperature dependence $P(\theta)$ for an InGaAsP/InP injection laser ($\lambda > 1$ μm) is determined by all the components of formula (2).

A great number of works are devoted to a detailed investigation of the mechanism of the temperature dependence of the threshold current of an injection laser. Among the reasons for the temperature dependence of $I_{thr}(\theta)$, we recognize the following ones: temperature broadening of the amplification spectrum [27, 28] (it is most characteristic of GaAs/GaAlAs injection lasers with a double heterostructure and a stripe geometry of the active region), temperature activation of nonradiative recombination centers [29] (structures with an increased concentration of defects), Auger recombination [27, 30] (it is most characteristic of injection lasers with $\lambda > 1$ μm), and leakage currents [31] (they are most substantial in injection lasers with a stripe geometry of the active region without electronic restriction).

Experimental dependences $I_{thr}(\theta)$ are most often approximated using one or two exponents $I_{thr} \sim \exp(\theta/\theta_0)$ [22, 26, 32, 33]. The approximation of $I_{thr}(\theta)$ as a power function $I_{thr} \sim \theta^m$, $m > 2$, is also known [34].

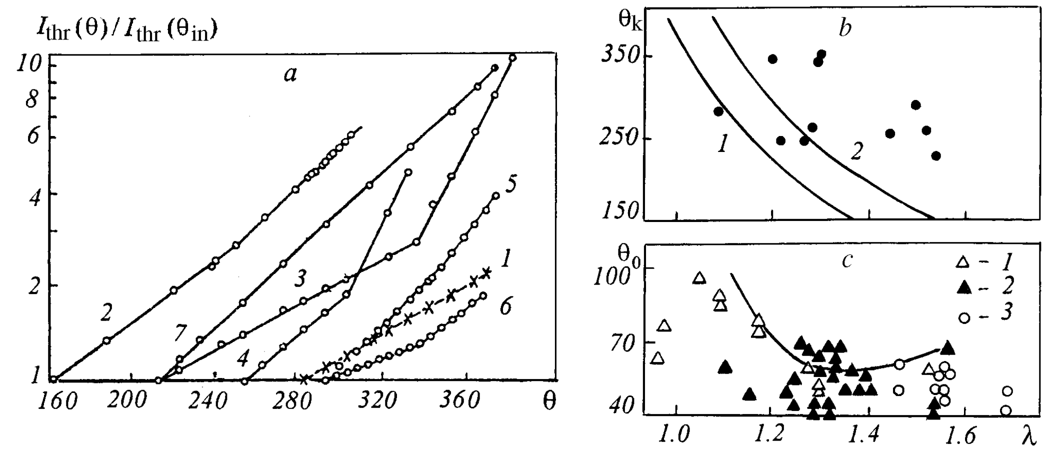

Fig. 1. Dependence of the relative threshold of lasing $I_{thr}(\theta)/I_{thr}(\theta_{in})$ on the temperature θ (a) and the dependence of the parameters θ_k (b) and θ_0 (c) on the wavelength λ. θ, θ_k, and θ_0, K; λ, μm.

TABLE 2. Temperature Parameters of Injection Lasers

System	Lasing wavelength, μm	Thermal resistance, K/W	Characteristic temperature, K				Temperature of the knee on the dependence log $[I_{thr}(\theta)/I_{thr}(\theta_{in})]$, K	Temperature shift of the radiation wavelength, nm/K
			θ_0	θ_{01}	θ_{02}	Number of curve in Fig. 1a		
AlGaAs/GaAs	0.7–0.9	20 [39]	120			*1* [40]		0.2–0.3 [41]
InGaAsP/InP	1.0–1.7	30 [31], 40 [39]	–	–	–	–	–	0.4–0.5 [39]
InGaAsP			–	68	52	*5* [42]	343 [42]	
InGaAsP			–	96	63	*2* [43]	255 [43]	
InGaAsP			–	110	30	*3* [31]	336 [31]	
InGaAsP			–	75	35	*4* [44]	303 [44]	
InGaAsP			69	180	95	*6* [45]	338 [45]	
InGaAsP				–	–	*7* [46]	–	

It is convenient to compare the temperature dependences of the lasing threshold of different types of lasers by the change in the relative threshold of lasing $I_{thr}(\theta)/I_{thr}(\theta_{in})$ with temperature. Figure 1a shows typical dependences of the relative threshold of lasing on the temperature for different types of injection lasers in the temperature range 160–383 K [21]. When the dependence $I_{thr}(\theta)$ for a GaAlAs injection laser with λ = 0.8–0.9 μm (Fig. 1a, curve 1) is described by an exponential function, the parameter θ_0 falls within the range 120–190 K and there are no knee points on the dependence log $[I_{thr}(\theta)/I_{thr}(\theta_{in})] = f(\theta)$. For an InGaAsP/InP-based injection laser (Fig. 1a, curves 2–6) the dependence $I_{thr}(\theta)$ is described by two exponents. The first portion of this dependence corresponds to the characteristic temperature θ_{01} in the range 60–110 K. After the temperature θ_k corresponding to the knee point on the dependence log $[I_{thr}\theta/I_{thr}(\theta_{in})] = f(\theta)$, the rate of rise of the function $I_{thr}(\theta)$ increases sharply and is characterized by the parameter θ_{02} in the range of values 30–65 K. Figure 1b shows calculated curves 1 and 2 [21] and experimental points [35] of the parameter θ_k in relation to the lasing wavelength for an InGaAsP-based injection laser at room temperature. Curve 1 in Fig. 1b corresponds to the case where the probability of radiative transitions exceeds the probability of nonradiative transitions by a factor of five, and curve 2 corresponds to their equality. Figure 1c shows the calculated dependence of the parameter θ_0 [21] (curve) and experimental points [36–38] (1–3 respectively) on the wavelength λ for an InGaAsP injection laser. InGaAsP injection lasers, in which $I_{thr}(\theta)$ is described by one exponent (Fig. 1a, curve 7), are less common.

The behavior of the radiation power of a pulsed injection laser under varying temperature conditions depends, besides all other factors, on the structural features of heterostructures that form its basis. The values of the parameters determining and describing the temperature dependence of the radiation power of injection lasers are presented in Table 2.

Moreover, a characteristic of an injection laser is a change in the threshold current and in the quantum yield of lasing in the process of its operation. According to the data of [39, 47], GaAlAs/GaAs injection lasers based on a double heterostructure are characterized by an increase in the threshold current with a rate of about 1%/1000 h during their operation. The value of η_g changes by 20–25% in the temperature range 278–328 K.

In spectrometric laser information-measuring systems based on an injection laser, in addition to the above-considered problems, one should take into account that the pulsed mode of operation of the laser causes the so-called "chirping" (shift) of the lasing frequency during the action of a pumping pulse [48]. Moreover, the injection-current surges that can arise in the pumping system of the injection laser, together with the above factors of temperature and degradation variation of the injection- laser parameters, can cause uncontrolled changes in the radiation spectrum of the injection laser. These factors limit the accuracy of laser information-measuring systems based on an injection laser.

Thus, there are many factors and mechanisms which cause changes in the parameters of the pulse radiation of an injection laser when the temperature conditions vary and in the process of its operation. Because of this, a system of stabilization of the injection-laser power must be developed in each concrete case with consideration for the main requirements imposed on the laser information-measuring system.

2. Methods of Stabilization of the Pulse-Radiation Power of Injection Lasers under Actual Temperature Conditions. As is seen from expression (1), the radiation power of an injection laser can be controlled by tuning the amplitude of the current pulse I, the constant bias current I_0, and the temperature of the laser crystal by changing its threshold current I_{thr}, as well as using combined control. In the simplest case, the stabilization of the pulse power of an injection laser is based on control of its excitation level depending on temperature conditions. In [49], it has been proposed to use a dividing circuit of ohmic resistances in the excitation system of the injection laser. A temperature-sensitive resistor whose resistance depends on the temperature of the laser diode is installed in one arm of the circuit. As the resistance changes, the optimum ratio between the pulse pumping current and the constant bias current is maintained for a given temperature. It is known [50] that the temperature departure of the radiation power of an injection laser can be compensated for with the temperature-dependent base–emitter voltage of a bipolar transistor with a sign opposite to the temperature dependence of the radiation power of the laser. For compensation for the temperature change in the differential quantum yield of an injection laser, elements accounting for a change in η_g with temperature are incorporated in the circuit of pulse power supply of the laser [51].

Stabilization of the radiation power of an injection laser under conditions of a varying ambient temperature can be based on the maintenance of the laser temperature at a constant level. In [52], a Peltier element was used for this purpose. In the range of ambient temperatures 253–323 K, the temperature of the injection laser was maintained at 298 K with an accuracy of $2 \cdot 10^{-3}$ K. In this case, the departure of the radiation power of the injection laser was no more than 5 μW/h.

Methods of thermostabilization of the radiation power of an injection laser, which are based on control of the pumping depending on the ambient temperature, compensation for the temperature change in the laser parameters, and maintenance of the temperature of the laser crystal at a constant level, cannot track in full measure changes in laser-radiation parameters, especially those attributed to the simultaneous action of several destabilizing factors (temperature, degradation, etc.). Under these conditions, more perfect methods of stabilization, which are based on the use of photoelectric feedback (PEF), are applied.

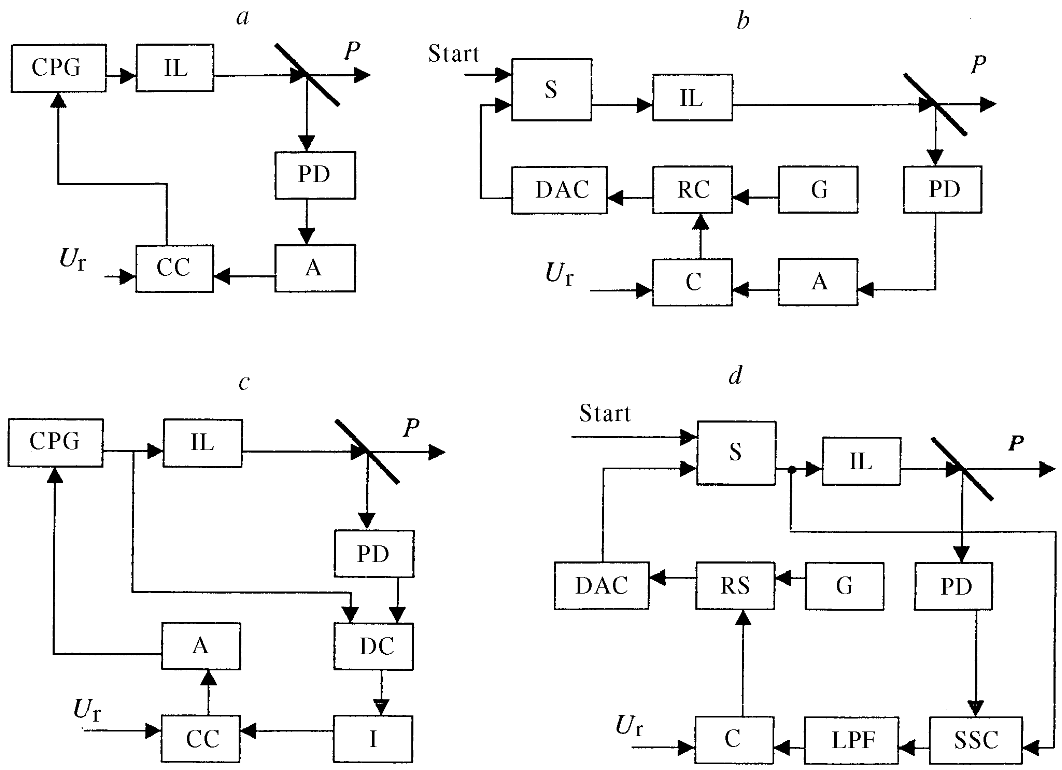

Fig. 2. Functional diagrams of the systems of stabilization of the power of a pulsed injection laser.

In the classical case where photoelectric feedback is used for stabilization of the radiation power of an injection laser (Fig. 2a), part of the radiation of an injection laser IL is detected by a photodiode PD, from whose output the signal through an amplifier A arrives at one input of a comparison circuit CC. To its second input, a reference voltage U_r is supplied. The difference signal from the output of the comparison circuit controls a current-pulse generator CPG. According to Fig. 2a, the employment of the photoelectric-feedback principle is appropriate for stabilization of the power of a continuously operating injection laser. In this case, the instability of the power of the injection laser operating in the continuous mode decreases to 10^{-1}–10^{-2}% [53]. In the case of pulsed operation of an injection laser, the speed of response of the elements of the feedback circuit has a finite value: this being so, photoelectric feedback in such a form is more often used for control of the constant bias current of the injection laser. Figure 2b shows the functional diagram of a device for the maintenance of the radiation power of an injection laser at a given level; in this device, a comparator C is used as the comparison circuit. The output signal of the comparator controls the direction of counting of pulses coming from a generator G by a reversible counter RC. By the code of the reversible counter, a digital-to-analog converter DAC forms the signal that, through a summator S, controls the constant bias current I_0 of the injection laser. Figure 2c shows a variant of system for stabilization of the radiation power of a pulsed injection laser [55], in which the comparison of signals from the outputs of a photodiode PD and a current-pulse generator is performed using a difference cascade DC. In this case, the output signal of the difference cascade passes through an integrator I and is compared to the reference signal, as in [54].

In the opinion of Kogayashi [56], a system of stabilization of the radiation power of a pulsed injection laser in which a peak detector is used has a long-duration stability and is simple in circuit implementation. Since the recorded peak value of the signal at the output of the photodiode is proportional to the pulse-radiation power of the injection laser, it can be used in the photoelectric-feedback loop for the formation of the error signal, for example, as in Fig. 2c.

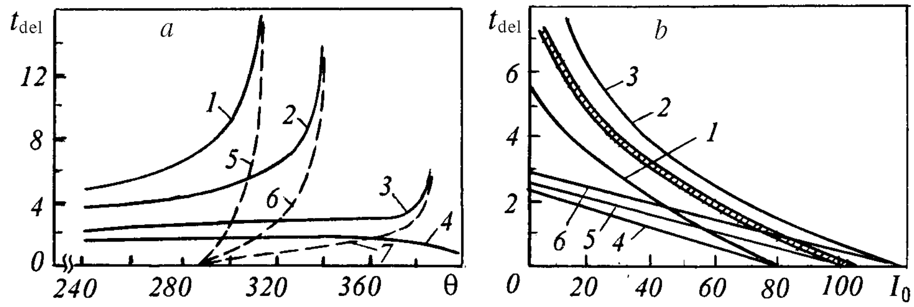

Fig. 3. Calculated dependences of the stimulated-radiation delay in the injection laser t_{del} on the temperature θ (a) and the constant bias current I_0 (b) at different excitation levels. t_{del}, nsec; θ, K; I_0, mA.

In systems of stabilization of the pulse-radiation power of an injection laser, selection and storage circuits (SSCs) are widely used [57, 58]. A variant of selection and storage circuit is shown in Fig. 2d. In the circuit, part of the radiation of an injection laser IL is directed to a photodiode PD the signal from which arrives at one input of a comparator C through a selection and storage circuit SSC energized simultaneously with the pumping-current pulse of the injection laser, and only for the time of its action, and through a low-pass filter LPF. To the other input of the comparator, a reference voltage U_r is supplied. The output signal of the comparator was used in much the same way as in [54] (Fig. 2b).

When an injection laser is used in data transmission and processing systems for stabilization of their radiation power, methods based on modulation of the pumping current by special test signals can be used [59–61]. In [59], a low-frequency test signal that is compared in the differential-amplifier circuit to a low-frequency component in the signal of the photodetector detecting part of the injection-laser radiation is superimposed on the pumping signal carrying useful information. In this case, it becomes possible to control the position of the operating point of the laser by the difference signal. It has been proposed in [60] to perform the tuning of the position of the operating points of an injection laser in both "0" and "1" of the desired signal using two independent control loops. Stabilization of the operating point of an injection laser can also be performed with the use of the diode properties of the laser near the threshold [61]. In this case, a test signal of small amplitude is fed to the injection laser and nonlinear distortions at the frequencies of its harmonics are investigated. The system described in [61] is designed for compensation for changes in the threshold current and in the differential quantum efficiency, which are caused by temperature variations and the aging of the laser.

In a number of practical applications (systems of dynamic storage of data, recirculation range finders, and others), the radiation source should provide, in addition to the power stability, the stability of the time position of the stimulated-radiation pulse relative to the injection-current pulse. Because of the temperature dependence of the threshold current of an injection laser, the delay in its radiation is also temperature dependent [62]. Thus, the power and the radiation delay turn out to be interdependent in the case of pulsed operation of an injection laser.

With allowance made for the temperature dependence of the lasing threshold I_{thr} and the spontaneous lifetime τ_{sp} of nonequilibrium charge carriers in an injection laser [21, 22, 62], the expression for the delay of stimulated radiation in it can be written in the following form:

$$t_{del}(\theta) = [\tau_{in} - k_\tau(\theta - \theta_{in})] \ln \left\{ I/[I - I_{thr0} \exp(\theta/\theta_0) + I_0] \right\}. \qquad (5)$$

Using (5) for τ_{in} = 4 nsec, I_{thr0} = 9 mA, θ_0 = 120 K, and $k_\tau = 3.6 \cdot 10^{-2}$ nsec/K and for the threshold current I_{thr}^{st} = 75 mA at θ_{in} = 295 K, we calculated [62] $t_{del}(\theta)$ and $t_{del}(I_0)$ for different amplitudes of the pulses of the excitation current I and the constant bias current I_0 (see Fig. 3). It has been shown that under

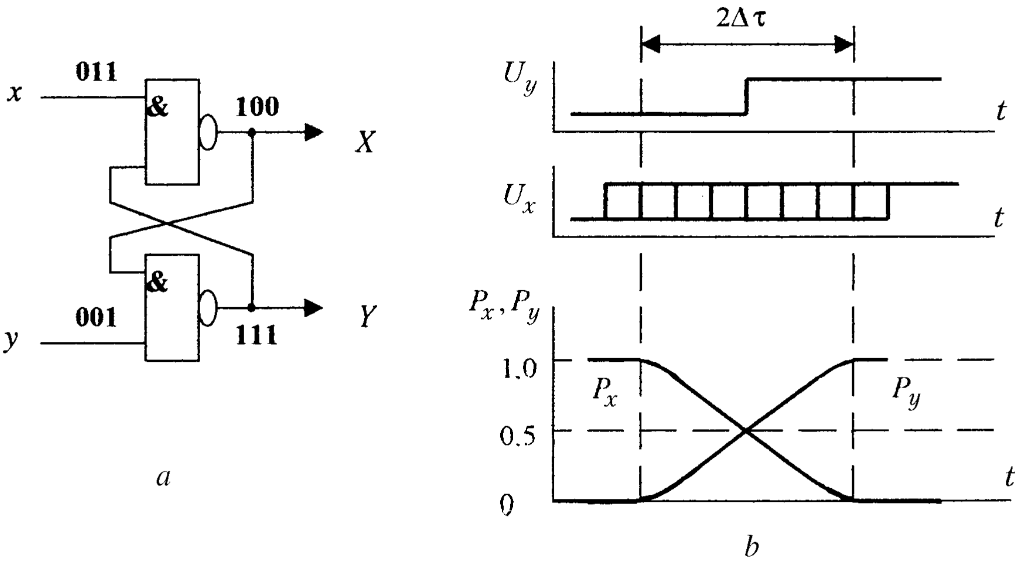

Fig. 4. Functional diagram (a) and time diagram (b) explaining the principle of operation of a priority discriminator.

varying temperature conditions, t_{del} is most unstable when an injection laser operates with a small excess of the injection current over the threshold value. In Fig. 3a, this operation for $I = 1.1I_{thr}$ and $I_0 = 0$ is illustrated by curve 1. With increase in the excitation level, the length of the portion of a weak temperature dependence of t_{del} increases (curves 2 and 3 correspond to the injection currents of $I = 1.36I_{thr}$ and $I = 2I_{thr}$ at $I_0 = 0$), and at $I = 2.5I_{thr}$ the function $t_{del}(\theta)$ becomes nonmonotone (curve 4). A slight increase in the delay with increase in the temperature for $I = 2.5I_{thr}$ in the temperature range 240–350 K and even a decrease in t_{del} with increase in θ in the range of $\theta > 330$ K are apparently attributed to the competition between two dependences $\tau_{sp}(\theta)$ and $I_{thr}(\theta)$. At $I = 2.5I_{thr}$, the linear function $\tau_{sp}(\theta)$ compensates for the dependence $I_{thr}(\theta)$ in the temperature range 240 K $< \theta <$ 330 K, and it becomes predominating in the temperature range of $\theta > 330$ K.

Changes in t_{del} with temperature at $I + I_0 = 1.1I_{thr}$, $I + I_0 = 1.36I_{thr}$, and $I + I_0 = 2I_{thr}$, where $I_0 = 100$ mA, are illustrated by curves 5, 6, and 7, respectively. It is seen as the temperature ranges characterized by a strong dependence $t_{del}(\theta)$ are the same that for the case $I = 1.1I_{thr}$, $I = 1.36I_{thr}$, and $I = 2I_{thr}$ at $I_0 = 0$. However, at $I_0 \neq 0$ the function $t_{del}(\theta)$ is stronger than for the case $I_0 = 0$, and this difference increases with decrease in the excess of the injection current over the threshold value (see curves 5 and 7).

It follows from (5) that t_{del} depends strongly on the constant bias current I_0. This makes it possible to use an injection laser in laser information-measuring systems as a source with a controlled radiation delay. For practical applications, of interest is the tuning range and the thermostability of such an optoelectronic delay line. Dependences of t_{del} on the constant bias current I_0, obtained for $I = 1.1I_{thr}$ at $\theta_1 = 260$ K, $\theta_2 = 295 \pm 1$ K, and $\theta_3 = 309$ K, are presented in Fig. 3b (curves 1, 2, and 3, respectively). Dependences $t_{del} = f(I_0)$ obtained for the same temperatures but at $I = 2I_{thr}$ are presented by curves 4, 5, and 6. It can be seen that at room temperature (295 K), for $I = 1.1I_{thr}$ the range of tuning of the radiation delay in an injection laser with parameters $\tau_{in} = 4$ nsec and $I_{thr} = 110$ mA (at 295 K) is ~8 nsec. The tuning characteristic of the delay is nonlinear in this case. The coefficient of temperature instability of the delay changes from 150 psec/K at $I_0 = 0$ to 27 psec/K at $I_0 = 100$ mA (see curve 2 in Fig. 3b). At $I = 2I_{thr}$, the range of tuning of the delay in an injection laser is equal to ~2.5 nsec (at $\theta = 295$ K). In this case, the tuning characteristic is approximately linear, and the temperature coefficient of the delay is ~15 psec/K.

It follows from (1) and (5) that the accuracy parameters of recirculation-type laser information-measuring systems and of laser information-measuring systems that use threshold recording of pulsed signals are determined not only by the stability of the pulse power P, but also by the change in t_{del} under varying tem-

TABLE 3. Characteristics of Priority Discriminators

Type of microelectronic circuit	Type of logic	Time resolution of discriminator, psec	Reference
130LA3	TTL	33	[66]
130LA3	TTL	42	[64]
K155LA3	TTL	44	[64]
158LA3	TTL	35	[64]
136LA3	TTL	53	[64]
1533LA3	TTL-S	22	[64]
K137	ECL	20	[67]
K100TM133	ECL	20	[68]

perature conditions. In this case, the strong temperature dependence of these parameters, which is a consequence of a number of the above-considered factors, requires the development of methods of stabilization of the power and the delay of the pulse radiation of an injection laser that would be insensitive to the mechanism of the destabilizing action on the laser. The solution of the problem of stabilization of the delay by a direct method (for example, with the use of a pulse-phase detector for tuning the injection current of an injection laser by its signal [63]) requires the measurement of nanosecond time intervals with a picosecond accuracy (or the use of the "time-to-amplitude" conversion), which in itself is a complex problem. In [64, 65], it has been shown that control and stabilization of the time position of the stimulated-radiation pulse of an injection laser relative to the injection-current pulse can be performed with a picosecond time resolution on the basis of the method of priority discrimination of two pulsed signals. This method is based on the use of the properties of a device called the priority discriminator (PD), which recognizes the order (priority) of arrival of signals at its inputs. By the priority discriminator, ordinary RS triggers based on NOR gates or NAND gates in the initial states $S = R = 1$ (NOR) or $S = R = 0$ (NAND) can be used. By the time resolution $\Delta\tau$ of discriminators of this type we mean the minimum difference between the times of arrival of pulses at its inputs Δt, at which the priority discriminator is switched to the states corresponding to the order of arrival of these pulses. Such discriminators have a time resolution of up to 20–30 psec [64, 65].

The principle of operation of priority discriminators based on NAND gates is illustrated by Fig. 4. In the initial state, $x = y = 0$ and, consequently, $X = Y = 1$. If, for example, a logical unit appears at the input x earlier than at the input y, the RS trigger begins to switch to the state $X = 0$, $Y = 1$, and thereafter the arrival of the logical unit at the input Y with a delay $\Delta t > \Delta\tau$ no longer influences the result of switching of the priority discriminator. The characteristics of priority discriminators of different types are presented in Table 3.

In [69], the temperature dependence of the pulse-radiation power of an injection laser operating in the regime in which the delay of stimulated radiation is maintained at a given level was investigated. The operation of an injection laser in such a regime can be explained in the following manner. It follows from (5) that in order that the regime t_{del} = const be maintained, the bias I_0 of the injection laser must change with temperature in accordance with the expression

$$I_0 = I\,[\exp\,(-\,t_{del}/\tau_{sp}\,(\theta)) - 1] + I_{thr}\,(\theta)\,. \tag{6}$$

Substituting (6) into (1), we obtain an expression for the radiation power of an injection laser operating in the regime of stabilized radiation delay:

$$P_{stab}\,(\theta) = \frac{h\nu}{e}\,\eta_g\,(\theta)\,I\,\exp\,[-\,t_{del}/\tau_{sp}\,(\theta)]\,. \tag{7}$$

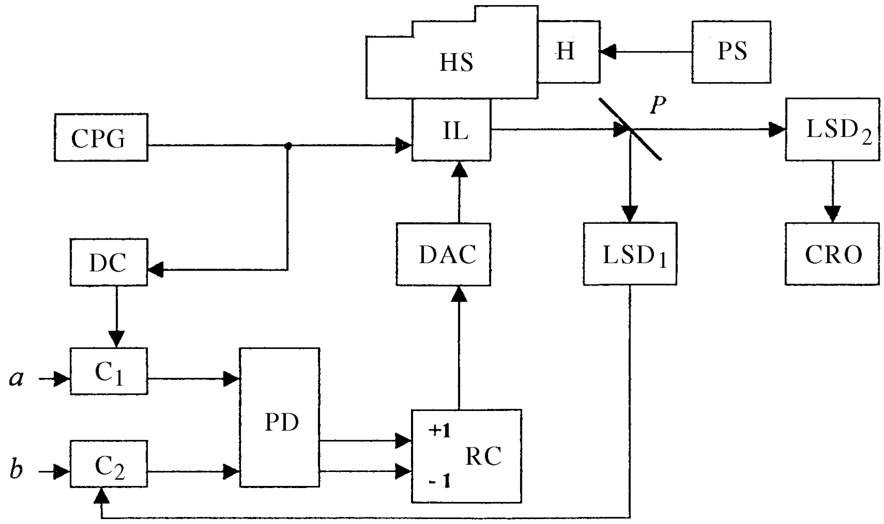

Fig. 5. Functional diagram of the experimental setup for investigation of the temperature dependence of the pulse-radiation power of an injection laser.

It follows from (7) that in the regime t_{del} = const, which is attained by tuning the constant bias current I_0, the compensation for the temperature dependence of the lasing threshold of an injection laser occurs, and the dependence $P_{stab}(\theta)$ is determined by the functions $\tau_{sp}(\theta)$ and $\eta_g(\theta)$.

Analyzing (1) and (7), we can obtain

$$\left|\frac{dP}{d\theta}\right| > \left|\frac{dP_{stab}}{d\theta}\right| . \tag{8}$$

Expression (8) shows that the stabilization of the delay in the lasing of a laser can serve as a method of increasing the thermostability of its power in the pulsed mode [69].

The efficiency of this method [69–72] was investigated on an experimental setup (Fig. 5), including an injection laser IL excited by the signal from a current-pulse generator CPG. The constant bias I_0 was supplied to the injection laser from a digital-to-analog converter DAC. The output signals of the current-pulse generator (through a delay circuit DC) and of a light-sensitive detector LSD1 recording part of the radiation of the injection laser studied arrived at comparators C_1 and C_2 with operation thresholds a and b. The times of appearance of pulsed signals at the outputs of the comparators were compared in a priority discriminator PD, and its output pulses were counted in a reversible counter RC. The output code of the reversible counter was fed to the information inputs of the digital-to-analog converter. The injection laser studied was positioned on a massive heat sink HS whose heating (along with heating of the injection laser) was performed by a heater H connected to a controlled power supply PS. The output power P of the laser was controlled by a cathode-ray oscillograph CRO in accordance with the signal of a light-sensitive detector LSD2.

The process of stabilization by the method of [72] can be explained in the following manner. For linear fronts of the pulses at the inputs of the comparator C_1 and C_2, the time difference between the arrival of pulses at the inputs of the priority discriminator has the form

$$\Delta t = \tau_2 b/U_2 + t_{del}(\theta, I_0) - \Delta t_{del} - \tau_1 a/U_1 . \tag{9}$$

If $|\Delta t|$ determined from (9) is more than $\Delta\tau$, then for each pulse from the current-pulse generator in the system, the constant bias of the injection laser is automatically tuned by the value δI_0. Such a process of automatic control lasts until the condition $|\tau_2 b/U_2 + t_{del}(\theta, I_0) - \Delta t_{del} - \tau_1 a/U_1| \leq \Delta\tau$ is fulfilled.

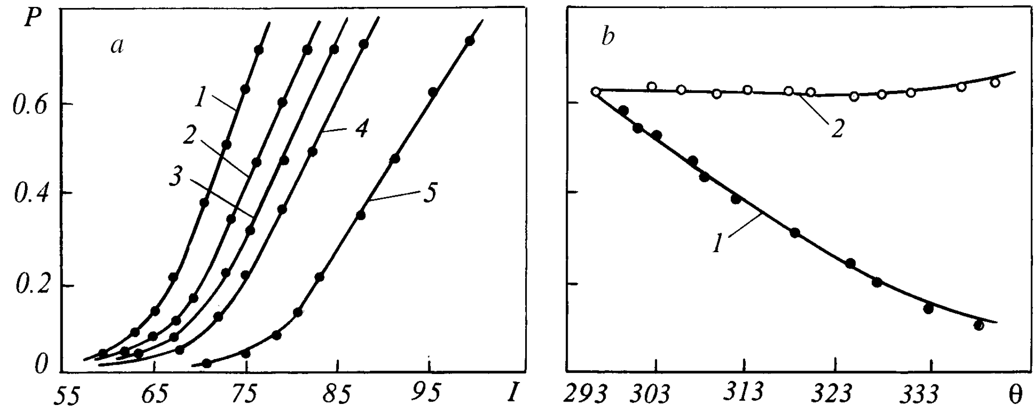

Fig. 6. Dependence of the pulse-radiation power P of an InGaAsP injection laser in relative units on the injection current I at temperatures of 293, 300, 308, 314, and 328 K [a) curves 1, 2, 3, 4, 5] and on the temperature θ [b: 1) without stabilization, 2) in the regime of stabilization]. I, mA.

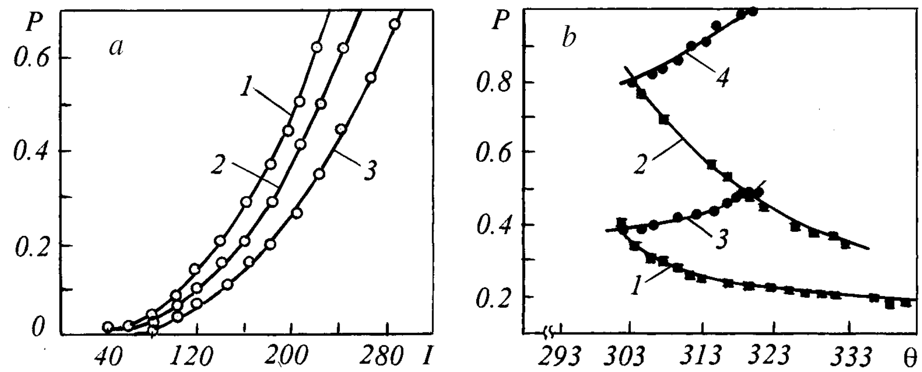

Fig. 7. Dependence of the pulse-radiation power P of a GaAlAs injection laser in relative units on the injection current I at temperatures of 294, 300, and 311 K [a) curves 1, 2, 3] and on the temperature θ [b: 1, 2) without stabilization of the delay, curve 1 at $\theta > 305$ K corresponds to the regime of spontaneous radiation, 3, 4) in the regime of stabilization of the delay, injection currents 150 and 190 mA].

In [70], the temperature dependence of the pulse radiation power of InGaAsP injection lasers with a radiation wavelength λ = 1.3 μm was investigated. Figure 6a shows watt-ampere characteristics of these lasers at different temperatures. It is seen that their quantum efficiency decreases significantly with increase in the temperature. Figure 6b (curve 1) shows the dependence $P(\theta)$ for an InGaAsP injection laser at I = 75 mA and I_0 = 0 without control of delay in the laser. In this case, in the temperature range 290–300 K the radiation power of the injection laser decreases with increase in the temperature, and the temperature coefficient of variation of the power is $\Delta P_\theta > -1\%$/K. If the delay in the lasing is maintained constant by tuning of I_0, the lasing power becomes stable, in practice, in the above temperature range (see Fig. 6b, curve 2).

Investigations of the temperature dependence of the pulse-radiation power of AlGaAs injection lasers operating in the regime of stabilized delay (Fig. 7) [69] show that for them $\Delta P_\theta \cong +0.25\%$/K (the power increases with temperature). Comparison of the dependences in Figs. 6 and 7 shows that in the case where this method [72] of stabilization of the pulse-radiation power is used, in an InGaAsP injection laser, in contrast to

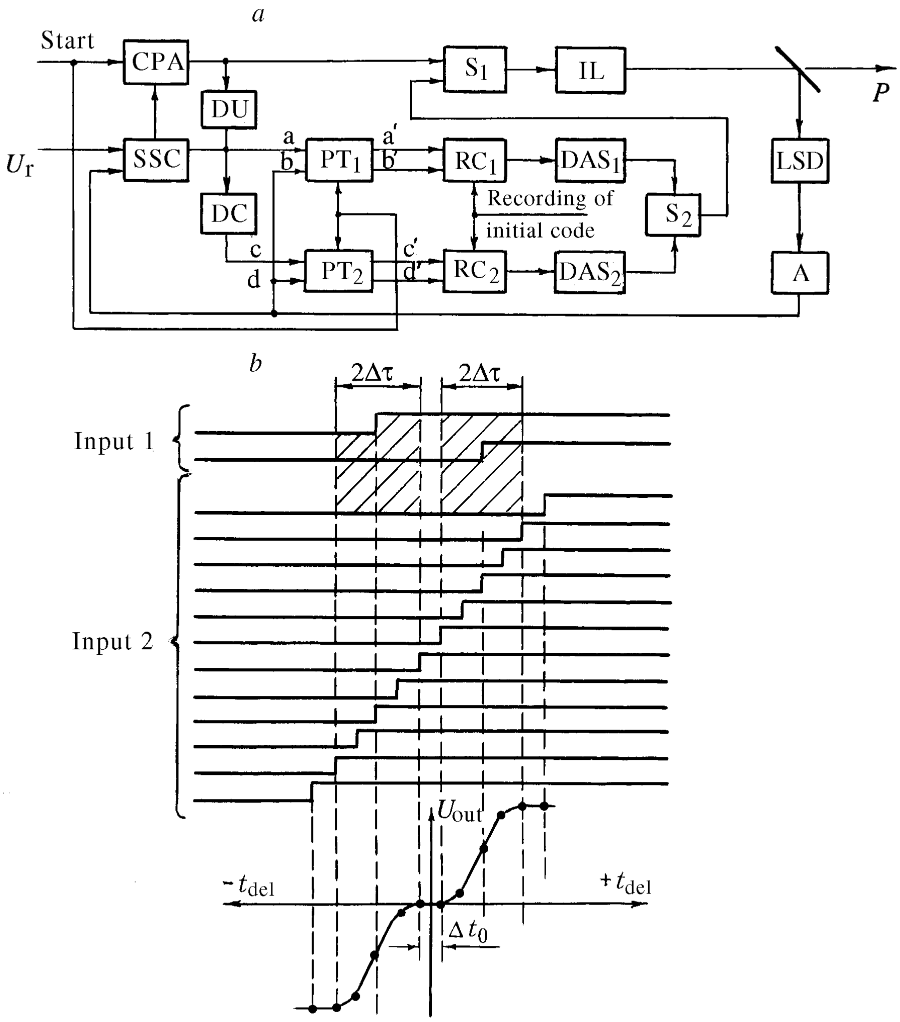

Fig. 8. Functional diagram (a) and time diagrams of operation (b) of the stabilizer of the pulse-radiation power of an injection laser based on a two-channel priority discriminator.

a GaAlAs injection laser, recompensation for pumping does not occur as the temperature increases. Evidently, this is due to the stronger dependence $\eta_g(\theta)$ in InGaAsP lasers.

Thus, for both AlGaAs and InGaAsP injection lasers, stabilization of the delay in the lasing improves the stability of the laser-radiation power (the two important problems are solved simultaneously). This method is fairly simple in apparatus implementation. However in the case where the method of [72] is used, when the condition $|\Delta t| \leq \Delta\tau$ is attained, each triggering pulse is accompanied by periodic switchings (oscillations) of the pumping current of the injection laser in the system of control of I_0 in the range $I_0 \pm \delta I_0$. An analogous problem exists for the methods of [54, 57, 58], too. Such oscillations of I_0 can be excluded if a two-channel priority discriminator is used in the control system [73]. The principle of operation of such a system is illustrated by Fig. 8. Initially in this system the constant bias current of the injection laser IL is set, through a summator S_1, by the output voltage of a summator S_2 in accordance with the code established in advance in reversible counters RC_1 and RC_2. By a triggering pulse, the injection laser radiates a light pulse with a delay determined by (5). If the delay τ in a delay unit DU relative to the output pulse of the current-pulse amplifier CPA is chosen such that $\tau = t_{del} + t_p$, comparison of the output voltage of an amplifier A with the reference voltage set in an output-signal amplifier OSA begins at the moment of appearance of an electric signal at the output of the amplifier. In this case, the output signal of the output-signal amplifier corrects the amplification

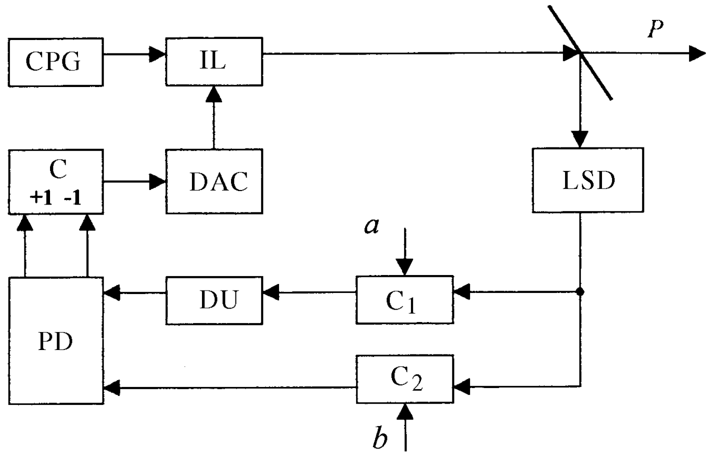

Fig. 9. Functional diagram of the system of stabilization of the pulse radiation power of an injection laser based on the method of two-threshold discrimination of pulses.

in the current-pulse amplifier. A change in the radiation characteristics of the injection laser causes a change in the lasing and accordingly in the difference between the times of arrival of pulses at inputs 1 (input a of priority trigger PT_1) and 2 (inputs b and d of priority triggers PT_1 and PT_2) $|\tau - (t_{del} + t_p)|$. After the operation of the priority discriminators, the constant bias current of the injection laser changes by the value δI_0 by the output signal of a summator S_2. The process described lasts until the following condition is fulfilled:

$$\Delta\tau/2 < \left|\tau - (t_{del} + t_p)\right| < \Delta\tau/2 + \Delta t_0 . \quad (10)$$

The fulfillment of condition (10) means that the front of the output pulse of the amplifier A falls within the time range of width Δt_0; the output voltage of the two-channel priority discriminator is U_{out} = const. Since Δt_0 is determined by the delay line set between the inputs a and c of the priority triggers PT_1 and PT_2 (see Fig. 8), the condition $\Delta t_0 \le \Delta\tau$ is easily realized.

Under the steady-state conditions of stabilization, the voltage at the output of the two-channel priority discriminator does not change from pulse to pulse, since the switching of the priority triggers PT_1 and PT_2 of the discriminator is performed in antiphase, which eliminates periodic variations of the constant component I_0, as in the case where a single-channel priority discriminator is used [64–72]. In order that the voltage across the output of the discriminator be zero under the steady-state conditions, the value of Δt_0 must satisfy the condition

$$\left|\delta t_{del}\right| < \Delta t_0 < \Delta\tau , \quad (11)$$

$$\delta t_{del} = \tau_{sp}(\theta) \ln \left\{[I - I_{thr}(\theta) + I_0]/[I - I_{thr}(\theta) + I_0 + \delta I_0]\right\} . \quad (12)$$

The priority principle of discrimination of pulsed signals for stabilization of the pulse power of an injection laser can be used in combination with the two-threshold method of recording (discrimination) of signals [74, 75]. In this case, to obtain a control signal at the output of a light-sensitive detector LSD, comparators C_1 and C_2 with operation thresholds a and b, respectively, are used (see Fig. 9). If the threshold voltage $a < b$ and Δt_{del} is the delay in a delay unit DU, the control system is at rest for $\tau_c a/U_{pd} + \Delta t_{del}$ = $\tau_c b/U_{pd}$. When the radiation power of the injection laser decreases or increases, the state of rest of the control system is disturbed because of a temperature change, and, at each pulse, the current of constant bias I_0

is tuned in the direction of power stabilization by the signal of the digital-to-analog converter. This method of stabilization provides a maximum rate of control if $a \to 0$ and $b \to U_{pd}$. In actual practice, the variant $a > U_n$ is used. In [75], where this method was used for stabilization of a GaAlAs injection laser of the type ILPN-108 in the temperature range 273–330 K, the change in the output power did not exceed 5%, while without stabilization the power of the injection laser changed by more than 90% under the same conditions.

Analysis of the properties and the circuit-engineering design of stabilization systems [69–74] points to the effectiveness and simplicity of application of the principle of discrimination of signals by the priority of their arrival for the development of thermostabilized injection emitters based on injection lasers for laser information-measuring systems. In combination with a two-threshold discrimination of pulses [75], this principle makes it possible in fact to realize the possibility of control of the shape of the entire radiation pulse under conditions of varying temperature and degradation of the injection laser. These considerations form the basis of the method of stabilization of the energy of stimulated-radiation pulses of an injection laser [76].

The essence of this method of stabilization of the energy of stimulated-radiation pulses of an injection laser is as follows. Let the delay in the lasing have an initial value $t_{del.in}$ differing from the reference value $t_{del.r}$ by $\Delta t_{del} = |t_{del.in} - t_{del.r}| > \delta t_{del}^{min}$. As the results of a comparison of $t_{del.in}$ with $t_{del.r}$ show, after the first pulse and a discrete tuning of the excitation level, the deviation of the delay from the reference value decreases by the value

$$\delta t_{del} = f(\xi_{del0}) - f(\xi_{del0} + \Delta\xi_{del0}) . \quad (13)$$

If φ is a function inverse to f, after N_{del} cycles of comparison

$$N_{del} = \left| \varphi(t_{del.r}) - \varphi(t_{del.in}) \right| / \Delta\xi_{del} \quad (14)$$

the condition

$$\left| t_{del.in} - t_{del.r} \right| \le \delta t_{del}^{min} , \quad (15)$$

corresponding to the regime where the beginning of tuning of the excitation level is coincident with the beginning of lasing of an injection laser with an accuracy attributed to the minimum resolved time interval δt_{del}^{min} in the loop of control of a radiation delay in the laser is fulfilled.

Let by the moment of attainment of condition (15) in the pumping system of the laser the duration of the excitation interval be $\tau_0 \ne t_{del}$, and ψ and μ be mutually inverse functions determining the relation between the duration of the excitation interval τ and the output action ξ_τ in the loop of control of the excitation-pulse duration. By analogy with (13)–(15) we can write

$$\delta\tau = \psi(\xi_{\tau 0}) - \psi(\xi_{\tau 0} + \Delta\xi_\tau) , \quad (16)$$

$$N_\tau = \left| \mu(\tau_r) - \mu(\tau_0) \right| / \Delta\xi_\tau , \quad (17)$$

$$\left| \tau - \tau_r \right| \le \delta t_\tau^{min} . \quad (18)$$

After $N_{del} + N_\tau$ cycles of correction (of excitation pulses), conditions (15) and (18) are simultaneously fulfilled in the system of stabilization. This means that independently of the reasons for the changes in the energy of the stimulated-radiation pulses, a lasing regime with a given duration and a given pulse radition power is realized in the system. In this regime, the energy W_{pulse} of a stimulated radiation pulse with an instantaneous

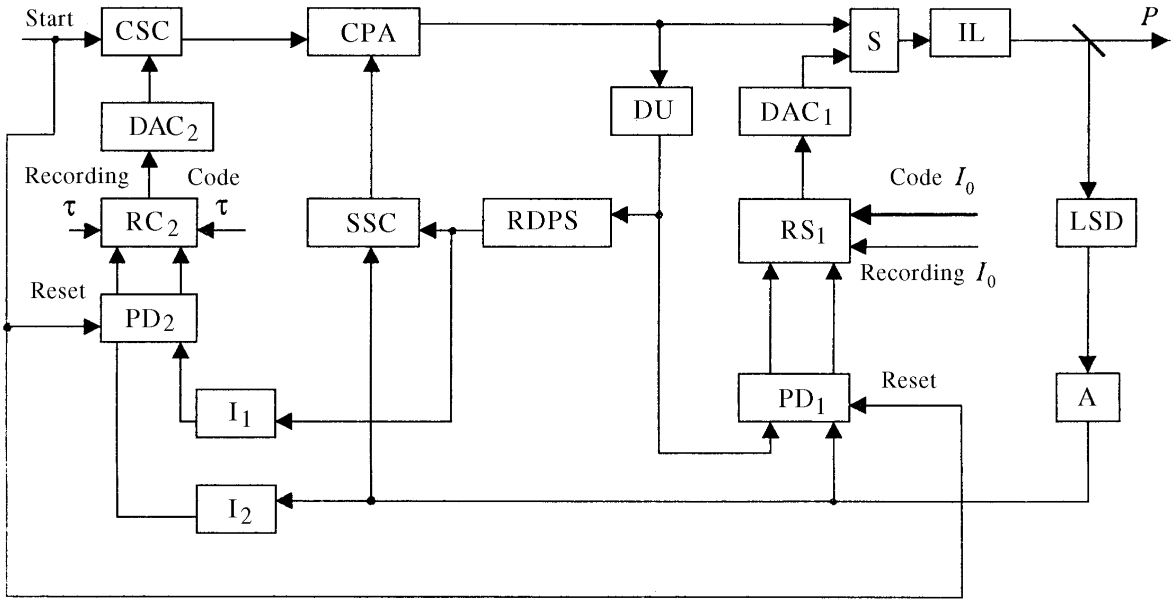

Fig. 10. Functional diagram of the system of stabilization of the pulse radiation power of an injection laser.

power $P(t)$, which is determined by the expression $W_{\text{pulse}} = \int_0^{\tau_r} P(t)dt$, is maintained constant with an accuracy of up to the value

$$\delta W_{\text{pulse}} \approx 2\,[P\,(t_{\text{del.r}})\,\delta t_{\text{del}} + P\,(\tau_r)\,\delta t_\tau]\,. \tag{19}$$

It can be seen that if the rate of change of the duration ν_τ under the action of disturbing factors satisfies the condition $\nu_\tau < f_{\text{rep}}\Delta\xi_\tau$ and the accuracy of stabilization of W_{pulse} in accordance with (19) is sufficient, there is no need to measure the error signal in the case of realization of the method described. Such a situation is observed when an injection laser is used as the source of pulse radiation in recirculation-type laser information-measuring systems, laser technologies, medicine, and other cases.

The functional diagram of the system realizing the method of [76] is shown in Fig. 10. It includes three loops of control of the delay, amplitude, and duration of stimulated-radiation pulses of an injection laser. The operation of the loop of control of the delay (light-sensitive detector LSD, amplifier A, priority discriminator PD_1, reversible counter RC_1, digital-to-analog converter DAC_1, delay unit DU) is similar to the operation of the analogous loop described above. Control of the amplitude of radiation pulses of an injection laser IL is performed by a selection and storage circuit SSC in which the amplitude of the pulse at the output of the amplifier A is compared with the reference voltage U_r during the time interval set by a reference-duration-pulse shaper RDPS. The output signal of the selection and storage circuit corrects the amplification in a current-pulse amplifier CPA, the current pulses from the output of which are fed through a summator S to the injection laser. The loop of automatic control of the excitation-pulse duration τ includes a priority discriminator PD_2 recording the priority of arrival of pulses from the reference-duration-pulse shaper and the amplifier, which are inverted using inverters I_1 and I_2 (comparison of the positions of the trailing edges of the pulses from the amplifier and the reference-duration-pulse shaper on the time axis). The output signal of the priority discriminator PD_2 is converted using a digital-to-analog converter DAC_2 to the control signal of a control-signal conditioner CSC.

If initially the deviation of the delay in the lasing pulse is $(t_{del} - t_{del.r})$, using (14) and (15) we can obtain that the number of correction cycles N_{del} after which the regime of delay stabilization is attained is

$$N_{del} = I \exp(-t_{del}/\tau_{sp}) \left\{\exp[(t_{del} - t_{del.r})/\tau_{sp}] - 1\right\}/\delta I_{del} . \quad (20)$$

In [76], a conditioner based on charge-storage diodes (CSDs) was used as the control-signal conditioner. The direct bias current of the charge-storage diodes was set by the output voltage of the digital-to-analog converter DSC_2. In a narrow range, the duration of the output pulse of such a conditioner depends practically linearly on the direct bias current of the charge-storage diodes and, consequently, on the output voltage of the digital-to-analog converter operating in the current-generator regime. Because of this, according to (17), the number of cycles N_τ to the end of the regime of correction of the lasing-pulse duration is

$$N_\tau = \left| U_\tau - U_{\tau r} \right| / \delta U . \quad (21)$$

Then, after $N_{del} + N_\tau$ excitation pulses determined according to (20) and (21), the regime of stabilization of the energy of stimulated-radiation pulses of the injection laser is attained in the system. In this case, the stability of the energy of the stimulated-radiation pulses increases not only owing to the stabilization of the lasing-pulse duration, but also due to the time coincidence of the lasing pulse and the time interval of correction of the amplification in the current-pulse amplifier, which eliminates the uncontrolled surges of excitation current of the injection laser at both the leading and trailing edges of the lasing pulse.

Evaluating the potentialities of the methods of stabilization of the pulse-radiation power and the energy of an injection laser that are based on the principle of discrimination of pulsed signals [69–76], it is necessary to take into account the following. As has been shown in [64, 65], the best values of the time resolution of a priority discriminator are ~10–12 psec. They are comparable with a temperature drift of a delay (~0.02 %/K [66]) in a coaxial cable line with a delay time of several tens of nanoseconds, which, for example, is a time-interval standard in a stabilization system. This demonstrates clearly the potentialities of these methods and simultaneously shows that the application, for example, of the method of tuning of injection-laser radiation pulses with the use of a measuring time-amplitude converter, which is fairly difficult to implement, does not solve the problem of improving the stability of the energy of injection-laser radiation pulses if the delay in a cable line with given parameters [66] is used as the tentative standard.

To provide stable operation of an injection laser under varying temperature conditions, it is important to solve the problem of protection of the laser structure against thermal damage. The overheating of the active region of the laser, in combination with a high density of the optical power in the cavity, causes their rapid, sometimes catastrophic, degradation. Protection of the laser crystal against thermal overloads can be achieved by compensation for variations in its temperature. In [77], for example, this problem was solved by installation of a compensation circuit based on an operational amplifier and having thermal contact with it on one heat sink with the laser. Temperature variations cause changes in the output voltage of the amplifier, which is used as the control signal for control of the pumping of the laser. In this case, the pumping current is tuned so as to compensate for the temperature change. To prevent the failure of an injection laser because of thermal overloads, it has been proposed to cut off the power supply of the laser [78] or limit it at a given level [79] when the error signal in the system of stabilization of the laser power exceeds a given value.

To eliminate the redundant signal (a surge of pulse-radiation power) at the moment of initiation of lasing in an injection laser, it has been proposed in [80] to use a combined supply of the laser. In this case a signal of negative polarity is fed to the laser. In the summator, this signal is added to the positive bias, and the resulting positive underthreshold bias of the injection laser is obtained. At the initial moment of pulsed excitation of the injection laser, instead of the negative signal, a feedback signal proportional to the deviation of the output radiation from the nominal value is fed to the summer of the pumping signal. In such a way, the redundant output signal of the injection laser is suppressed at the edge of the pumping pulse.

For limitation of surges of optical power radiated by an injection laser when the supply of the system is switched on as well as when a given value of the output power of the laser is exceeded, the shunting of the laser diode is used [81]. To eliminate the failure of an injection laser because of current and thermal overloads in the case of interruption of an optical or electric signal in the feedback system, it has been proposed in [82] to use signals of two photodiodes, one of which records the signal from the back side of the cavity and the other from its front side. When the signal is interrupted in one arm, the injection current corresponding to the radiation power received from the back side of the resonator to the moment of interruption is maintained in the system.

In spectrometric laser information-measuring systems, the problem of simultaneous stabilization of the output power and the radiation wavelength is posed. In this case, in addition to the system of thermostabilization of the injection laser, control of the radiation wavelength depending on the temperature is used. In [83], control accounting for the influence of the injection current and the temperature on the deviation from given values of the power and the radiation wavelength was realized using a microprocessor. The use of a programmed control of the pumping of an injection laser in accordance with the temperature conditions under which the injection laser operates and its aging makes it possible to broaden the ranges of permissible temperatures [94] and track several parameters of laser radiation simultaneously, which allows one, for example, to realize stabilization of the energy of laser-radiation pulses [84, 85].

In addition to individual injection lasers, strips and matrices of such lasers are coming into wide use in laser information-measuring systems. In [86], a device for stabilization of the output power of a strip of injection lasers has been proposed. The system includes an optical selector using which the radiation of each laser is directed in the form of a time pulse sequence to a photodetector and a feedback circuit using which the injection current of each laser is automatically controlled in accordance with the reference signal.

Thus, taking into account the reasons for and mechanisms of the temperature dependence of the pulse-radiation power of an injection laser allows one to develop systems of its stabilization for the purpose of using these lasers in laser information-measuring systems designed for the solution of various problems. The methods developed cover in fact the entire set of problems on the use of injection lasers under unstable temperature conditions. The application of methods [69–75] based on the use of photoelectric feedback and priority time discrimination of pulsed signals makes it possible to approach an accuracy of stabilization of the pulse power of 10^{-1}–10^{-2}%, which is characteristic of the continuous operation of an injection laser [53]. However, it should be emphasized that the problem of forecasting of the lifetime of injection lasers and rapid analysis of their service life in laser information-measuring systems in the case of active stabilization of the parameters of the injection laser is still not clearly understood. The phenomenological approach to the estimation of the lifetime of an injection laser, which has been developed by now [39], allows one to estimate the maximum lifetime of the injection laser in the case of automatic tuning of its power under conditions of an unstable ambient temperature and aging of the laser. In our opinion, the solution of these problems requires a detailed investigation of the properties of an injection laser operating in the underthreshold mode (radiation spectra, inversion threshold, and others) and an analysis of the temperature variations in its other characteristics (excitation threshold, directivity diagram, etc.).

NOTATION

P, pulse-radiation power of the injection laser, W; h, Planck constant, J·sec; ν, frequency of laser radiation, Hz; e, electron charge, C; η_g, differential internal quantum yield of generation (lasing); I, amplitude of the injection-current pulse, A; I_{thr}, threshold current of the injection laser, A; I_0, constant bias current of the injection laser, A; F, function of the yield of radiation from the laser crystal; θ, absolute temperature, K;

R, rate of radiative recombination, $\sec^{-1}\cdot m^3$; Q, rate of nonradiative recombination, $\sec^{-1}\cdot m^3$; $R_{s.lum}$, rate of transitions stimulated by luminescence including enhanced luminescence, $\sec^{-1}\cdot m^3$; V, volume of the active region of the injection laser, m^3; I_{leak}, leakage current, A; ν_1 and ν_2, frequency boundaries of the luminescence-power spectrum, $W_{lum}(\nu)$, Hz; c, velocity of light, $m\cdot\sec^{-1}$; $k(\nu)$, gain factor; k_{loss}, coefficient of luminescence loss in the active region of the injection laser; θ_{in}, initial temperature, K; θ_0, characteristic temperature, K; θ_k, temperature corresponding to the knee point of the dependence of the relative threshold on the temperature, K; θ_{01} and θ_{02}, characteristic temperatures corresponding to the first and second portions of the temperature dependence of the lasing threshold of the injection laser, K; λ, radiation wavelength, m; t_{del}, delay of stimulated radiation in the laser, sec; I_{thr}^{st}, threshold current of the injection laser operating in the stationary lasing mode, A; τ_{sp}, spontaneous lifetime of nonequilibrium charge carriers, sec; τ_{in}, initial spontaneous lifetime of nonequilibrium charge carriers, sec; k_τ, coefficient of temperature variation of τ_{sp}, $\sec\cdot K^{-1}$; I_{thr0}, parameter of approximation of the temperature dependence of the threshold current, A; P_{stab}, radiation power of the injection laser operating in the regime of stabilized radiation delay, W; $\Delta\tau$, time resolution of the priority discriminator, sec; Δt, difference between the times of arrival of pulses at the inputs of the priority discriminator, sec; U_y and U_x, voltage at the inputs y and x of the priority discriminator, V; t, running time, sec; P_y and P_x, probabilities of switching of the priority discriminator to state "1" at the inputs y and x; δI_0, step of quantization of the constant bias current, A; τ_1 and τ_2, durations of the pulse fronts at the inputs of comparators C_1 and C_2, sec; U_1 and U_2, amplitudes of the voltage pulses at the inputs of comparators C_1 and C_2, V; a and b, thresholds of operation of comparators C_1 and C_2, V; δt_{del}, change in the delay in the injection laser as I_0 changes by δI_0, sec; ΔP_θ, temperature coefficient of change of the power, $W\cdot K^{-1}$; t_p, time of propagation of an injection-laser signal in the photodetector and the amplifier; τ, delay of the signal in the delay unit of the system with a two-channel priority discriminator, sec; U_r, reference voltage, V; Δt_0, time region (if the fronts of the discriminating pulses fall within this region, the output voltage of the two-channel priority discriminator is U_{out} = const), sec; τ_c, duration of the pulse front at the inputs of the comparators in the two-threshold method of recording of optical signals from the injection laser, sec; U_{pd}, amplitude of the pulse at the output of the photodetector, V; Δt_{del}, delay of the signal in the electric-delay unit in the two-threshold method of discrimination of pulsed signals, sec; U_n, noise voltage at the output of the photodetector, V; $t_{del.in}$, initial value of the radiation delay in the injection laser, sec; $t_{del.r}$, reference (stabilized) value of the radiation delay in the injection laser, sec; δt_{del}^{min}, minimum resolved time in the circuit of tuning the delay of the beginning of lasing of the injection laser, sec; f and φ, mutually inverse functions describing the dependence of the delay in the radiation generation in the injection laser on the output action ξ_{del} (for example, constant bias) in the loop of its control; $\Delta\xi_{del}$, step of quantization of the output action in the loop of control of the radiation delay in the injection laser, A; ξ_{del0}, value of the output action of the control system, corresponding to the delay in the lasing $t_{del.in}$, A; N_{del}, number of cycles of tuning the bias of the injection laser to the moment of attainment of the regime of stabilization of the stimulated-radiation delay in it; ψ and μ, mutuallyinverse functions determining the relation between the duration of the excitation interval of the injection laser and the output action ξ_τ in the loop of control of the duration of excitation of the injection laser; δt_τ, change in the duration of the interval of excitation of the injection laser as the output action ξ_τ in the system of control of the duration changes by the step of its quantization $\Delta\xi_\tau$, $\sec\cdot A^{-1}$; δt_τ^{min}, minimum resolved time in the loop of control of the duration, sec; $\xi_{\tau 0}$, value of the output action of the control system, corresponding to the duration of the interval of excitation of the injection laser τ_0, A; N_τ, number of comparison cycles to the moment of attainment of the steady-state condition in the loop of control of the duration; W_{pulse}, energy of the radiation pulse of the injection laser, W·sec; δW_k, error in the stabilization of the pulse-radiation energy of the injection laser, W·sec; v_τ, rate of change of the pulse duration, for example, under the action of disturbing factors, $\sec\cdot K^{-1}$; f_{rep}, repetition rate of radiation pulses of the injection laser, Hz; R and S, inputs of the trigger (R is the input of the trigger in the initial state, S is the signal input). Subscripts and superscripts: g, generation; thr, threshold; s.lum, stimulated luminescence; leak, leakage; lum, luminescence; loss, loss; in, initial; del, delay; st, stationary; sp, spontaneous; stab, stabilized; r, reference; p, propagation; out, output; c, comparator; pd, photodetector; n, noise; pulse, pulse; rep, repetition.

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