*Journal of Engineering Physics and Thermophysics, Vol. 73, No. 6, 2000*

# TEMPERATURE DEPENDENCE OF THE DELAY IN PULSE RADIATION OF AN INJECTION LASER

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UDC 681.327.68

*A theoretical analysis of the temperature dependence of the delay in stimulated radiation of an injection laser is made with allowance for the temperature dependence of the lifetime of the current carriers and the threshold current at different excitation levels. In admissible regimes of excitation the dependence of the delay on the temperature is investigated experimentally. The experimental results agree satisfactorily with those predicted. A method of stabilization of radiation delay in an injection laser based on priority discrimination of pulse signals is described, and its efficiency is investigated experimentally.*

In light range finder systems of recirculation type and systems of dynamic storage and processing of information based on injection lasers, the emitter, along with a stable power, must ensure a stable time position of the light pulses relative to the excitation-current pulse. The pulse delay in stimulated radiation of injection lasers is a function of the temperature; therefore its investigation under changing temperature conditions and the development of methods for its stabilization are urgent problems.

With allowance for the temperature dependence of the generation threshold $I_{\text{thr}}$ and the spontaneous lifetime $\tau_{\text{sp}}$ of nonequilibrium charge carriers in the laser [1] the expression for the delay in stimulated radiation in an injection laser can be written in the form

$$t_{\text{d}}(\theta) = [\tau_{\text{in}} - k(\theta - \theta_{\text{in}})] \ln \left\{ I/[I - I_{\text{thr0}} \exp(\theta/\theta_0) + I_0] \right\} . \tag{1}$$

Using Eq. (1) for $\tau_{\text{in}}$ = 4 nsec, $I_{\text{thr0}}$ = 9 mA, $\theta_0$ = 120 K, $k = 3.6 \cdot 10^{-2}$ nsec/K, and the threshold current $I_{\text{thr}}$ = 75 mA at $\theta_{\text{in}}$ = 295 K, the calculation of $t_{\text{d}}(\theta)$ for different values of the amplitude of the pulses of the excitation current $I$ and the current of constant bias $I_0$ gives results (see Fig. 1) that indicate that the greatest instability of $t_{\text{d}}$ under conditions of a varying temperature is characteristic of the operating mode of an injection laser with a small excess of the injection current over the threshold value. In Fig. 1a this mode for $I = 1.1 I_{\text{thr}}$ and $I_0 = 0$ is illustrated by curve 1. With increase in the excitation level, the extent of the portion of a weak temperature dependence of $t_{\text{d}}$ increases (curves 2 and 3 correspond to injection currents of 1.36 $I_{\text{thr}}$ and 2 $I_{\text{thr}}$ at $I_0 = 0$), whereas for $I = 2.5 I_{\text{thr}}$ the function $t_{\text{d}}(\theta)$ becomes nonmonotonic (curve 4). The weak increase in the delay with increase in the temperature for $I$ = 2.5 $I_{\text{thr}}$ in the temperature range (240–350) K and even the decrease in $t_{\text{d}}$ with increase in $\theta$ for $\theta > 330$ K seem to be due to the competition of two relations: $\tau_{\text{sp}}(\theta)$ and $I_{\text{thr}}(\theta)$. At $I = 2.51 I_{\text{thr}}$ for the temperature range 240 K $< \theta <$ 330 K the linear function $\tau_{\text{sp}}(\theta)$ compensates for the dependence $I_{\text{thr}}(\theta)$, and for $\theta > 330$ K it becomes predominant. Of course, the function of the form exp $(\theta/\theta_0)$ that characterizes the behavior of the generation threshold of an injection laser as the temperature changes will become predominant on further heating of the laser. However, for $I > 2.5 I_{\text{thr}}$ the region of a strong dependence $t_{\text{d}}(\theta)$ lies in the temperature range $\theta > 370$ K, and from the viewpoint of the maximum permissible temperature of the injection-laser crystal it is of no practical interest.

The change in the delay of radiation in an injection laser with change in the temperature for the operating mode of the laser at $I + I_0 = 1.1 I_{\text{thr}}$, $I + I_0 = 1.36 I_{\text{thr}}$, and $I + I_0 = 2 I_{\text{thr}}$, where $I_0$ = 100 mA, is illustrated by curves 5, 6, and 7, respectively. It is seen that the regions of temperatures characterized by a strong depend-

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Belarusian State University, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 6, pp. 1213-1219, November–December, 2000. Original article submitted April 27, 2000.

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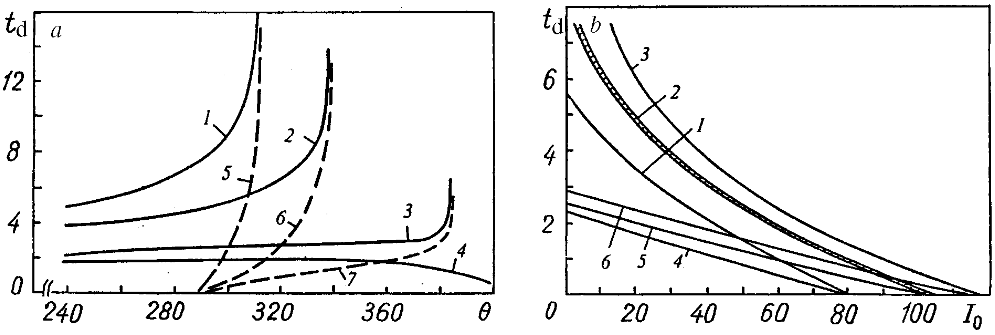

Fig. 1. Calculated dependences of the radiation delay in an injection laser $t_d$ on the temperature θ (a) and the constant-bias current (b) under different excitation conditions. $t_d$, nsec; θ, K; $I_0$, mA.

ence $t_d(\theta)$ are the same as for the case $I = 1.1I_{thr}$, $I = 1.36I_{thr}$, and $I = 2I_{thr}$ at $I_0 = 0$. It should be noted that the function $t_d(\theta)$ for $I_0 \neq 0$ is more pronounced than for $I_0 = 0$, and this difference is greatest for the injection-laser operating mode with an amplitude of the injection-current pulses slightly exceeding the threshold value (see curves 5 and 7).

Comparing curves 1 and 5, 2 and 6, 3 and 7, we may note that the delay in stimulated radiation in an injection laser depends strongly on the constant bias $I_0$. This allows one to use an injection laser as an element of controlled delay in the recirculation circuit of a measuring system. It is of interest to investigate the range of adjustment and the thermal stability of this optoelectronic delay line. Calculation of $t_d = f(I_0)$ was done using expression (1). For $I = 1.1I_{thr}$ at $\theta_1 = 260$ K, $\theta_2 = 295 \pm 1$ K, and $\theta = 309$ K the dependences of $t_d$ on the constant bias $I_0$ are given in Fig. 1b (curves 1, 2, and 3, respectively). For the same temperatures but for $I = 2I_{thr}$, the dependences $t_d = f(I_0)$ are represented by curves 4, 5, and 6. It can be seen that at room temperature (295 K) for $I = 1.1I_{thr}$ the range of adjustment of the delay in the injection-laser radiation with the parameters $\tau_{in} = 4$ nsec and $I_{thr} = 110$ mA (at 295 K) is a value of the order of 8 nsec. The adjustment characteristic of the delay is nonlinear in this case (especially in the region of currents 0–30 mA). Here, 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. 1b). At $I = 2I_{thr}$ the range of adjustment of the delay in an injection laser is equal to a value of the order of 2.5 nsec (at $\theta = 295$ K). Here, the regulating characteristic is close to linear, and the temperature coefficient of the delay is equal to a value of about 15 psec/K.

An analysis of $t_d(\theta)$ according to (1) shows that the accuracy parameters of a measuring system that uses an injection laser as a source of pulse radiation will be determined largely by the change in $t_d$ with change in the temperature conditions. This determines the necessity of developing methods of stabilization of $t_d$ in an injection laser. Solution of this problem by a direct method (for example, using a pulse-phase detector signal to adjust the injection current of the injection laser [2]) requires measurement of time intervals in the nanosecond range with picosecond accuracy (or use of "time-amplitude" transformation), which in itself is a formidable problem. In [3] the possibility of monitoring the time position of a stimulated-radiation pulse of an injection laser with picosecond time resolution based on the method of priority discrimination of two pulse signals is shown. It is of interest to use this method to stabilize $t_d$.

A functional diagram of the setup on which experimental investigations of $t_d(\theta)$ in an injection laser were carried out is shown in Fig. 2. The setup includes the investigated injection laser (IL) excited by an output signal from a current-pulse generator (CPG) through a coupling capacitance $C_c$. The temperature θ of the active region of the injection laser investigated was assigned by heating (by means of a heater (H)) a massive heat sink (HS) on which the laser is mounted. Radiation of the investigated injection laser was directed to the receiving pad of an avalanche photodiode with the aid of an optical system (OS) (two microscope objectives with a focal length of 5 mm). The diameter of the input hole (15 mm) of the receiving objective ensured collection of the entire luminous flux of the investigated laser in all the temperature modes of its operation. Control of the parallelism of the radiation beam and the broadening of the directional diagram was effected using adjustable diaphragms installed in front of the first and second microscope objectives. The injection laser

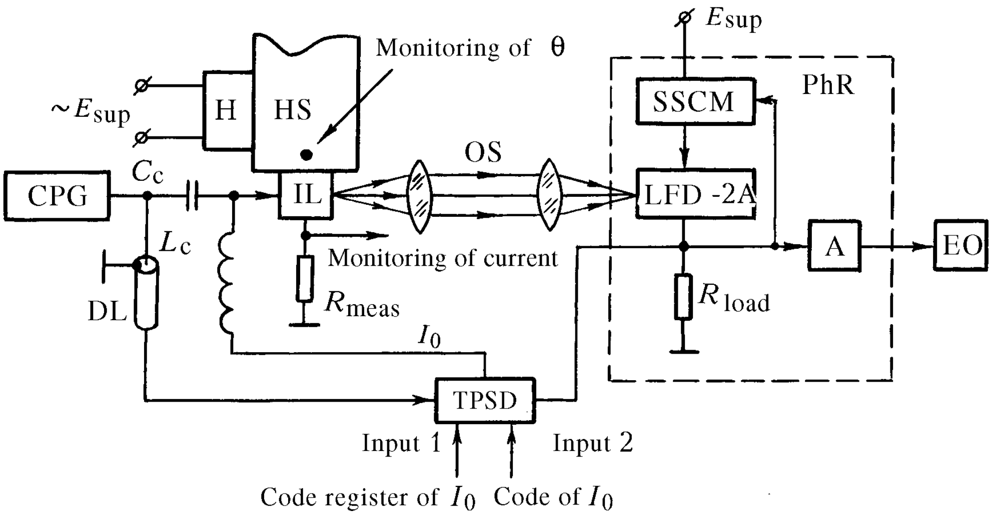

Fig. 2. Functional diagram of the experimental setup.

radiation pulse was recorded by a photoreceiving device (PhR) based on an LFD-2A avalanche photodiode with an amplifier (A) at its output. The internal amplification in the LFD-2A photodiode was stabilized with the aid of a system for stabilization of the coefficient of avalanche multiplication (SSCM) [4]. The amplifier in the photoreceiving device had a nonuniformity of the amplitude-frequency characteristic of less than 2 dB in the frequency band 470 MHz. Electric pulses from the output of the photoreceiving device and the measuring resistor $R_{\text{meas}}$ connected in series with the investigated laser were supplied to the input of a two-channel electronic oscillograph (EO).

The temperature of the injection laser was monitored with an accuracy no worse than $1^{\circ}$. Recording in the temperature range (295–340) K was carried out during both heating and cooling of the massive heat sink. The noted hysteresis of the results was within the limits of the temperature-measurement error.

To eliminate the temperature effect on the delay of the pulse radiation of the injection laser, in the experiment we used a device [5] that stabilizes the time position (TPSD) of the stimulated-radiation pulse of the injection laser relative to the excitation-current pulse. The output signal of the TPSD, which ensures an adjustable constant bias at different temperatures, was supplied to the injection-laser input through the decoupling inductance $L_c$. Inputs 1 and 2 of the TPSD were connected, respectively, to the output of the current-pulse generator (via a delay line (DL)) and to the LFD-2A output. The stabilized value of $t_d$ in the injection laser was established by selecting the signal delay in the delay line.

The principle of operation of the TPSD is based on comparison of the times of arrival of pulses from the outputs of the current-pulse generator and the LFD-2A of the photoreceiving device with the aid of a priority (time) discriminator and discrete correction of $I_0$ up to coincidence of the times of their arrival. This comparison is made for each pulse from the current-pulse generator output. The time resolution $\Delta\tau$ of this discriminator may attain tens of picoseconds [6]. To elucidate the principle of operation of the TPSD, the difference of the times of arrival of the pulses at the TPSD input $\Delta t$ will be written in the following form [1]:

$$\Delta t = \tau_2 b/U_2 + t_d(\theta, I_0) - \Delta t_d - \tau_1 a/U_1 \,. \tag{2}$$

If $\Delta t$ in (2) satisfies the condition $|\Delta t| > \Delta\tau$, then for each pulse from the current-pulse generator the tuning of the current of constant bias $I_0$ is carried out with the aid of the TPSD to decrease $\Delta t$ by the value $\delta I_0$ = const. To the value $\delta I_0$ there corresponds a change in the delay of the injection laser by a value $\delta t_d$ determined from the expression

$$\delta t_d = \tau_{sp}(\theta) \ln \left\{[I - I_{thr}(\theta) + I_0]/[I - I_{thr}(\theta) + I_0 + \delta I_0]\right\} . \tag{3}$$

To attain the condition $|\Delta t| \le \Delta\tau$, $N$ cycles of tuning are performed in the TPSD:

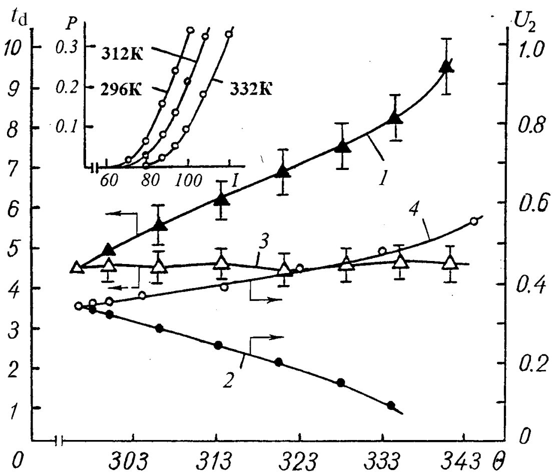

Fig. 3. Dependence of the radiation power of the injection laser $P$ on the injection current $I$ at different temperatures (inset) and dependences of the radiation delay in the injection laser $t_d$ (curves 1, 3) and the amplitude of the pulse response $U_2$ at the output of the photoreceiver (curves 2 and 4) on the temperature $\theta$; curves 3 and 4 correspond to the delay-stabilization regime. $P$, rel. units; $I$, mA; $t_d$, nsec; $U_2$, rel. units; $\theta$, K.

$$N = \frac{1}{\delta I_0}\left\{ I\left[\exp\left(\frac{\Delta t}{\tau_{sp}(\theta)}\right) - 1\right] + I_n(\theta) - I_0\right\}. \qquad (4)$$

After $N$ tunings, only switchings of the current $I_0$ with increase and decrease in $\Delta t$ by the value $\delta t_d$ determined from formula (3) will occur alternately in the TPSD. This algorithm of operation of the TPSD shows that stabilization of $t_d$ in an injection laser on the basis of priority discrimination of pulse signals in selecting $\delta t_d \approx \Delta t$ can be carried out with an accuracy $\Delta\tau + 2\delta t_d \approx 3\Delta\tau$. Taking into account the actual value of $\Delta\tau$ [6], we obtain a value of $3\Delta\tau$ equal to 60 psec. Comparison of the results of calculation by (1) for $I = 1.36 I_{thr}$ with the value of $3\Delta\tau$ shows that by using the described method of elimination of the temperature effect on the radiation delay in an injection laser, it is possible to improve its stability in this mode by about two orders of magnitude.

We investigated 32-DL106-type injection lasers based on GaAlAs. The lasers were excited by current pulses of length 90 nsec with a rise and decay time of 6 nsec and a repetition rate of 1 MHz. Using the TPSD in the mode of delay stabilization, we selected the mode of excitation of the lasers investigated (for reasons of the admissible degree of degradation with allowance for heating of the lasers to $\theta = 340$ K and an increase in $I_0$ with $\theta$) such that we could obtain $I + I_0 = 1.36 I_{thr}$ at $\theta = \theta_{in}$. For $\theta = \theta_{in}$ the value of $I_0$ did not exceed $0.1 I_{thr}$.

Initially, for the investigated lasers at different temperatures of the massive heat sink we recorded watt-ampere characteristics (see the inset in Fig. 3), the dependence $t_d(\theta)$, and the amplitude of the pulse response of the photoreceiving device (Fig. 3, curves 1 and 2). It is seen that in the temperature range (295–340) K the delay for the investigated laser changes by a value of about 5 nsec, while the amplitude of the pulse response at the exit of the photoreceiving device decreases by about a factor of 3.5. Thus, comparing the dependences represented by curve 2 in Fig. 1a and curve 1 in Fig. 3, satisfactory agreement can be seen between the calculated and experimental results. In approximating the experimental dependence $I_{thr}(\theta)$ by a function of the form $I_{thr0}\exp(\theta/\theta_0)$ the parameter $\theta_0$ for the GaAlAs lasers investigated had the value ~120 K, which is in agreement with the data of [7]. Thus, it is shown experimentally that the changes in the indicated parameters of the radiation of the lasers under the action of a changing temperature can strongly influence the accuracy characteristics of measuring and information systems based on injection lasers.

Next, for the indicated types of lasers we investigated the dependences $t_d(\theta)$ and $U_2(\theta)$ for the switched-on TPSD. In this case the function $t_d(\theta)$ is represented by curve 3 and $U_2(\theta)$ by curve 4. It is seen that $t_d$ in the temperature range indicated is practically constant (lies within the limits of measurement error), while $U_2(\theta)$, which is proportional to the generation power $P_g$ of the injection laser, increases by a law close to linear. Here, the temperature coefficient of the power is considerably smaller than in the mode of injection-laser operation without delay stabilization, but it changes sign ($P_g$ increases with increase in the temperature).

Analyzing the algorithm of operation of the TPSD, we see that after $N$ cycles of tuning of the constant bias of the injection laser, determined from (4), and satisfaction of the condition $|\Delta t| \leq \Delta\tau$ alternate switchings of the current of constant bias by the value $\delta I_0$ in opposite directions will be observed in the system. At $\delta t_d$ = $\Delta\tau$ = 40 psec in the mode $I + I_0$ = $1.36 I_{thr}$ for $\tau_{sp}$ = 4 nsec at room temperature we obtain from (3) that $\delta I_0 \approx 400$ μA. Using the expression for the radiation power of an injection laser of the form $P_g$ = $(h\nu\eta_{dif}/e)(I - I_{thr} + I_0)$ [1], for $\eta_{dif}$ = 0.8 and $\lambda$ = 0.85 μm at $\theta = \theta_{in}$ we find that a change of about 0.6% in the generation power $\Delta P_g$ of the injection laser corresponds to $\delta I_0 \approx 400$ μA. With the phase-pulse method of processing signals it is possible to neglect this spurious modulation of the amplitude in a pulse sequence. However, in systems with amplitude modulation and precision systems that use threshold discrimination, these fluctuations of $P_g$ already become a source of error. To eliminate the indicated spurious periodic fluctuations of the injection current, a two-channel priority discriminator can be used in the TPSD [8].

The algorithm of operation of a TPSD based on a two-channel priority discriminator is similar on the whole to that described above; however, in this case the stabilization regime occurs on condition that $\Delta\tau/2 < \Delta t < \Delta\tau/2 + \Delta t_0$. Satisfaction of this criterion means entry of the front of a stabilized pulse into the time region of width $\Delta t_0$ prescribed instrumentally by a delay at the input of one of the discriminator channels. In other words, $\Delta t_0$ is the relative shift of the discrimination characteristics of the discriminators of the two channels of the priority discriminator. In selecting $\Delta t_0 \approx \Delta\tau$ and organizing the operation of the channels of the two-channel discriminator in such a way that switchings of their discriminators cause opposite changes in the current, an accuracy of stabilization of $t_d$ is attained that is no worse than in the case of a single-channel discriminator without spurious amplitude modulation.

Thus, the analysis of the effect of temperature on the delay of stimulated radiation in a GaAlAs injection laser on the basis of expression (1) and its experimental investigation confirm the correctness of the model of $t_d(\theta)$ in the lasers indicated. The above model is based on allowance for the combined effect of the dependences $\tau_{sp}(\theta)$ and $I_{thr}(\theta)$ on the radiation delay in the temperature range (295–340) K. For the regimes of injection-laser excitation most admissible in practical applications ($1.2 I_{thr} \leq I \leq 1.6 I_{thr}$) use of a $t_d$-stabilization method that is based on priority discrimination of the pulses of their excitation and radiation allows one to increase the temperature stability of the delay of stimulated radiation in the indicated lasers by more than an order of magnitude. Use of a two-channel priority discriminator eliminates spurious amplitude modulation of a pulse sequence. The method can be rather simply implemented in apparatuses and can be used to improve the metrological characteristics of laser measuring systems based on injection lasers.

## NOTATION

$t_d$, delay of the stimulated-radiation pulse in the injection laser relative to the excitation-current pulse; $\theta$, absolute temperature; $\theta_{in}$, initial temperature (room temperature); $\tau_{sp}$, spontaneous lifetime of nonequilibrium charge carriers in the injection laser; $\tau_{in}$, spontaneous lifetime of nonequilibrium charge carriers at the initial (room) temperature; $k$, coefficient of the temperature dependence of the lifetime of nonequilibrium charge carriers; $I$, amplitude of the excitation-current pulse; $I_{thr0}$ and $\theta_0$, parameters of the approximation of the temperature dependence of the generation threshold; $I_0$, current of constant bias; $I_{thr}$, threshold current; $U_1$, amplitude of voltage pulses at the exit from the delay line; $U_2$, amplitude of the pulse response at the exit from the photoreceiving device; $\Delta\tau$, time resolution of the priority discriminator; $\delta I_0$, step of discrete tuning of the current $I_0$; $\delta t_d$, retuning of the delay in the injection laser with a change of $\delta I_0$ in the injection current; $\tau_1$ and $\tau_2$, lengths of the pulse fronts from the outputs of the delay line and the avalanche photodiode, respectively; $a$ and $b$, thresholds of operation of the comparators at inputs 1 and 2 of the TPSD; $\Delta t_d$, delay in the signal in the delay line; $\Delta t$, difference between the times of arrival of pulses at the inputs of the TPSD; $P_g$, power of injection-laser radiation; $h$, Planck constant; $\nu$, radiation frequency of the injection-laser; $\eta_{dif}$, differential quantum yield of the injection laser; $L_c$, variable-signal decoupling inductance; $C_c$, coupling capacitance; $e$, electron charge; $\Delta t_0$, relative time shift of the discrimination characteristics in the first and second channels of the two-channel priority discriminator; $E_{sup}$, supply voltage; $R_{load}$ and $R_{meas}$, load and measuring resistances. Subscripts: d, delay; sp, spontaneous; thr, threshold; sup, supply; c, coupling; dif, differential; in, initial; g, generation.

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