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TEMPERATURE ERROR COMPONENT OF THE RECIRCULATION OPTICAL RANGE FINDER BASED ON THE INJECTION LASER

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The present paper analyzes the range determination error caused by the temperature instability in recirculation range finders of the simplest type, range finders with quartz frequency stabilization, and those based on a controlled injection laser. The analysis was performed taking into account the temperature dependence of the radiation power, the lifetime of nonequilibrium charge carriers, and the threshold current of the injection laser as well as the pulsed signal delay in the range finder's photodetector. It is shown that under the conditions of unstable temperature recirculation range finders based on controlled injection lasers have the least temperature component of the error in ranging.

The ease of controlling the radiation parameters, the high efficiency, and the fairly high output lasing power in the pulsed mode of operation as well as the miniature design of injection lasers (IL) permit their use in optical ranging [1, 2]. Due to the above advantages of injection lasers the possibility of developing new types of range finders arose. This explains the fact that in the last few years the recirculation method of range monitoring has been widely used [3]. Recirculation optical range finders (RORF) operating by the principle of periodic circulation of pulses in a closed optoelectronic loop formed by the injection laser, the optical path between the emitter and the object the distance to which is being determined, and the photodetector (PhD), compare favorably with other types of range finders owing to their higher speed and ease of information processing in the course of taking measurements. The possibility of controlling the spacing between stimulated radiation and injection current pulses permits using the injection laser as an optoelectronic element with a controlled delay of the optical signal and realizing on its basis a recirculation frequency-locking recirculation optical range finder with an external stable generator. This makes it possible to abandon the use in recirculation optical range finders of difficult-to-realize and tuning schemes nonius schemes of distance "measure difference" within the oscillation period of a stable generator. Thus, the application of an injection laser in a recirculation optical range finder permits making compact, convenient-to-use, high-precision distance meters.

However, the strong temperature dependence of the radiation power, threshold current, stimulated radiation pulse delay, spontaneous lifetime of nonequilibrium charge carriers (NCC) in the injection laser, and photodetector parameters influences the recirculation frequency in the recirculation optical range finder loop, which leads to errors in the ranging [2]. Thus, analysis of the influence of temperature on the recirculation optical range finder precision and the working out of measures for its elimination are needed.

At present, three types of injection laser-based recirculation optical range finders are known: the simplest recirculation optical range finder [4], the recirculation optical range finder with quartz recirculation frequency stabilization [5], and the recirculation optical range finder based on a controlled injection laser [6]

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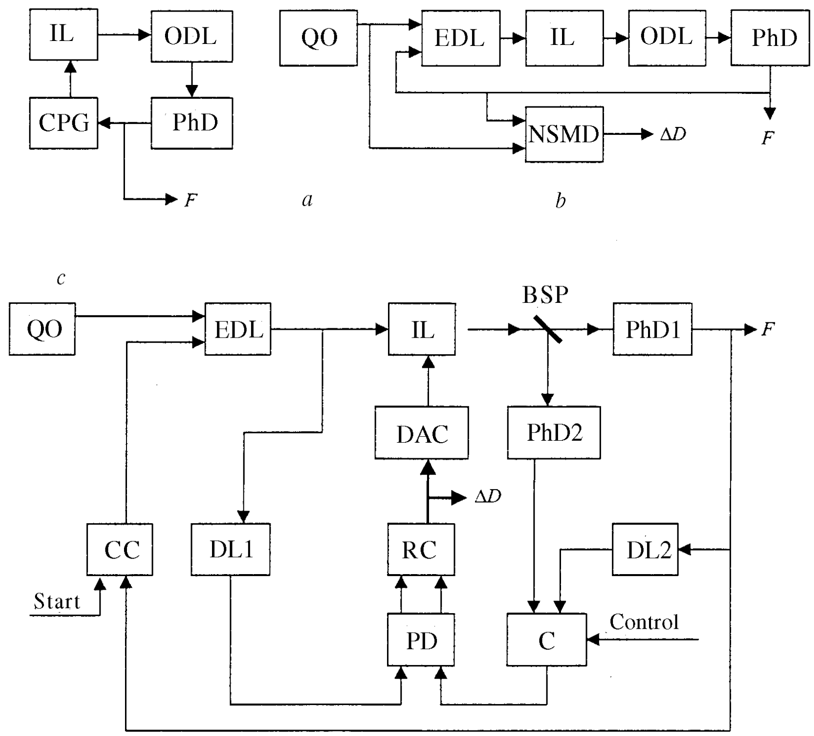

Fig. 1. Functional schemes of injection-laser-based recirculation optical range finders.

(Fig. 1a, b, and c, respectively). Because of the high speed and internal gain due to the avalanche multiplication of current carriers, the recirculation optical range finder photodetector is most frequently realized with the use of avalanche photodiodes (APD). When a light emitter based on a GaAsAl injection laser is used in the recirculation optical range finder, a Ge-avalanche photodiode is used as a photodetector [1, 2].

The recirculation optical range finder of the first type (Fig. 1a) contains a closed loop formed by the injection laser-emitter, the optical delay line ODL (its role is played by the optical path along which the radiation propagates to the object and back), the photodetector detecting the radiation reflected from the object, and the generator of current pulses by which the laser is excited. The recirculation frequency F in the recirculation optical range finder loop is determined by the sum of pulsed signal delays in the above-mentioned units and the electrical part of the range finder:

$$F = (t_{\text{laser}} + t_{\text{o.d.l}} + t_{\text{phd}} + t_{\text{c.p}} + t_{\text{p}})^{-1} . \tag{1}$$

The terms $t_{\text{c.p}}$ and t_{p} in (1) weakly depend on temperature, and their contribution to the error of ranging under varying temperature conditions can be neglected. Hereinafter, by the signal propagation delay time in the electrical part of the recirculation optical range finder loop the time $t_{\text{el}} = t_{\text{c.p}} + t_{\text{p}}$ will be meant.

Since $t_{\text{o.d.l}} = 2D/c$, from (1) we obtain the expression for the sought distance D in the form

$$D = \frac{c}{2}\left[\frac{1}{F} - (t_{\text{laser}} + t_{\text{phd}} + t_{\text{el}})\right]. \tag{2}$$

Using (2) and taking into account that the main temperature-dependent parameters of the recirculation optical range finder influencing the accuracy of measuring the distance D are t_{laser} and t_{phd}, we can write the expression for the temperature error ξ_θ in determining the distance by means of the recirculation optical range finder as

$$\xi_\theta(\theta) = \frac{d\left(D - \frac{c}{2F}\right)}{d\theta} = -\frac{c}{2}\left[\frac{dt_{\text{laser}}}{d\theta} + \frac{dt_{\text{phd}}}{d\theta}\right]. \quad (3)$$

We make use of the expressions for the temperature dependence of the stimulated radiation delay in the injection laser, the nonequilibrium charge current (NCC) spontaneous lifetime, the threshold current, the injection laser radiation power, the signal delay in the photodetector for the case of a linear pulse front, the electric signal on the avalanche photodiode load, and the avalanche multiplication factor [7–9]:

$$t_{\text{laser}}(\theta) = \tau_{\text{sp}}(\theta) \ln\left[\frac{I}{I - I_{\text{thresh}}(\theta)}\right], \quad (4)$$

$$\tau_{\text{sp}}(\theta) = \tau_{\text{in}} - k(\theta - \theta_{\text{in}}), \quad (5)$$

$$I_{\text{thresh}}(\theta) = I_{\text{thresh0}} \exp\left(\frac{\theta}{\theta_0}\right), \quad (6)$$

$$t_{\text{phd}}(\theta) = \frac{U_{\text{thresh}}}{U_{\text{phd}}(\theta)} \tau_{\text{f}}, \quad (7)$$

$$P_{\text{las}}(\theta) = \frac{h\nu}{e} \eta_{\text{laser}} [I - I_{\text{thresh}}(\theta)], \quad (8)$$

$$U_{\text{phd}}(\theta) = \eta_{\text{phd}} RGM(\theta) \frac{e}{h\nu} P_{\text{las}}(\theta), \quad (9)$$

$$M(\theta) = \frac{M_{\text{in}} \exp[bn(\theta - \theta_{\text{in}})]}{M_{\text{in}}\{\exp[bn(\theta - \theta_{\text{in}})] - 1\} + 1}. \quad (10)$$

Taking into account (4)–(10), we write the equation for the error ξ_θ in the recirculation optical range finder of the first type in the form

$$\xi_\theta(\theta) = \frac{c}{2} k \ln\left[\frac{I}{I - I_{\text{thresh}}(\theta)}\right] - \frac{c}{2}\left[\frac{\tau_{\text{sp}}(\theta)}{\theta_0}\right]\left[\frac{I_{\text{thresh}}(\theta)}{I - I_{\text{thresh}}(\theta)}\right] - \frac{c}{2} \frac{U_{\text{thresh}}\tau_{\text{f}} h\nu}{\eta_{\text{phd}} RGe} \times$$

$$\times \left\{bn[I - I_{\text{thresh}}(\theta)] M_{\text{in}} \exp[bn(\theta - \theta_{\text{in}})] - \left[bn\{I - I_{\text{thresh}}(\theta)\} - \frac{I_{\text{thresh}}(\theta)}{\theta_0}\right][M_{\text{in}}\{\exp[bn(\theta - \theta_{\text{in}})] - 1\} + 1]\right\} \times$$

$$\times \left\{P_{\text{las}}^2(\theta) M_{\text{in}} \exp[bn(\theta - \theta_{\text{in}})]\right\}^{-1}. \quad (11)$$

In (11), the first two terms describe the temperature error of the recirculation optical range finder caused by the instability of the stimulated radiation delay and by the nonequilibrium charge carrier lifetime in the injection laser, and the third one — by the change with temperature in the pulsed signal delay in the avalanche photodetector.

The principle of operation of the recirculation optical range finder of the second type [5] (Fig. 1b) is that the moments of sending excitation pulses to the injection laser are synchronized with the signals of the quartz oscillator QO by means of a discretely controlled electronic delay line EDL. In this case, it becomes possible to determine, by the recirculation frequency F, the distance D_T to an accuracy of the oscillation period of the synchronizing quartz oscillator, and the distance "measure difference" ΔD within period T by an additional meter of time intervals. In such recirculation optical range finders, tuning schemes of the "measure difference" NSMD are most commonly used.

Analyzing the error sources in ranging by means of a recirculation optical range finder of the second type, it can be noted that, as in the previous case, the main temperature-dependent parameters influencing the recirculation frequency and, consequently, the ranging accuracy, are t_{laser}, τ_{sp}, and t_{phd}. Therefore, the temperature error in determining the distance using the recirculation optical range finder with quartz stabilization of the recirculation frequency [5] will also be determined according to expression (11).

The third type of recirculation optical range finders based on a controlled injection laser [6] (see Fig. 1c) use active stabilization of stimulated radiation delay in the injection laser t_{laser} as well as its control for attaining the regime of rigid recirculation frequency locking in the optoelectronic circuit of the range finder with the oscillation frequency of the quartz oscillator. In so doing, by the control signal for which the locking regime is attained the distance "measure difference" ΔD is determined. In such a recirculation optical range finder, t_{laser} stabilization is carried out on the basis of priority discrimination of pulsed signals from the output of the first delay line DL1 and photodetector PhD2 recording a portion of the injection laser radiation by means of a beam-splitting plate BSP or from the rear side of the injection laser. The signals from the PhD2 (via the commutator C) and DL1 outputs are sent to the inputs of the priority discriminator PD whose output signals are recorded by the reversible counter RC. By the output code of the reversible counter, with the aid of the digital-to-analog converter DAC the injection laser excitation level is adjusted until the signal delay in the DL1 unit becomes equal to the stimulated radiation delay in the laser at a given temperature. In the regime of distance measurement, in such a recirculation optical range finder the distance D_T is determined by the recirculation frequency F, and the "measure difference" ΔD is determined by the code increment at the reversible counter output with time (priority) discrimination of signals from the output of the DL1 and the PhD1 recording the radiation that has arrived from the distance. In this case, the PhD1 signal is applied to the priority discriminator PD through the second delay line DL2 and C. Recirculation in the recirculation optical range finder contour is initiated via the combiner circuit CC.

The use of active stabilization of the stimulated radiation delay in the GaAlAs injection laser leads to the fact that the temperature dependence of its radiation power is described by an expression of the form

$$P_{\text{las}}(\theta) = P_{\text{in}}\,[1 + k_\theta\,(\theta - \theta_{\text{in}})]\,. \tag{12}$$

In this case, the temperature coefficient of power of the recirculation optical range finder's injection laser-emitter is positive (with increasing temperature there is an increase in the radiation power) and has a value of $k_\theta \approx 2.5{\cdot}10^{-3}\ \text{K}^{-1}$ [9]. Then the error in ranging by means of a recirculation optical range finder based on a controlled injection laser under the conditions of varying temperature is determined by the expression

$$\xi_\theta(\theta) = -\frac{c}{2}\left[\left.\frac{dt_{\text{laser}}}{d\theta}\right|_{t^{\text{st}}_{\text{laser}}(\theta)} + \left.\frac{dt_{\text{phd}}}{d\theta}\right|_{P^{\text{st}}_{\text{las}}(\theta)}\right]. \tag{13}$$

The use of the method of priority discrimination of pulsed signals of injection and lasing current in the injection laser makes it possible to stabilize the stimulated laser radiation delay under the conditions of

TABLE 1. Values of Injection Laser and Photodetector Parameters Given in the Analysis

IL and PhD parameters	RORFs of the first and second types		RORFs of the third type with stabilization of the IL radiation delay and avalanche multiplication factor of the APD	
	variant 1	variant 2	variant 1	variant 2
Spontaneous lifetime of NCC in IL τ_{in}, nsec	4	1	4	1
Quantum yield of IL η_{laser}	0.4	0.9	0.4	0.9
Excess of IL pumping current over the threshold value, times	1.1, 1.2, 1.3, 1.4, 1.5, 2, 2.5	1.1, 1.2, 1.3, 1.4, 1.5, 2, 2.5	1.5, 2, 2.5	1.5, 2, 2.5
Temperature coefficient of IL power k_θ, $W{\cdot}K^{-1}$	–	–	0.0025	0.0025
Pulse rise time at the threshold PhD input τ_f, nsec	5.2	1	5.2	1
Quantum yield of the PhD η_{phd}	0.6	0.9	0.6	0.9
Initial avalanche multiplication factor of the APD M_{in}	1, 5, 10	1, 5, 10	1, 5, 10	1, 5, 10

varying temperature to an accuracy no worse than $3\Delta\tau$. Here $\Delta\tau$ is the time resolution of the priority discriminator (it can have a value of ≈10–20 psec [10]). In this case, in expression (13), the first term is temperature-independent and has a constant value determined by $\Delta\tau$. If in the recirculation optical range finder no special measures are provided for stabilizing the avalanche multiplication factor of the avalanche photodiode under the conditions of varying temperature, then, taking into account (12), we can write the explicit form of (13) as follows:

$$\xi_\theta(\theta) = -\frac{c}{2}\frac{U_{thresh}\tau_f h\nu}{\eta_{phd}RGe}\frac{bnP_{las}(\theta)\,M_{in}\exp[bn(\theta-\theta_{in})] - [bnP_{las}(\theta) + P_{in}k_\theta]\,[M_{in}\{\exp[bn(\theta-\theta_{in})]-1\}+1]}{P_{las}^2(\theta)\,M_{in}\exp[bn(\theta-\theta_{in})]}. \quad (14)$$

With stabilization of the coefficient M, taking into account (7)–(9) and (13), the expression for $\xi_\theta(\theta)$ takes on the form

$$\xi_\theta(\theta) = \frac{c}{2}\frac{U_{thresh}\tau_f h\nu}{\eta_{phd}RGe}\frac{P_{in}k_\theta}{M_{in}P_{las}^2(\theta)}. \quad (15)$$

On the basis of (11), (14), and (15), we analyzed the influence of temperature on the error of the recirculation optical range finders of the above types. In so doing, we assumed that a GaAlAs injection laser with a radiation wavelength of $\lambda = 0.85$ μm was used as a radiation source and the recirculation optical range finder's photodetector was based on a germanium avalanche photodiode of the APD-2A type. The values of the injection laser and photodetector parameters given in the analysis are presented in Table 1. For all variants of analysis in the approximation of the temperature dependence of the injection laser radiation power and lasing threshold, with the use of (6), (8), and (9) we chose the values of $\theta_{in} = 293$ K, $I_{thresh0} = 9$ mA, $\theta_0 = 120$ K [7] and the photodiode parameters $U_{thresh} = 0.01$ V, $b = 1.2{\cdot}10^{-3}$ K^{-1}, $n = 4$, $G = 23$, and $R = 50$ Ω in expressions (10), (11), and (14) [9].

Figure 2 gives the temperature dependences of the distance measurement error ξ_θ for the recirculation optical range finders of the first and second types. In the analysis, it was assumed that the thermostability of the injection laser parameters and of the avalanche multiplication factor in the avalanche photodiode was not used. A characteristic feature of the $\xi_\theta(\theta)$ dependence is an increase in the absolute value of the temperature component of the error with increasing temperature for all regimes of injection laser excitation and of the

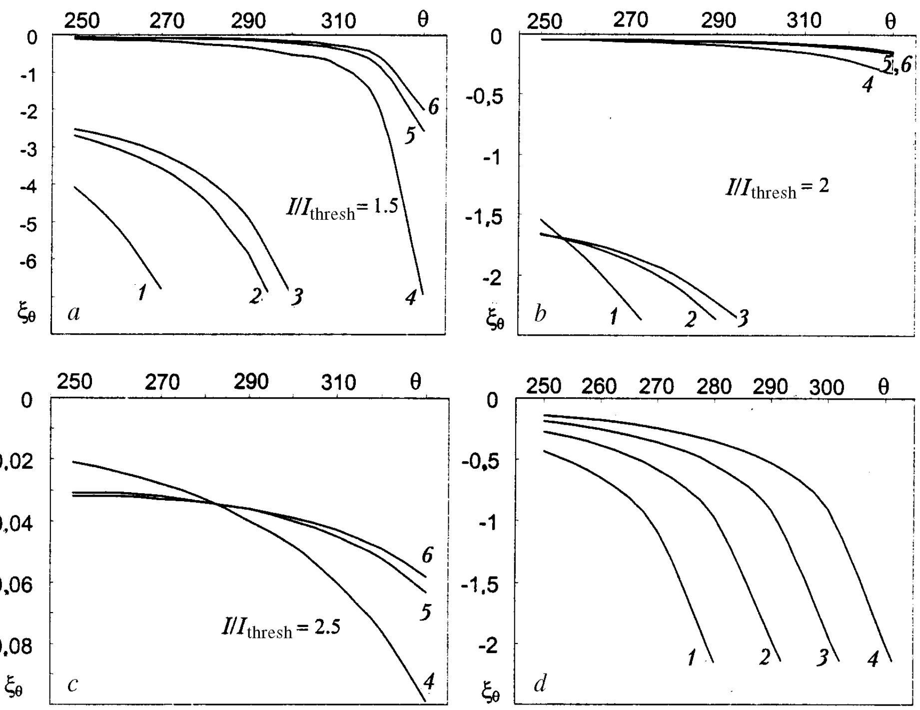

Fig. 2. Temperature dependence of error ξ_θ for recirculation optical range finders of the first and second types. Curves (Fig. 2a, b, and c) 1, 2, and 3 (variant 1) and 4, 5, and 6 (variant 2) correspond to M = 1, 5, and 10. Curves 1, 2, 3, and 4 (Fig. 2d) correspond to I/I_{thresh} = 1.1, 1.2, 1.3, and 1.4 at M = 10 (variant 2).

multiplication factor of carriers in the avalanche photodiode. It is noteworthy that with increasing M and I/I_{thresh} ratio the $\xi_\theta(\theta)$ function becomes weaker for all variants of calculation. The ξ_θ value of the error of distance measurement by the recirculation optical range finders of the first and second types strongly depends on the parameters τ_{sp} and t_f (compare, for example, curves 1, 2, 3, and 4, 5, 6, respectively, in Fig. 2a, b). The $\xi_\theta(\theta)$ dependences at different excesses of injection currents over the threshold value differ in both the absolute value of the error θ_θ for a given temperature and the position on the temperature axis of the characteristic value of the temperature θ_1 at which the value of ξ_θ begins to increase rapidly with increasing θ (see Fig. 2d). Such a behavior of the $\xi_\theta(\theta)$ function is attributed to the fact that at temperatures of $\theta > \theta_1$, the condition $I < I_{thresh}$ is fulfilled and the laser goes over to the mode of spontaneous radiation, which is characterized by a low radiation intensity and is not suitable for use in recirculation optical range finders. In Fig. 2d, the form of the $\xi_\theta(\theta)$ function for I/I_{thresh} values increasing from 1.1 to 1.4 with a step of 0.1 is shown by curves 1, 2, 3, and 4, respectively. With increasing I/I_{thresh} the θ_1 value is shifted into the region of higher temperatures. For the case of injection laser excitation by current of $I = 2.5I_{thresh}$ in the vicinity of the temperature θ_2 = 283 K, the ξ_θ error is independent of the avalanche multiplication factor (see Fig. 2c), and with decreasing I/I_{thresh} the value of θ_2 decreases (for example, to the injection current of $I = 2I_{thresh}$ there corresponds θ_2 = 255 K (see Fig. 2b)).

The $\xi_\theta(\theta)$ dependences for the recirculation optical range finder based on an injection laser in which active stabilization of the stimulated radiation pulse delay is realized are shown in Fig. 3. In this case, it was assumed that no stabilization was carried out for M. Calculations were performed for two variants of parameters (see Table 1). Unlike the previous case, with increasing temperature the absolute value of ξ_θ decreases, and it should be noted that for all variants of calculation at M = 1 (curves 1, 4) and M = 1.6 (curves 2, 3, 5, and 6) in Fig. 3a, c, and d the error ξ_θ has a different sign. For $M \approx 1.5$ and other parameters of the

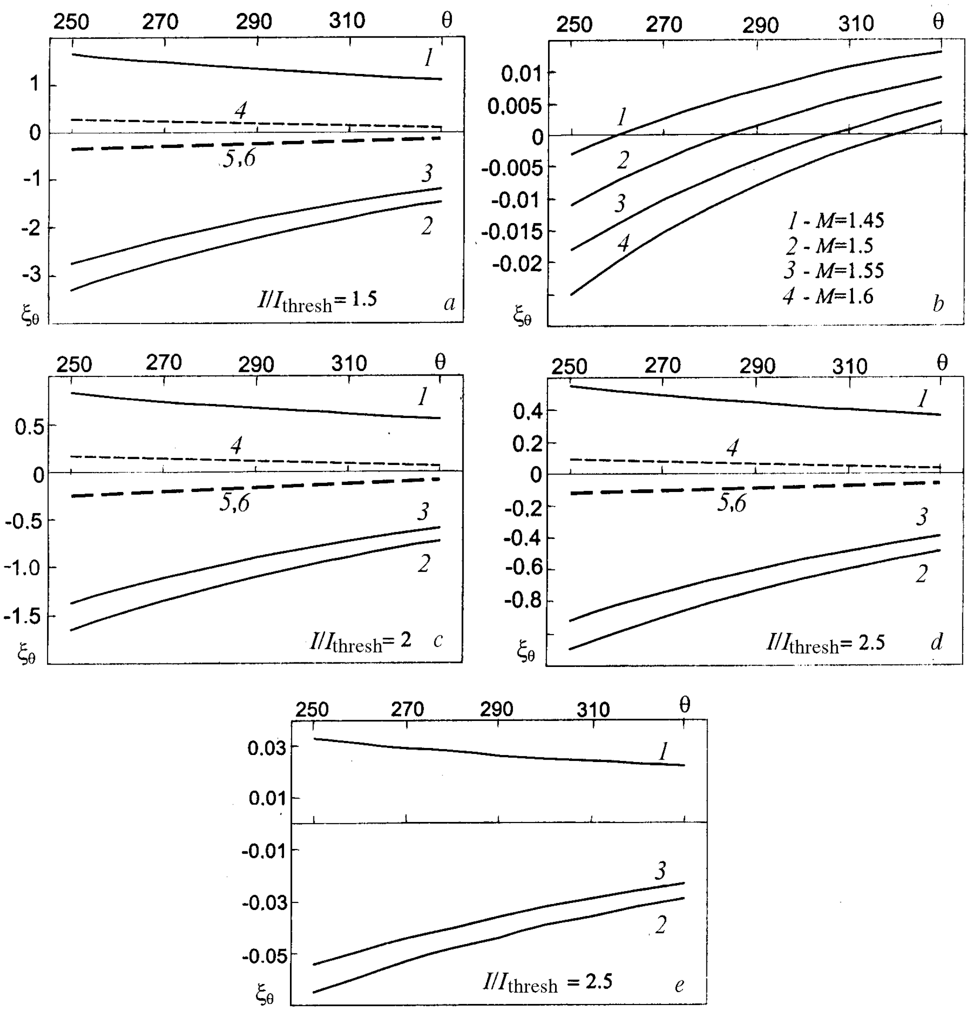

Fig. 3. Temperature dependence of error ξ_θ for recirculation optical range finders of the third type without stabilization of *M*. Curves (Fig. 3a, c, and d) 1, 2, and 3 (variant 1) and 4, 5, and 6 (variant 2) correspond to the initial values of M_{in} = 1, 5, and 10. Curves 1, 2, 3, and 4 (Fig. 3b) show the shift of the θ_3 value. Curves 1, 2, and 3 (Fig. 3e) correspond to M_{in} = 1, 5, and 10 in the calculation according to variant 2.

model given according to variant 2, with increasing temperature in the 250–330 K range the sign of the error ξ_θ changes (see curves 1–4 in Fig. 3b). The temperature θ_3 at which the ξ_θ sign changes depends on the values of *M*, I/I_{thresh}, τ_f, and τ_{sp}. As *M* increases, the θ_3 value shifts into the region of higher temperatures. This means that by selecting the above parameters for a given temperature one can choose the mode of operation of the recirculation optical range finder where $\xi_\theta < \xi_{p.d}$. Here $\xi_{p.d}$ is the recirculation optical range finder error component caused by the finite value of the priority discriminator (PD) time resolution. In the recirculation optical range finder of the third type without stabilization of *M* in the avalanche photodiode, with increasing I/I_{thresh} there is a decrease in the absolute values of ξ_θ without a change in the qualitative character of the dependence $\xi_\theta(\theta)$ (see, for example, curves 1, 2, and 3 in Fig. 3a, c, d, and e). The value of $\xi_\theta \approx \xi_{p.d}$ at I/I_{thresh} = 2.5 and M = 10 for the parameters given according to variant 2 is attained in such a recirculation optical range finder approximately in the region of room temperatures (see curve 3 in Fig. 3d).

Figure 4 shows the $\xi_\theta(\theta)$ dependences for the recirculation optical range finder based on a controlled injection laser for the case where, in addition to the stabilization of the radiation delay in the injection laser,

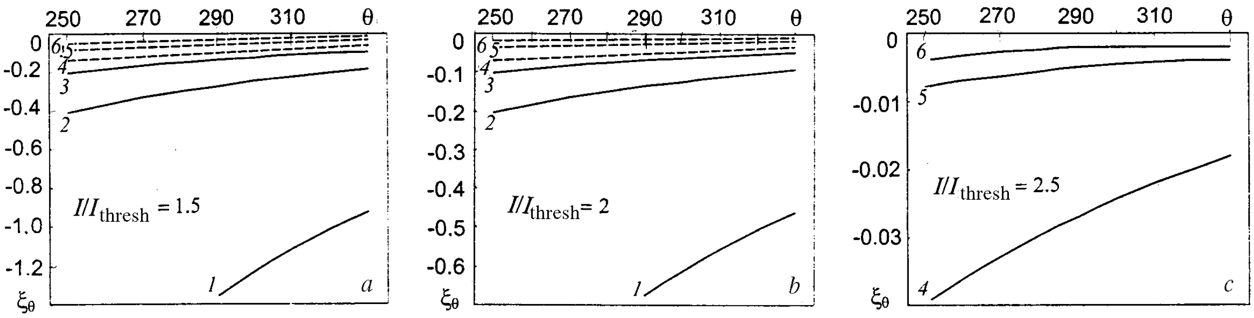

Fig. 4. Temperature dependence of error ξ_θ for recirculation optical range finders of the third type with stabilization of *M*. Curves 1, 2, and 3 (variant 1) and 4, 5, and 6 (variant 2) correspond to the initial values of M = 1, 5, and 10 at different I/I_{thresh} (a, b, and c).

the avalanche multiplication factor of the avalanche photodiode is stabilized. For all variants of parameters given in the calculation (see Table 1), with rising excitation level of the injection laser and increasing *M* there is a monotonic decrease in the ξ_θ error. An increase in *M* leads to a decrease in the $\xi_\theta(\theta)$ slope and an asymptotic approximation of the dependence to the θ axis. It can be seen (curves 5 and 6 in Fig. 3b) that for the photodetector parameters given according to variant 2, for $M = 10$, a recirculation optical range finder error which is already limited to the time resolution of the priority discriminator is attained. Thus, the parameters according to variant 2 for the recirculation optical range finder based on a controlled injection laser are close to optimum from the point of view of the ξ_θ error minimum and practical realizability of the range finder.

To obtain the total value of the temperature component of the recirculation optical range finder error, it is also necessary to take into account the temperature dependence of the signal propagation time in the electrical part of the recirculation optical range finder loop $t_{el}(\theta)$. This influence can be estimated on the basis of the following reasoning. For example, in [10] it is noted that the temperature drift of the electronic delay line can constitute ≈0.02%/K. Then, assuming that the real delay value in the electrical part of the recirculation optical range finder loop can amount to 10–30 ns, we can obtain that ξ_{el} is an order of magnitude lower than the value of $\xi_{p.d}$.

Thus, under the conditions of unstable temperature recirculation optical range finders of the first and second types are characterized by the largest temperature component of the distance determination error. This component even for fairly high parameters of the injection lasers and photodetectors used in recirculation optical range finders (see Table 1, variant 2) at $I/I_{thresh} = 2$ in the vicinity of room temperature is about 0.1 m/K (Fig. 2a, curves 5, 6). In this case, an increase in I/I_{thresh} to 2.5 leads to a decrease in ξ_θ to 0.04 m/K. However, such a regime is no longer suitable for the majority of GaAlAs injection lasers in terms of their degradation rate because of the high current density and optical power in the laser cavity [11]. Therefore, for the recirculation optical range finders of the first and second types the most reasonable solution for decreasing ξ_θ is the thermostabilization of the injection laser and the avalanche photodiode in the photodetector of the range finder [12]. For the recirculation optical range finder parameters given according to variant 1 (see Table 1), at $I/I_{thresh} = 2$ for room temperatures and $M = 10$ the value of $\xi_\theta \approx 2.2$ m/K (see curve 3, Fig. 2b). Consequently, to attain the condition $\xi_\theta < \xi_{p.d}$, thermostabilization of the injection laser and the photodetector with an accuracy of about 10^{-2} K is required. For the recirculation optical range finder parameters given according to variant 2 for the same I/I_{thresh} and *M*, the condition $\xi_\theta < \xi_{p.d}$ is fulfilled when the injection laser and the photodetector are thermostabilized with an accuracy of about $5 \cdot 10^{-1}$ K in the 250–330 K range. In the recirculation optical range finder of the third type without stabilization of *M*, due to the fact that with increasing θ an increase in the lasing power P_{las} and a decrease in the avalanche multiplication factor *M* are observed, a partial compensation for the increase in ξ_θ with temperature occurs. This makes it possible by selecting I/I_{thresh} and τ_f to realize in the recirculation optical range finder the mode of operation where $\xi_\theta < \xi_{p.d}$ and $\xi_\theta \approx 0$ at a given temperature. The recirculation optical range finder of the third type in which stabilization of the delay t_{laser} and M is realized is characterized by the fact that with increasing M and I/I_{thresh} and decreasing τ_f and τ_{sp} a monotonic decrease in ξ_θ is observed. In so doing, the condition $\xi_\theta \sim \xi_{p.d}$ can be attained relatively easily by decreasing τ_f and increasing M even at small values of I/I_{thresh} (see curves 5, 6 in Fig. 4a, b).

NOTATION

F, recirculation frequency; t_{laser}, stimulated radiation pulse delay in the injection laser; t_{phd}, pulsed signal delay in the recirculation optical range finder's photodetector; t_{el}, signal propagation delay in the electrical part of the loop (in the current pulser and conductors of the electrical part of the circuit); $t_{o.d.l}$, signal propagation delay at a distance; ξ_θ, temperature component of the error of distance measurement with the aid of a recirculation optical range finder; $\xi_{p.d}$, recirculation optical range finder error caused by the priority discriminator time resolution; ξ_{el}, error component of the recirculation optical range finder caused by the temperature change in the signal propagation delay in the electric part of the loop; D, distance to the object; c, velocity of light; θ, absolute temperature; θ_1, temperature corresponding to the injection laser going out from the stimulated radiation mode; θ_2, temperature at which ξ_θ is independent of the avalanche multiplication factor of the avalanche photodiode; θ_3, temperature at which the ξ_θ sign changes; τ_{sp}, spontaneous lifetime of the nonequilibrium charge carrier in the injection laser; I, injection current pulse amplitude; I_{thresh}, threshold current of the injection laser; k, coefficient of the temperature dependence of the nonequilibrium charge carrier lifetime in the injection laser; τ_{in}, initial value of the nonequilibrium charge carrier lifetime; θ_{in}, initial value of the temperature; $I_{thresh0}$, θ_0, approximation parameters of the temperature dependence of the injection laser lasing threshold; U_{thresh}, threshold voltage; U_{phd}, voltage at the photodetector output; τ_f, pulse front duration at the input of the threshold device; P_{las}, injection laser lasing power; P_{in}, injection laser radiation power at $\theta = \theta_{in}$; η_{laser}, injection laser quantum efficiency; η_{phd}, photodetector quantum yield; h, Planck constant; ν, injection laser radiation frequency; e, electron charge; R, photodetector load resistance; G, transfer coefficient of the photodetector amplifier; M, avalanche multiplication factor of the avalanche photodiode; M_{in}, initial value of the avalanche multiplication factor; $b = (0.7–1.5)\cdot 10^{-3}$ K^{-1}; n = 4–5 for the Ge avalanche photodiode [9]; k_θ, temperature coefficient of the injection laser radiation power in the mode of stabilized delay; T, oscillation period of the synchronizing generator; D_T, distance determined to an accuracy of the synchronizing generator oscillation period; ΔD, distance "measure difference"; I_0, injection laser constant bias current; t^{st}_{laser}, value of the stimulated radiation delay in the injection laser in the stabilization mode; P^{st}_{las}, value of the injection laser radiation power in the stabilization mode; $\Delta\tau$, time resolution of the priority discriminator; λ, injection laser lasing wavelength. Subscripts and superscripts: laser, laser; phd, photodetector; el, electric; c.p, current pulser; p, propagation; sp, spontaneous; thresh, threshold; in, initial; f, pulse front; las, lasing; st, stabilization; o.d.l, optical delay line; e.d.l, electrical delay line.

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