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THE LIMITING CAPABILITIES OF INJECTION-LASER-BASED RECIRCULATING OPTICAL RANGE FINDERS UNDER ACTUAL TEMPERATURE CONDITIONS

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Using a method of mathematical simulation, it is shown that the maximum range measured by a GaAlAs injection-laser-based recirculating optical range finder decreases linearly with increase in the environment temperature. The steepness of its decrease depends on the excess of the laser injection current over a threshold value. At temperatures nearly equal to room temperature, the maximum measured range increases nonlinearly with increase in the injection current, and for $I > 2.5I_{thr}$ this dependence is close to saturation, but it decreases nonlinearly with increase in the divergence angle of the injection laser radiation.

Contemporary injection lasers (IL) are superior to other types of lasers in mass and overall dimension; they are quite durable (their working life lasts as long as 10^5 h [1]) and provide a power in a pulse of up to several watts to tens of watts [2]. For this reason, injection lasers are being used all the more extensively in optical-range-finding technology. The possibility of simply controlling the injection-laser radiation parameters (power, delay of stimulated radiation, etc.) by changing the strength of the injection current has made it possible to apply injection lasers for developing a new type of a recirculating optical range finder (RORF), whose operation is based on synchronization of a recirculation frequency with an oscillation frequency of a stable oscillator [3]. As regards the case of fabrication, these range finders closely resemble pulse rangers, while as regards their precision parameters, they are comparable with phase rangers [4].

At the same time, the temperature dependence of a large number of injection-laser characteristics (threshold current, spontaneous lifetime of nonequilibrium charge carriers, quantum efficiency, etc.) imposes restrictions on the characteristics of this kind of RORF (limiting range and accuracy). Therefore, it is of current interest to analyze the limiting capabilities under actual temperature conditions of the RORF that are based on controlled injection lasers.

The functional circuit of an RORF with frequency synchronization is presented in Fig. 1a. The recirculation loop of the range finder includes: an injection laser; a photodetector (PhD) of the radiation reflected from an object the distance to which is measured; a threshold former (ThF) and a counter of the number of periods (CP) of oscillations of a quartz oscillator (QO) that are fitted into the period of recirculation. In measuring the distance to the object, the RORF uses the signals of a time discriminator (TD) in a control signal shaper (CSS) and produces a trimming signal of stimulated radiation delay in the injecion laser to attain synchronization of the recirculation frequency F_{rec} in the recirculation loop with the oscillation frequency of the quartz oscillator. From the number of the oscillation periods of the quartz oscillator that are fitted into the recirculation period, the distance to the object D_T is determined to within the oscillation period in the quartz oscillator, while the signal from the control signal shaper allows determination of ΔD within the limits of the oscillation period of the quartz oscillator $T_{\text{q.o}}$.

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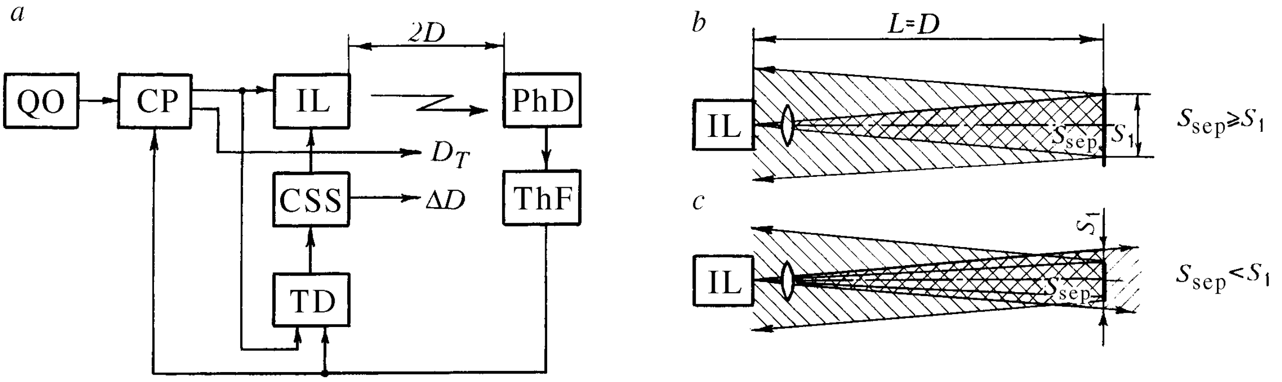

Fig. 1. Functional circuit of the controlled injection laser-based RORF (a); optical circuits that explain the principle of measurement by means of RORF (b and c).

The range of action of the finder is one of its main characteristics. For the RORF it depends on the injection laser radiation power determined by the temperature conditions and on the laser excitation mode [3], on the state of the medium between the range finder and the object, and on the reflecting characteristics of the object the distance to which is measured [4]. The majority of injection lasers are characterized by a strong dependence of the pulse radiation power on temperature due to the temperature dependence of their threshold for oscillation. Moreover, the delay in the stimulated radiation pulse at the injection laser output changes greatly with temperature relative to the excitation-current pulse.

For pulse, pulse-phase, and some other injection laser-based range finders the influence of a change in radiation power with temperature on the accuracy of measuring distances can be eliminated by resorting to a start–stop principle of measuring the time interval that corresponds to the distance measured. Then, the delay in the stimulated radiation pulse of the injection laser relative to the excitation-current pulse is not included in the measured time interval and, consequently, it does not affect the accuracy of the measurement of distances. The RORF does not provide the possibility of eliminating the influence of the temperature change in the delay (power) of the injection laser radiation on the accuracy of the measurement of distances, since all the delays of a signal in the recirculation loop determine the recirculation frequency by which the distance is determined.

The influence of the state of the medium between the range finder and the object and also of the reflecting characteristics of the object on the range of action of the RORF can be taken into account instrumentally in the same way as in other range finders (automatic gain control of a signal in the photodetector, time locking of the signal in the threshold former, etc.).

The distance to the object measured by a light-pulse method can be written in the form

$$D = ct_{\mathrm{opt}}/2n_{\mathrm{med}} \,. \tag{1}$$

If the time of radiation propagation over the distance measured is the delay in a feedback circuit of the optoelectronic recirculation oscillator, then, with allowance for delays in other units of the recirculation loop, for the recirculation period the following expression can be written:

$$T_{\mathrm{rec}} = I/F_{\mathrm{rec}} = t_{\mathrm{las}} + t_{\mathrm{opt}} + t_{\mathrm{del}} \,. \tag{2}$$

The temperature dependence of the stimulated radiation delay of the injection laser can be taken into account by the expression [5]

$$t_{\mathrm{las}}(\Theta) = \tau_{\mathrm{sp}}(\Theta) \ln\left[I/(I - I_{\mathrm{thr}}(\Theta))\right] . \tag{3}$$

In the range of temperatures (270–320 K) for a GaAlAs-based injection laser the dependences $\tau_{sp}(\Theta)$ and $I_{thr}(\Theta)$ can be approximated by the expressions [5]

$$\tau_{sp}(\Theta) = \tau_{rm} - k_\tau (\Theta - \Theta_{rm}) , \quad I_{thr}(\Theta) = I_{thr0} \exp (\Theta / \Theta_0) . \tag{4}$$

Here $k_\tau \approx 3.6 \cdot 10^{-2}$ nsec/K, $I_{thr0} \approx 9$ mA, and $\Theta_0 \approx 120$ K [5, 6].

By virtue of the temperature dependence of the oscillation threshold $I_{thr}(\Theta)$ and the quantum efficiency of the injection laser (slope of the watt-ampere characteristic), the injection laser radiation power also turns out to be temperature dependent:

$$P_{las}(\Theta) = \eta_{las}(\Theta) \frac{h\nu}{e} [I - I_{thr}(\Theta)] . \tag{5}$$

The radiation attenuation in propagation over the distance measured can be taken into account by the expression [7]

$$P_L = P_{las} \exp (-\alpha L) . \tag{6}$$

The magnitude of the power received by the RORF photodetector is determined from dimension–energy calculations in which the characteristics of the optical system must be taken into account. Let us assume that there is a corner reflector in the RORF in which only that area S_{ref} reflects without losses which is defined by the radius of the inscribed circle r_{ref}:

$$S_{ref} = \pi r_{ref}^2 = 3\pi b^2 / 144 , \quad r_{ref} = b \sqrt{3} / 12 . \tag{7}$$

If radiation from the injection laser is focused to a beam shape with a divergence angle φ. then the light-spot area at the distance L is

$$S_1 = \pi [L \tan (\varphi/2) + d/2]^2 . \tag{8}$$

When $S_{ref} \ge S_1$ (Fig. 1b), the magnitude of the injection laser radiation power sent back by the reflector is determined according to Eq. (6).

For $S_{ref} < S_1$ (see Fig. 1c), expression (6) takes the form

$$P_L = \frac{S_{ref}}{S_1} P_{las} \exp (-\alpha L) . \tag{9}$$

Likewise taking into account the passage of the injection laser radiation from the reflector to the detector, the light-spot area in the RORF photodetector plane S_2 can be represented as

$$\begin{aligned} S_2 &= \pi [2D \tan(\varphi/2) + d/2]^2 \quad \text{for} \quad S_{ref} \ge S_1 ; \\ S_2' &= \pi [2D \tan(\varphi/2) + r_{ref}]^2 \quad \text{for} \quad S_{ref} < S_1 . \end{aligned} \tag{10}$$

Taking into account expressions (6)–(10) for the power received by the RORF photodetector, we write

$$P_{rd} = \frac{S_{rd}}{S_2} P_{las} \exp (-2D\alpha) , \quad S_{ref} \ge S_1 ; \quad P_{rd}' = \frac{S_{rd}}{S_2'} P_{las} \exp (-2D\alpha) , \quad S_{ref} < S_1 . \tag{11}$$

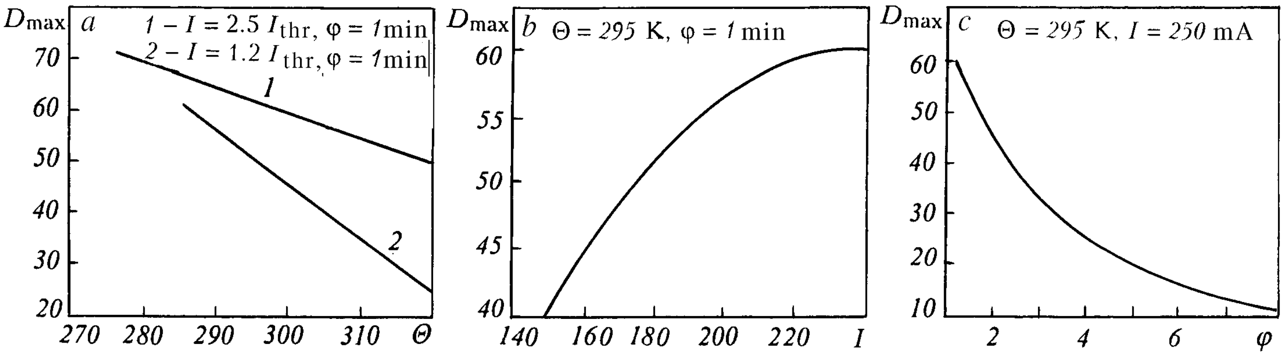

Fig. 2. Dependence of the maximum measured distance $D_{\max}$ on the temperature Θ (a), current I (b), and the radiation divergence angle φ (c). $D_{\max}$, m; Θ, K; I, mA; φ, min.

The optical signal received by the photodetector is converted into an electric one according to the law

$$U_{\text{phd}} = I_{\text{phd}} R_{\text{load}} = \eta_{\text{phd}} \frac{e}{h\nu} P_{\text{rd}} R_{\text{load}} \,. \tag{12}$$

If the optical power received by the photodetector exceeds the minimum admissible one, the signal at the output of the photodetector is so strong that at the threshold-former output its amplitude is ensured sufficient for the operation of the time discriminator and counter of periods, so that the recirculation is conducted in the loop. If the power received is below the minimum admissible one, the threshold-former signal is not formed, the counter of periods is idle, the next pulse is not sent to the distance, and the recirculation is absent. In this case, the RORF is inoperative. This situation is observed for distances that exceed the limiting one.

At the threshold-former output, a signal of standard amplitude is formed with a delay that depends on the amplitude of the light pulse received by the photodetector. If the optical signal received has a linear front of length τ_{fr}, the time delay in the threshold former is

$$t_{\text{del.thf}} = \tau_{\text{fr}} U_{\text{thr}} / U_{\text{phd}} \,. \tag{13}$$

Then, with account for Eqs. (1)–(3) and (13), analysis of the effect of temperature on the result of measurement of the RORF range can be carried out using the expression

$$D(\Theta) = \frac{c}{2n} \left\{ nT_{\text{q.o}} - \tau_{\text{sp}}(\Theta) \ln \left[\frac{I}{I - I_{\text{thr}}(\Theta)} \right] - \frac{\tau_{\text{fr}} U_{\text{thr}}}{U_{\text{phd}}(\Theta)} \right\}, \tag{14}$$

where $\tau_{\text{sp}}(\Theta)$, $I_{\text{thr}}(\Theta)$, and $U_{\text{phd}}(\Theta)$ are described by relations (4) and (12).

For the RORF based on a GaAlAs-injection laser with a radiation wavelength of $\lambda = 0.87$ μm, threshold current 100 mA, and quantum efficiency $\eta_{\text{las}} = 0.6$, we determined the maximum distance $D_{\max}$ that corresponds to the minimum admissible received power $P_{\text{rd}}^{\min}$. The dependences $D_{\max}(\Theta)$, $D_{\max}(I)$, and $D_{\max}(\varphi)$ were investigated (Fig. 2). As the RORF photodetector we used an avalanche photodiode with $P_{\text{rd}}^{\min} = 10^{-7}$ W that ensured continuous recirculation in the RORF loop. In the model the medium was assumed to be homogeneous with the radiation-attenuation coefficient $\alpha = 5 \cdot 10^{-5}$ m^{-1}. The temperature dependence of the injection laser quantum efficiency was ignored, since in the temperature range under consideration it was only slightly expressed ($k_{\eta} \approx 0.1\%$/K [5]). The radiation-divergence angle was taken to be equal to $\varphi = 1$ min; as the most general case it was assumed that $S_{\text{ref}} < S_1$.

Based on the model (1)–(14), it is established that the maximum distance D_{max} measured by the injection laser-based RORF depends practically linearly on temperature, but for different excesses of an operating current over the threshold one there are different values of the coefficient of the change in the distance with temperature k_θ. Thus, for $I = 2.5I_{thr}$ the coefficient $k_\theta = 0.36$ m/K (Fig. 2a; curve 1), while for $I = 1.2I_{thr}$ it increases up to 0.5 m/K (curve 2). The dependence $D_{max}(\Theta)$ can be approximated by the expression

$$D_{max}(\Theta) = D_{max}(\Theta_{rm}) - k_\theta(\Theta - \Theta_{rm}) . \tag{15}$$

The investigations of the dependence of the maximum measured distance on an injection current at fixed temperature and radiation divergence angle (Fig. 2b) made it possible to establish that this dependence has the form

$$D_{max}(I) = \psi I^z , \tag{16}$$

where $z \approx 0.87$ and $\psi \approx 190$ m/A for $\Theta = 295$ K and $I = 2.5I_{thr}$.

The influence of the radiation divergence angle on D_{max} is also described by a dependence similar to (16):

$$D_{max}(\varphi) = \xi\varphi^q , \tag{17}$$

where $\xi \approx 63$ m/min, $q \approx 0.7$ for $\Theta = 295$ K, and $I = 2.5I_{thr}$.

Expression (14) makes it possible to evaluate an error in measuring distances under actual temperature conditions. For $I = 1.2\ I_{thr}$ and $\varphi = 1$ min, the error in measuring the distances which is attributable to the temperature instability ΔD_θ can reach $10^{-3}D$ m/K. The latter fact emphasizes the importance of thermal stabilization of the injection lasers used in RORF. Moreover, taking into account the mutual influence of temperature stability and radiation attenuation at a distance on the accuracy of its measurement, the stabilization of the injection laser temperature with an accuracy of up to 10^{-2} K turns out to be practically suitable. This criterion ensues from the following arguments. The coefficient of temperature instability of the delay in stimulated radiation for the GaAlAs- and InGaAsP-injection lasers most widely used in RORF can reach the value of up to 150 psec/K depending on the mode of excitation [6, 8]. It is also well known that the time resolution of a priority discriminator that determines the limiting accuracy of the controlled injection laser-based RORF [3] can amount to about 20 psec [8]. Then, in order to eliminate the influence of the environment temperature on the accuracy of RORF due to the temperature instability of the laser radiation delay, stabilization of the injection laser temperature with the indicated accuracy turns out to be practically advisable. Systems for stabilizing the injection laser temperature accurate to 10^{-2} K can be materialized on Peltier elements [9]. Stabilization of higher accuracy can be attained using probes based on a Mach–Zehnder interferometer. These probes are capable of recording temperature with a resolution of up to 0.002 K in the range up to 973 K [10]; however, their construction is rather complicated.

It is evident from Eq. (16) that the maximum measured distance increases nonlinearly with increase in injection current. Taking Eq. (15) as a basis, in order to increase D_{max} under actual temperature conditions, one has to select the excitation mode of an injection laser with the maximum ratio I/I_{thr}. However, taking into account the increasing rate of degradation of the injection laser quantum yield at large ratios I/I_{thr} and the character of dependence (16), the ratio $I/I_{thr} \approx 2.5$ is considered to be close to the optimum one for the indicated type of laser.

The analysis of the dependence $D_{max}(\varphi)$ (Fig. 2c) shows that the radiation pattern of an injection laser of the indicated type most significantly affects D_{max} in the range $\varphi <$ (4–5) min. Thereby the joint account for dependences (15)–(17) makes it possible to optimize RORF using the parameters of a specific injection laser, its excitation mode, and the optical circuit of the facility.

Thus, the analysis of the effect of temperature on the limiting capabilities of the controlled injection laser-based RORF reveals the considerable influence of temperature on the maximum measured distance and measurement accuracy, and points to the need for thermal stabilization of the injection laser and for the maintenance of constant excess of injection current over the threshold value. The procedure of the evaluation of the temperature influence can be used in developing RORF that are based on other types of lasers, injection laser-based pulse optical range finders, and also in interpreting the experimental results obtained in investigations of the parameters of range-finding and navigation systems under different temperature conditions.

NOTATION

F_{rec}, recirculation frequency; D, distance to the object; D_T, distance to the object determined to within the oscillation period of the quartz oscillator; $T_{\text{q.o}}$, oscillation period of the quartz oscillator; n, whole number of the oscillation periods of the quartz oscillator fitted into the time interval that corresponds to the distance measured; c, speed of light in vacuum; n_{med}, refractive index of the medium; L, distance from the radiator to the reflector; r_{ref}, radius of the inscribed circle for the corner reflector; T_{rec}, recirculation period; t_{las}, delay of stimulated radiation in the injection laser; t_{opt}, time of propagation of the laser pulse over the optical measured distance; t_{del}, total delay of the signal in the electrical part of the recirculation loop of the range finder; Θ, absolute temperature; τ_{sp}, spontaneous lifetime of the nonequilibrium charge carrier in the injection laser; τ_{rm}, lifetime of the nonequilibrium charge carrier in the injection laser at room temperature; I, amplitude of injection current pulse; I_{thr}, threshold current of the injection laser; k_τ, parameter approximating the temperature dependence of τ_{sp}; Θ_{rm}, room temperature; I_{thr0} and Θ_0, parameters approximating the temperatuire dependence of the injection laser oscillation threshold; η_{las}, quantum efficiency of the injection laser; k_η, parameter approximating the temperature dependence of the injection laser quantum efficiency; P_{las}, power emitted by the laser; P_L, power received from the injection laser at the distance L; S_{ref}, reflecting surface area of the corner reflector; b, length of the side of the corner reflector; α, coefficient of radiation attenuation in the medium; d, diameter of the outlet radiator lens of RORF; φ, divergence angle of the light beam; S_1, light-spot area at the distance L from the radiator; S_2, light-spot area in the plane of the RORF photodetector for the case of $S_{\text{ref}} \geq S_1$, light-spot area in the plane of the RORF photodetector for the case of $S_{\text{ref}} < S_1$; P_{rd}, power received by the RORF photodetector for the case of $S_{\text{ref}} \geq S_1$; P'_{rd}, power received by the RORF photodetector for the case of $S_{\text{ref}} < S_1$; S_{rd}, receiving area of the photodetector; $P_{\text{rd}}^{\text{min}}$, minimum admissible received power; I_{phd}, photodetector current; R_{load}, resistance of the photodetector load; η_{phd}, quantum efficiency of the photodetector; e, electron charge; h, Planck constant; ν, radiation frequency of the injection laser; λ, radiation wavelength; $t_{\text{d.thr.f}}$, delay of a signal in the threshold former; U_{thr}, operation threshold of the threshold former; U_{phd}, voltage across the load resistance of the photodetector; τ_{fr}, front length of radiation pulse; k_θ, coefficient of a change in the measured distance with temperature; $D_{\max}(\Theta_{\text{rm}})$, maximum measured distance at room temperature; ψ and z, parameters approximating the dependence of the maximum measured distance $D_{\max}$ on the injection laser injection current; ξ and q, parameters approximating the dependence of the maximum measured distance $D_{\max}$ on the radiation divergence angle φ of the injection laser; ΔD_θ, error in measurement of the distance due to temperature instability. Subscripts and superscripts: rec, recirculation; q.o, quartz oscillator; med, medium; las, laser; opt, optical; del, delay; sp, spontaneous; rm, room; thr, threshold; ref, reflector; rd, received; phd, photodetector; load, load; fr, front; thr,f, threshold former.

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