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TEMPERATURE STABILIZATION OF AVALANCHE PHOTODETECTORS IN RECIRCULATION-TYPE INFORMATION SYSTEMS

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The influence of the temperature on the signal-to-noise ratio ξ *in the optoelectronic recirculation circuit of an information-measuring system with an avalanche photodetector has been analyzed. It has been established that the temperature dependence of the pulse power of an injection laser has an influence on the width and position of the maximum in the temperature dependence of* ξ *at the output of the photodetector in a recirculation-type system. Methods of maintenance of the avalanche multiplication factor of a photodetector at a given level have been proposed and their efficiency has been estimated.*

In systems of optical processing and storage of data, the principle of recirculation of impulse signals is commonly used [1]. Its use in optoelectronic and purely optical variants is the most promising. The first variant provides the greatest possibilities for processing and control of signals in a recirculation-type system (RTS). However, in a recirculation-type system whose operation is based on the circulation of an information pulse train in an optoelectronic recirculation circuit (ORC) formed by an injection laser (IL), an optical delay line (ODL), and a photodetector, closed in a ring, the rate of accumulation of distortions in a pulse train increases more rapidly with every recirculation cycle as compared to a purely optical recirculation-type system. This is explained by the fact that in an optoelectronic recirculation-type system, we observe a double transformation of signals – "current–light" in the injection laser and "light–current" in the photodetector.

The characteristics of a photodetector, in addition to the spectral-dynamic effects in an injection laser and dispersion effects in optical fibers (OF) acting as optical delay lines [2, 3], have a great impact on the parameters of optoelectronic recirculation-type systems. In the recirculation circuit of such recirculation-type systems, it is most promising to use avalanche photodiodes for photodetectors, since they, as photodetectors, possess a high operating speed and a high internal gain [4, 5], which makes it possible to increase the signal-to-noise ratio at the output of the photodetector. Therefore, the development of methods for eliminating the action of temperature on the parameters of avalanche photodetectors as part of a recirculation-type system is urgent.

Analysis of the present-day element basis of injection lasers and the dispersion and loss characteristics of optical fibers shows that the most promising elements for recirculating-type systems are GaAlAs and InGaAsP injection lasers, quartz optical fibers, and germanium avalanche photodiodes. The wavelength ranges 0.85–0.87 and 1.3 μm are most frequently used in optoelectronic recirculation-type systems [5–7].

To analyze the action of temperature on the photodetector parameters, we can write the signal at the output of an avalanche photodetector as part of a recirculation-type system based on an injection laser in the following form:

$$U_{\text{pd}}(\theta) = \eta_{\text{pd}}(\theta)\, P(\theta)\, R_{\text{load}} M(\theta)\, G\,. \tag{1}$$

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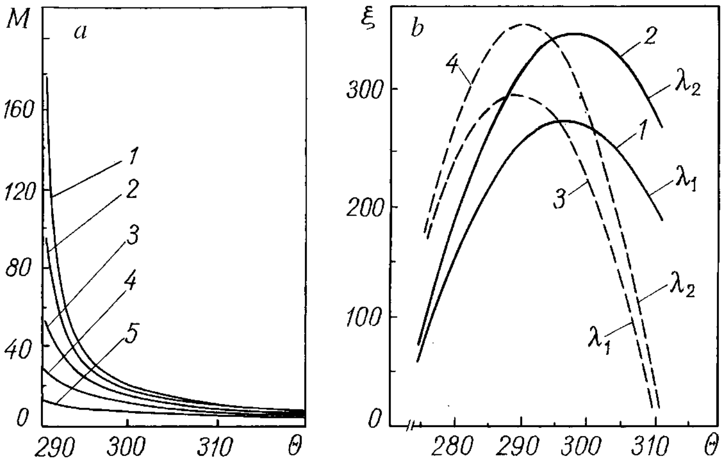

Fig. 1. Dependences of the avalanche multiplication factor M for different initial values of M_{in} (a) and of the signal-to-noise ratio ξ for different values of the IL radiation wavelength λ (b) on the temperature θ.

As is seen from (1), U_{pd} is determined by a number of temperature-dependent parameters of both the photodetector itself (M, η_{pd}) and the laser (P).

When the bias voltage across the avalanche photodiode is U = const, the dependence $M(\theta)$ has the form [4]

$$M(\theta) = \frac{M_{in}\exp[bn(\theta-\theta_{in})]}{M_{in}\left\{\exp[bn(\theta-\theta_{in})]-1\right\}+1}. \tag{2}$$

For $b = 1\cdot10^{-3}$ deg^{-1}, $n = 4$, which corresponds to a Ge avalanche photodiode [4], and $\theta_{in} = 293$ K, dependence (2) obtained for different M_{in} is shown in Fig. 1a. Curves 1–5 correspond to M_{in} = 50, 40, 30, 20, and 10, respectively. It is seen that for all M_{in} temperatures $\theta < 300$ K correspond to the region where the dependence $M(\theta)$ is the strongest. Hence, the regime of operation of the avalanche photodiode, in which U = const, does not provide a stable value of U_{pd}. Because of this, special measures are required to stabilize M in the avalanche photodiode.

A change in the internal gain in the avalanche photodiode with temperature leads to a change in the signal-to-noise ratio ξ in the optoelectronic recirculation circuit, which, in the end, influences the metrological characteristics of a recirculation-type system (probability of error in storage of information in the optoelectronic dynamic device, accuracy of ranging by the recirculation range finder, etc.). We now analyze the dependence $\xi(\theta)$, taking into account $M(\theta)$ in the avalanche photodiode.

The signal-to-noise ratio at the output of the photodetector $\xi(\theta)$ can be written, with account for the temperature dependence of the energy band gap of the semiconductor material, the quantum yield of the internal photoeffect and the dark current for a Ge avalanche photodiode [5], and the radiation power of an injection laser [3], as

$$\xi(\theta) = \frac{I_{pc}^2(\theta)\,M^2(\theta)\,R_{load}}{2eR_{load}B\left\{k_i\,M^4(\theta)\left[I_{pc}(\theta)+I_d(\theta_{in})\exp\left(\frac{\Delta E(\theta)(\theta-\theta_{in})}{ak\theta\theta_{in}}\right)\right]\right\}+2k\theta B}, \tag{3}$$

where $I_{pc}(\theta) = \{e\lambda(1-r))[1-\exp(-k_{in}(\theta)L)]I_{in0}\exp(\theta/\theta_0)\}/hc$; $k_a(\theta) = A[h\nu-\Delta E(\theta)-E_{ph}]^2/[1-\exp(-E_{ph}/k\theta)]$; $\Delta E(\theta) = \Delta E(0)-\alpha\theta^2/(\theta+\beta)$.

We investigated the dependence $\xi(\theta)$ in the optoelectronic recirculation circuit (Fig. 1b) for $\lambda_1 = 0.87$ μm (curves 1 and 3) and $\lambda_2 = 1.3$ μm (curves 2 and 4) at $I_d(\theta_{in}) = 1$ μA, $B = 2$ GHz, and $\eta = 0.4$. For a GaAlAs injection laser, $I_{in0} = 6.5$ mA and $\theta_0 = 120$ K, and for an InGaAsP injection laser ($\lambda = 1.3$ μm), $I_{in0} = 2.8$ mA and $\theta_0 = 90$ K. In this case, curves 1 and 2 have been obtained for the case $I_{in0}\exp(\theta/\theta_0) =$ const, and curves 3 and 4 have been obtained with account for the temperature dependence of the injection-laser pulse power. In the temperature range under study, $\eta_{pd}(\theta)$ manifests itself weakly [6]; this being so, we did not take into consideration its contribution to $\xi(\theta)$. It is seen that account for the dependence $P(\theta)$ for both values of λ leads to a shift of the dependence $\xi(\theta)$ at the output of the photodetector toward lower θ, and the θ range itself in which ξ is maximum becomes narrower. This result underlines the need for stabilization of the pulse radiation power of the injection laser used in a recirculation-type system under varying temperature conditions for the maintenance of ξ in the optoelectronic recirculation circuit at a given level. Under constant temperature conditions, the above-mentioned shift of $\xi(\theta)$ can be used for optimization of the circulation-type system in accordance with the ξ-maximum criterion by choosing the power of the injection-laser radiation.

In [8, 9], the systems for stabilization of the injection-laser pulse power under varying temperature conditions on the basis of the priority discrimination of the impulse signals of excitation and the injection-laser radiation have been developed and investigated. It has been shown that in the temperature range 230–330 K, such systems provide the following temperature dependence of the laser-radiation power for a GaAlAs injection laser:

$$P(\theta) = P_{in}\,[1 + k_\theta\,(\theta - \theta_{in})]\,, \tag{4}$$

where k_0 is positive and accounts for only about $2.5 \cdot 10^{-3}$ K^{-1}. For InGaAsP injection lasers, the use of stabilization systems [8, 9] provides $k_\theta = 0$ in the above temperature range. Thus, the contribution of the component $P(\theta)$ to the dependence $U_{pd}(\theta)$ can be decreased by using the above stabilization systems. For GaAlAs injection lasers, for which $P(\theta)$ is described by expression (4), the dependence $\xi(\theta)$ is practically coincident with curve 1 in Fig. 1b (it is not shown in the figure).

The provision of the operating regime of avalanche photodetectors with $M =$ const, in which a given signal-to-noise ratio is attained, in an optoelectronic recirculation circuit under varying temperature conditions, has its own features. In practice, to maintain the avalanche multiplication factor M at a given level, the repetition rate of the noise pulses at the output of the avalanche photodiode is held constant [10]. However, one should take into account the fact that when the bias voltage across the avalanche photodiode is controlled to ensure that M remains constant, the output mismatch signal inevitably includes a signal from the noise amplifier itself of the avalanche photodiode. Because of the temperature dependence of the intrinsic noise of the amplifier, the relative contribution of the avalanche photodiode noises (desired information signal) to the noise signal at the output of the amplifier (total signal) changes with temperature. This leads to a deviation of M from a given value as the temperature changes.

The above problem can be solved using the correlation processing of signals in the circuit of control of M by the criterion of constancy of noise dispersion at the output of the avalanche photodiode [11]. The essence of such a method of maintenance of the regime with $M =$ const is as follows. If the noises at the input of the amplifiers 2 and 3 (see Fig. 2a) with the transmission coefficient K_1 are equal, respectively, to n_1 and n_2, at the output of these amplifiers an additive mixture of their intrinsic noises and the avalanche-photodiode noises S acts. In this case, the output signals U_1 and U_2 of the amplifiers 2 and 3 have the following form:

$$U_1 = K_1\,(S + n_1)\,, \quad U_2 = K_1\,(S + n_2)\,. \tag{5}$$

If the transmission coefficients of the summing 4 and subtracting 5 cascades are the same and equal to K_2, the signal at the outputs of the square-law detector (6) can be written, in view of (5), in the form

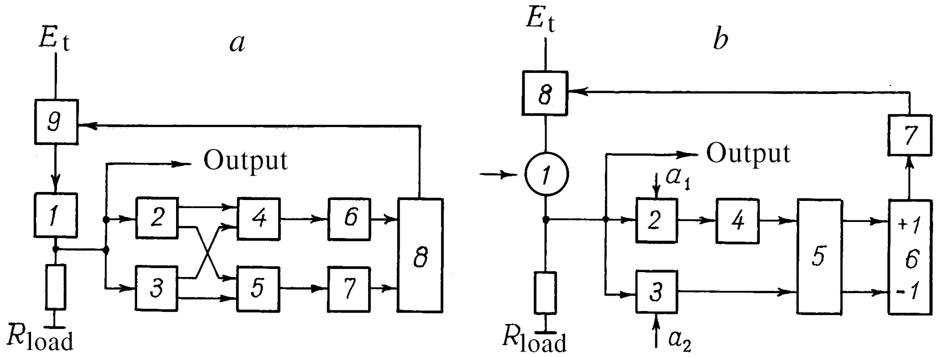

Fig. 2. Functional diagrams of the devices for maintenance of the operating regime of the photodetector with M = const by the principle of correlation processing of signals (a) and automatic control using priority discrimination of impulse signals (b).

$$U_1^{s.d} = M\left\{K_2^2\,[K_1\,(S + n_1) + K_1\,(S + n_2)]\right\}, \tag{6}$$

where $M\{\ \}$ is the symbol of the mathematical expectation operation. By analogy, the signal at the output of the square-law detector 7 is

$$U_2^{s.d} = M\left\{K_2^2\,[K_1\,(S + n_1) - K_1\,(S + n_2)]\right\}. \tag{7}$$

Considering the noises of the amplifiers 2 and 3 as independent centered random processes, we obtain, using (6) and (7), the following signal at the output of the subtracting cascade 8:

$$U_2^{s.c} = K_3\,(U_1^{s.d} - U_2^{s.d}) = 4K_1K_2K_3\,(\sigma + m^2). \tag{8}$$

It follows from (8) that in the output signal of the cascade 8, by which the voltage source 9 of the avalanche photodiode 1 is controlled, the noise component of the noise amplifier of the avalanche photodiode is absent; therefore its temperature dependence has no influence on the accuracy of maintenance of M in the avalanche photodetector of a recirculation-type system.

An efficient method of stabilization of the amplitude of the impulse response at the output of the photodetector under varying temperature conditions is automatic control of amplification (ACA) in the avalanche photodiode using the two-threshold method of recording and priority discrimination of the impulse signals corresponding to these thresholds. The essence of the method is explained by the functional diagram presented in Fig. 2b [12]. In this case, the signal picked off the load resistance R_{load} of the avalanche photodiode 1 is fed to the comparators 2 and 3 with operation thresholds a_1 and a_2. In this case, $a_1 < a_2$ and the signal at the output of the comparator 3 is delayed relative to the signal at the output of the comparator 2 by a certain value of Δt_{del}. The delay of the impulse signal in the delay unit 4 is chosen to be such that for a given amplitude of the impulse response at the output of the avalanche photodiode (a given M), signals are fed simultaneously to both inputs of the priority discriminator 5 and the system of automatic control of amplification is at rest. For example, as the amplitude of the impulse signal at the output of the avalanche photodiode decreases, for constant a_1 and a_2 the times of arrival of signals to the inputs of the discriminator 5 change so that the output signal of the discriminator 5 causes an increase in the code of the counter 6 and, correspondingly, in the output voltage of the digital-to-analog converter 7. In this case, the output signal of the block 7 increases the voltage of the controlled bias-voltage source 8 of the avalanche photodiode, which leads to an increase in M and, consequently, in the amplitude of the impulse response at the output of the avalanche photodiode.

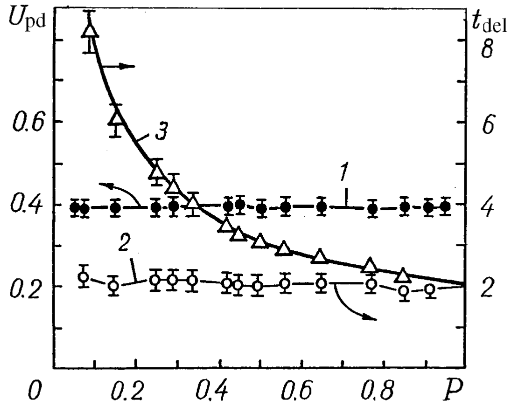

Fig. 3. Experimental dependences of the amplitude of the impulse response U_{pd} (curve 1) and its delay t_{del} (curve 2) at the output of the photodetector in the RTS with automatic control of M on the basis of priority discrimination (curve 2) and without automatic control (curve 3) on the power P of the radiation incident on the receiving site of the avalanche photodiode. U_{pd}, V; t_{del}, nsec; P, rel.units.

A peculiarity of the two-threshold system of automatic control of amplification using priority discrimination is that the rate of control increases with increase in the duration of the input-pulse fronts.

The experimental dependences of the amplitude U_{pd} and the delay t_{del} of the impulse response of the photodetector in a long-range recirculation-type system are shown in Fig. 3. For the emitter in the system we used a GaAlAs injection laser whose radiation spectrum had a maximum at λ = 0.87 μm. A two-threshold system of automatic control of amplification, based on a 597SA2 comparator and a priority discriminator with a time resolution of 60 nsec, was used in the recirculation-type system. For injection-current pulses with a front duration τ_f = 10 nsec and comparator thresholds a_1 = 35 mV and a_2 = 250 mV, the amplitude of the impulse response at the output of the avalanche photodiode changed by no more than 5% (its value measured by a V7-27 measuring device was within the measurement error) and its delay changed by no more than 350 psec when the power of the radiation incident on the avalanche photodiode changed by a factor of ten.

Taking into account the dependences $t_{del}(\theta)$, $P(\theta)$ [3], $t_{del}(P)$, and $U_{pd}(P)$ (Fig. 3), we can consider that the standard error of storage of a time interval in an information recirculation-type system may be as large as $\Delta t = (\Delta t_{IL}^2 + \Delta t_{pdet}^2)^{1/2} \approx 2.3$ nsec when the temperature changes by 10 K without a stabilization system. Stabilization performed by the above-described method decreases this error to a value of less than 300 nsec, which causes an error of 70 and 9 cm, respectively, in the ranging by a long-range recirculation-type system.

Thus, the temperature dependences of the avalanche multiplication factor, the dark current, the energy band gap of the semiconductor, and other parameters of the avalanche photodiode determine the strong relation between the signal-to-noise ratio and the temperature $\xi(\theta)$ in the optoelectronic recirculation circuit of an information measuring system. In parallel with this, as the pulse power of the injection laser changes with change in temperature conditions, the maximum of the signal-to-noise ratio shifts toward lower temperatures. Account for the action of temperature on the injection-laser pulse power allows one to control (optimize) the signal-to-noise ratio at the output of the photodetector in a recirculation-type system. The proposed methods of maintenance of the avalanche multiplication factor make it possible to solve the problem of optimization of the signal-to-noise ratio in a recirculation-type system. The results obtained can be used for the development of recirculation and pulsed optical range finders and also of optoelectronic dynamic storage units with avalanche photodetectors.

NOTATION

U_{pd}, amplitude of the voltage pulse at the output of the avalanche photodiode; η_{pd}, quantum efficiency of the photodiode; P, power of the injection-laser radiation incident on the receiving site of the photodetector; θ, absolute temperature; R_{load}, resistance of the photodetector load; M, avalanche multiplication factor of the avalanche photodiode; G, gain factor of the photodetector amplifier; θ_{in}, room (initial) temperature; M_{in}, avalanche multiplication factor at room temperature; b and n, empirical coefficients (b = (0.7–1.5)$\cdot 10^{-3}$ K^{-1} and n = 4–5 for a Ge avalanche photodiode [4]); ξ, signal-to-noise ratio; I_{pc}, initial photocurrent; e, electron charge; B, threshold frequency; k_i, ratio between the ionization coefficients of electrons and holes, k_i = 0.8 for Ge; a, constant coefficient equal to 1–2 [6]; I_d, dark current of the avalanche photodiode; ΔE, energy band gap of the semiconductor; k, Boltzmann constant; λ, radiation wavelength of the injection laser; r, reflection coefficient of the receiving site of the avalanche photodetector; k_a, absorption coefficient of Ge; L, width of the space-charge region; h, Planck's constant; c, velocity of light; I_{t0} and θ_0, approximation parameters of the temperature dependence of the injection-laser threshold current; A, temperature-independent constant, $A = 1.2\cdot 10^5$ (eV$^2\cdot$cm^{-1}) for Ge [7]; E_{ph}, phonon energy, E_{ph} = 0.0274 eV for Ge [7]; ν, radiation frequency; $\Delta E(0)$, energy band gap of the semiconductor at 0 K, $\Delta E(0)$ = 0.75 eV for Ge; $\alpha = 4.774\cdot 10^4$ eV/K; β = 235 K [6]; P_{in}, injection-laser radiation power at room temperature; k_θ, temperature coefficient of change in the injection-laser radiation power; K_1, n_1, and n_2, transmission coefficient and noise of the amplifiers in the system for correlation processing of signals in the circuit of M control; K_2, transmission coefficients of the summing and subtracting cascades 4 and 5; S, noise of the avalanche photodiode; U_1 and U_2, output signals of the amplifiers 2 and 3; $U_1^{s.d}$ and $U_2^{s.d}$, output signals at the output of the square-law detectors 6 and 7; K_3, transmission coefficient of the subtracting cascade 8; $U_2^{s.c}$, output voltage of the subtracting cascade 8; σ and m, dispersion and constant component of the noise of the avalanche photodiode; a_1 and a_2, operation thresholds of the comparators 2 and 3; Δt_{del}, delay of the signal in the block 4; t_{del}, delay of the impulse signal at the output of the photodetector; Δt, standard error of storage of the time interval; Δt_{IL} and Δt_{pdet}, errors of storage of the interval which are due to the instability of the laser and photodetector parameters. Subscripts: pd, photodiode; load, load; in, initial; pc, photocurrent; a, absorption; t, threshold; ph, phonon; s.d, square-law detector; s.c, subtracting cascade; del, delay; IL, injection laser; pdet, photodetector.

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