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Two-wavelength opto-electronic vernier and synthesizer of reference optical scales

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ABSTRACT

For registration and processing optical information signals was offered and realized opto-electronic vernier method of temporary situation definition of pulse information sequences, which used one opto-electronic recirculation generator with two optical wavelengths. On one wavelength in a recirculation mode there are information pulses, and on other wavelength - pulses of reference temporary scale. The developed method of automatic digital-to-analog correction of scales is used. The signal-to-noise ratio in fiber-optic processing systems with avalanche photodiode was investigated.

Keywords: opto-electronic vernier, recirculation generator, two-wavelengths laser.

1. INTRODUCTION

Many modern applications such as high-speed optical communications, data processing, environment monitoring, remote sensing, etc. operate with information streams at extremely high bit rates. The increasing of the measurement accuracy of pulses temporary situation in information sequences is a urgent problem. The decision of the given task is especially important for optical location systems, atmosphere and environment turbulence laser probing systems and etc. In these systems the information signal represents a number of optical pulses reflected from environment heterogeneous, coming during 1–10 μs depending on probing range. For registration and processing such signals the synthesizer of precision optical influences, opto-electronic vernier method of definition of a temporary situation of pulse information sequences were developed and increase of signal-to-noise ratio methods in such systems was investigated.

2. SYNTHESIZER OF REFERENCE OPTICAL SCALES

The creation of the precision means for formation of optical reference scales for various measuring systems is a urgent task in connection with a wide circulation of laser systems of diagnostics of an environment both control of industrial and technological processes.

Wide range control system of synthesis of optical reference signals is developed and realized by us. It is containing block of synthesis and stabilization of a coherent optical radiation wave length and device of the form and frequency generation of optical influence constructed on the basis of semiconductor laser with using the reference frequency scale.

The stabilization and synthesis of a wave length of optical radiation is provided with introduction of auto tuning of a wave length radiation of the semiconductor laser by change of a pump current. In a loop of auto tuning are used dispersion fiber optical delay line, external microwave modulator, phase detector and comparator (Fig. 1). The returning and stabilization of radiation wave length is carried out by a managing signal of a phase mismatch and by choosing of the appropriate threshold of the comparator operation. The system provides stabilization of the laser wave length in spectral range λ=0,8–1,55 μm with accuracy 0,1–0,3 Å and smooth retuning of a wave length in a range ±50 Å.

The system of the form and frequency generation of optical influence contains time intervals synthesizer and intensity grid. Feature of construction optical synthesizer is the generation of a stable phase grid of time intervals synthesized by reference signal, which further is transformed semiconductor laser in high stability grid of intensities and time intervals.

The developed method of automatic digital-to-analog correction of scales with work in the closed systems is used. The carried out researches have allowed to create synthesizer of optical signals with a large dynamic range intensities and to synthesize time intervals with small temperature dependence and a simple control system.

The basic algorithms, on which the pulse sequences are synthesized, are represented as follows:

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–digital signal sequence

$$a^{(i)}(t) = \sum_n a_n^{(i)} \Phi_n \left(\frac{t - t_n^{(i)}}{T_n^{(i)}} \right), \tag{1}$$

where a_n–random amplitude; t_n– random temporary situation; $\Phi_n^{(i)} \left(\frac{t - t_n^{(i)}}{T_n^{(i)}} \right)$ – function of the n-th pulse form in i-th realization; T_n–duration of the n-th pulse.

–analog signal sequence

$$a^{(i)}(t) = \sum_n a_n^{(i)} \Phi_n^{(i)} (t - t_n) \sin(\omega t + \alpha), \tag{2}$$

Specific feature of process (2) is that the time moments $t_n^{(i)}$ describing temporary structure of process, appear function of voltage threshold values on amplitude quantization.

Developed synthesizer of optical reference signals generates uniform, normal and Poisson distribution laws of test influences, and also carries out their reproduction in an optical range.

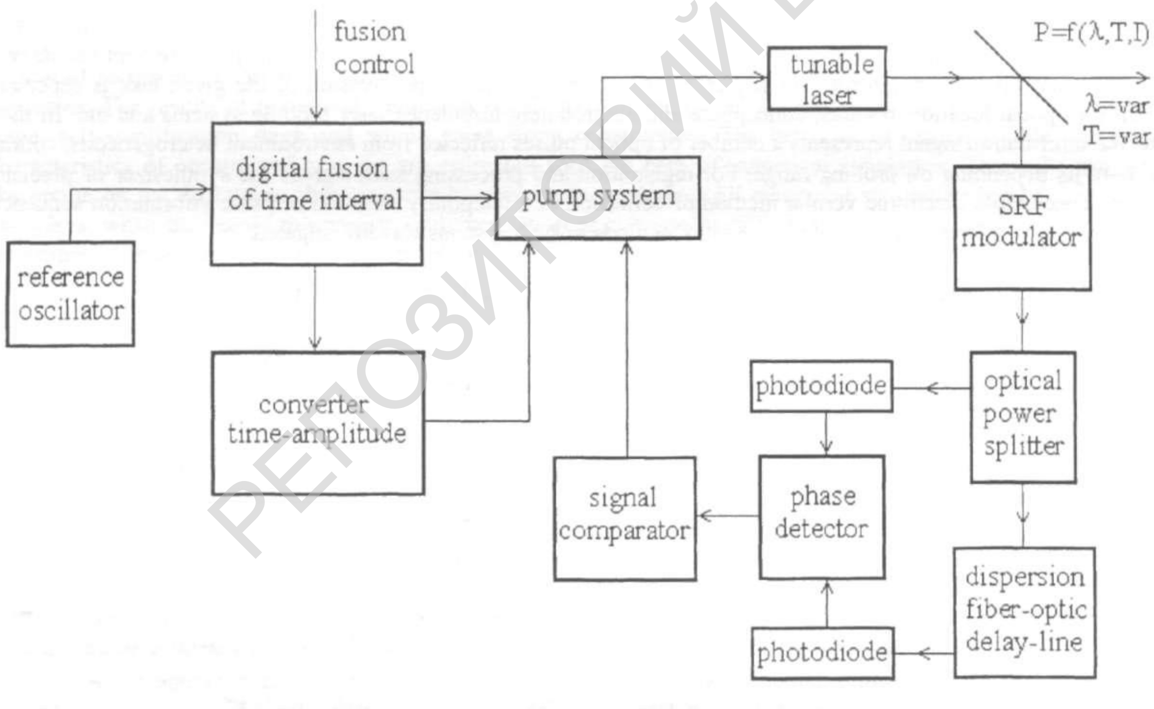


Fig. 1. The block scheme of synthesizer of optical reference signals.

The analysis of devices of transformation of parameters of a basic scale on an optical scale is carried out. The questions of stability, noise stability of the synthesized scales are investigated in the field of small meaning of intensity and short time intervals.

It is shown, that a case statistically independent fluctuation of separate periods total dispersion of borders of synthesized intervals is equal:

$$\sigma^2_{\Sigma}(T_c) = \sigma^2_{\Delta} + \frac{T_c}{\Delta t} 2(\gamma T)^2 + \frac{\Delta t}{12}, \tag{3}$$

where T_c– formed time interval; T–reference scale period; γ–relative instability; σ^2_{Δ}–error sampling dispersion; Δt–sampling step.

The received expression allows to estimate dependence of a sampling step and dynamic range of synthesized intervals from a value of the dispersion T_c in a station mode. In a mode of phasing synthesizer by random signals the basic contribution in total dispersion $\sigma^2_{\Sigma}(T_c)$ is determined by σ^2_{Δ}. For in-phase mode it is determined by instability of a locking signal.

Dynamic range synthesized intensities is 40 dB. The step of retuning is set by the program. A range of synthesized time intervals from 0,1 s up to 5 ns. The stability of a temporary sequence is determined by stability of a basic reference frequency and makes 10^{10}. Synthesizer allows to form optical pulses by duration from 0,3 ns up to 1 µs.

It is shown, that the synthesis of reference optical signals on the basis of a uniform reference frequency signal with using optoelectronic system of autotuning a wave length of semiconductor laser coherent optical radiation allows to decide tasks of formation anyone precision optical influences. Offered synthesizer can be used as in quality probing signal in laser location and measuring systems, systems of the gas analysis and diagnostics of an environment, and for the control the characteristics of various equipment.

3. TWO-WAVELENGTH OPTO-ELECTRONIC VERNIER

For registration and processing such signals was offered and realized opto-electronic vernier method of definition of a temporary situation of pulse information sequences. The method allows to make simultaneous measurement of the temporary situation of all entrance information signals with the permission in tens picoseconds. As against electronic vernier methods, in which two generators (clock and measuring) are used, in the offered device is used one opto-electronic recirculation generator with two optical wavelengths .

The block-diagram of a two-wavelength opto-electronic vernier is shown in Fig. 2. For realisation of opto-electronic vernier measurer the original method of the semiconductor laser operation is used, in which the generation of

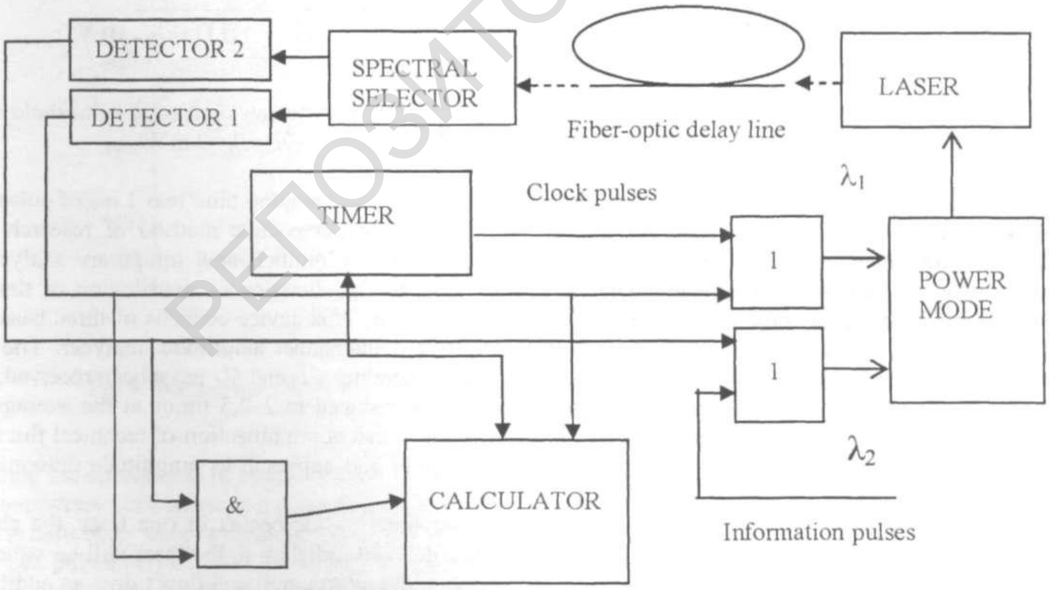


Fig. 2. The block-diagram of a two-wavelength opto-electronic vernier.

radiation occurs on two various wavelengths. The structure of a such laser is described in Ref. 1. The active region of the laser diode contains two quantum wells of different width. The laser wavelength switching from λ_1 to λ_2 occurs at the change of the injection current from I_1 to I_2. The duration of electrical pulses and, accordingly, of emitted light pulses at the different wavelengths can be made as low as 1 ns. The difference of the laser wavelengths $\Delta\lambda=\lambda_1-\lambda_2$ for the asymmetric quantum-well laser diodes achieve a value of 20 to 70 nm. When use a Peltier thermoregulator and stabilisation of the injection current pulses, it is possible to receive the relative instability of the laser wavelength difference not worse than 10^{-3}.

Thus on one wavelength in a recirculation mode there are information pulses, and on other wavelength - pulses of clock frequency giving a temporary scale, relatively which occurs reading the useful information.

The stability of a recirculation period in opto-electronic vernier without external synchronization and termostabilisation was investigated. The analysis of experimental results has shown in Fig. 3, that the basic contribution to long-term instability of a recirculation period bring in fluctuations of parameters IL, dispersion of optical fiber and variation of a steepness of optical pulses front. The constant bias I_0 of the laser raises stability of recirculation in the contour equally as well as increase of amplitude of an injection current pulse I. Choice of a ratio U_{th} and I_0 it is possible to receive the mean-square relative long-term instability $1.2\cdot10^{-6}$ at time of measurement of 1 s and time of observation 30 min.

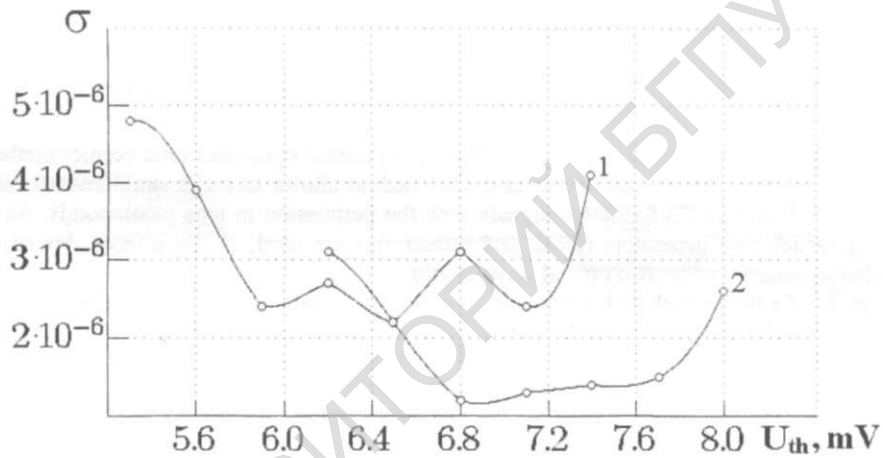


Fig. 3. The dependence of relative long-term instability of recirculation frequency on size of a threshold of the regeneration block. 1– I_0=0,8I_{th}; P_L=1,5 mW 2– I_0=0,9I_{th}; P_L=2 mW

The exact analysis short-term fluctuations of a recirculation period with averaging time less 1 ms of pulse sequences requires the application of special methods of measurement. The most perspective method of research short-term fluctuations of circulation periods is represented the method based on the multichannel temporary analysis. For the decision of the given task the special experimental stand allowing to find function of distribution of time intervals between any pairs of pulses in an information sequences was developed. This device consists of three basic parts: the block of selection of time intervals, converter time-amplitude and multichannel amplitude analyzer. The temporary permission of this device makes 15 ps in a range 1–100 ns. For chosen value of I_0 and U_{th} have been received, that short-term fluctuations are 60–70 ps for first cycle of circulation and then reduced in 2–2,5 times at the average period of 290 ns. Comparison of calculations and experimental data have shown, that at minimization of technical fluctuations the accuracy of such optical fiber systems can be increased in 4-5 times and approach to magnitude determined by the fundamental error components.

Because of the generation of information pulses and clock temporary scale occurs in one laser, the changes of a temporary situation of recirculation information pulses owing to a delay of radiation in the laser will be same as well as clock temporary scale. That will be taken into account with reading the information and don't give an additional error. Because of the generation of information pulses and clock temporary scale occurs on various wavelength, owing to dispersion properties of optical fibre (dependence of refraction index from wavelength), there will be a smooth displacement in time of a clock temporary scale relatively information pulses. Thus is realised precise vernier measurement of a pulses temporary situation, that allows to fix their temporary situation with accuracy in tens picoseconds.

The difference of optical delays is equalled[2]:

$$\Delta t = \frac{Ln_1}{c} - \frac{Ln_2}{c} = \frac{L}{c}(n_1 - n_2), \tag{4}$$

where L–optical fibre length, c–speed of light in vacuum, n_1, n_2–optical fiber refraction index on wavelengths λ_1 and λ_2 accordingly.

Since under condition of $\lambda_2>\lambda_1$ is received $n_2<n_1$, hence, the clock pulses on wavelength λ_1 will be moved together (to lag behind) relatively of pulse sequence on wavelength λ_2 each recirculation period on Δt. The value Δt defines the temporary permission of opto-electronic vernier system.

Thus, the temporary situation of the coincide information pulse will be defined as follows

$$t_i = kT + N\Delta t, \tag{5}$$

where k–number of a pulse of clock frequency; T–period of clock frequency pulses; N–number of a recirculation period; Δt–difference of optical delays of radiation (4) on wavelengths λ_1, λ_2 for one recirculation period.

Dependencies of the temporary permission of opto-electronic vernier system (optical delay difference Δt) from optical fibre length L for various λ and $\Delta\lambda$ are shown in Fig. 4, 5. As seen, for fibre lengths L from 100 to 600 m, the value Δt changes within the limits of $4\cdot10^{-11}$ to $5\cdot10^{-10}$ s for λ=1,55 μm. For λ=0,9 μm. the value Δt changes within the limits of $6\cdot10^{-11}$ to $7{,}5\cdot10^{-10}$ s.

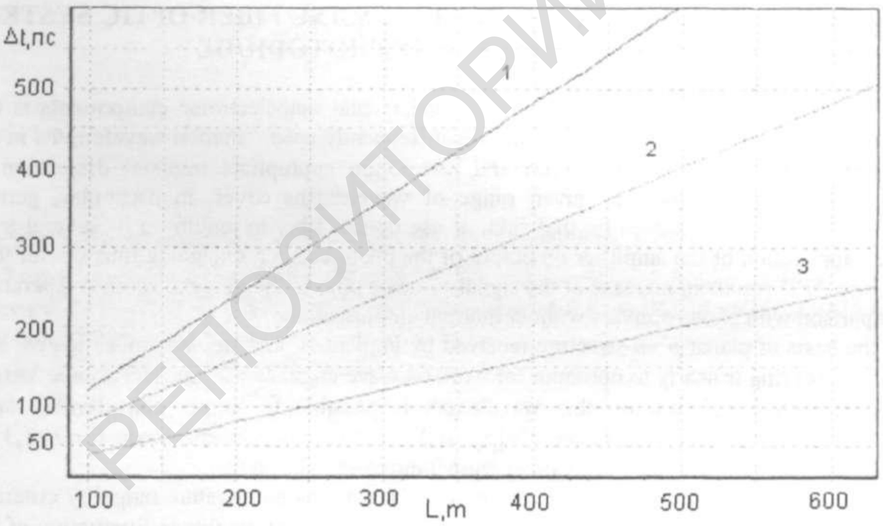


Fig. 4. Dependencies of the temporary permission Δt from optical fibre length L for λ=1,55 μm, 1–$\Delta\lambda$=30 nm, 2–$\Delta\lambda$=20 nm, 3–$\Delta\lambda$=10 nm.

Choosing the appropriate fibre-optic length L and the difference of optical wavelengths $\Delta\lambda$ is possible to achieve the required temporary permission in a range from tens up to hundreds picoseconds. The duration of a registered temporary sequence is defined by time of distribution of laser radiation in optical fibre and will make units, tens microseconds.

The clock pulses period T will be defined by the time necessary for the computing circuit reception and record of the information about a temporary situation of a registered pulse. So, for example, with a period of clock pulses T=100 ns and temporary permission Δt=100 ps for complete reading of the useful information to system is required $N=10^3$ recirculation periods.

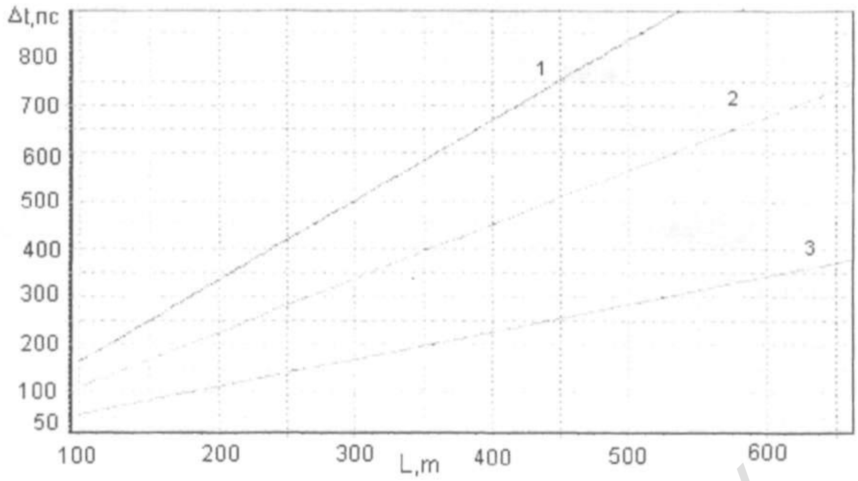


Fig. 5. Dependencies of the temporary permission Δt from optical fibre length L for λ=0,9 μm, 1–$\Delta\lambda$=30 nm, 2–$\Delta\lambda$=20 nm, 3–$\Delta\lambda$=10 nm.

Thus, as against electronic vernier measurer, ensuring measurement with high accuracy of a temporary situation only of one pulse developed system allows to measure large number of pulses simultaneously with the high temporary permission, because in this system is used only one opto-electronic recirculation generator.

4. SIGNAL-TO-NOISE RATIO IN PROCESSING FIBER-OPTIC SYSTEMS WITH AVALANCHE PHOTODIODE

In described processing fiber–optic systems one of fundamental optoelectronic components is the photoreception device on the basis of the semiconductor photodiode. Most frequently used radiation wavelengths in systems on a basis singlemode optical fiber (SMOF) are λ=1,3 μm and λ=1,55 μm appropriate minimal dispersion and the minimal radiation power losses, accordingly. The given range of wavelengths cover, in particular, germanium avalanche photodiodes (APD). Use APD is caused by that first, at use optical fiber in length up to several tens kilometers it is possible to refuse application of the amplifier on output of the photoreceiver, excluding thus one of the basic sources of noise; secondly, use APD results in increase of the signal-to-noise ratio in the range of room temperatures approximately on 10 dB in comparison with photoreceivers without internal amplification.

Ge APD on the basis of planar p^+–n-structure received by implant B^+ and Be^+ was investigated. Such structure with thin p^+ layer and protect ring is nearly to optimum for work on wavelength λ=1,3 μm. The choice λ=1,3 μm is connected that in comparison with λ=1,55 μm on this wavelength is possible to supply considerably large bandwidth B_f (B_f=2,9 GHz at avalanche multiplication factor M=15), and also in a unavalanche mode for λ=1,3 μm the change of current sensitivity does not exceed 10% in a range of temperatures –60^{0}C...+60^{0}C.

For finding APD optimum operation regime and choice of a working temperature range by criterion of the maximal signal-to-noise ratio ξ the mathematical model which is taking into account amplitude fluctuation of injection laser (IL) radiation, APD shot noise, and also thermal noise of loading resistance and effects of crosspulse interference of optical signals in optical fiber was developed:

$$\xi = \frac{[I_f(\theta)M(\theta)]^2 R}{\left[2e\left(I_f(\theta)+I_d(\theta)\right)M^2(\theta)FR + N_L(\theta)[I_f(\theta)M(\theta)]^2 R + 4k\theta\right]B_f}, \tag{6}$$

where θ–absolute temperature; I_f and I_d–initial photocurrent and dark current of APD accordingly; N_L–relative spectral density of IL radiation intensity fluctuation; $F(M)$–excess noise factor; R–APD loading resistance.

As the initial photocurrent I_f is determined by IL radiation power P_{IL}, which is function of a threshold current $I_{th}\sim\exp(\theta/\theta')$ in model the change of IL thermal operation mode is taken into account:

$$I_f(\theta) = 10^{-0,1(k_1+k_2L)}\eta_{IL}\eta\left[I - I'_{th}\exp(\theta/\theta')\right]\delta_p\,, \tag{7}$$

where η–APD external quantum efficiency; η_{IL}–IL external quantum output; I– IL pump current; I'_{th}, θ'–approximation parameters of dependence $I_{th}(\theta)$; k_1+k_2L–power radiation losses on connections of IL-SMOF-APD and at distribution in SMOF; δ_p–optical power losses from crosspulse interference, which can be e approximate by expression:

$$\delta_p[\text{dB}] = \frac{a_p\sigma_i}{T}\exp\left(\frac{b_p\sigma_i}{T}\right), \tag{8}$$

where σ_i–root-mean-square of pulse duration on the SMOF output; T–clock period; a_p and b_p– approximation parameters (a_p=2, b_p=4,5-for gaussian pulse form; a_p=4, b_p=1-for exponential).
It is shown, that reduction of ξ value from δ_p does not exceed 1 dB at performance of a condition $\sigma_i \le T/5$.

Dependence of APD parameters from temperature are described by the following expressions:

$$F(M) = k_iM + \left(2-\frac{1}{M}\right)(1-k_i)\ , \tag{9}$$

$$I_d(\theta) = I_d(\theta_0)\exp\left[\frac{\Delta E(\theta)(\theta-\theta_0)}{ak\theta\theta_0}\right], \tag{10}$$

$$\Delta E(\theta) = \Delta E(0) - \alpha_z\theta^2/(\theta+\beta_z)\,, \tag{11}$$

where k_i–hole-to-electron ionization-rates ratio (k_i=0,8 for Ge); $I_d(\theta_0)$–dark current at the room temperature θ_0; a–constant equal 1-2 (a=1 for $\theta=-10^0$C...+60^0C and a=2 for $\theta=-10^0$C...-60^0C); $\Delta E(\theta)$–width of the forbidden zone of the Ge-semiconductor, $\Delta E(0)$=0,75 eV–width of the forbidden zone at 0 K, α_z=4,774 eV/K, β_z=235 K. It was shown[3], that k_i is relatively temperature insensitive.

For APD operations at a constant reverse bias U=const:

$$M(\theta) = \frac{\exp\left[\beta_0 n(\theta-\theta_0)\right]}{\exp\left[\beta_0 n(\theta-\theta_0)\right]-1+1/M_0}\,, \tag{12}$$

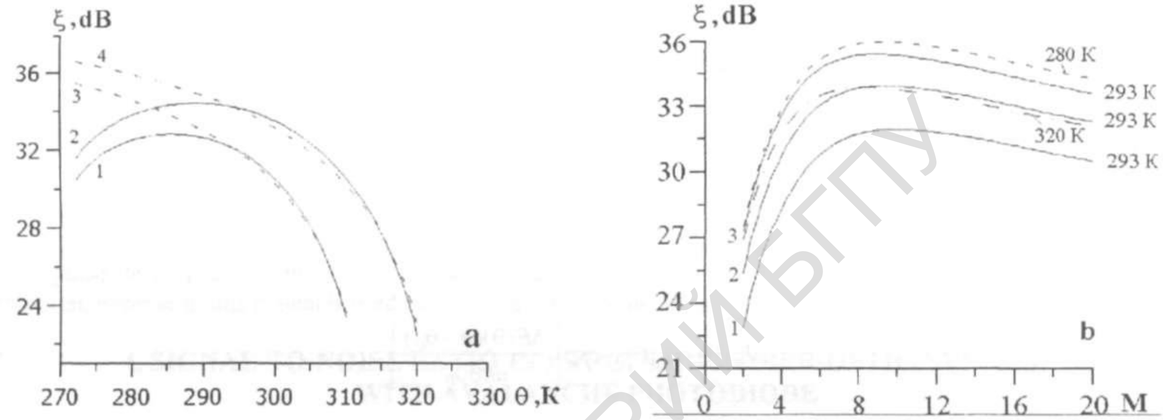
where n–parameter determined by distribution of impurity in p-n and relation of k_i, β_0–constant, not dependent from temperature; M_0–avalanche multiplication factor at $\theta=\theta_0$ (for Ge-APD $\beta_0=(0{,}7-1{,}5)\cdot10^{-3}$ K^{-1}, n=3–5, M_0=10).

From comparison of different various of noise components follows, that the noise connected with IL radiation amplitude fluctuation, are comparable with other noise sources of optical fiber system for SMOF lengths up to $L\approx$20 km. For $I\approx(1{,}2–1{,}5)\,I_{th}$ the sharp increase of N_L value is observed at temperature of IL active area θ>35^{0}C.

The calculations were carried out under following conditions: η=0,65; η_{IL}=0,4; I'_{th}=1,5 mA, θ'=90 K; k_1=5 dB with use matching elements; k_2=0,6 dB/km; θ_0=293 K; R=50 Ω.

In case U=const at temperature increase at the expense of breakdown voltage increase there is a reduction of avalanche multiplication factor M according to Eq. 12. The given law is fair in all a researched range of temperatures while APD mode remains avalanche. Signal power and various sources of noise change differently with increase of temperature (see Eq. 6): the signal power decreases proportionally M^2, shot noise power ~ M^2F, amplitude fluctuation of injection laser ~ M^2, the thermal noise linearly increase. Hence, the dependence of signal-to-noise ratio from temperature must has a maximum at some temperature, as is observed at accounts in Fig. 6,a.

The carried out researches of dependence of the signal-to-noise ratio from temperature at various modes of APD operations have shown that at room temperatures and is higher by most effective is the operation mode at the constant reverse bias voltage (Fig. 6,a). At temperatures below room for achievement of the greatest signal-to-noise ratio in the device it is necessary to apply a mode of APD detecting with constant factor of avalanche multiplication. The signal-to-noise ratio can be increased at the expense of increase of avalanche multiplication factor M so long as growing proportionally M^{2+x} (x-factor of excess noise, for Ge-APD x=0,8–1) shot noise will not become to prevail above others noise sources. It is received, that at room temperature for analyzed system optimum avalanche multiplication factor for Ge-APD lays within the limits of 8–12 and practically does not depend on IL radiation power, as depicted in Fig. 6,b. The given conclusions were confirmed by the received experimental results.



1,2–U=const; **3,4**–M=const; **1**–P_L=1,5 mW; **2**–P_L=2 mW;

1,3–$P_L(\theta_0)$=1,5 mW; **2,4**–$P_L(\theta_0)$=2,5 mW **3**–P_L=2,5 mW. L=20 km

Fig. 6. Dependence of the signal-to-noise ratio ξ from temperature θ (a) and APD avalanche multiplication factor M (b) at various modes of APD operations and IL power radiation.

At the bit rate more then 1 Gbit/s one of the limitation reasons of recording speed and storage time of the information in such architecture are the random deviations (timing jitter) of the delay time between pulse of a pump current and stimulation radiation in the semiconductor laser from average value. The researches timing jitter at two registration methods of a digital pulse sequence: threshold method (TM) and constant part of the pulse method (CPPM) for the RZ and NRZ encoding formats were carried out. In accordance to TM the temporal position of the signal corresponds to the moment at which the signal exceeds constant threshold. For the CPPM the threshold is variable and is equal to half of the amplitude of the each received pulses. It was shown, that it is better to use CPPM for reduction timing jitter at RZ encoding format. This method gives good results, when the increase time of a pulse front practically does not change. At NRZ encoding format practically there is no difference between these methods and from the point of view of technical realization simplicity more preferable method TM.

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