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TEMPERATURE ERROR OF FIBER-OPTIC MEASURING SYSTEMS

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The temperature-measurement error that arises in using a phase sensor based on the homodyne Mach–Zehnder interferometer has been estimated. Criteria for choosing the radiation wavelength and the stabilization accuracy of the injection-laser radiation power with allowance for the temperature dependence of the spectral sensitivity of semiconductor photodetectors have been obtained.

The development of automatic control systems and systems for controlling various objects, processes, and enterprises is largely determined by the achievements in the area of measurement transducers (sensors). In the last few decades, a trend in using optical radiation and the unique properties of optical media to register various physical actions has evolved. Advances in the field of semiconductor radiation sources, photodetectors, and low-decay fibers have led to the appearance and rapid development of optoelectronic measuring systems (MS). Further development of recording and measuring facilities calls for increasing the level of noise immunity of MSs as well as the possibility of operating under conditions of explosiveness, high radiation, an aggressive medium in a wide range of temperature differences, etc., which can be achieved by using optical and fiber-optic elements forming a fiber-optic sensor (FOS). As a sensor, any measurement transducer representing a segment of an optical fiber or another element whose optical properties depend on the external action can be used.

An optical system in which amplitude, phase, polarization, frequency, spectral, temporal, or spatial modulation is carried out transforms the optical parameter x_i of the medium induced by the measured physical quantity to the value of the parameters characterizing the optical wave y_j passing through the sensor. As these parameters, the amplitude, phase, rotation of the polarization plane, wavelength, and response-pulse delay time can act. The transform function of the FOS optical parameter x_i represents a complex multistage dependence of X on the parameter of the external action F_{inp}:

$$X = P_{\text{r.s}}\,(I_{\text{r.s}})\, f_{\text{phd}} \left\{ y_j \,[x_i\,(F_{\text{m}}\,(F_{\text{inp}}))]\right\} S_{\text{phd}} k_{\text{loss}}\,.$$

An MS with optimal characteristics cannot be created without developing a mathematical model and computer modeling of the operating conditions of the FOS, which will permit estimating the compliance of the chosen design to the given service conditions. The efficiency of this depends on the accuracy of the mathematical description of the physical processes adequately reflecting the phenomena taking place in the fiber-optic information system.

One of the main parameters by which the quality of the sensor is estimated is the value of the maximum admissible temperature error [1]:

$$\delta_T = \frac{|X_T - X_{T_{\text{in}}}|}{X_{T_{\text{in}}}} \cdot 100\%\,. \tag{1}$$

Since the fiber-optic channel is fairly thermostable, the main contribution to the temperature error will be made by the transmitter–receiver unit. In this case, to estimate the temperature dependence of the FOS, it is necessary to find analytical expressions describing the temperature dependence of the parameters of injection lasers (IL) and semiconductor photodetectors (PhD).

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Let us estimate the temperature error of measurements that arises in using a phase sensor based on the homodyne Mach–Zehnder interferometer, which is most commonly used as a hydrophone — a device for detecting a submarine sound field. The laser radiation in such a phase sensor is divided by a semireflecting mirror, part of which is directed to the single-mode optical fiber located in the measurement zone and part of which is passed through the control fiber sealed against external actions. The resulting interference signal on the light-sensitive surface of the photodetector depends on the change in the difference of the optical paths ΔL_{opt} that the radiation passes over in the two interferometer arms. In this case, the change in the photodetector photocurrent

$$\Delta I_{phd} = P_{laser} \tau S_{phd} \,(1 + \cos\,(\Delta\varphi))\,, \quad \Delta\varphi = \frac{2\pi \Delta L_{opt}}{\lambda}\,. \tag{2}$$

For small variants of the phase $\Delta\varphi$ near $\pi/2$, where the function $F_{out} = f(\Delta\varphi)$ is practically linear, the change in the photocurrent can be written as

$$\Delta I_{phd} = P_{laser} \tau S_{phd} \frac{2\pi \Delta L_{opt}}{\lambda}\,. \tag{3}$$

In present-day fiber optics, to transmit an information signal, radiation with a wavelength of 1.3 μm (corresponding to the minimum material dispersion) and 1.55 μm (corresponding to the minimum radiation power loss) is most commonly used. In the indicated spectral range, InGaAsP injection lasers and germanium and InGaAs/InP photodiodes (PDs) operate.

For practical use of expression (3), let us analyze the temperature properties of semiconductor photodetectors. As follows from (3), one of the parameters in the transform function of the FOS is the spectral sensitivity S_{phd} of the PD. To describe the S_{phd}, one usually uses empirical curves (obtained with the aid of specialized attestation equipment or reference material) of the wavelength dependence of the spectral sensitivity at some fixed parameters or analytic bell-shaped or triangular approximations, which can differ considerably from the experimental values at different points of the spectral range. The chief disadvantage of such an approach is its complexity, determined by the necessity of calculating the approximating *n*th-order polynomials (depending on the desired accuracy), as well as the absence of the possibility of investigating by means of it the continuous dynamics of the change in the S_{phd} function depending on the temperature. In the present paper, we propose a method for determining the S_{phd} with the use of analytical expressions describing the physical laws of operation of the PD.

The spectral sensitivity of the PD is defined by the relation [2]

$$S_{phd}\,(\lambda) = \frac{e\lambda}{hc} T_{tr} \exp\,(-\,\alpha x)\,(1 - \exp\,[-\,\alpha L])\,. \tag{4}$$

Since, for Ge under the action of the incident radiation of the near-IR range, indirect transitions with the emission of a Raman phonon are most probable, the expression for the interband adsorption coefficient is of the form [3]

$$\alpha\,(T) = N^{*} \sigma_b \left(\frac{\lambda_{cut}\,(T)}{\lambda}\right)^2 \left(1 - \frac{\lambda}{\lambda_{cut}\,(T)}\right)^2 \Bigg/ \left[1 - \exp\left(-\frac{E_{ph}}{kT}\right)\right], \tag{5}$$

where

$$N^{*} = \frac{N_a N_d}{N_a + N_d}\,; \quad \lambda_{cut}\,(T) = \frac{1.24}{\Delta E\,(T) + E_{ph}}\,; \quad \sigma_b \approx \frac{1.25 \cdot 10^{-18}}{\lambda_{cut}^2}\,.$$

The temperature dependence of the energy-gap width is approximated by the expression [4]

$$\Delta E\,(T) = \Delta E\,(0) - \frac{\alpha_z T^2}{T + \beta_z}\,. \tag{6}$$

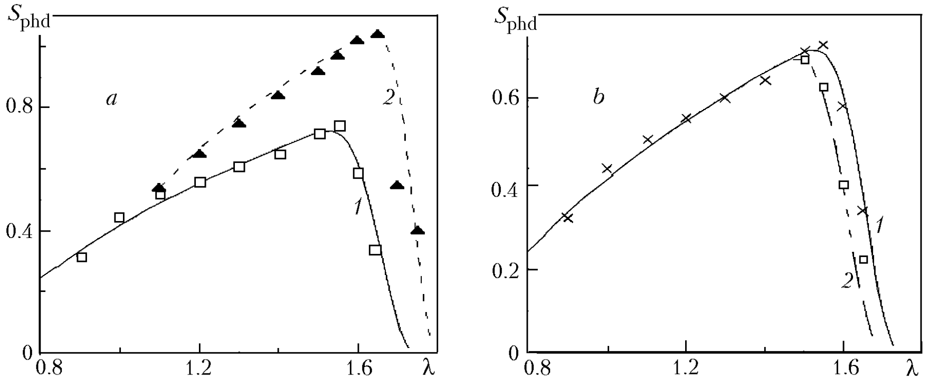


Fig. 1. Spectral sensitivity of the photodiodes: a) germanium pin-photodiode (1) and InGaAs/InP-pin-photodiode (2) at $T = 20^oC$; b) germanium PD at $T = 20^oC$ (1) and $T = -30^oC$ (2). $S(\lambda)$, A/W; λ, μm.

For Ge, $\Delta E(0) = 0.75$ eV, $\alpha_z = 4.774 \cdot 10^{-4}$ eV/deg, and $\beta_z = 235$ deg [4].

The depletion-layer width L in a PhD with a sharp asymmetric *p–n* transition is independent of the radiation wavelength and is determined by the doping level of the semiconductor, its dielectric constant ε, the concentration of intrinsic carriers n_i, the back-bias voltage U, and the temperature [3]. The investigations in the temperature range from -30^oC to $+70^oC$ have shown that with increasing temperature the depletion-layer width increases practically linearly and this increase is very insignificant. The relative change in the depletion-layer width as the temperature increases by one degree is $2.7 \cdot 10^{-5}$ 1/K. Therefore, throughout the practically important temperature range the quantity L can be considered to be temperature-independent.

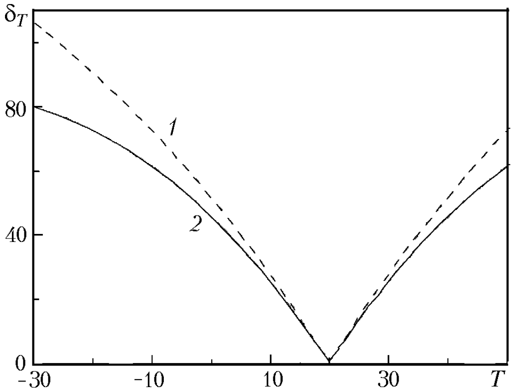
Figure 1a shows the experimental values (dots) obtained in investigating J16 germanium pin-photodiodes of the EC&G Optoelectronics company and the function $S_{phd}(\lambda)$ calculated by (4)–(6) for Ge-PD (curve 1) at a temperature of 20^oC. In the calculations, we used the following values: $L = 1.2 \cdot 10^{-4}$ cm, $x = 10^{-7}$ cm, $N_a = 2 \cdot 10^{16}$ cm^{-3}, $N_d = 10^{18}$ cm^{-3}, $T = 293$ K, $E_{ph} = 0.037$ eV, $T_{tr} = 0.6$–0.65.

The quantity T_{tr} is related to the Fresnel reflection of light from the air–semiconductor PD interface. To reduce this effect, the germanium PD surface is usually covered with a transparent quartz film of quarter-wave thickness with a refractive index $n_0 = 1.46$. In this case, the transmission coefficient can increase to 0.78–0.82, and the maximum sensitivity of the photodetector will be equal to $S_{phd} = 0.85$–0.9 A/W.

The proposed mathematical model for calculating the $S_{phd}(\lambda, T)$ adequately describes the behavior of other semiconductor photodetectors as well. For instance, Figure 1a shows also the spectral sensitivity of the InGaAs/InP pin-photodiode with an antireflection layer calculated with the aid of the proposed analytical model (curve 2) on the basis of the following data: $\lambda_{cut} = 1.8$ μm, $L = 3.2 \cdot 10^{-4}$ cm, $T_{tr} = 0.8$, and $x = 3 \cdot 10^{-7}$ cm. Symbols represent the experimental data obtained in investigating the specimens of InGaAs/InP pin-photodiodes of series C30617 of EG&G Optoelectronics and of series FDIGA041C of the Photonic company, especially designed for fiber-optic systems. Figure 1b gives the calculated and experimental data on the spectral sensitivity for the germanium photodiode at two different temperatures. As is seen, for all PD specimens the experimental and calculated values differ by no more than 5% throughout the spectral range and the analytical approximations obtained are much more accurate than the known bell-shaped or triangular approximations [5]. Analysis of the results presented in Fig. 1b has shown that the greatest change in the sensitivity caused by a change in the temperature will be observed in measuring systems working at $\lambda = 1.55$ μm, and this effect will be most appreciable upon cooling of the PD or with increasing radiation wavelength.

It should be noted that for other types of semiconductor PhDs it is necessary to take into account that the absorption coefficient $\alpha \sim (h\nu - E)^\gamma$, where $\gamma = 1/2$ for allowed direct transitions, and $\gamma = 3/2$ for forbidden transitions, $\gamma = 2$ for indirect transitions [6].

As follows from (3), in determining the value of the temperature error, it is necessary to take into account the fact that a change in the temperature influences not only the spectral sensitivity of the PD but also the radiation power and the lasing wavelength of the IL. The temperature dependence of the lasing wavelength is expressed as follows:



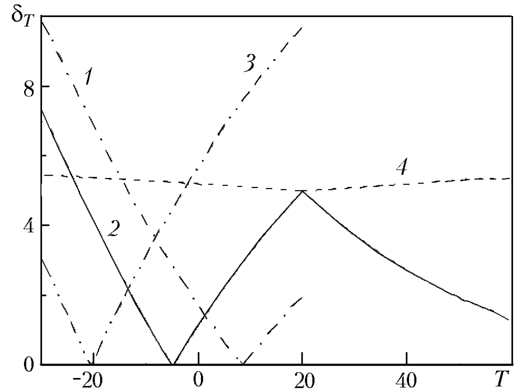


Fig. 2. Temperature error of the phase interferometer: 1) λ_0 = 1.3; 2) 1.55 μm. δ_T. %; T, °C.

Fig. 3. Relative temperature error in the stabilization of the injection-laser radiation power: 1) δ_c = 2; 2 and 4) 5; 3) 10% [1–3) λ_0 = 1.55; 4) 1.3 μm]. δ_T. %; T, °C.

$$\lambda(T) = \lambda_0(T_{in}) + \delta_\lambda (T - T_{in}) . \tag{7}$$

The radiation power of the IL with changing temperature can be calculated by the formula

$$P_{laser} = \eta_{laser} \frac{hc}{e\lambda} \left(I - I_{thr}(T_{in}) \exp \frac{T - T_{in}}{T_0} \right). \tag{8}$$

The investigation of the InGaAsP-IL specimens supplied by the FGUP NII Polyus yielded the following results: I_{thr}/T_{in} = 37 mA at T_{in} = 293 K, T_0 = 50–70 K, η_{laser} = 0.2, δ_λ = 0.09 nm/K for λ_0 = 1.55 μm, and δ_λ = 0.11 nm/K for λ_0 = 1.3 μm. For the calculations, the pumping current was chosen to be constant and equal to I = $1.5I_{thr}$ (T = 293 K).

Figure 2 shows the dependences of the temperature error in the temperature range from –30°C to +50°C for two wavelengths calculated by formulas (1) and (3) in view of (4)–(8). As the initial temperature, we chose the temperature (20–25°C, as a rule) at which calibration of the instrument was carried out, and the corresponding initial wavelengths were equal to λ_0 = 1.3 and 1.55 μm. The difference of the geometrical length of the interferometer arms was 5 m, and the refractive indices of the quartz fiber doped with 13.5% GeO_2 had the value of n = 1.47 for λ_0 = 1.3 μm and n = 1.462 for λ_0 = 1.55 μm. From the calculations performed it follows that the value of the temperature error can reach 80–100%. The lower temperature error for λ_0 = 1.55 μm is explained as follows. As follows from (8), as the temperature increases, there is a decrease in the threshold lasing current of the IL (at a constant pumping current this leads to an increase in the radiation power) and a simultaneous decrease in the maximum value of the S_{phd} and its shift into the short-wave region (Fig. 1b). Thus, the decrease in the spectral sensitivity of the photodetector in the vicinity of 1.55 μm partly compensates for the increase in the radiation power in the injection laser. For a wavelength of 1.3 μm, the spectral sensitivity of the photodiode remains practically unchanged with changing temperature, and in this case the temperature error is practically fully determined by the change in the IL radiation power that makes the dominant contribution to the temperature error. Therefore, it is necessary to take additional measures to stabilize the laser-radiation power.

Figure 3 presents the calculations of the temperature error of the interferometer for λ_0 = 1.55 μm provided that the IL radiation power has been stabilized with a relative error δ_c = 2% (curve 1), 5% (curve 2), and 10% (curve 3). Changes in the radiation power may be due to both variations in temperature and fluctuations of the IL pumping current. Analysis of the data obtained has shown that the best value for practical use is δ_c = 5%. This will provide a fairly good temperature error throughout the practically important temperature range, and a decrease in δ_T is thereby observed with both decreasing and increasing temperature. For comparison, Fig. 3 shows the temperature error for λ_0 = 1.3 μm and δ_c = 5%. In this case, to decrease δ_T, it is necessary to increase the stability of the IL radiation power.

The proposed analytical model makes it possible to estimate, as early as at the design stage, the temperature error of any optoelectronic information-measuring systems, for which, besides fiber-optic sensors, optical pulsed reflectometers, optic radiation power meters, fiber loss meters, etc. can be used.

NOTATION

c, velocity of light; e, electron charge; E_{ph}, Raman photon energy; $\Delta E(0)$, energy-gap width at 0 K; f_{phd}, function of the photodetecting transducer; h, Planck constant; I, IL pumping current; $I_{thr}(T_{in})$, threshold current at the initial temperature T_{in}; k, Boltzmann constant; k_{loss}, loss factor of the optical radiation power at E_{inp} = 0; L, depletion-layer thickness of the PD material, cm; N^*, reduced concentration of impurities; N_a, concentration of acceptors; N_d, concentration of donors; $P_{r.s}(I_{r.s})$, optical radiation power generated by the radiation source as current $I_{r.s}$ flows on it; P_{laser}, radiation power of the semiconductor injection laser (IL); S_{phd}, spectral current sensitivity of the photodetector; T, temperature, K; T_0, characteristic temperature; T_{tr}, transmission coefficient of radiation; x, depletion-level depth of the depletion layer with respect to the surface on which the radiation is incident; $X_{T_{in}}$ and X_T, value of the registered quantity at the output from the FOS at the calibration temperature T_{in} and at an arbitrary temperature T; α, absorption coefficient, cm^{-1}; α_z and β_z, constant coefficients in the formula of the temperature dependence of the energy-gap width of the semiconductor; η_{laser}, external quantum yield of the IL; λ, radiation wavelength, μm; λ_{cut}, long-wavelength radiation absorption cutoff, μm; $\lambda_0(T_{in})$, IL radiation wavelength at the initial temperature T_{in}; ν, frequency; σ_b, boundary value of the photoionization cross section, cm^2; τ, transmission coefficient of the optical channel. Subscripts: cut, absorption cutoff (λ_{cut}), b, boundary (σ_b); r.s, radiation source; laser, laser; in, initial; thr, threshold; loss, loss; tr, transmission; ph, photon; phd, photodetector; a, acceptors; d, donors; z, zone; inp, input; opt, optical; out, output; m, measurement; c, calculation.

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