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Fiber-optic Temperature Sensing with Silicon Fabry–Perot Interferometer Using Spectral Low-coherence Interferometry

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Abstract—A fiber-optic temperature sensor with a silicon Fabry–Perot interferometer (FPI) using spectral low-coherence interferometry (channeled spectrum) was implemented to measure cryogenic temperature. The sensitivity of a silicon FPI with a cavity length of 36 μm in the temperature range 77–300 K was about 1.5 K.

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Interferometric methods based on the determination of variations in the optical path (OP) of Fabry–Perot interferometers are widely used for temperature measurement. Of considerable interest are the developments of fiber-optic sensors (FOS) based on a Fabry–Perot (FPI) microinterferometer. FPI made of various materials can be used to design such sensors in which the OP depends on external conditions [1–4]. In [3], a sensitive element in the form of an optically thin silicon etalon (FPI) with a thickness of 675 nm was formed on the fiber tip. Transmissions and reflection spectra of the silicon etalon have a strong FP interference structure in the wavelength range of 900–1500 nm. The dependence of the reflection intensity on temperature has a maximum slope at 965 nm and was used to measure the temperature. The maximum temperature resolution was about 3 K in the temperature range from 303 до 673 K and is mainly caused by intensity fluctuations.

This letter describes a relatively simple method for measuring low temperature using a silicon FPI, which is a monocrystalline silicon plate with a thickness of 36 μm glued to the tip of a single-mode fiber. The OP length in FPI depends on the refractive index of silicon and changes with temperature. The variations in OP are measured using spectral low-coherence interferometry, the advantage of which is independence from optical power fluctuations in the fiber link.

Fiber-optic low-coherence reflectometry (FOLCI) is of interest for the remote measurement of quasi-static parameters, such as temperature and refractive index. FOLCI methods are based on the measurement of the autocorrelation function of the probing radiation after its interaction with the sample (a sensitive element made in the form of an FPI). The autocorrelation function can be measured either by a reference interferometer with a modulated arm difference (optical correlator [4, 5]), or by a spectral method [5, 6] (channeled spectrum).

The scheme of the setup, implementing the spectral method of fiber-optic low-coherence interferometry, is shown in Fig. 1. It consists of a radiation source, a fiber-optic link with a splitter and a minispectrometer containing a reflective diffraction grating (echelette) and a CCD matrix with a lens (a simple camera). The temperature-sensitive FPI (silicon plate) was glued with epoxy directly to the tip of the single-mode fiber and placed in a metal container together with a calibrated thermocouple with a resolution of 0.5 K.

Radiation from a superluminescent diode (SLD) with a wavelength range $\lambda = 920–960$ nm and a central wavelength $\lambda_0 \approx 940$ nm is transmitted through the optical fiber to the FPI formed at the end of the fiber. The signal reflected from the FPI is fed through the splitter to the input of the spectrometer. The spectrometer is built according to the autocollimation scheme, and the light passes through the lens twice (back and forth). In addition, the camera registers the first-order radiation spectrum reflected from the grating. The optical path (OP) or gauge length of the FPI can be measured by various methods, in particular, by the method described in [6, 7], which is implemented by comparing the experimental reflected FPI spectra with a set of theoretical curves. The gauge length of the FPI (OP) is determined by the results of this comparison with a suitable curve. The OP or the gauge length

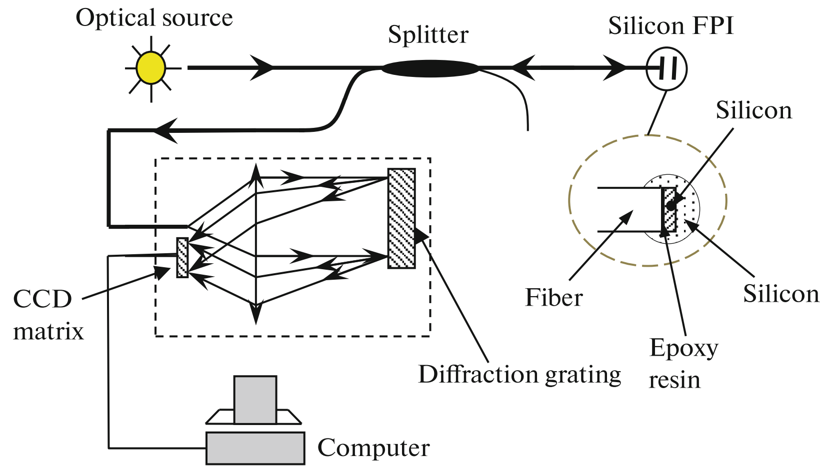

Fig. 1. The scheme of the setup.

of the FPI is the product of the thickness of a silicon plate and its refractive index. This value is measured experimentally, since it determines the change in the phase Φ of the radiation reflected by the FPI. This phase change depends on the temperature according to the well-known relation:

$$\frac{d\Phi}{dt} = \frac{4\pi nl}{\lambda}\left(\frac{1}{n}\frac{dn}{dT} + \frac{1}{l}\frac{dl}{dT}\right) = \varphi_0\left(\frac{1}{n}\frac{dn}{dT} + \frac{1}{l}\frac{dl}{dT}\right), \quad (1)$$

where l is the length of FPI cavity (thickness of a silicon plate), n is the refractive index of silicon, λ is the wavelength in vacuum, T is the temperature, $\varphi_0 = 4\pi nl/\lambda$.

Crystalline silicon has a relative thermal change of the refractive index of about $(1/n)(dn/dT) \approx 4.5 \times 10^{-5}$ K^{-1} which is much larger than the coefficient of thermal expansion $\alpha = 2.6 \times 10^{-6}$ K^{-1} [3, 7]. Therefore, the thermal expansion in (1) can be neglected and only the change in the refractive index can be taken into account.

It is known [1, 2] that the spectrum of a superluminescent diode (SLD) can be described by a Gaussian

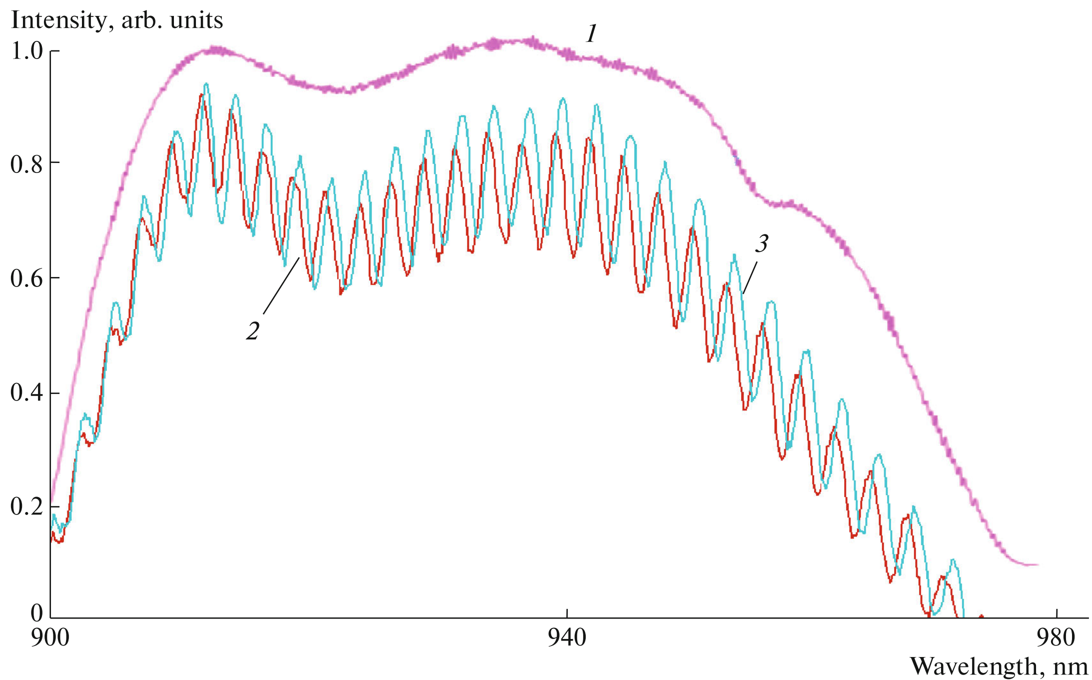

Fig. 2. The reflection spectra of SLD-471 (*1*) and the silicon FPI (*2*, *3*) obtained at temperatures of 293 (*2*) and 246 K, 246 K (*3*).

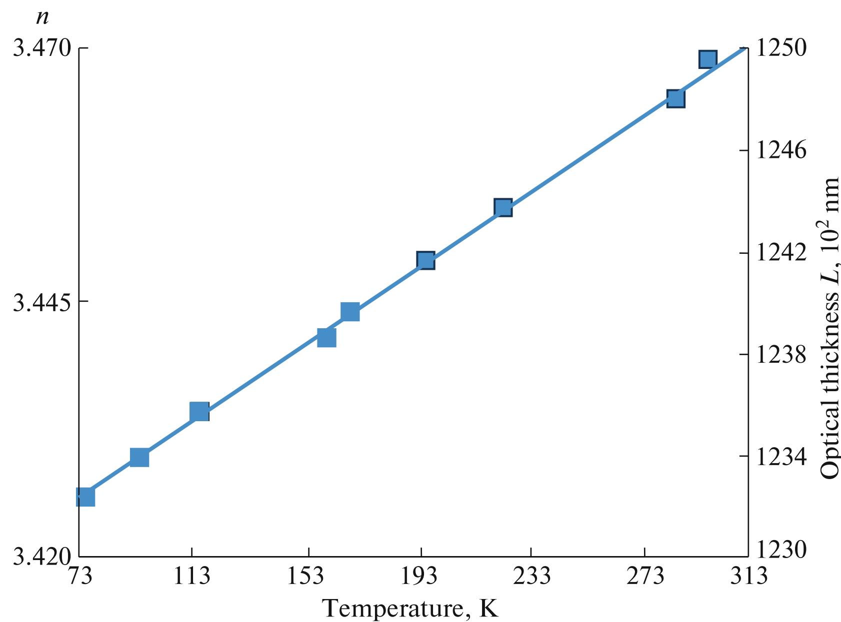

Fig. 3. Temperature dependence of FPI gauge and the refractive index n of silicon.

function and, in this case, with a center at $\lambda = 940$ nm. Therefore, the intensity of the reflected signal is described by the product of the reflection functions of the FPI and the Gaussian function of the source, i.e. it can be written as:

$$I(\lambda) \sim I_0 \exp\left[-\frac{(\lambda-\lambda_0)^2}{2(\Delta\lambda)^2}\right]\left(1 - V\cos\left(\frac{4\pi nL}{\lambda}\right)\right), \quad (2)$$

where I_0 is the radiation power at the input of the fiber link, V is the constant characterizing the interference visibility and depending on the radiation loss and efficiency of coupling between the FPI and the optical fiber, λ_0 and $\Delta\lambda$ are the central wavelength and the width of the SLD radiation spectrum, respectively, and $L = ln$ is the FPI gauge length.

Figure 2 shows two spectra of reflected signals from FPI (thickness of silicon plate ≈36 μm) formed at the tip of the fiber at temperatures of 20°C and –27°C, recorded by the camera. As can be seen from Fig. 2, these spectra are SLD spectra modulated by the FPI interference pattern described by (2).

In order to find the value $L = ln$, the interference part of this signal is separated from the entire signal and converted into a periodic signal, which is a sinusoidal (cosine) function: $I(\nu) \equiv I(\lambda^{-1})$, where $\nu = c\lambda^{-1}$ is the optical frequency. From this dependence $I(\nu)$, the spectrum of the reflected signal FPI is determined using bandpass filtering. To find L, we calculate the set of theoretical FPI reflected spectra in the wavelength range $\lambda_0 - \lambda_1$ (SLD-471 spectra) with a step $\Delta(L) = \Delta(nl) \cong 10$ nm, not exceeding the resolution of the minispectrometer. From this set of calculated spectra with different, the closest to the experimentally recorded spectrum was selected and the values of the FPI gauge length L and the corresponding value of the refraction index were determined.

Figure 3 shows the temperature dependence of $L = ln$ and the refractive index of Si, obtained in this way for the temperature range from 73 to 293 K. As can be seen from Fig. 3, the FPI gauge length and the refractive index of Si depend linearly on the temperature with a gradient $dn/dT = 2.5 \times 10^{-4}$.

From this we get that the relative value of the thermal change in the refractive index is equal to $(1/n)(dn/dT) \approx 7 \times 10^{-5}$ K^{-1}, which is approximately about 40% larger than the value presented in [7]. This discrepancy is probably caused by the fact that the thermal expansion of silicon plate was neglected, as well as by the errors in measuring the thickness of this silicone plate (±1 μm). The temperature sensitivity of the silicon FPI is determined by the dependence of $n(T)$ and the properties of the minispectrometer. With a silicon plate thickness of 36 μm, the measurement time is 1 sec. The obtained temperature sensitivity is about 1.5 K in the temperature range from 73 to 293 K. The temperature sensitivity can be increased by increasing the thickness of the silicon plate and narrowing the frequency band.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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