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Measurement of spectra of fiber Bragg gratings by tuning the wavelength of a laser diode

Yuriy S. Borisov [a,b], Azat M. Nizametdinov [a], Oleg V. Ivanov [a,c,*], Aleksey A. Chertoriyskiy [a]

[a] Ulyanovsk Branch of Kotel'nikov Institute of Radio Engineering and Electronics of Russian Academy of Sciences, Ulitsa Goncharova 48, Ulyanovsk 432071, Russia
[b] Ulyanovsk State Technical University, Ulitsa S. Venets 32, Ulyanovsk 432027, Russia
[c] Ulyanovsk State University, Ulitsa L. Tolstogo 42, 432017 Ulyanovsk, Russia

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ABSTRACT

We demonstrate the possibility of measuring reflection spectra of fiber Bragg gratings by tuning the wavelength of an off-the-shelf laser diode. Two methods of tuning are studied: temperature tuning at a frequency of 0.5 Hz and current tuning at a frequency of tens of kHz. A wavelength resolution of 2 pm is achieved for both methods. It is shown that by current tuning it is possible to interrogate fiber Bragg gratings at frequencies up to 100 kHz. Using the methods proposed, we have measured the shift of the reflection spectra of a fiber Bragg grating upon heating.

1. Introduction

Sensors and measuring systems based on fiber Bragg gratings (FBGs) are widely used in various fields of technology. They are used to measure such physical parameters as vibration [1], acceleration [2], pressure [3], temperature [4], humidity [5], etc. [6–8]. Due to chemical resistance and immunity of the optical fiber to electromagnetic fields, such sensors are applicable for measurements in chemically active environments, under strong electromagnetic interference, and ionizing radiation [9].

The parameter of a FBG sensor carrying information about the measured physical process is usually the shift of maximum wavelength of the reflection spectrum. Another option is to obtain the transmission spectrum and to find the wavelength of its minimum. The spectrum shifts in wavelength under the physical influence. The measurement of the wavelength shift is carried out using special interrogation and processing devices. Numerous solutions have been developed to obtain information about the shift of the maximum of the reflection spectrum of FBGs [6,10]. Specialized tunable lasers can be used for such interrogation [11–14]. Interrogation methods based on the use of a reference stabilized grating have been used to track the shift of the wavelength of the grating sensor [15]. Interferometric interrogation methods are proposed, where a Mach–Zehnder interferometer is used to determine the wavelength of the reflection of the grating sensor and the wavelength shift of the optical signal reflected from the sensor is converted into the phase shift of the interference pattern [16,17]. A tunable optical filter can be used in such systems instead of the interferometer [18,19]. It is possible to measure the wavelength using an optical spectrum analyzer based on a CCD spectrometer (see, for example, [20]).

The existing interrogation methods that are based on tunable lasers have a disadvantage – they require using special tunable lasers, which are usually quite expensive [21–24]. On the other hand, off-the-shelf stabilized laser diodes (LDs) are much cheaper. Therefore, it is promising to design a method for FBG interrogation using such LDs.

It is known that the wavelength of light emitted by a LD depends on temperature of its active area of the semiconductor structure [25–27]. This dependence can be employed for tuning the wavelength of laser emission by changing the pump current of the LD [28–30]. In this case, the wavelength tuning range is limited by about 0.5 nm. This tuning range may be sufficient for a number of applications of FBG sensors. Tuning of diode lasers has also been used in molecular spectroscopy [31–33]. For example, the methane spectrum was analyzed by a LD with tuning range 0.3 nm [34]. A tunable LD with several frequency-spaced Bragg gratings formed in a single fiber section was proposed in [35]. The emission wavelength changed due to shifting of the maximum gain of the LD. Light was generated at the wavelength of the grating for which the reflection coefficient was maximum at given temperature and pump current. This solution allowed the authors to significantly expand the tuning range (up to 20 nm), but resulted in discrete tuning with a step of 500 pm.

Interrogation techniques using distributed feedback lasers tuned by

* Corresponding author.
E-mail addresses: rgitars@rambler.ru (Y.S. Borisov), olegivvit@yandex.ru (O.V. Ivanov).

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current modulation and temperature variation had been described for static applications of FBGs in [36,37]. The temperature variation was used for rough wavelength tuning to access different gratings, while current modulation tuning with small wavelength range was used for interrogation of a particular grating. The reflection of an FBG was measured at two time spans during current modulation corresponding to different wavelengths. The shift of the FBG's spectrum was detected from the relation between signal amplitudes at two wavelengths using power-based interrogation technique with its disadvantages mitigated by the division of two amplitudes. The relation between two signals was proportional to the curvature of the spectral curve of the FBG reflectance at the short or long wavelength side. The current modulation frequency was 1 kHz, and the interrogation scheme was suggested for static applications. For dynamic applications, when fiber gratings are used to detect fast signals, for example acoustic signals that are in the kilohertz range, the interrogation speed should exceed 10 kHz. The power-based techniques still had some problems such as dead zone, where different wavelength shifts were undistinguishable. The emitting wavelength was found from the laser mount temperature, which was controlled and stabilized. This temperature is different from the temperature of the semiconductor LD structure, when it is heated and cooled quickly. Therefore, these methods are slow and suitable for static applications only.

Dither demodulation of fiber Bragg grating sensors illuminated with light from laser diodes had been employed in quasi-static regime in [38]. The pump current of the laser diodes was modulated to measure small ac signals by using a synchronous detection referenced to twice the dither frequency, which had allowed to realize temperature and strain sensing.

In this paper, we investigate the possibility of measuring the reflection spectra of FBGs by tuning the wavelength of a LD in two ways: by changing temperature (with scanning time of order of seconds) and by changing LD pump current (at frequency of order of tens kilohertz). We propose to use the value of the voltage drop on the LD with known value of the pump current as an information parameter for calculating the emission wavelength of the LD. The method is used to measure the shift of reflection spectra of a heated FBG.

2. Experimental setup

For demonstration of the possibility of measurement of the FBG spectrum by tuning the emission wavelength of the LD, we use an off-the-shelf distributed feedback LD. The distributed feedback LDs are designed to operate at a fixed wavelength; at the same time, there is a possibility of some tuning of the laser wavelength by changing temperature of the emitting structure or the pump current. The temperature of the LD can be changed by an external heat source or by increasing pump current heating the internal structure [25]. In the first case, it is convenient to use thermoelectric converters, which are able to heat or cool the LD with the required speed. In the second case, when the LD is heated by the pump current, the temperature change can be only positive with respect to the ambient temperature. In this case, the temperature of the LD depends on the value and duration of the current flowing through the laser. We use the first method with an external thermoelectric converters to adjust the temperature, since we can obtain a larger range of temperature changes and wavelengths, accordingly.

The scheme of the experimental setup used for the measurement of FBG spectra by tuning the laser wavelength is shown in Fig. 1. We use an off-the-shelf LD module LDI-1550-DFB-1.25 G-20/80 manufactured by LLC "Lazerscom" (Minsk, Belarus). The module emits light in a single-mode regime with a spectral width of 500 kHz. In addition to the LD itself, the module includes a built-in photodetector (P1) that allows one to measure the output power of the laser emission, a thermistor that can be used at the calibration stage, and a heating–cooling device based on a 1.1 W Peltier element, on the cold side of which all the elements described above are mounted. The pump current of the laser is set by a current source controlled by the corresponding unit. The voltage drop on the LD of the laser is amplified by a voltage amplifier and enters the input of the control unit. The built-in thermistor is connected to a conversion device, the output voltage of which is proportional to the resistance of the thermistor.

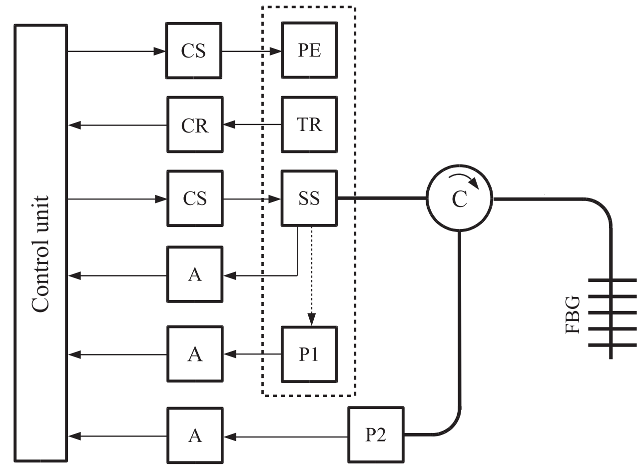

Fig. 1. Scheme of LD-based spectrometer containing the following elements: fiber Bragg grating (FBG), photodetectors (P1, P2), amplifiers (A), circulator (C), Peltier element (PE), current sources (CS), built-in thermistor (TR), converter (CR), semiconductor structure (SS). The dash line encloses the elements that are inside of the laser module.

The light from the laser is transmitted through the circulator to the FBG. The grating was fabricated using a phase mask and has a maximum reflection coefficient of more than 98%. The light reflected from the FBG is transmitted through the circulator to the input of the photodetector P2. The power of the light reflected from the FBG is directly proportional to the reflection coefficient of the FBG at the laser wavelength. Therefore, it is possible to obtain information about the reflection spectrum of the FBG by tuning the laser wavelength. Since the output power of the LD depends on its temperature, the scheme is provided with a system measuring the light power using the photodetector P1. The control unit consists of a data acquisition board and a calculation and control module based on an ARM microcontroller. A 16-bit analog-to-digital converter, filters of electrical signals, and a circuit for selecting the measured parameter are installed on the data acquisition board. This solution allows us to use a single analog-to-digital converter to measure several signals, such as the signals from external and internal photodetectors, the current voltage drop, and the laser pump current. The amplified signal from the photodetector P2 is normalized in the control unit by the amplified signal from the photodetector P1. This approach minimizes the measurement errors in the reflection spectrum of the FBG related to the changes in the output power of the laser.

The use of the circulator provides protection of the LD from light reflected by the FBG. It is possible to use an optical insulator with a fiber coupler instead of circulator. However, this variant would result in additional losses of optical power and an increase in the number of optical elements.

3. Tuning wavelength by changing temperature

In order to measure spectra using the setup described above, it is necessary to do pre-calibration and to find the dependences of the emission wavelength and the voltage drop across the LD on temperature. For this, the laser output was connected directly to an optical spectrum analyzer. The circulator, the FBG, and the external photodetector P2 were not used in this case. A fixed value of the pump current was set in the current source. By changing the value of the direct current through the Peltier element, the temperature of the LD was controlled. After each change of the current through the Peltier element, we waited the time necessary for stabilization, when all transient thermal processes in the LD are finished (about 5 min). Then, the voltage drop across the LD and the wavelength of the laser emission were measured. The temperature change was recorded by the internal thermistor of the laser module. This thermistor can be used only for measuring the temperature changes during calibration, but it is not suitable for determining the wavelength of light. This is because the thermal time constant of the thermistor is of order of seconds, which is comparable to the time of tuning of the laser wavelength.

The main functions of the control unit (Fig. 1) in the case of wavelength tuning by changing the LD temperature are the following: periodical measurements of the voltage drop across the LD and signals from the photodetector amplifiers, calculation of the wavelength, and switching between heating to cooling, when the extreme temperature values are reached.

Fig. 2 shows the experimental dependences of the emission wavelength and the voltage drop across the LD on temperature. It is seen that the obtained dependencies are almost linear. For our laser module, the coefficient between wavelength and temperature is $k_{\lambda t} = 0.12$ nm/°C, and the coefficient between voltage and temperature is $k_{Ut} = 0.28$ mV/°C, which is almost seven times lower than the typical values for silicon diodes. Dividing $k_{\lambda t}$ by k_{Ut}, we can obtain the coefficient that relates the change in emission wavelength with the change in the voltage drop across the LD: $k_{U\lambda} = 0.43$ nm/mV.

Similar measurements for other laser modules of the same brand have shown that the values of the coefficients $k_{\lambda t}$ and k_{Ut} are module dependent and, in addition, depend on the magnitude of the pump current. Thus, it is necessary to perform calibration procedure for each sample of the laser module.

Further, the reflection spectra of the FBG were measured by our experimental setup using the coefficients found at the previous step. The grating spectra are shown in Fig. 3a. Since the output optical power of the laser changes with temperature, the signal from the photodetector P2 was normalized by the signal from the photodetector P1. The solid line shows the reflection spectrum of the fiber grating obtained during heating, and the dotted line is obtained during cooling.

The duration of one heating–cooling cycle was 2.6 s, while the laser wavelength changed by 0.7 nm. Fig. 3a shows that the spectrum obtained during cooling is quite close to the one obtained during heating with a slight shift to longer wavelengths (0.43 pm). It is also seen that the reflection spectrum of the FBG obtained using our setup with laser wavelength tuning (lines 1 and 2) has much higher resolution than the spectrum measured by Anritsu MS9710A spectrum analyzer with a resolution of 70 pm (line 3). The setting of video bandwidth of the optical spectrum analyzer was 10 Hz.

The factor that limits resolution of our system is the stepwise change in the wavelength of the laser emission, which is shown in close view in Fig. 3b. The area outlined by the dotted line in Fig. 3a is enlarged in Fig. 3b. The steps are caused by back reflection from the fiber optic connector of the laser. The nature of these steps (or sawtooth modulation at shorter wavelengths) is the mode hoping of the longitudinal modes of the resonator formed by the laser and the fiber section before

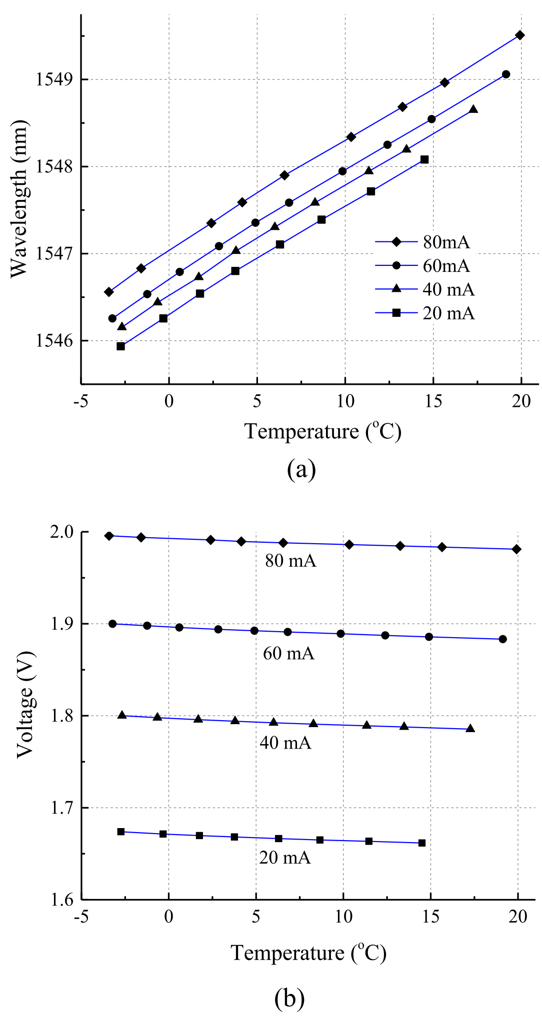

Fig. 2. Dependence of the emission wavelength and the voltage drop across the LD on its temperature for four values of the pump current.

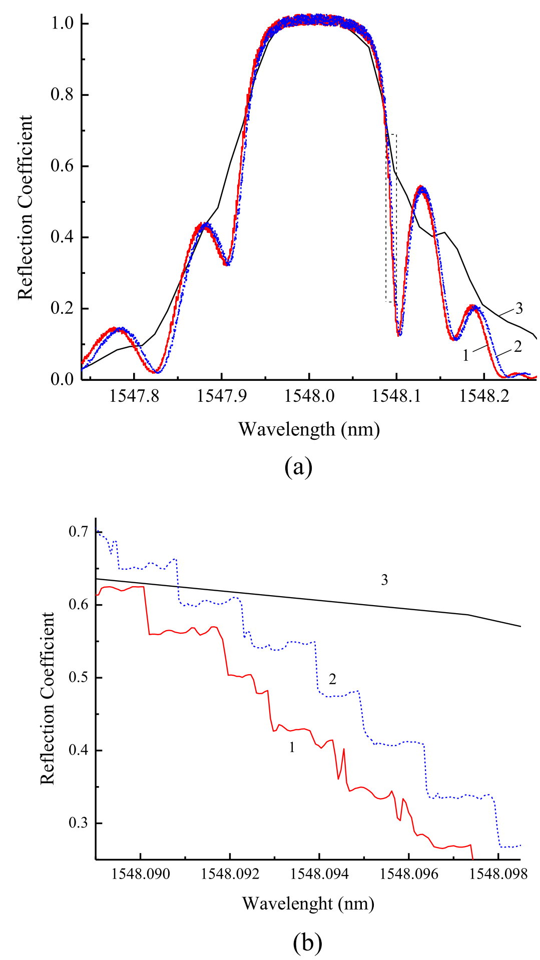

Fig. 3. Experimental reflection spectra of a FBG at temperature 25 °C. The spectra are measured during heating and cooling of the LD (curves 1 and 2, respectively) and obtained by an optical spectrum analyzer (curve 3). Figure b shows close view of the dashed rectangle from Figure a.

the connector. For our laser module, the value of the step size in wavelength is about 1.7 pm, which corresponds to the fiber length between the laser and the connector of 0.5 m. Taking this into account, we can consider that the wavelength resolution of the experimental setup is 1.7 pm.

Fig. 4 shows the evolution of the FBG reflection spectrum measured with changing temperature. It is demonstrated by the figure that the LD-based spectrometer with its wavelength tuned by changing temperature can be used for measurements of the FBG reflection spectrum. From the figure, we estimate that the temperature sensitivity of the grating is 12.7 pm/°C, which lies in the typical range of temperature sensitivities 10–13 pm/°C.

Thus, the study of the LD-based experimental setup has shown the possibility of using the temperature tuning of the LD emission wavelength for measurements of reflection spectra of FBGs. The advantages of the proposed method are relative simplicity of the system and high wavelength resolution. The disadvantages are significant scanning time of about 2 s and small full wavelength scanning range not greater than 3 nm.

4. Tuning wavelength by changing pump current

The wavelength tuning speed can be increased by using the dependence of the LD wavelength on the pump current. In this way, it is possible to tune the wavelength of laser emission with a frequency of more than 1 MHz [39]. To investigate the possibility of controlling lasing wavelength by changing the pump current of the LD, some changes were made in the experimental setup described above (Fig. 1). A triangular signal was applied to the control input of the current source. The laser pump current repeated the shape of the triangular control signal and changed linearly in the range from 10 to 110 mA. The linear current dependence was chosen due to simplicity of the subsequent analysis of thermal processes in the LD. For a triangular signal, the moment of transition from increasing to decreasing current (and vice versa) is clearly observed. The current range is defined between the threshold current and the maximum current permissible for this laser.

It was shown in [30] that the wavelength tuning range achievable by changing the LD pump current reaches 0.28 nm. This is sufficient for the interrogation of a FBG with a narrow Bragg peak. However, the initial wavelength of the laser emission may be significantly shifted with respect to the Bragg peak of the grating. In this case, it is necessary to adjust the wavelength of the laser emission by changing the temperature of the LD so that the current adjustment range corresponds to the Bragg peak in the grating reflection spectrum.

A change in the pump current leads not only to a change in the emission wavelength, but also to a change in the voltage drop across the LD and its temperature. The modulation of pump current was carried out at frequencies up to 100 kHz. The Peltier temperature controller is not able to change temperature with such a frequency. A typical Peltier temperature element cannot provide more than 1 deg/s. In this regard, for additional temperature adjustment of the laser emission wavelength, the calibration dependences of the emission wavelength and the voltage drop on the pump current and the temperature of the LD in the stationary regime were measured. Using these dependencies, the working wavelength of the laser emission was tuned by changing the LD temperature, which was controlled by the current through the Peltier element. At the same time, the temperature was determined by the average voltage across the LD during one period.

Fig. 5 shows the dependencies of the amplified output signals of the photodetectors P1 and P2 for one scanning period with the current tuning of the laser wavelength at a frequency of 100 kHz. The emission wavelength is equal to 1547.85 nm for a current value of 10 mA at the beginning of the period and temperature about + 10 °C, which approximately corresponds to the short wavelength side of the grating reflection spectrum. For a current value of 110 mA in the middle of the period and the same temperature of the LD (+10 °C), the emission wavelength is equal to 1548.15 nm and reaches the long wavelength side of the grating reflection spectrum.

When the pump current increases, in addition to a shift in emission wavelength, there is also an increase in power. Therefore, in order to find the reflection coefficient, it is necessary to normalize the signal of the photodetector P1 by the signal of the photodetector P2. The result of such normalization is shown in Fig. 5b.

The curve in Fig. 5b has two symmetric parts: the left part is obtained

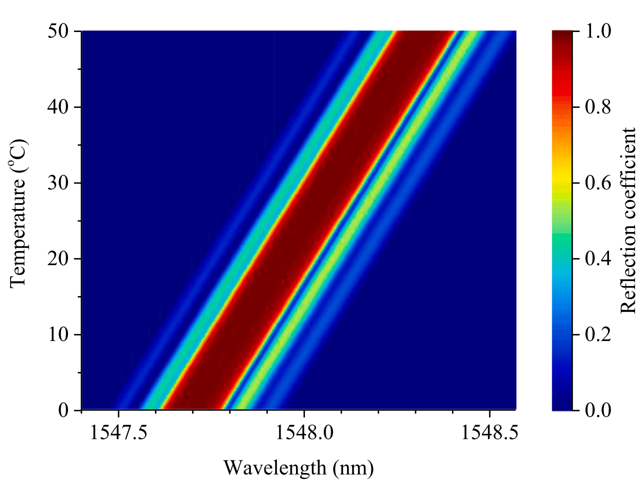

Fig. 4. Evolution of reflection spectrum with changing temperature of the FBG.

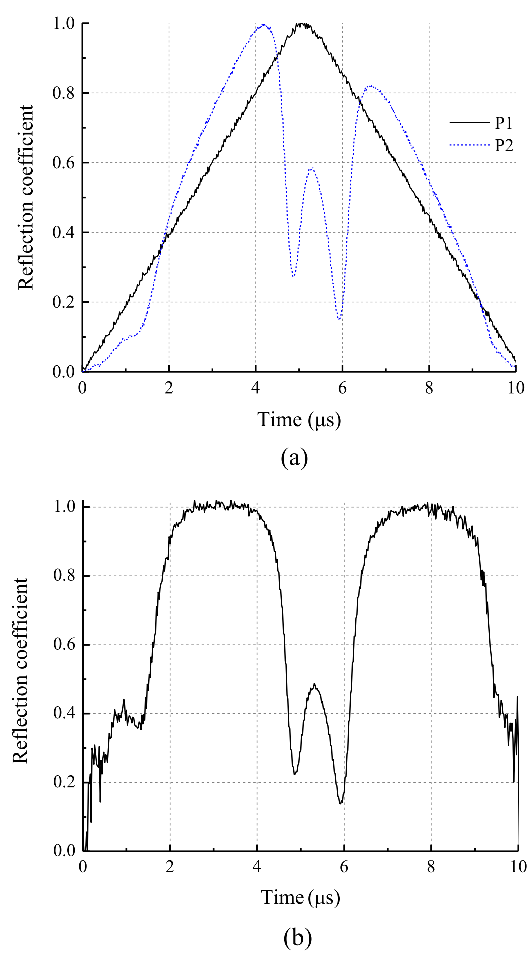

Fig. 5. Experimental measurements of the signal of the photodetectors P1 and P2 (a) and the signal of the photodetector P1 normalized to the signal P2 (b).

by scanning with increasing pump current, the right part – with decreasing pump current. The curve should be mirror-symmetric in time with respect to the point of maximum pump current. However, there is some shift of the curve in positive time direction. The shift of the curve can be explained by the inertia of thermal processes in the LD.

In order to reconstruct the FBG spectra from the measured dependence of the photocurrent on time, it is necessary to find the dependence of the emission wavelength on temperature, which in turn is a function of time. To do this, we calculate the dynamics of heating and cooling of the structure with changing current. We assume that the wavelength of the laser emission is determined by the temperature of the LD and does not directly depend on the pump current. The change in the LD temperature with flowing current is directly proportional to the magnitude of the current and the difference between the temperatures of the LD and the surrounding medium. This can be described by the following differential equation:

$$\frac{dT}{dt} = aI(t) - b(T - T_{\mathrm{av}}) \tag{1}$$

where t is the time, T is the LD temperature; a and b are some coefficients, $I(t)$ is the current flowing through the LD; T_{av} is the average temperature to which the temperature of the LD tends in the absence of the variable component of the current (in the presence of the constant pumping current).

Since the dependence of the current through the LD has a triangular shape, we have.

$$I(t) = \begin{cases} I_{\mathrm{m}} t/t_1, & 0 \leqslant t \leqslant t_1 \\ I_{\mathrm{m}}(2 - t/t_1), & t_1 < t \leqslant 2t_1 \end{cases} \tag{2}$$

where I_{m} is the maximum current, t_1 is the time after which the maximum current is reached (half of the period of the variable component of the current flowing through the laser). Then the solution of Eq. (1) has the following form:

$$\begin{aligned} T_1(t) &= -\frac{aI_{\mathrm{m}}}{b^2 t_1}(1 - bt) + C_1 e^{-bt} + T_{\mathrm{av}}, && 0 \leqslant t \leqslant t_1 \\ T_2(t) &= \frac{aI_{\mathrm{m}}}{b^2 t_1}(1 - b(t - 2t_1)) + C_2 e^{-bt} + T_{\mathrm{av}}, && t_1 < t \leqslant 2t_1 \end{aligned} \tag{3}$$

where C_1, C_2 are constants that can be found from the boundary conditions.

The first boundary condition requires continuity of the two solutions at time t_1:

$$T_1(t_1) = T_2(t_1) \tag{4}$$

The second boundary condition follows from stationarity of the periodic process:

$$T_1(0) = T_2(2t_1), \tag{5}$$

Taking into account these relations, it is possible to obtain the constants C_1 and C_2:

$$\begin{aligned} C_1 &= \frac{2aI_{\mathrm{m}}}{b^2 t_1} \frac{e^{bt_1}}{e^{bt_1} + 1}, \\ C_2 &= -C_1 e^{bt_1}. \end{aligned} \tag{6}$$

Based on the experimental data, it is possible to find the coefficients a and b as follows. The magnitude of the coefficient b is chosen so that the reflection spectrum obtained by heating the LD coincides with the spectrum obtained by cooling. The magnitude of the coefficient a is chosen from the condition of equality of the widths of the reflection spectra obtained during current and temperature scanning. It was found that these conditions are satisfied for the following magnitudes of the coefficient: $a = 0.58 \frac{^\circ C}{A \cdot c}$, $b = 0.0322 \frac{1}{c}$. After the coefficients a and b are found, the solution of Eq. (3) allows us to construct the dependence of the temperature of the LD on time (Fig. 6). It can be seen from the figure that there is a delay in the temperature dependence with respect to the current dependence and a kind of hysteresis related to heat capacity of the LD. Correct choice of the coefficients a and b excludes hysteresis from the measured spectrum. Fig. 7 shows the spectrum of the light reflected from the FBG recalculated taking into account the dependence of temperature of the structure on time and the coefficient $k_{\lambda t} = 0.12$ nm/°C, which relates the emission wavelength to the LD temperature and was obtained previously in the stationary regime.

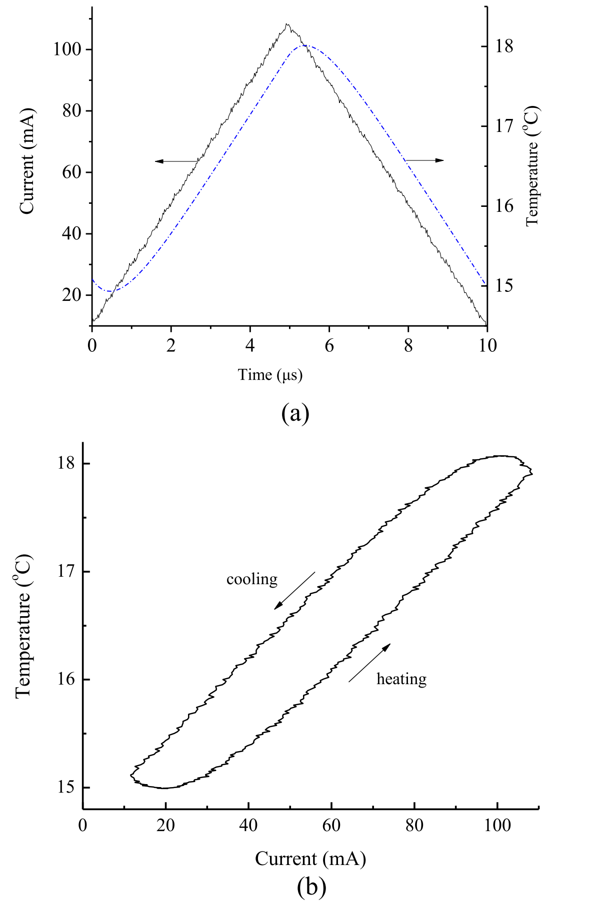

Fig. 6. Dependence of current and temperature of the LD with time.

The designed system was used to measure the shift of the FBG

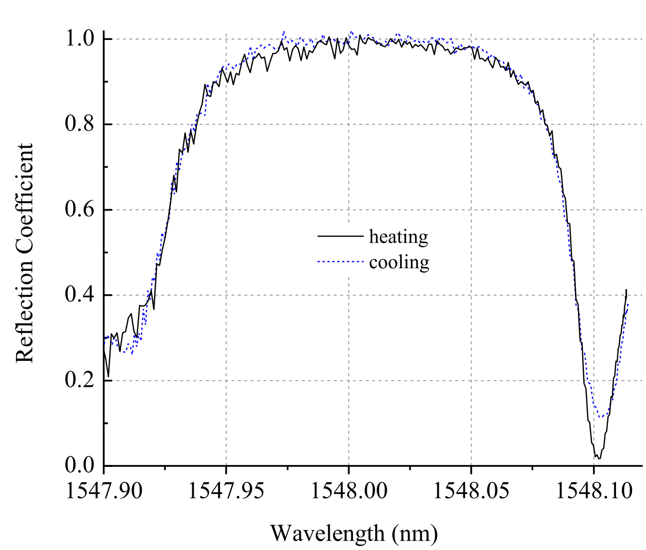

Fig. 7. Reconstructed reflection spectrum of the FBG at 25 °C.

spectrum with temperature. Fig. 8 shows the evolution of the FBG reflection spectrum with temperature. The spectra were measured by scanning along wavelength tuned by the pump current of the LD. Scanning was carried out at a frequency of 100 kHz for a fixed LD temperature corresponding to a fixed range of wavelengths. The Peltier temperature controller was used for this slow stabilization of average temperature of the LD. First, the temperature of the grating was set at 25 °C, and the laser wavelength was tuned by the Peltier temperature controller so that the grating spectrum is in the center of the wavelength span of the current tuning range. Second, the LD temperature was fixed, and the temperature of the grating was changed from 0 to 50 °C with continuous scanning of the spectrum by the current tuning.

It can be seen that the full reflection spectrum of the grating does not fit into the available wavelength range during single scan. However, by changing the temperature of the grating, its spectrum is shifted and the full spectrum is covered by the whole set of measurements. From the dependence in Fig. 8, it is possible to estimate the temperature sensitivity of the grating as 12.8 pm/°C, which approximately corresponds to the sensitivity obtained previously. The presence of noise in the wavelength range from 1547.91 to 1547.92 nm is due to unstable operation of the laser and its low power for current values close to the threshold. In general, the resulting spectra are similar to the spectra shown in Fig. 3. Fig. 9 demonstrates a good match between the spectra measured by temperature tuning and current tuning. The spectrum measured by the current tuning is obtained a concatenation of two spectra obtained for Bragg grating temperatures 19.5 and 33.5 °C with compensating wavelength shifts corresponding to these temperatures.

To estimate the accuracy of single wavelength measurement, we retrieved the characteristic curve of Bragg wavelength vs temperature from Figs. 4 and 8. For the case of scanning with temperature, we have calculated the root-mean-square error in wavelength, which is equal to 4 pm. For the case of scanning with current at a frequency of 100 kHz, the root-mean-square error is equal to 5 pm.

5. Conclusion

Thus, we have demonstrated the possibility of tuning the wavelength of an off-the-shelf diode laser for measuring the spectra and interrogation of fiber Bragg gratings. A wavelength resolution of up to 1.7 pm was obtained, which exceeds the characteristics of typical optical spectrum analyzers used in fiber optics. Two methods of wavelength tuning are investigated: slow temperature tuning with a scanning time of 2 s and fast pump current tuning with a scanning frequency of up to 100 kHz. It is shown that it is possible to measure the shift of the reflection spectrum of fiber Bragg gratings when they are heated.

As compared to [36,37], the emitting wavelength is found through the temperature of the LD, which is measured by the voltage drop across the semiconductor LD structure with recalculation taking into account the pump current. Direct measuring of the emitting wavelength allowed us to achieve interrogation at frequencies up to 100 kHz and dynamic scanning of full grating spectrum. In this work in contrast to two-point amplitude-based interrogation, the spectrum of the FBG is reconstructed from the reflected signal, which allows us to observe and measure the shift of FBG spectrum using wavelength-based interrogation.

The advantages of the proposed methods are simplicity, high resolution and high speed for current tuning. The use of an inexpensive off-the-shelf laser and the absence of any specialized fiber-optic devices significantly reduce the cost of the interrogation device. The main limiting factor of the considered methods for interrogation at frequencies of more than tens of kilohertz is a small tuning range comparable to the spectrum width of a fiber Bragg grating.

To overcome this limitation and apply the proposed methods in the interrogation of fiber sensors, it is possible to use Bragg gratings with a π-shift, whose spectra have a very narrow peak with a width of about several picometers [40,41]. The position of this peak can be controlled with much greater accuracy than the position of much wider Bragg peak.

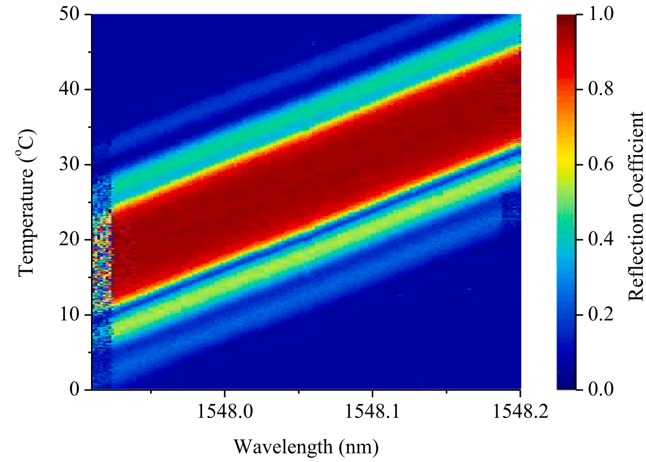

Fig. 8. Evolution of the reflection spectrum of heated FBG obtained by scanning with current at a frequency of 100 kHz.

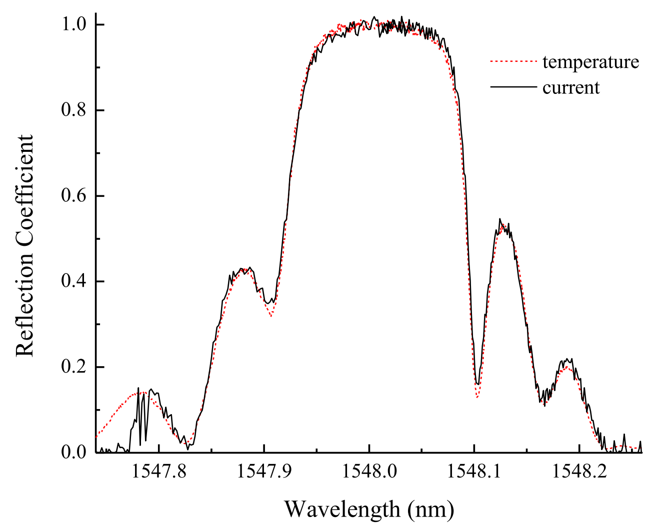

Fig. 9. Comparison of reflection spectra of the FBG at 25 °C measured by temperature tuning and current tuning.

CRediT authorship contribution statement

Yuriy S. Borisov: Investigation, Writing – review & editing. **Azat M. Nizametdinov:** Conceptualization, Investigation, Writing – review & editing. **Oleg V. Ivanov:** Writing – review & editing. **Aleksey A. Chertoriyskiy:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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