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Optoelectronic sensor for simultaneous and independent temperature and elongation measurement using Bragg gratings

Streszczenie. *W niniejszym artykule zaproponowano układ czujnika do równoczesnego pomiaru wydłużenia i temperatury, wykorzystującego dwie światłowodowe siatki Bragga o różnych długościach fal rezonansowych. Dla pomiarów wydłużenia uzyskano liniowość charakterystyki przetwarzania rzędu 0.06% i 0.08% odpowiednio dla pierwszej i drugiej siatki Bragga. Błędy nieliniowości charakterystyki przetwarzania temperatury wyniosły w przypadku zaproponowanego czujnika 3,43% oraz 2,36% odpowiednio dla siatki pierwszej i drugiej.* ***(Optoelektroniczny czujnik do równoległego i niezależnego pomiaru temperatury i wydłużenia wykorzystujący światłowodowe siatki Bragga).***

Abstract*. The present article proposes a system for a sensor for simultaneous measuring of elongation and temperature, using two fibers Bragg gratings with different resonance wavelengths. For measuring the elongation, linearity was obtained for the conversion characteristic of 0.06% and 0.08% respectively for the first and second Bragg gratings. In the case of the sensor proposed, the non-linearity errors of the temperature conversion characteristic were 3.43% and 2.36% respectively for the first and second gratings.*

Słowa kluczowe: światłowodowe siatki Bragga, czujniki optoelektroniczne, czujniki wydłużenia, nieczułe na zmiany temperatury.
Keywords: fiber Bragg gratings, optoelectronic sensors, elongation sensors, temperature insensitive.

Introduction

The existing optoelectronic sensor solutions, allowing the elongation or strain value to be defined regardless of the temperature of the measurement, can be categorized according to information about the temperature at which the measurement was taken. In some cases the inverse problem solution is necessary. Inverse analysis is required because the elongation and temperature detection belongs to indirect measurement [1] and boils to the spectra reconstruction. A value without information about temperature [2] is an adjusted result (by the missing value, i.e. that resulting from the influence of temperature only), while a value including information about the temperature (simultaneous measurement of elongation and temperature) [3], additionally allows correction of the spectral characteristic and enables the measurement systems to be calibrated. An analogous division of FBG-based measuring systems can be made with regard to the dynamic of the loads and measurement - static systems [4] and dynamic systems [5]. An optical wavelength discriminator based on a Sagnac loop is often used, for signals detection from fiber Bragg gratings sensors [6]. Differentiating the changes from the types of loads is the subject of research by many institutions. Another categorization of FBG-based measuring systems can also be made according to the method of temperature compensation – into systems with internal compensation, e.g. operations making use of the properties of the material [7], and systems with external compensation, which use a relevant installation of gratings on appropriately selected mechanical convertors [8]. Measuring techniques are being developed using fiber Bragg gratings sensitive only to strain [9] and methods displaying different sensitivity to strain and to temperature, but therefore requiring initial calibration of the gratings for each sensitivity, thus increasing the complexity of the system itself [10].

Simultaneous measurement of strain and temperature is possible by defining the wavelength shift of two gratings in a situation where their sensitivities to both measurands are different [11]. It is often the case that an approach involves simultaneous measuring of strain and temperature, using a hybrid sensor consisting of two FBG (fiber Bragg gratings) and an LPG (long period grating). A separate group consists of elongation and temperature sensors using a combination of fiber Bragg gratings with a fiber optic interferometry system [12,13]. Most systems require the application of an ordinary Bragg grating along with another optoelectronic element (long-term Bragg grating, oblique Bragg grating, fiber optic interferometer) which increases the complexity of the sensor system. The inverse analysis for the two parameters simultaneous measurement using FBG sensors on the base of its spectra often pertain to ill-conditioned inverse problem [14,15].

In the present article we present a possibility to use a sensor based on two ordinary, homogeneous Bragg gratings for simultaneous measurement of elongation and temperature which does not require the use of additional optoelectronic systems such as fiber interferometers or even special Bragg gratings (long-term, chirped or tilted). The paper proposes the use of differences in the ratios of FBG sensitivity to temperature and relative elongation using gratings of two different Bragg wavelengths.

Design of the sensor system and principle of operation

In order to obtain the matrix equations of the system with two Bragg gratings for simultaneous measuring of relative elongation and temperature, we begin by recording the dependency on the Bragg wavelength for the uniform grating, which takes the following form:

$$\lambda_B = 2n_{eff} \cdot \Lambda \tag{1}$$

where n_{eff} is the effective refraction index in the fiber core on which the grating is written, Λ is the grating period, also known as the grating constant. The occurrence of changes in temperature ΔT and elongation $\Delta\varepsilon$ cause a change in the Bragg wavelength according to the relationship:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial\varepsilon} + n_{eff}\frac{\partial\Lambda}{\partial\varepsilon}\right)\Delta\varepsilon + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{2}$$

in which T designates the temperature of the grating, ε is its relative elongation, described by the relation:

$$\varepsilon = \frac{\Delta l}{l_0} \tag{3}$$

where Δl defines the change in the length of the grating, l_0 is its initial length.
Let P_1 and P_2 designate two different parameters of the Bragg grating which change as a result of the elongation produced or changes in the temperature of the grating. We then note the matrix equation of conversion of the temperature and elongation sensor in the following form:

$$\begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} K_{T1} & K_{\varepsilon 1} \\ K_{T2} & K_{\varepsilon 2} \end{bmatrix} \times \begin{bmatrix} T \\ \varepsilon \end{bmatrix} \tag{4}$$

where K_{T1} is the sensitivity of parameter P_1 to temperature, K_{T2} is the sensitivity of parameter P_2 to temperature, $K_{\varepsilon 1}$ is the sensitivity of parameter P_1 to elongation, while $K_{\varepsilon 2}$ designates the sensitivity of parameter P_1 to elongation. Analyzing the equation (4), we see that it is possible to contact simultaneous measurement of relative elongation and temperature when we find two different grating parameters for a given measuring system (or grating), which show different sensitivities to those measurands, and $P_1 \neq P_2$. Analysis of the equation (4) also suggests the conclusion that knowing (or determining, e.g. experimentally) the sensitivity of individual parameters P_1 and P_2 to distortion, respectively K_{T1}, $K_{\varepsilon 1}$ and K_{T2}, $K_{\varepsilon 2}$ we can determine the temperature and distortion simultaneously.

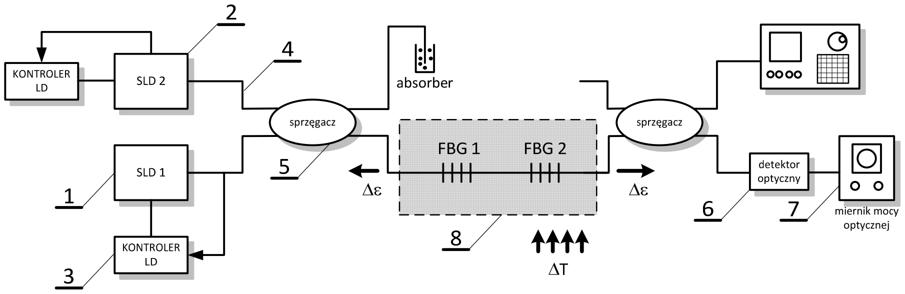

Fig.1. Diagram of measuring system used for simultaneous measuring of relative elongation and temperature. SLD 1 and SLD 2 – superluminescent diodes at wavelengths of 1325 nm and 1550 nm respectively

Description of the experiment

In order to test the possibility to use a sensor with Bragg fiber gratings to measure elongation, two gratings were used with different Bragg wavelengths. The measuring system is illustrated in figure 1. Light from a tunable superluminescent diode (no. 1 in fig. 1) with a central wavelength of 1050 nm and a full width at half maximum (FWHM) equal to 50 nm, operated using a diode power and temperature controller (no. 3 in fig. 1) is aimed with an SMF-28 single-mode fiber at the fiber optic coupler (no. 5 in fig. 1). At the same time light from the second diode SLD 2 (no. 2 in fig. 1), with a central wavelength of 1550 nm and bandwidth equal to 110 nm, is directed by the same coupler to the system of two gratings FBG1 and FBG2.

The gratings were written on a single-mode hydrogen pumped optical fiber using the phase mask technique so that their Bragg wavelengths were λ_{B1}=1035.250 nm and λ_{B2}=1565.035 nm respectively. After passing through the grating system the signal was integrated using an optical detector, and the spectrum was recorded using an optical spectrum analyzer (OSA) with a resolution of 0.01 nm. The gratings were placed in a specially designed temperature chamber (no. 8 in fig. 1), enabling temperature changes to be regulated and controlled. In the case of the system using two Bragg gratings with different lengths, the matrix equation presented above for converting the sensor (4) takes on the following form

$$\begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} = \begin{bmatrix} K_{T1} & K_{\varepsilon 1} \\ K_{T2} & K_{\varepsilon 2} \end{bmatrix} \times \begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} \tag{5}$$

where $\Delta\lambda_{B1}$ and $\Delta\lambda_{B2}$ designate the change (understood as a shift) in the Bragg wavelength of the respective grating FBG1 and FBG2, K_{T1} and $K_{\varepsilon 1}$ are in the system in question, the sensitivities of grating FBG1 to temperature and elongation respectively, while K_{T2} and $K_{\varepsilon 2}$ designate the sensitivity of grating FBG2 to temperature and elongation. The sensitivities to elongation of both gratings $K_{\varepsilon 1}$ and $K_{\varepsilon 2}$ were defined experimentally by measuring the shifts in their wavelengths by causing them to elongate at a constant temperature, while temperature sensitivities K_{T1} and K_{T2} were also designated experimentally, by measuring the shits in the gratings' wavelengths at various temperatures, but at a constant elongation.

The gratings were elongated by attaching them to metal samples of specially selected dimensions, then stretching the samples with a known force, in the arrangement presented in figure 2

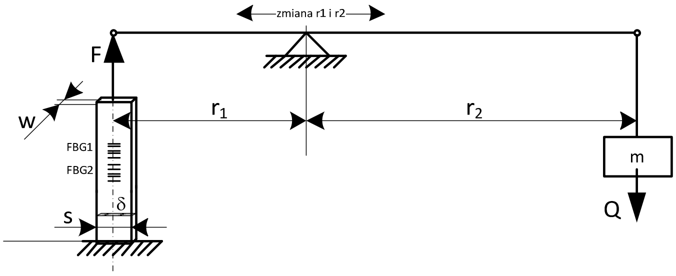

Fig.2. Diagram of the experimental system used to induce the elongations measured by the proposed sensor

Taking into consideration the fact that the moments of force F and Q are equal, and the lengths of the arms on which the forces act, the tension in sample δ, and its physical dimensions, we can designate the value of the elongation to which the sample yields, according to the relation

$$\varepsilon = \frac{m \cdot g \cdot r_2 / (r_1 \cdot t \cdot w)}{E} \tag{6}$$

where r_2 is the length of the arm on which force Q acts, r_1 is the arm on which force F, caused by load Q, acts, m is the mass of the weight attached to the end of arm r_2, g is acceleration of gravity, w and t are the width and thickness of the sample respectively (w=10mm, t=1mm), while E is Young's modulus ($E \approx 20.55 \times 10^{10}$N/m^2).

The temperature was then measured using a specially designed thermal chamber. The fact that the temperature was measured directly eliminates the necessity to determine the temperature on the basis of indirect values, as was the case with the previous measurand, in accordance with equation (6). A photograph of the chamber used to conduct the temperature experiments is shown in figure 3.

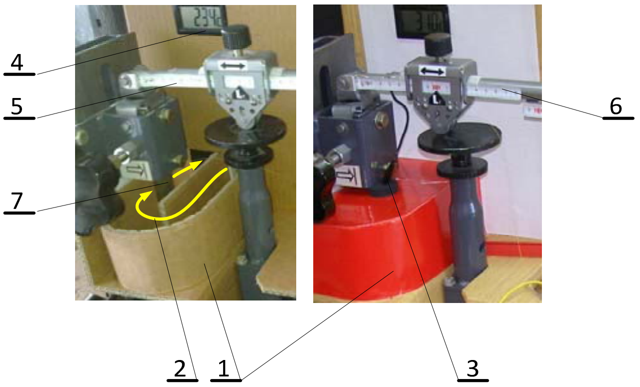

Fig.3. Photograph of the thermal chamber used in the experiment, with characteristic parts. 1 – thermal chamber, 2 – direction of air flow, 3 – thermometer probe, 4 –temperature measurement, 5 – arm r1, 6 – arm r2, 7 – stretched sample

Results of experimental measurements and calculations

After experimental measurement of the individual sensitivities of the gratings located in the matrix in equation (5), it is possible to specify the changes in temperature and elongation by reversing the matrix. Involution of the matrix was possible due to its good conditions – the matrix in equation (5) has a low conditioning index. Figure 4. presents the results of the measurements of the wavelengths in the temperature function, while the analogous measurements in the case of elongation are shown in figure 5.

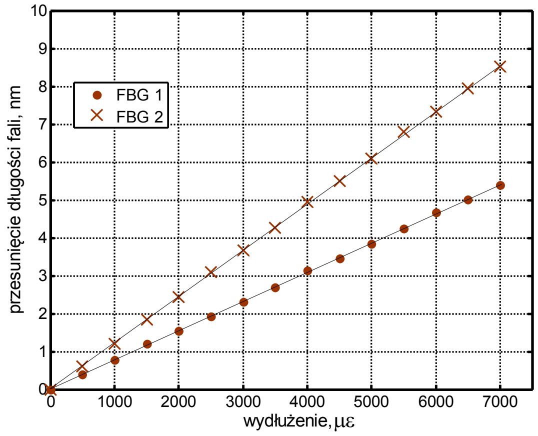

Fig. 4. Results of the experimental measurements for variable relative elongation and a constant temperature of 23.5°C

The results obtained during the experiments with variable elongation, collected in figure 4., were subjected to linear regression, in accordance with [16], marking the straight lines on which form the basis for determining the non-linearity error of the sensor conversion characteristic. The straight line of the regression is shown in figure 4. as an continuous line. Non-linearity was defined based on the extent of the non-linearity error, calculated according to the relationship

$$\delta_{nl} = \frac{\Delta(\Delta\lambda_{Bi})_{MAX}}{(\Delta\lambda_{Bi})_{MAX} - (\Delta\lambda_{Bi})_{MIN}} \cdot 100\% \tag{7}$$

where $\Delta(\Delta\lambda_{Bi})_{MAX}$ is the maximum value of the absolute differences between the straight line of the regression, determined on the basis of the equation, and the results of the measurements, index *i* represents the number of the grating for which the error is calculated (*i*=1 or 2) respectively for FBG1 and FBG2), $(\Delta\lambda_{Bi})_{MAX}$ and $(\Delta\lambda_{Bi})_{MIN}$ are the maximum and minimum values, respectively, of the Bragg wavelength shift of the *i*-th grating.

The values of non-linearity errors determined in this way stood at $\delta_{nl\varepsilon 1}$=0.06% and $\delta_{nl\varepsilon 2}$=0.08% for gratings FBG1 and FBG2 respectively. Errors in the correlations of the linear regression (determined as coefficients of the Pearson linear correlation [17]) were 0.987 for FBG1 and 0.985. Based on the angle of incline of the simple regressions, elongation sensitivities were determined for the gratings used in the tests - these were $K_{\varepsilon 1}$=0.77 nm/mε and $K_{\varepsilon 1}$=1.22 nm/mε.

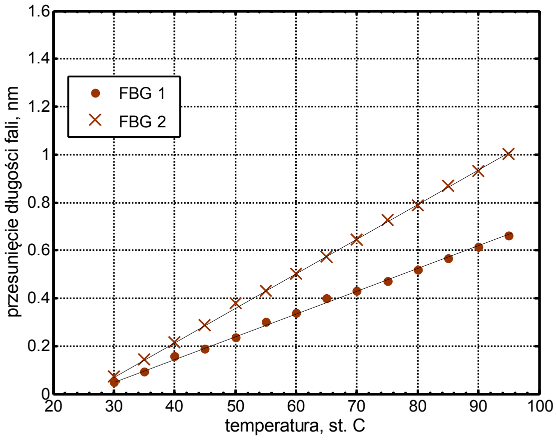

Fig. 5. Results of the experimental measurements for variable temperature and constant elongation

We can now determine the algebraic complements of all the sensitivities K_{T1}, $K_{\varepsilon 1}$, K_{T2} and $K_{\varepsilon 2}$ from the equation (5):

$$\begin{aligned} d_{11} &= (-1)^{1+1} \cdot K_{e2} = K_{\varepsilon 2}, \quad d_{12} = (-1)^{1+2} \cdot K_{T2} = -K_{T2} \\ d_{21} &= (-1)^{2+1} \cdot K_{e1} = -K_{\varepsilon 1}, \quad d_{22} = (-1)^{2+2} \cdot K_{T1} = K_{T1} \end{aligned} \tag{8}$$

which, when meeting the condition of the non-zero matrix determinant from equation (4) allows complements to be constructed for its matrix, on the basis of equation (8), which we write as:

$$\begin{bmatrix} T \\ \varepsilon \end{bmatrix} = \frac{1}{D} \begin{bmatrix} K_{\varepsilon 2} & -K_{\varepsilon 1} \\ -K_{T2} & K_{T1} \end{bmatrix} \times \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \tag{9}$$

where *D* is the determinant of the matrix from equation (4) and is equal to:

$$D = K_{T1}K_{\varepsilon 2} - K_{T2}K_{\varepsilon 1} \tag{10}$$

We can record the new matrix from equation (9), after taking into account the values determined in the experiment, in the form:

$$\begin{bmatrix} T \\ \varepsilon \end{bmatrix} = \frac{1}{0.49} \begin{bmatrix} 1{,}22 nm/m\varepsilon & -0.77 nm/m\varepsilon \\ -14.34 pm/{}^{\circ}C & 9.45 pm/{}^{\circ}C \end{bmatrix} \times \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \tag{11}$$

The non-zero determinant of matrix *D* testifies to the fact that a matrix containing coefficients of wavelength sensitivity to temperature and elongation is well conditioned.

Summarising the inductive and deductive considerations above, we may conclude that simultaneous measurement of relative elongation and temperature is possible using two Bragg gratings with different resonance Bragg wavelengths. Errors in the measurement of the wavelength shift are determined by the resolution of the spectral analyser (0.01 nm). Knowing the resolution of the OSA, we can define the errors in determining the coefficients K_{T1}, $K_{\varepsilon 1}$, K_{T2} and $K_{\varepsilon 2}$. This in turn enables the standard error of the determinant of matrix D to be determined. Achieving great sensitivity involves constructing a measuring system to obtain the greatest possible absolute value of the determinant of matrix $|D|$.

This is possible in the solution presented above, as the two components in equation (10) $K_{T1}K_{\varepsilon 2}$ and $K_{T2}K_{\varepsilon 1}$ will have opposite signs. This is worthy of particular attention, as in many papers the absolute values of analogous factors are very similar [18]. We should note that, for example, in the paper [19] a greater difference could have been achieved between the factors in question by selecting a different type of fiber with a high birefringence (for example fiber with an elliptical core).

Conclusions

It can be concluded from the analysis conducted above that if we use two fiber optic elements (e.g. Bragg gratings) with similar sensitivities as a sensor for measuring relative elongation and temperature, we should chose elements with different reaction directions for one type of measurand (e.g. elongation) while at the same time using elements with the same direction of reaction to the second measurand (e.g. temperature).

By generalizing broadly to transfer this principle into the realm of other uses of measurements, we should note that the two types of fiber optic elements (they do not have to be just Bragg gratings) should be selected, or the way they are arranged and mounted on the object measured should be organized in such a way that their sensitivities to one of the values being measured are of an opposite sign, while at the same time having the same sign and value for the other value measured.

The parameters of the sensor presented for simultaneous measuring of elongation and temperature may be improved by increasing the determinant of matrix D, which can be achieved by selecting two gratings whose Bragg wavelengths differ more. Another way to improve the conditioning of the matrix of the sensor conversion equation may be to use two different Bragg gratings characterized by a greater difference in their sensitivities to elongation (e.g. by locating the gratings on appropriate bases enabling transfer of elongation in different degrees to each of the gratings).

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