Fibre-Optic Temperature Sensor Using Bragg Structure

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Fiber-optic sensing has established itself as an innovative and versatile measurement technology for various physical parameters, such as temperature. Moreover, particular properties of optical fibers, in some cases, make fiber-optic sensing only suitable choice due to operation conditions, precision and accuracy, possibility of remote operation. In this paper we present the simple fiber optic temperature sensor system that utilizes reflective Bragg element as a sensing head. The main advantage of the proposed approach relies on the use of widely available low-cost telecommunication devices, such as a DFB laser as a light source and commonly used fiber optics components. Another advantage of the sensor is measurement technique that doesn't require optical spectrometer or other precise optical measurements such as interferometry. It is shown that by implementing various Bragg structures for the sensing element it is possible to alter optical response thus achieving required characteristics of the sensor. Calculations for Bragg structures are presented for both narrow range sensor suitable for medical use and wide range temperature sensor with $\Delta T \sim 200$ °C. In addition, this paper provides brief review of commonly used fiber-optic temperature sensing techniques, their advantages and application.

Keywords: Temperature sensor, Optical fiber, Fiber Bragg grating, Reflection index, DFB Laser.

1. INTRODUCTION

Fiber-optic sensing has become essential in transport safety, medicine, precision engineering, etc., due to significant technological achievements in the field of telecommunications that have been made during past decades. Fiber-optic sensors allow measurements of wide variety of physical parameters, such as displacements, accelerations, pressure, temperature, humidity, intensity of electric, magnetic and radiation fields, spectral measurements, etc. High accuracy, fast response times and ability to provide combined flexible multiparameter systems that include large number of sensors have significantly expanded interest in fiber-optic sensing for various applications [1].

Among physical quantities that require measurements with high accuracy, temperature presents great importance. Technically, temperature measurements can be performed via various methods and technical means based on electrical, chemical, mechanical principles. However, there are a number of applications that impose strict requirements on temperature sensors, regarding the measurement accuracy, ability of detecting small changes in real time, ability to operate remotely in harsh conditions.

First of all, the operation conditions for a number of applications are crucially important. For instance, the presence of high-intensity fields does not allow the use of standard techniques. Such areas include nuclear energy and the medical applications [2,3]. In the latter case, the use of optoelectronic sensors for temperature measurement is preferable, primarily for measuring the temperature of tissues during radiotherapy and other procedures. Miniature dimensions and inert materials of the optical fiber (mainly SiO₂) are also beneficial in some cases.

In general, the main advantages of fiber-optic sensors are:
– Suitable for in-situ measurements;
– Immune to electromagnetic fields, chemical inertness;
– Suitable for operation at high temperatures;
– Miniature size and flexibility (250-500 microns);
– Capable to perform remote measurements using multiple sensors.

Fiber optic sensors use variety of techniques to detect the measurands based on intensity, phase or wavelength changes.

Regarding the principle of operation, fiber sensors can be divided into two classes: extrinsic - in which an optical fiber is used to transmit signals with a separate sensor attached at the end of the fiber and extrinsic – that implements optical fiber as a sensor itself. Fiber temperature sensors mainly belonging to the second class have significant advantages in terms of miniaturization and simplicity of design. The principle of operation of such sensors is based on internal fiber mechanisms, intensity/frequency modulation, or phase measurements [4].

The intrinsic sensor proposed in this article is based on wavelength modulation principle, namely on the change of reflected radiation intensity registered due to temperature change. This sensor system includes an ordinary telecommunication fiber with a Bragg structure at the end of the fiber, DFB laser diode as a light source and other commonly available optical telecommunication parts. Advantages and operation principle is discussed further in the article.

2. FIBER OPTIC TEMPERATURE SENSORS

Most fiber sensing systems utilize optical fibers that are typically used for telecommunications or other trivial fiber optic applications. Those include multimode optical fibers (MOF), single mode fibers (SMF). In some particular cases, mainly for strain measurements, polymer optical fibers are used but their application is fairly limited due attenuation that can exceed 100 dB/km. Multimode optical fibers have quite large core diameter thus coupling

to broadband light sources, such as LEDs is much facilitated. Also, tolerances related to alignment not as strict as for SMF fibers. However, high attenuation (1 dB/km) along with temporal dispersion limiting the use of such sensing systems to short distances of just few hundred meters. Contrary, SMF have clear advantage when it comes to high spatial resolution techniques and fiber Bragg sensors. The main limitations of SMFs are requirements related to precision coupling and use of laser sources. Due to low attenuation coefficients (< 0.2 dB/km) SMF's are very well suited for remote long range measurement systems. Typically, optical fibers and fiber sensors made of fused silica glass (amorphous SiO_2) and have high temperature endurance up to $800 - 1000°C$.

Temperature fiber optic sensors are classified based on operation principle, which are commonly:

– Interferometric optical fiber sensors. These sensors rely on the changes of optical resonator length or refractive index due to temperature fluctuations. There are different approaches available including various Fabry-Perot and Mach-Zender implementations [5-9]. These sensors generally benefit from high reliability and a nearly path-independent transmission along optical fibers. This type of sensors based on interferometric measurements, which imposes strict requirements to precision and mechanical vibrations.

– Distributed temperature sensors using Raman and Brilliuon scattering. Optical fiber distributed temperature sensors enable temperature profile monitoring along the fiber length. These sensors operate according to optical time domain reflectometry principle. A laser pulse is sent through the fiber and the backscattered light is detected with high temporal resolution. The intensity of the Raman light provides information about losses and temperature along the fiber whereas the time delay provides distance measurements. Both Raman and Brillouin scattering, which are temperature dependent, can be used for temperature measurements but Raman is more practical due to much larger spectral offset [10, 11]. Rayleigh scattering is not particularly useful due to very weak effect. Complex design and necessity for sensitive techniques for scattering measurements are main disadvantages of these sensors.

– Fiber Bragg sensors. The sensing principle of FBG-based sensors - wavelength modulation of a Bragg structure due to temperature change. In other words they rely on Bragg resonance peak shift measurements. Compared to other optical fiber sensors, the grating-based temperature sensors possess good linearity apart from cryogenic temperatures, where nonlinear behavior prevails. Recent developments Disadvantage of FBG sensing (and other fiber sensors as well) is the simultaneous sensitivity to strain and temperature which gives rise to cross-talk as typically only one quantity must be measured.

Generally FBG sensors are able to operate at high temperatures with some examples such as Sapphire-FBG up to 1800 °C. More information on sensitivity of optic fiber sensors and operational range, including FBG, can be found in work [12].

Most commercially available Bragg sensors of this type are used to measure absolute temperature, mechanical stretch, or measure temperature-compensated stretch (Fig. 1). Silicon fibers with Bragg structures of types I (mainly germanium doped and germanosilicates,

$\Delta n < 10^{-3}$) and II ($\Delta n \sim 10^{-2}$) are usually used for this purpose. First type involves monotonous growth while the second type includes high power single pulse damage fibers. Type I gratings are suitable for applications bellow 300 °C, type II can be stable up to 800 °C and preferred for high temperature measurements [13, 14]

Using other various dopants it is possible to achieve wide range of Δn for Bragg structures. It's been reported application of different dopants and corresponding refractive index change: Nitrogen $\Delta n = 10^{-2} - 10^{-4}$, pure silica $\Delta n = 5 \cdot 10^{-5}$, Phosphorous $\Delta n = 3 \cdot 10^{-4} - 7 \cdot 10^{-4}$, Lead $\Delta n = 0.09$ [15].

Bragg structures can be produced for a wide range of wavelengths $\lambda = 450 - 2000$ nm, but are usually implemented at the wavelengths that corresponds to transparency windows of optical fibers, namely 850 nm, 1310 nm, 1550 nm. Reflectivity indexes can be achieved from 1 % to 99 % with FWHM of around $0.2 - 2$ nm. Typical Fiber Bragg sensors schematics for strain and temperature measurements are presented on Fig. 2.
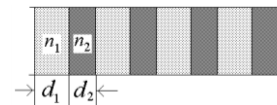

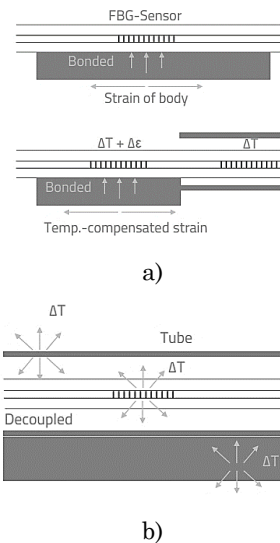**Fig. 1** – Bragg structure

a)

b)

Fig. 2 – Bragg sensors: a) mechanical stretching, b) temperature

Another advantage of this type of sensors is the possibility to implement an array of sensors in one single optical fiber with Bragg structures at different wavelengths, as shown on Fig. 3.
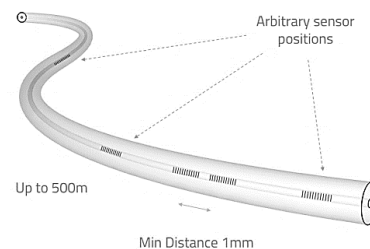

Fig. 3 – Array of Bragg sensors formed in a single optical fibre

The main disadvantage of an array of Bragg sensors and individual Bragg sensors is necessity of broadband radiation sources (mainly IR LEDs) and the need to accurately measure the shift of the peaks of reflected radiation using optical spectrum analyzers and subsequent wavelength multiplexing.

3. BRAGG FIBERS

The Bragg waveguide is an elongated structure of circular cross-section, in which sections with a high and low refractive index alternate along the fiber axis and the thickness of each layer is multiple of $\lambda/4$.

$$d_{1,2} = (2m+1)\frac{\lambda}{4n_{1,2}} \qquad (3.1)$$

where $n_{1,2}$ are the refractive indices of the layers, $m = 0, 1, 2$.

In general, the Bragg waveguide is a multilayer of homogeneous films. Provided that $n = const$, the layer matrix can be calculated using equations:

$$M_{11} = M_{22} = \cos\left(\frac{2\pi}{\lambda}nd\right);$$

$$M_{12} = \frac{1}{n}\sin\left(\frac{2\pi}{\lambda}nd\right);$$

$$M_{21} = n\sin\left(\frac{2\pi}{\lambda}nd\right).$$

$$\qquad (3.2)$$

where d is the thickness of the layer.

For a single layer:

$$M = \begin{bmatrix} \cos\left(\frac{2\pi}{\lambda}nd\right) & i\frac{1}{n}\sin\left(\frac{2\pi}{\lambda}nd\right) \\ in\sin\left(\frac{2\pi}{\lambda}nd\right) & \cos\left(\frac{2\pi}{\lambda}nd\right) \end{bmatrix}. \qquad (3.3)$$

The multilayer matrix can be calculated using the formula:

$$M = M_1 M_2 M_3 ... M_p . \qquad (3.4)$$

Transmission and reflective coefficients can be calculated using formula:

$$T = 1 - R = 4 \Bigg/ \begin{array}{l} 2 + \dfrac{n_M}{n_s}M_{11}{}^2 + \\ + \dfrac{n_s}{n_M}M_{22}{}^2 + n_M n_s M_{12}{}^2 + \dfrac{1}{n_M n_s}M_{21}{}^2 \end{array} .(3.5)$$

Here $n_M n_s$ – refractive indexes before and after Bragg structure.

4. TEMPERATURE DEPENDENCE OF THE BRAGG WAVELENGTH

Bragg resonance, which is the peak center wavelength of back-reflected light from a grating, depends on the effective index of refraction of the core and the grating period. A change in temperature will directly affect these two indicators.

$$\Delta\lambda_b = 2\left(d\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial d}{\partial T}\right)\Delta T , \qquad (3.6)$$

where: d is the layer thickness, n_{eff} is the effective refractive index

Also, this indicator can be presented in the form [15]

$$\Delta\lambda_b = \lambda_b(\alpha_d + \alpha_n)\Delta T . \qquad (3.7)$$

Where α_d represents temperature coefficient of expansion for silica and its value is approximately $\alpha_d = 0.55 \cdot 10^{-6}$. The second term α_n is thermo-optic coefficient αn is approximately $8.6 \cdot 10^{-6}$ for silica fibers. The second indicator is far more dominant.

In general, the shift at 1550 nm is 14 pm/C° for silica fibers doped with germanium [15, 16]. Furthermore temperature response is strongly wavelength dependent, at 830 nm and 1300 nm shifts correspond to 6.8 pm/°C and 10 pm/°C respectively. Therefore, in sensing applications Bragg optical fibers can be effectively utilized for temperature measurements.

4.1 Bragg Temperature Sensor with Laser DFB Diode

As mentioned above, FBG sensors require precise wavelength measurements which in many cases involve spectrum analyzers. Being the most complex and expensive part of measurement system, presence of optical spectrum analyzers significantly increase overall cost of the system. Instead of broadband light source, such as LED, and spectrum analyzer we propose to use DFB semiconductor laser as part of the system [17]. Such lasers are commonly used in telecommunications and characterized by single mode operation with FWHM of 100 MHz or less. Utilization of a monochromatic light source requires temperature measurements to be performed by measuring the power of the reflected back radiation. The schematic diagram for the measurement system is presented on Fig. 4. The system comprises of a semiconductor DFB laser operating at 1550 nm, a fiber optic circulator, laser source power, wavelength stabilization unit, signal recording unit, a Bragg sensor element at 1550 nm.

Characteristics of the sensor are determined by the Bragg structure and its reflection spectrum, whereas the temperature measurement will depend on reflected wavelength shift. Therefore, the laser source must be thermally stabilized.
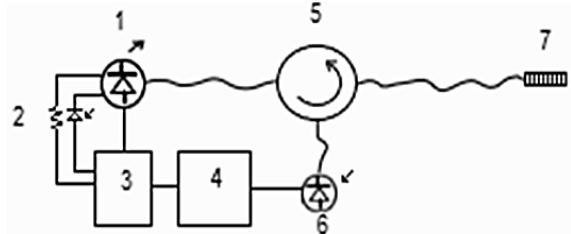

Fig. 4 – System for temperature measurement utilizing Bragg sensor: 1 – DFB laser diode 1550 nm, 2 – thermal resistance and photodiode for monitoring the output optical power and temperature of the laser crystal, 3 – thermal stabilization unit of the laser source, 4 –unit for signal acquisition, 5 – fiber circulator, 6 – photodiode, 7 – Bragg temperature sensor

Modern laser telecommunication diodes have built-in photodiode, thermistor and Peltier element which allow controlling the output optical power and emitting wavelength with high precision. Stabilization of the laser source and registration of the optical signal is carried out by separate units 3 and 4. The operation principle is as follows: laser radiation from the source 1 is directed along an optical single-mode fiber to the optical Bragg sensor 7, whereas the reflected radiation is redirected using a fiber circulator 5 to the photodiode 6. Due to the temperature change the Bragg resonance peak will drift resulting in changes of laser power reflected to the photodiode 6. So in our case temperature measurements are conducted via photodiode current.

Considering the measurement technique it becomes obvious that the parameters of the temperature sensor and its sensitivity will primarily depend on the spectral characteristics of the Bragg structure, stabilization precision of emitting power and wavelength of the laser source. Modern DFB lasers have thermal wavelength shift of approximately 0,1 nm/°C and current tuning coefficients lie in the range of 10^{-3} nm/mA, so sensor accuracy of 0,1 °C should be easily achievable for wide ranges of temperature measurements.

Appropriate limits at which these sensors can operate are in accordance to general operational range of silica fibers for up to $800 - 1000$ °C. Operation at negative temperatures is also possible, but it worth mentioning that at 77 K sensitivity of bare FBG reduces by five folds compared to room temperature exhibiting a nonlinear optical response [18] Measurement range (spectral position of Bragg peak) within operational range of the sensor is determined by Bragg structure characteristics and can be chosen during fabrication. Small adjustments within 10 °C are also possible via fine tuning of the lasers wavelength.

The calculations of the Bragg structure and the corresponding response of the sensor are provided below.

Spectral response and temperature shift calculations were carried out using formulas 3.1-3.5, 3.7. For this purpose, typical values of the refractive index of the Bragg structure were taken. In the first case, the calculations were carried out for Bragg structure within silicon fiber doped with germanium using parameters: modulation of the reflection coefficient $\Delta\lambda = 5 \cdot 10^{-4}$, number of layers is 1500. The spectral characteristics and response of the sensor are presented in Fig. 5. Such sensor has narrow range, but nevertheless should provide high resolution. It can be suitable for biomedical applications due to limited spectral range.

Below is an example of a Bragg structure suitable for wide range temperature measurements ($\Delta T \sim 200$ °C). In this case the modulation of the reflection coefficient is $\Delta\lambda = 10^{-2}$, the number of layers is 100. The sensor spectral characteristic and temperature response are shown on Fig. 6.

It should be noted that calculated Bragg spectra serve as an example. The required spectral response of the BRG sensor can be tailored to specific needs via type of fiber/grating and geometric properties of a grating. It is also possible to create temperature

measurement systems with multiple BRG sensors that involve multiple laser light sources and utilize multiplexing technique.
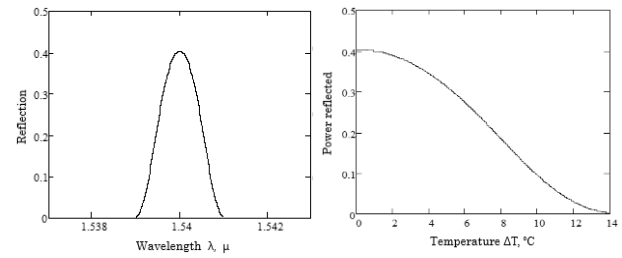

Fig. 5 – Spectral characteristics of the Bragg structure and temperature response of the sensor ($\Delta\lambda = 5 \cdot 10^{-4}$, the number of layers is 1500)

The spectral response of Bragg structure is greatly affected by the length of a grating/number of layers. Increasing the number of layers will result in narrowed bandwidth and increased refractive index. However, if the value of refractive change Δn is reduced with increased number of layers it is possible to keep reflective index unchanged with considerably reduced bandwidth.

Ultimately, increased value of refractive change Δn will result in both bandwidth and reflective index increase. Adjusting these parameters allows flexibility of sensor design for required purposes.
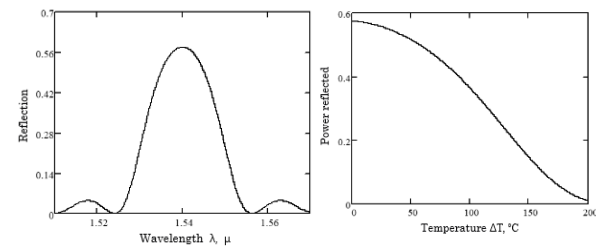

Fig. 6 – Spectral characteristics of the Bragg structure and the temperature response of the sensor ($\Delta\lambda = 10^{-2}$, the number of layers is 100)

5. CONCLUSIONS

In this work, the main types of fiber-optic temperature sensors are discussed including their advantages, principle of operation, limitations and general overview of optical fibers. This article also provides overview of FBG sensing technique and Bragg structures. In this article a simple Fiber Bragg temperature sensor system has been proposed that incorporate generally available telecommunication components and does not require spectrum analyzer. It is shown that it is possible to effectively control the parameters of the sensor response by altering the characteristics of the Bragg structure. Calculations of spectral characteristics of Bragg structure and temperature response for narrow range sensor $\Delta T \sim 14$ °C suitable for medical application and a wide range sensor $\Delta T \sim 200$ °C are also presented in this article.

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Волоконно-оптичний сенсор температури з брегівською структурою

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Волоконно-оптичні сенсори зарекомендували себе як інноваційна та універсальна технологія вимірювання різних фізичних величин, таких як температура. Окрім цього, особливі властивості оптичних волокон, у деяких випадках, роблять волоконно-оптичне зондування єдино прийнятним вибором зважаючи на умови експлуатації, точність, можливість дистанційної роботи. У цій статті нами представлено простий волоконно-оптичний сенсор температури, що використовує відбиваючий елемент Брегга як чутливий елемент. Основна перевага запропонованого підходу полягає у використанні широко доступних недорогих телекомунікаційних компонентів, таких як РЗЗ лазер як джерело світла та широко доступні компоненти волоконної оптики. Ще однією перевагою датчика є методика вимірювання, яка не потребує оптичного спектрометра, чи інших точних оптичних вимірювань, таких як інтерферометрія. Показано, що реалізуючи різні брегівські структури для чутливого елемента, можна змінювати оптичний відгук, таким чином досягаючи необхідних характеристик сенсора. Розрахунки для сенсорної головки Брегга представлені як для датчика вузького діапазону, придатного для медичного використання, так і для датчика температури з широким діапазоном вимірювань $\Delta T \sim 200\ °C$. Також ця стаття містить короткий огляд широко використовуваних волоконно-оптичних методів вимірювання температури, їх переваги та застосування.

Ключові слова: Сенсор температури, Оптичне волокно, Брегівська структура, Коефіцієнт відбиття, РЗЗ лазер.