Modelling and record technologies of address fiber Bragg structures based on gratings with two symmetrical pi-phase shifts

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Abstract. Address fiber Bragg structures (AFBS) make it possible to effectively solve the problems of interrogation and multiplexing of sensors in multi-sensor networks with microwave photonic processing of information. Based on a complex method of transmission matrices and the coupling of directional modes, a mathematical model was constructed to determine the spectral profile of a fiber Bragg grating (FBG) with two discrete symmetric phase π shifts and parameters of 2π-FBG AFBS based on them. Based on the study of the mathematical model, the possibility of selecting the necessary parameters of 2π-FBG AFBS is shown, which allow forming its spectral profile in such a way that the specified structure can be used as a sensitive element of the sensor and provides the necessary linear displacement in the optical range and preserves the required frequency separation between discrete symmetric phase shifts location in the radio frequency range. The analysis of the formation and recording methods for 2π-FBG AFBS was carried out. To implement given structures, the technology, using of an ultraviolet argon laser, the classic phase masks with sequential recording of several arrays with precise movement of the fiber were chosen.

1. Introduction

Recent papers [1-4] have shown that photonic sensors based on fiber Bragg gratings (FBG) are of particular interest for new fields of measurements, since these sensors have low rigidity, long lifespan, compact size, light weight and do not need complex power supply, while providing high measurement resolution and fast data transmission. However, despite the high amount of research work, a number of disadvantages still persist, the main of them is the high cost of optical interrogator.

A conventional FBG is a distributed Bragg reflector, i.e. it is a modified optical fiber with periodic variation in the refractive index of the fiber core. The reflected wavelength λ_B, also known as the Bragg wavelength, is defined by the following relationship: $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} is the effective refractive index of the grating, and Λ is the grating period. Λ and, consequently, the reflected wavelength deviate if the fiber is compressed or stretched, and if the temperature is changed, which makes it possible to use FBGs as sensing elements for measurement of various physical quantities.

Since the deviation of the Bragg wavelength depends both on mechanical stress and temperature, then deformation sensors usually include two FBGs, one of which is isolated from strain and is used to take into account the temperature influence [1-4]. In general, the FBGs in fiber-optic sensor systems are multiplexed by means of wavelength-division multiplexing (WDM) methods. In such systems, the sensors are distributed uniformly in the wide wavelength range, and their spectra do not superimpose on each other. In the modern photonic systems, the multiplexing of FBG-sensors is fulfilled using optoelectronic interrogators, which consist of broadband light sources for sensor probing and narrowband optical filters with wide tuning range for the sensor interrogation [6].

The complexity and high cost of these devices eliminate the wide usage of fiber-optic sensor systems in various industrial applications.

In order to solve the abovementioned problems, an alternative method for the FBG sensors interrogation was proposed, which utilizes microwave-photonic methods that have been developed at the MWPT department of KNRTU-KAI. The main distinctive feature of such microwave photonic sensor system (MWPSS) is the usage of addressed fiber Bragg structures (AFBS) with two symmetrical π-phase shifts as the strain sensors, and the frequency spacing between the π-phase shifts is used as a unique identifier (address) of the AFBS.

2. Sensors based on 2π-FBG AFBS

The introduction of the microwave-photonic sensor system will eliminate the disadvantages of the existing solutions, namely: to significantly decrease complexity of the probing and interrogation systems due to the usage of the addressed fiber Bragg structures with two symmetrical π-phase shifts, as well as to provide the simplicity of measurement signal transfer in radio frequency range.

The proposed measurement system is based on the addressed fiber Bragg structures (AFBS) that are realized using FBGs with two symmetrical π-phase shifts (2π-FBG) [4-6]. In that case, FBGs of all sensors have equal bandwidth and the same central wavelength, while their addresses are provided by the unique frequency spacing between the two transparency windows in the AFBS spectrum. The addressed 2π-FBG structure consists of three sequentially formed FBGs with π-phase shifts between them. Figure 1 presents a schematic depiction of the 2π-FBG structure and its spectral characteristics of reflection [4].

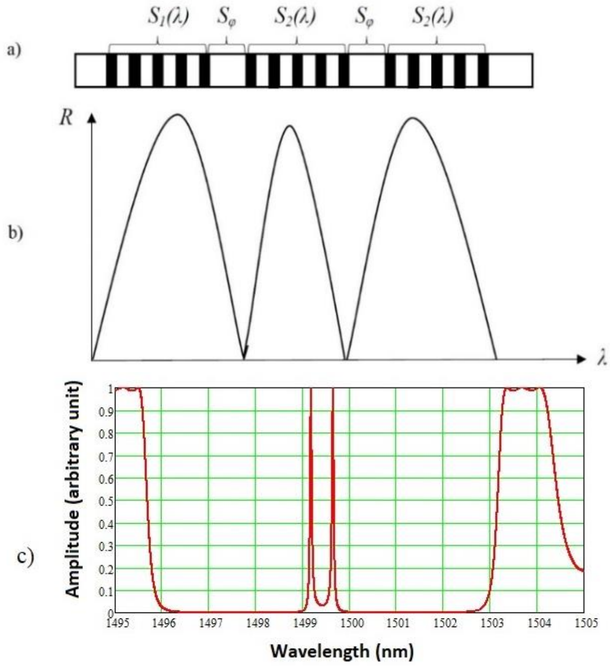

Figure 1. Structure of AFBS with 2π-FBG (a), its spectral characteristics of reflection (b), and example of suitable spectral characteristics of propagation [4].

By selecting the parameters of 2π-FBG and analyzing the obtained spectrum, it is possible to form any amplitude-frequency profile of the structure that is required in order to use the structures as sensing elements in MWPSS. An example of the suitable profile shape for the 2π-FBG is presented in Figure 1c.

In order to use the 2π-FBG structures or their set as sensing elements of measurement systems, the AFBSs and their interrogation system must satisfy the following requirements:

- The possibility to interrogate the AFBS π-phase shifts in the whole measurement range must be provided. This requirement is satisfied using wide 2π-FBG structure with nearly rectangular profile.
- Only the light response from π-phase shifts of 2π-FBG must reach the scope of measurement. This is provided by a laser source, the bandwidth of which is equal to the measurement range, or by an optical bandpass filter of the required range.
- The frequency spacing (Ω) between the components of AFBS two-frequency response must be much smaller than the optical carrier frequencies (ω_A and ω_B), and it must be located in the range of radio spectrum of frequencies: $\Omega << \omega_A, \omega_B$.
- The full width at half maximum of the spectral components that make up two-frequency response must be the same and equal to δ, and the absolute value of the width must be much smaller than the frequency spacing: $\delta << \Omega$.
- A linear inclined filter with the pre-defined characteristics must be placed before the photodetector.

AFBS with 2π-FBG is relatively easy to produce and can be manufactured using phase mask with minimal requirements for modulation coefficient parameters and uniformity of its profile characteristics. The address of such structure is provided by the fact that the frequency spacing between the two π-phase shifts does not change if strain or temperature field is applied to the 2π-FBG [5].

3. AFBS interrogation system

Figure 2 presents the block diagram of the interrogation system for two AFBSs with different address frequencies Ω_1 and Ω_2, one of which is used to measure tire strain, and the second one takes into account temperature variation [5, 7].

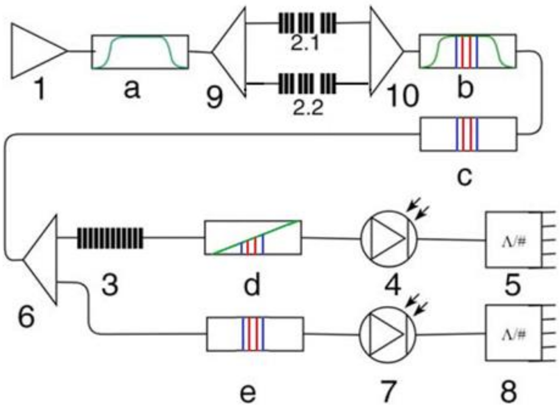

Figure 2. Block diagram of the interrogation system for two AFBS.

A broadband light source 1 generates continuous light radiation (diagram a), which corresponds to the measurement bandwidth. The light is transmitted through the optical coupler 9 enters the two AFBSs 2.1 and 2.2. Both AFBSs transmit two-frequency radiation that are summed into a combined radiation (diagram b) using another coupler 10. In the output of the coupler, a four-frequency radiation (diagram c) is formed, which is sent through a fiber-optic splitter 6. The splitter divides the optical signal into two channels – the measuring channel and the reference channel. In the measuring channel, a linear inclined filter 3 is installed that modifies the amplitudes of the four-frequency radiation into the asymmetrical radiation (diagram d). After that, the signal is sent to the photodetector 4 and is received by the measuring ADC. The signal from the ADC is used to define the measurement information from

the AFBS. In the reference channel, the signal (diagram e) is sent to the reference photodetector 7 for the optical power output control, and the it is received by the reference ADC 8. Thus, the normalization of output signal intensity is achieved, and all subsequent calculations are performed using the relations of the intensities in the measuring and reference channels.
Assume that $\Omega_1 > \Omega_2$, then the total optical response of the two AFBSs can be defined as:

$$F(t) = \begin{pmatrix} A_1 \sin(\omega_1 t) + B_1 \sin((\omega_1 + \Omega_1)t) \\ +A_2 \sin(\omega_2 t) + B_2 \sin((\omega_2 + \Omega_2)t) \end{pmatrix}^2, \tag{1}$$

where A_1, B_1 are the components' ampitudes of the first AFBS; A_2, B_2 are the components' ampitudes of the second AFBS; ω_1, ω_2 are the frequencies of the left components from the first and second AFBSs, respectively; Ω_1, Ω_2 are the address frequencies of the first and second AFBSs, respectively.
The luminous power received by the photodetector can be described by the following expression:

$$P(t) = \left[\frac{{A_1}^2 + {B_1}^2 + {A_2}^2 + {B_2}^2}{2}\right] + [A_1 B_1 \cos(\Omega_1 t) + A_2 B_2 \cos(\Omega_2 t)] + \underline{\begin{bmatrix} A_1 A_2 \cos(\omega_1 - \omega_2)\, t + A_1 B_2 \cos(\omega_1 - \omega_2 - \Omega_2)\, t + \\ B_1 A_2 \cos(\omega_1 - \omega_2 + \Omega_1)\, t + B_1 B_2 \cos(\omega_1 - \omega_2 + \Omega_1 - \Omega_2)\, t \end{bmatrix}} \tag{2}$$

The oscillations of luminous flux on the photodetector (which are proportional to the output electric power of the photodetector) are used to explicitly define the location of address frequencies of both AFBSs, except for the twelve particular cases, when the frequencies in any of the four components of the third sum (underlined in (2)) coincide with the address frequencies Ω_1, or Ω_2. In order to determine the presence of third component contribution in (2) and the value of this component, additional filters can be installed. The methodology of address frequency definition for all particular cases is presented in [5].
The microwave-photonic sensor system analyzes continuous optical response from the AFBSs, and its interrogation speed can be increased up to hundreds of MHz and resolution – to several Hz, which is defined by the parameters of an electronic (not optical) vector or scalar analyzer of the MWPSS output signal.

4. 2π-FBG AFBS writing technology

The analysis of the formation and recording methods for 2π-FBG AFBS was carried out. The addressed 2π-FBG structure consists of three sequentially formed FBGs with π-phase shifts between them. To implement given structures, the technology, using of an ultraviolet argon laser, the classic phase masks with sequential recording of several arrays with precise movement of the fiber were chosen.

5. Conclusion

The results of modelling and experimental application of record technologies of address fiber Bragg structures based on gratings with two symmetrical pi-phase shifts are presented. The proposed concept of the microwave-photonic sensor system eliminate the disadvantages of the existing solutions, namely: it enables the usage of a less complicated and cheaper interrogation system by implementing the addressed fiber Bragg structures, while providing the simplicity of the wireless measurement signal transmission, since it inherently lies in the radio spectrum. In this work, an example of the measurement system with a single strain sensor is described. The second AFBS is used here to compensate for the temperature influence.

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