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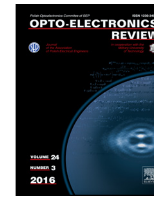

An interferometric structure with a dual-resonance long period grating for strain sensing

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ABSTRACT

Spectral characteristics and amplitude tunability of a long period grating with a dual- resonance inside fiber loop mirror are studied in terms of applied stress caused by elongation. Inserting the polarization controller between grating and part of polarization maintaining fiber in the loop structure enables tuning of resonance and interferometric peaks. The maximum sensitivity of demonstrated sensor is of 1.943 dB/mε for the range of 1.1–4.4 mε. Combination of these two optical components allows to measure strain in a wider range comparing with sensors based on standard long period grating.

1. Introduction

A long period grating (LPG) has become a very interesting optical structure in last few years because of its excellence in physical parameter sensing, e.g., refractive index (RI) [1], temperature [2], strain [3], torsion, bend [4], etc. Ability of monitoring physical properties leads to applying LPG in many practical fields including environmental and health monitoring [5] which expands capabilities for existing smart world era. LPG consists of periodic modulation of the core RI results in series of attenuation bands at discreet wavelengths on the transmission spectrum [6]. The coupling of the fundamental mode with a higher order cladding mode of the LPG is strongly dependent on grating periods: the smaller the period, $LP_{0,1}$ mode couples with higher order cladding mode, and, thus, the higher sensitivity of LPG can be obtained [7]. Dispersion curves showing the relationship between resonance wavelength (λ_{res}) and grating period (Λ) for modes higher than $LP_{0,11}$ indicate the presence of turn around point (TAP) where dispersion curve changes the sign from positive to negative [8]. The TAP region can be obtained by imposing the specific geometric of LPG, i.e., period, RI of the modulation and diameter of the fiber cladding, ensures ultra-high sensitivity for external perturbations, and such LPG is called dual-resonance long period grating (DR-LPG). By extra thin film deposition on the LPG surface, the RI sensitivity can be enhanced up to 40,000 nm/RIU [9]. Also, thin layer provides the fine tuning of the LPGs spectral properties, including their RI sensitivity over its wide range [10].

Since LPG with dual-resonance consists of two notches' characteristics in low extinction ratio, there is a need to introduce the wavelength filter. Taking into account several advantages of different interferometric structures, mainly input polarization independence or high extinction ratio [11], fiber loop mirror (FLM) with part of polarization maintaining (PM) fiber could resolve the problem of LPG flat dips as is shown in our previous paper [12]. Furthermore, considering the optical platform for a strain sensor, the FLM can protect cross-sensitivity associated with a direct impact of temperature change [13] or random stress influence. In particular, there are several solutions, including microstructure optical fiber based platform [14] which ensures extremely sensitive strain transducers. Although taking into account complexity and high cost of the microstructure optical fiber, influence of the temperature for different physical parameter measurement (e. g., the RI or strain) can be resolved by combination of the DR-LPG and FLM [15].

In this work we present a strain sensor based on DR-LPG embedded inside the FLM where the response is expressed as an amplitude difference between interferometric dips covered with resonance dips. When the PM fiber from interferometric structure is subjected to any tension, the transmission spectrum changes in an uncontrollable and disorderly way. Furthermore, the influence of stresses to the PM fiber appears only by the wavelength-shift, and, thus,

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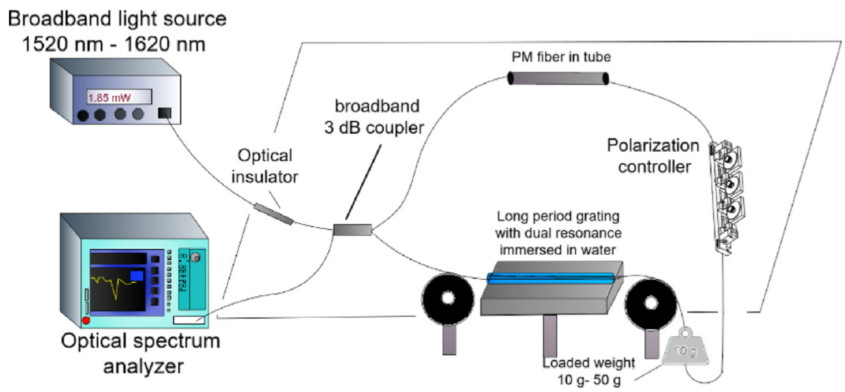

Fig. 1. The experimental setup for strain sensing.

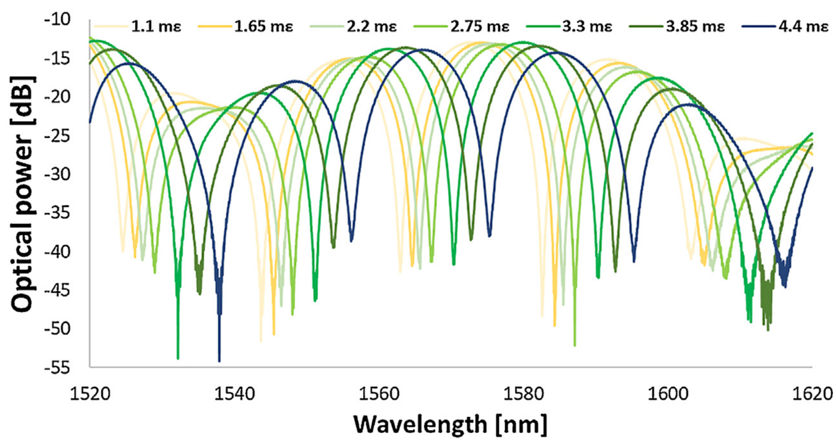

Fig. 2. The transmission spectra of experimental setup where the PM fiber was subjected to the strain.

amplitude change monitoring is not possible. For these reasons, the strain was applied only on the DR-LPG, whereas the PM fiber was immobile in a cylindrical tube.

2. Principle

2.1. Experimental setup

The setup for strain sensing which consists of FLM with DR-LPG is shown in Fig. 1. The FLM is formed of a broadband 3 dB – coupler with 50:50 power ratio, part of a 0.29 m PM fiber and a polarization controller (PC). The loop with all components was illuminated by the wideband light source which protects a bandwidth of 1520 nm −1620 nm. Transmission spectra were observed on the optical spectrum analyzer (OSA) with a resolution of 0.1 nm. In order to protect light source, an optical insulator was adopted just before the coupler. The PC was put between DR-LPG and a part of PM fiber in order to control transmission spectrum which comes from FLM in terms of interference and resonance dips adjustment [12,14]. All components were linked by the standard optical fiber SMF-28. The fiber was coiled 3 times before clamping to avoid possibility of getting out from the holder. The fiber under strain test was attached to the fiber holder on one side and loaded on the other side. Weights of the range from 10 g up to 40 g were lowered freely in terms of the force of gravity affected. The applied strain was transformed to the unit strain ε from equation [16]:

$$m{\cdot}g = \mathrm{E}{\cdot}\mathrm{A}{\cdot}\varepsilon, \qquad (1)$$

where m is the mass of the weight, g is the acceleration of gravity, E is the Young's modulus (for silica E ≈ 7.27·1010 [N/m^2]), and A is the cross section field of an optical fiber. In case of these tests the applied strains were from 1.1 mε to 4.4 mε.

2.2. Polarization-maintaining fiber under strain test

Before isolating the PM fiber in a tube, the spectrum characteristics of the PM fiber subjected to elongation was carried out. Figure 2 presents transmission spectra of the experimental setup where the PM fiber was weighted. The PM fiber was attached to the holder right before the splice of an SMF-PM fiber and weighted of the end of the PM fiber. Such mounting was aimed to avoid splices' influence for transmission spectrum.

As it was to be expected, the PM fiber response for applying strain is significant both as a wavelength shifting and as an amplitude change, and the sensitivity will be dependent on the fiber birefringence. However, taking into account reduction of setup costs, it is required to replace OSA by a power meter where amplitude will be monitored only. As one can see, dips amplitude varies non-linearly with increasing the strain. Moreover, for some strain the response can exceed the full period and interference dips could cover each other. For this reason, in the next tests the PM fiber is immobile in order to avoid any external perturbations and it acts only as a wavelength filter.

3. Results and discussion

DR-LPG used in the experiment was fabricated on a standard optical fiber SMF-28 with a grating period of Λ = 217 nm. The hydrogenated fiber was exposed to the UV radiation with an emitting wavelength of λ = 248 nm through the chromium mask. After

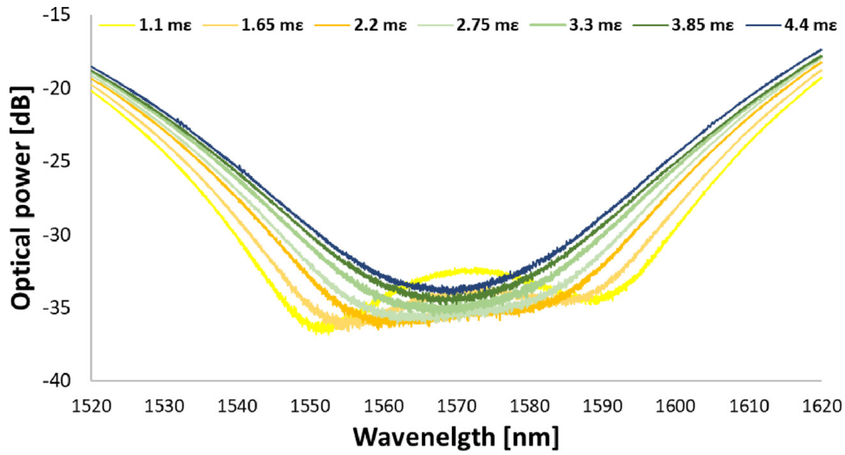

Fig. 3. The transmission spectra of the DR-LPG response to applying strain.

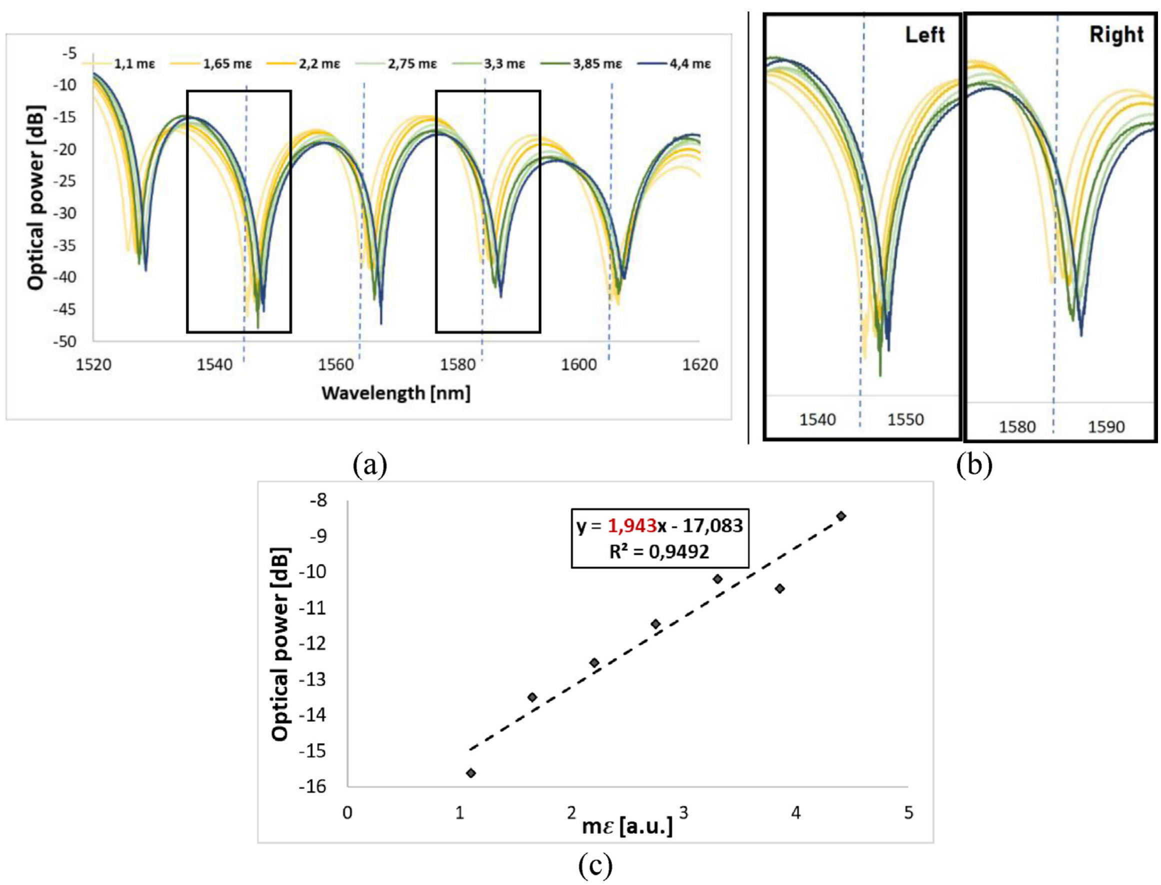

Fig. 4. The transmission spectra of the DR-LPG response to the increasing strain caused by the elongation -a), magnified of the left and right wavelength regions corresponding DR-LPG' notches - b), and intensity sensor response to strain increasing with linear fitting - c).

that, the grating was annealed and etched in hydrofluoric acid in terms of obtaining required spacing between notches [14]. Figure 3 shows the strain characteristics of the DR-LPG by itself.

As one can see both notches of DR-LPG shifts toward opposite direction and for some critical strain they merge to one very flat dip. In our tests, after applying a 2.75 mε unit strain on the DR-LPG, dual resonance effect has disappeared. It means that the strain sensor based only on the DR-LPG working for a relatively short range and some extra configuration is required for ultra-high strain sensing for monitoring stress more than 3 mε.

Figure 4(a) shows the spectral response of DR-LPG in FLM structure, where only grating was subjected to the strain measurement. The FLM spectrum was tuned by the PC in such a way that the interference peaks are in between both notches of the DR-LPG (close to 1552 nm and 1588 nm). Thus, the relationship from Fig. 3 is preserved, i. e., the transmission spectrum, which corresponds to the wavelength range between both DR-LPG' notches, increases until their merged. This phenomenon has direct impact for the peak amplitude at 1567 nm [see Fig. 4a)], where the amplitude increases and, therefore for strain sensitivity expression the difference interrogation method can be used. Here, the reference value (peaks at a wavelength of 1564 nm and 1606 nm) is subtracted from measured quantity (peaks at a wavelength of 1545 nm and 1583 nm) and this mathematical model of the interrogation scheme allows to get the approximately linear and most sensitive matched conditions [17]. Additional, as one can see, dips shift toward longer wavelength, whereas the amplitude is changing in terms of interference dips' wavelength position. In place of covering the left resonance notch, the amplitude of interference dips increases, while in place of the right resonance notch it decreases with strain increase (see Fig. 4b).

The relationship between the sensor response to a chosen wavelength and an applied strain is presented in Fig. 4c). The maximum sensor response to an increasing strain is obtained from linear fitting of the experimental data and is equal to 1.943 dB/mε with a correlation coefficient of 0.949.

4. Conclusions

Connecting unique spectral characteristics of an interferometric structure and ultra-high sensitivity of the DR-LPG, a good strain sensitivity response of the proposed setup was obtained. Since the fact that the strain was applied only to the DR-LPG and the PM fiber was isolated from the influence of external perturbations, the sensor can work in a relatively large measure range. Intensity of interferometric peaks covered with resonance notches change in different directions. Thus, sensitivity of the strain sensor was expressed using a differential interrogation method and is estimated as 1.943 dB/mε with the strain range of 1.1–4.4 mε. In the future, such configuration can be adopted to a multi-parameter sensor with selective response to different physical parameters. Comparing the available literature we have obtained a high sensitivity coefficient of strain sensing for wider range with linear response of intensity changing in the function of strain increasing.

Author statement

Renata Zawisza: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft, Visualization.

Leszek R. Jaroszewicz: Conceptualization, Writing – Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition.

Predrag Mikulic: Resources.

Wojtek J. Bock: Supervision, Project Administration, Funding Acquisition.

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