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# The strain distribution measurement by the use of the optoelectronic method based on the fibre bragg gratings

***Streszczenie.*** *W artykule przedstawiono metodę wyznaczania rozkładu naprężenia przy wykorzystaniu czujników ze światłowodowymi siatkami Bragga (FBG – ang. fiber Bragg gratings). Siatki zostały wykorzystane jako czujniki wydłużenia, w artykule przeprowadzono pomiary rozkładu wydłużenia przy wykorzystaniu algorytmów optymalizacyjnych. W przedstawionej metodzie do rozwiązania postawionego przez autorów problemu odwrotnego konieczne było wykorzystanie metod numerycznych. (**Pomiary rozkładu wydłużenia metodą optoelektroniczną przy wykorzystaniu światłowodowych siatek bragga**).*

***Abstract.*** *In the article the strain distribution recovery method for the fiber Bragg grating (FBG) sensor was presented. We use the fiber Bragg gratings as a strain sensor, and we have carried out distributed strain measurements by using of optimization algorithms. Numerical methods for resolve the inverse problem are necessary to recover the strain distribution, which was measured by using of FBG element.*

**Słowa kluczowe:** światłowodowe siatki Bragga, czujniki optoelektroniczne, wydłużenie względne, problem odwrotny.
**Keywords:** fiber Bragg gratings, optoelectronic sensors, strain, inverse problem.

## Introduction

Fiber Bragg gratings (FBGs) are proved to be one of the most significant developments in the fields of optical fiber technology (due to their flexibility and unique filtering performance). FBGs are well recognized as key components in dense wavelength-division-multiplexing (DWDM) systems, because of their low insertion loss, high-wavelength selectivity, low polarization dependent loss (PDL) and low polarization modal dispersion (PMD) [1]. Scatter by volume or thick gratings, which exhibit a strong Bragg effect, are of general importance in several areas of physics. Volume gratings are commonly encountered in the areas of reflection holography, dynamical holography and fiber Bragg gratings. FBGs, which are lossless phase reflection gratings, in which the refractive index along the core is modulated, are of great practical significance. It is since the narrow band high diffraction efficiency filtering can be manufactured in this way [2].

We use the fiber Bragg gratings as a strain sensor, and we have carried out distributed strain measurements by using of optimization algorithms. There is a need to knowledge the strain distribution in large accuracy on small sections. The present methods of the strain state evaluation (which are confirmed even by the tensometers) allow us to obtain average information. There are many different methods for strain measurement e.g. non-contact measurements of strain in construction steel [3] and methods form strain monitoring by using Barkhausen method [4]. Also methods for electromagnetic-temperature calculations with thermal stress [5] field monitoring [6] are developed. Our proposal to solve this problem is Fiber Bragg gratings application. The problem of the strain profile recovery, on the base of grating spectra, is so-called inverse problem [7]. There are no analytical methods for the recovery of the grating strain distribution on the base of it's spectra.

## Inverse problem for the Fiber Bragg grating

The problem of the strain profile recovery, on the base of grating spectra, is so-called "inverse problem". There are no analytical methods for the recovery of the grating strain distribution on the base of it's spectra. Accordingly to this, the following procedure was used (fig. 1).

First the initial values of the strain distribution was assumed. This values were used as an input data to built grating model. The model allowed to calculate optical spectrum and then this spectrum was compared together with the measured grating spectrum. Next the convergence criterion between these two spectra was checked. If the convergence occurred, optimal strain distribution was received. If no convergence occurred the object function was minimized and the strain values were selected according to the simulated annealing algorithm [8].

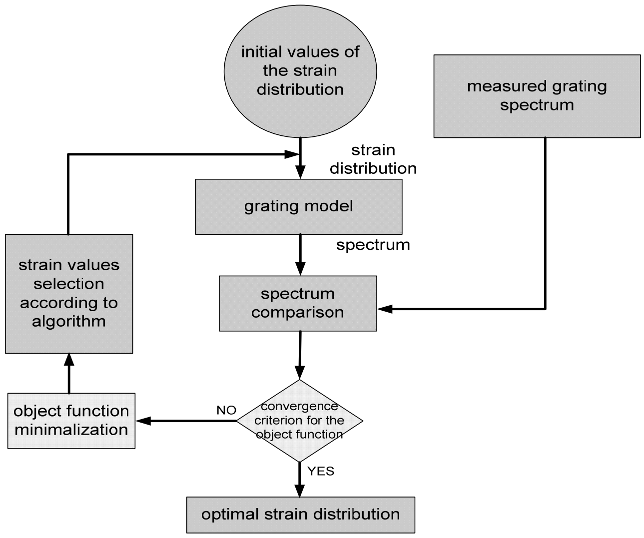


Fig.1. Inverse problem solution procedure

## Measurement system for the strain distribution recovery

The laboratory system for the strain generation was build for the measurement of the strain generation (fig. 2).

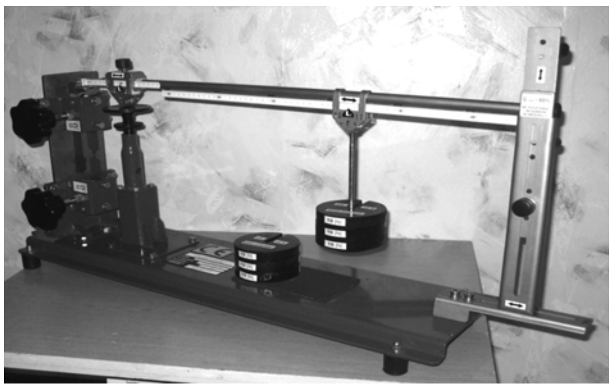

Fig.2. The laboratory system for the strain generation

As we can see the regulation of the load allows to continue an observation of the characteristic. This feature of this laboratory system prevents grating damage. We used two specimens, which were stressed in our strain generation system. Specimen number 1 (fig. 3) and specimen number 2 (fig. 4). Both were exposed to the same load. This load induced various strain distribution in Bragg gratings which were glued to the specimen.

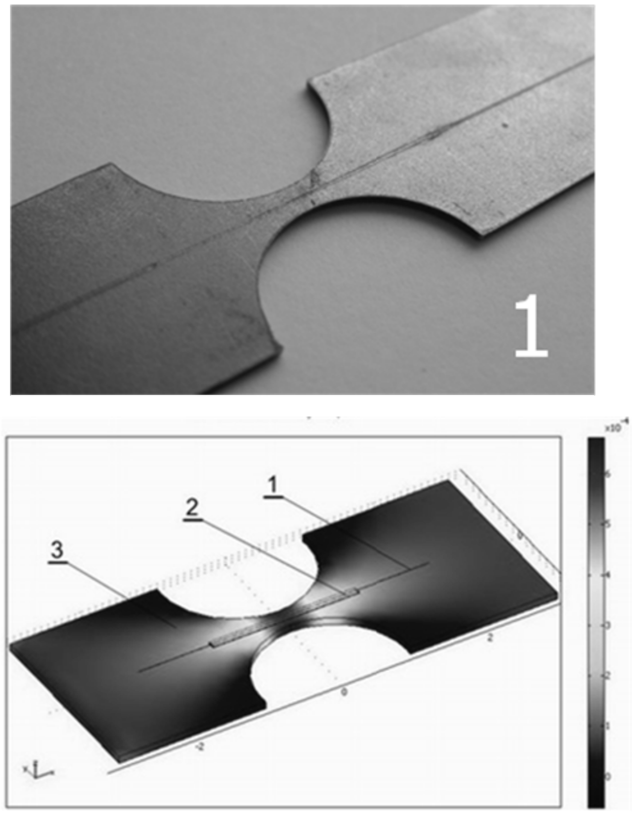


Fig.3. Specimen 1 for the strain distribution measurements: 1 – optical fiber with the FBG, 2 – glue, 3 – specimen

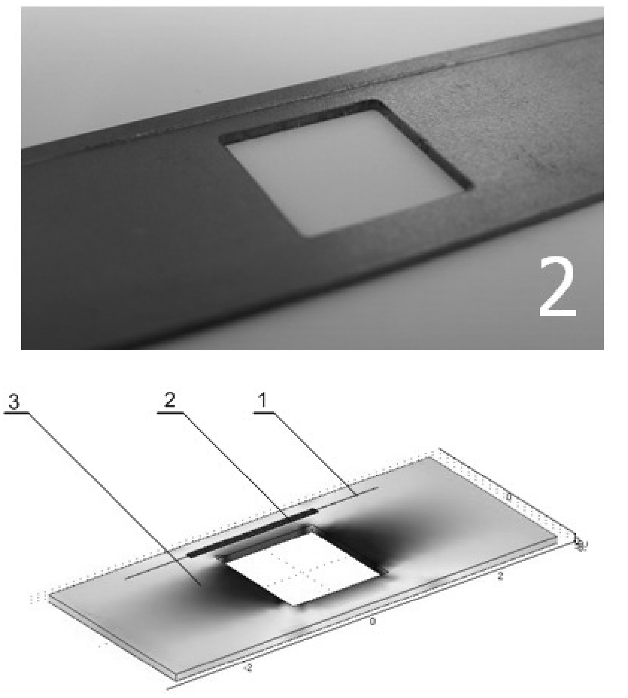


Fig.4. Specimen 2 for the strain distribution measurements: 1 – optical fiber with the FBG, 2 – glue, 3 – specimen

After creating the strain generation unit, the measurement system for the strain distribution recovery was build. This system is shown in the figure 5.

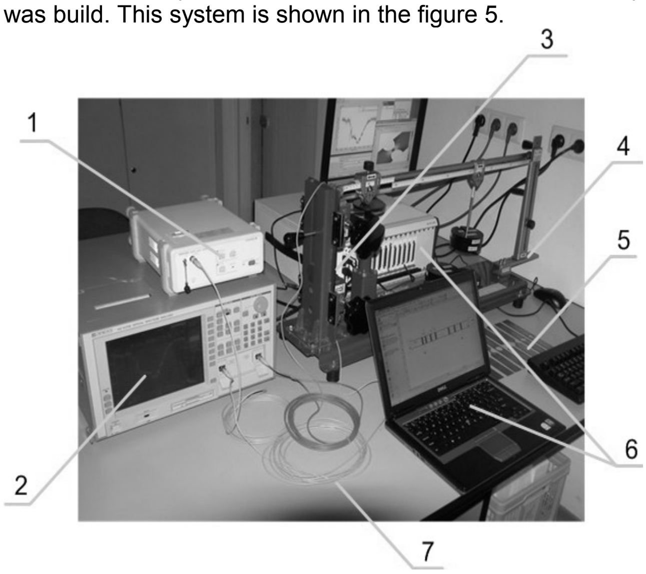


Fig.5. The measurement system for the strain distribution recovery: 1 – white light source, 2 – optical spectrum analyzer, 3 – specimen under load, 4 – strain generation unit, 5 – specimens for further measurements, 6 – computer, 7 – optical fiber with the grating

The light from the white light source was coupled to the optical fiber with the fiber Bragg grating. The grating was glued on the specimen, which was stressed by the use of the strain generation unit. Transmitted spectrum of the FBG was then measured by the optical spectrum analyzer (OSA). At the end this measured spectrum was compared with the calculated one.

In figure 6 we can see the measurements and simulations results. The real strain profile was depicted by the green line. The strain distribution profile - calculated by proposed method - was very similar with the real one. At the same time the initial profile was by far different than the real and calculated one. In the measurements simulated annealing algorithm was used for the sake of root mean square value. This error was calculated between the real and calculated curve and it’s value for the specimen number 1 equals 0.094.

The object function [9] for the method was calculated by the following equation:

$$F = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{T_m - T_c}{T_c}\right)^2} \quad (1)$$

where: $T_m$ – measured spectrum of the grating, $T_c$ – calculated spectrum (by the use of the simulated annealing algorithm).

This object function was minimized by the simulated annealing algorithm. The object function selection was very important both the time of the calculation procedure and the optimization method effectiveness [10].

In figure 7 we can see the result of the simulated annealing effect. The real strain profile was depicted by the green line. The strain distribution profile, calculated by proposed method, was also very similar with the real one.

As in the specimen 1 case the initial profile was by far different than the real and calculated one. In case of measurements simulated annealing algorithm was used for the sake of root mean square value. This error was calculated between the real and calculated curve and it's value for the specimen number 2 equals 0.09.

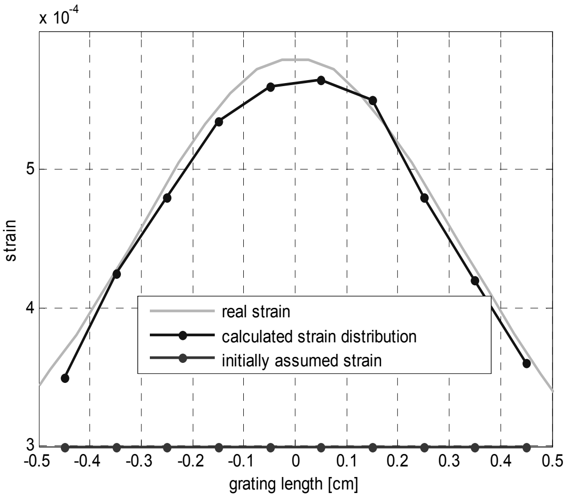


Fig.6. Strain distribution profiles (the real strain profile – green curve, the initial strain profile – red curve and the calculated strain profile – blue curve) in the FBG for the specimen number 1

Equation 2 presents the root mean square value calculations:

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\varepsilon_i^r - \varepsilon_i^c\right)^2} \qquad (2)$$

where: $\varepsilon^r$ – real strain profile, $\varepsilon^c$ – calculated strain profile (by the use of the simulated annealing algorithm and the fiber Bragg grating model).

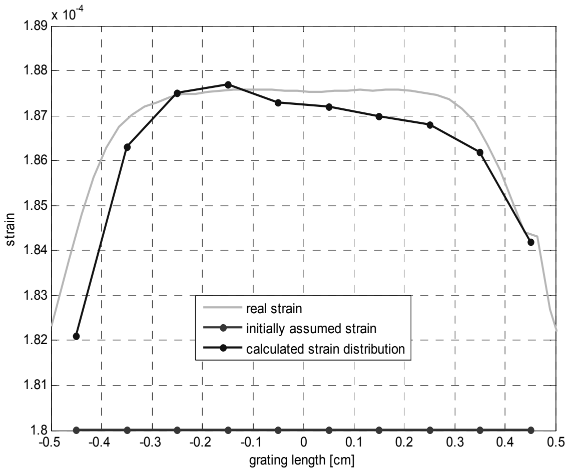


Fig.7. Strain distribution profiles (the real strain profile – green curve, the initial strain profile – red curve and the calculated strain profile – blue curve) in the FBG for the specimen number 2

**Conclusions**

The strain distribution may be recovered on the base of spectral characteristic of the fiber Bragg grating, which work as a sensor. Resolution of the strain localization responds the grating period size, thus in practical implementation it's in the order of micrometer.

Numerical methods for resolve the inverse problem are necessary to recover strain distribution, which was measured by using of FBG element. These methods will use next numerical algorithm of the global optimization. Selection of the algorithm for this kind of task is not indifferent for the accuracy of distribution recovery and time of the computation procedure.

Results suggest that the simulated annealing method will be the most suitable for the inverse problem solution, in spite of the biggest time-consuming character.

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