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Accuracy improvement of Fiber Bragg Grating peak wavelength demodulation using wavelet transform and various center wavelength detection algorithms

***Abstract**. The main feature of Fiber Bragg Gratings is that they perform a direct transformation of measured parameter into a shift in the center Bragg wavelength. This paper presents a possibility for extraction FBGs peak wavelength from spectra with high influence of noise by using wavelet transform. Spectra of tested FBG were measured in 20 points with different extending force applied to tested sample. Wavelet transform and various methods of center Bragg wavelength detection are jointly applied to improve wavelength detection accuracy. Experiment results shows that application of appropriate digital signal processing algorithms for denoising FBG spectra could greatly improve accuracy and linearity of fiber sensor processing characteristics.*

Streszczenie.** Najważniejszą właściwością światłowodowych siatek Bragga (Fiber Bragg Gratings) jest liniowe przetwarzanie zmian mierzonej temperatury bądź odkształcenia na przesunięcie centralnej fali. Artykuł ten prezentuje możliwości wyznaczenia długości fali Bragga z widm silnie zaszumionych przy zastosowaniu transformaty Falkowej .Spectra rejestrowano w 20 punktach o różnych wartościach siły rozciągającej próbkę. Transformacja Falkowa oraz różne algorytmy wyszukiwania centralnej fali Bragga zostały zastosowane jednocześnie dla uzyskania poprawy precyzji wykreślania charakterystyki przetwarzania elementu mierzącego. Wyniki eksperymentu wskazują, że zastosowanie odpowiednich algorytmów cyfrowego przetwarzania sygnałów do widm FBG może w dużym stopniu poprawić dokładność wyznaczania charakterystyki przetwarzania światłowodowego czujnika. **Poprawa dokładności demodulacji światłowodowych siatek Bragga dzięki użyciu transformaty falkowej i algorytmów detekcji centralnej długości fali

Słowa kluczowe: Siatka Bragga, długość fali Bragga, transformata falkowa, czujnik naprężenia.
Keywords: FBG, Bragg wavelength, wavelet transform, strain sensor.

Introduction

The main feature of fiber Bragg gratings is that they perform a direct transformation of measured parameter into a shift in the center Bragg wavelength. From the beginning of their development, FBGs have been considered as excellent optical fiber sensing elements, suitable for measuring force [1] and temperature [2]. Sensors based on fiber Bragg gratings have recorded a rapid research and development in recent years due to their advantages over a traditional sensors, for example immunity to electromagnetic interference, low cost and remote sensing [3]. They ale lightweight and have small physical dimensions, suitable for being embedded into or attached into a measured structure. Another advantage is that FBG sensors provides great multiplexing capabilities, even hundreds of sensing elements in single fiber.

Precision of FBG sensor depends on accuracy of wavelength dip in transmitted or wavelength peak in reflected spectrum. In engineering application, fiber Bragg gratings are usually a part of bigger structure which contains e.g. electronic elements and could be placed in environment which make sensor signal contain various types of noise which seriously influences on the precision of demodulation [4]. Received signal form FBG in systems which are using broadband source of light is usually very low. The result is high influence of noise in output signal especially when time-division multiplexing is used to multiplex a large number of sensors. Using laser or SLED sources to illuminate sensing elements provides high level of optical power but interferometic noise could be caused by residual reflections [5]. To improve accuracy of Bragg sensor there are reported several digital processing methods such as advanced methods of ascertaining peak wavelength and denoising measured spectrum. Two basic techniques to obtain information from signals are filtration and cross-correlation signal processing. Both have been used to analyze Bragg grating sensors spectra.

Cross-correlation technique is using correlation between reference spectra sequence and spectra measured from FBG subjected to temperature or strain changes which are causing shift in center Bragg wavelength [6]. Similar technique have been used to improve accuracy of peak wavelength detection [7].

One of the most widely used technique to denoising and analyzing signals is wavelet transform [8]. This method is also used in denoising light spectra from FBGs. The denoising efficiency is insignificantly dependent on type of the wavelet function [9]. Denoising of Gaussian shape spectra with using wavelet is developing in other branches of science, especially in spectroscopy [10]. An advanced detection scheme should consist of a good denoising method and a suitable peak detection algorithm.

Searching for a wavelength with the greatest amplitude is the easiest and most frequently used algorithm of center Bragg wavelength detection. Another widely used algorithm is a centroid which is based on searching geometrical center of top of the spectrum [11]. Least square fitting, which uses adjusting models to fit the spectrum is more complicated but currently developed method of center Bragg wavelength detection. Using Gaussian shape is natural in measuring spectra from illuminated FBGs [12][13]. Techniques of fitting measured or simulated spectra are developing in some spectroscopy analysis [14] [15]. Relatively new method of detecting peak is using the neural networks [11][16].

Principle and algorithms

The Gaussian distribution of fiber Bragg grating spectrum with a spectral FWHM of Δ and a center wavelength λ_B which is expressed by [7]

$$R(\lambda) = R_0 \cdot \exp\left[-4 \cdot \ln\left(2 \cdot \frac{\lambda - \lambda_B}{\Delta}\right)^2\right] \quad (1)$$

where R_0 is the maximum reflectivity that occurs at Bragg wavelength, λ is the wavelength in vacuum. Sensors based on fiber Bragg Grating in many applications could be embedded or attached into a surface of measured structure. Several reasons such as non uniform temperature distribution, strain gradients or another environmental influences could causes a serious distorsions in FBG spectra. This leads to inaccurate peak location with demodulation techniques designed for intact spectral shapes [16]. This inaccuracy could be avoided by application of adjusted models to fit the spectrum. It is natural to use Gaussian function as a model because it is the inherently closest profile to reflected or transmitted FBG spectrum. To compare effectiveness of Gaussian fitting, two another Bragg wavelength detecting algorithms were used to detect peak wavelength from noisy spectra.

Most widely used center Bragg wavelength detecting method is the maximum algorithm which is based on searching for the wavelength with the highest amplitude of optical power in measured spectrum. This method is naturally high sensitive for inherent noise and could be applicated in spectra with high signal to noise ratio.

Another algorithm is based on determining a geometrical center of FBG spectra and is called centroid. The point which corresponds to geometrical centroid of spectrum is calculated by equation (2), where N is the number of measured points of the spectrum, λ_i is the i-th point wavelength and A_i is the i-th point amplitude.

$$\lambda_b = \frac{\sum_{i=1}^{N} \lambda_i A_i}{\sum_{i=1}^{N} A_i} \qquad (2)$$

Centroid algorithm shows how the spectrum is being shifted. In comparison to maximum algorithm, this method is much less sensitive for noise, so could be used to detect peak wavelengt from spectra with some influence of noise. In application of centroid, it is necessary to centered input spectrum by choosing measured points around predicted peak wavelength before being fed to the centroid algorithm, exemplary by removing those points with amplitude lower than 0,4 of maximum [11].

WT is transform which decompose a signal into a set of basic functions, whereas the basis function can be easily obtained from a single basis wavelet which is usually called mother wavelet. WT is appropriate for the analysis of transient, non-periodic signals.

Experimental principles

Experiment was based on setting strain-to-wavelength shift processing characteristics of FBG strain sensor from spectra obtained for sensing element illuminated by two different sources of light. Sensing element was extended with 20 growing forces and for each force were measured two spectra. Reference characteristics with low influence of noise were obtained by using 1550 nm SLED high-power source with FWHM line-width of 50nm. Appropriate light source provides a smooth shape and high signal to noise ratio in measured spectra. Great properties of traced spectra allows to detect Bragg wavelength with good accuracy which provides a proper quality of sensor strain-to-wavelength shift processing characteristic.

To trace spectra with strong influence of noise (called noisy), sensing element was illuminated by halogen-based low powered source of light. Detection of center Bragg wavelength from this kind of spectra could cause high inaccuracies in calculating processing characteristic of strain sensor. It is necessary to use digital denoising algorithms for smoothing measured spectra which allows to improve accuracy of peak wavelength detection. This experiment also checked the possibility of using low powered but cheap source of light and application appropriate digital signal processing algorithms instead of application high powered and usually expensive source. Application of low power source could also simulate a sensing array with huge number of sensors where interference noise has great influence on shape of reflected spectrum.

Experimental setup

As sensing element was used a Gaussian apodized FBG with center wavelength of 1548 nm while unstrained. Light illuminated by source was passed by circulator and hits fiber Bragg grating. Reflected spectra were measured by optical spectrum analyzer (OSA) which has 0.02 nm resolution. A spectra traced by OSA were transferred to PC computer, which perform a digital filtering and peak wavelength detection algorithms. Figure 1 schematically shows experimental setup.

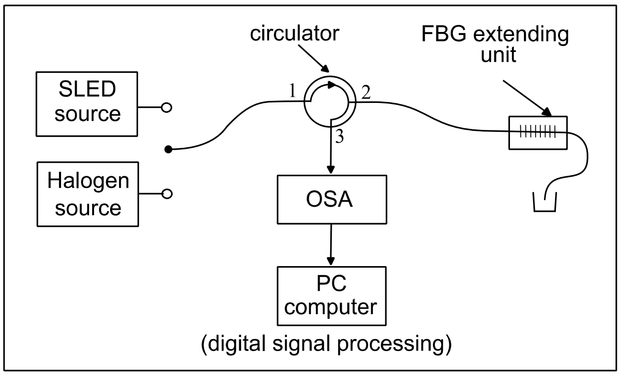

Fig. 1. Scheme of experimental setup for FBG reflected spectra receiving

FBG was glued to sample made of stainless steel. Shape of specimen provides an equal strain in full longitude of FBG. Extending unit is based on lever mechanism which extends the sample with forces adjustable by changing a load and longitude of lever arm. To fix FBG to stainless specimen was used glue with tensile modulus about $1{,}3 \cdot 10^4$ MPa which provides good accuracy of processing steel sample extension into fiber Bragg grating wavelength shift.

Experiment results

On Figure 2 are depicted spectra measured for one extending force with FBG illuminated by high-powered light source (black plot) and low-powered halogen source (grey plot). This comparison clearly shows, that extraction of Bragg wavelength of spectrum measured from sensor illuminated by inappropriate source of light will cause a strong inaccuracy.

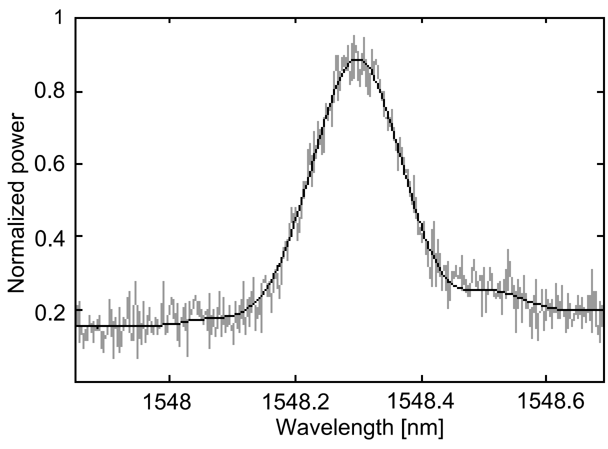

Fig. 2. Comparison of spectra measured with high power and low powered sources

To calculate strain sensor processing characteristics from smooth and noisy spectra were used a maximum and centroid algorithms. Figure 3. shows comparison of those strain-to-wavelength shift processing characteristics calculated from Bragg wavelengths detected with centroid. Graphs has colors respectively to figure 2, black traced from smooth reference and grey from noisy spectra.

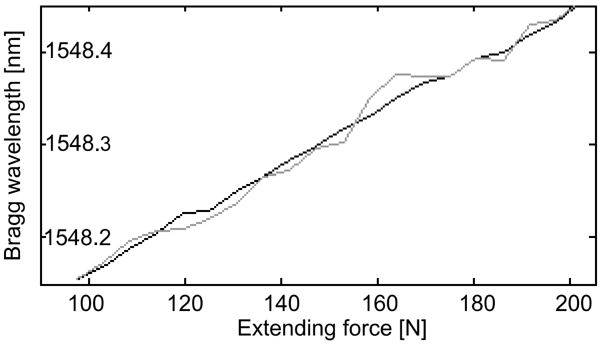

Fig. 3. Sensor processing characteristics received from reference and noisy spectra

Picture above clearly shows, that even application of specialized center Bragg wavelength detecting algorithm to spectra with strong noise provides high errors. The statistical data placed in Table 1. confirms that application of centroid instead of maximum provides better peak wavelength detecting accuracy.

Table 1. Comparison of standard deviation and linear correlation index of traced processing characteristics

Spectrum type	Wavelength detecting algorithm	Standard deviation	Line correlation index
Reference	Maximum	1,6018	0,9989
	Centroid	1,5433	0,9989
Noisy	Maximum	4,7607	0,9899
	Centroid	4,1119	0,9921

Denoising efficiency

The selections of wavelet function and signal decomposition level are essential for the implementation of wavelet transform. In order to test the noise suppression efficiency of wavelet transform with different decomposition levels was implemented to denoised measured spectra with high influence of noise. Calculations was realized by MatLab program. Applied wavelet belongs to Daubechies family and soft thresholding was used. Changing of decomposition level in denoising process has great influence on shape of reconstructed signal. Figure 4 shows comparison of spectra denoised with using wavelet transform with different decomposition levels.

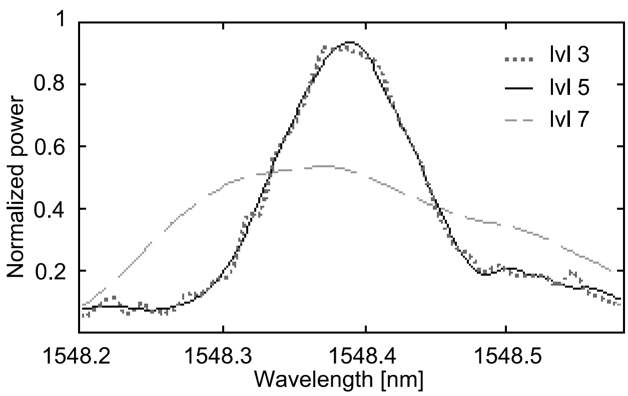

Fig. 4. Denoised spectrum with different decomposition levels

The characteristics plotted on Figure 4 shows, that setting decomposition level value at 7 causes strong flattening of denoised spectrum. It is clearly shown that center Bragg wavelength is also shifted and calculating processing characteristic from this kind of spectra will cause strong inaccuracies. Setting decomposition level at value 3 makes denoised plot much more similar shape to reference spectrum. However, in this wavelet setup, denoised plot contain some influence of noise. Best solution in experiment is setting decomposition level 5. Received shape is very similar to reference spectrum and contain low noise coefficient.

Naturally, determination accuracy of strain to wavelength processing characteristic strongly depends on denoised spectra shape. Irregular shape of resulted spectrum promotes to generation inaccuracies in Bragg wavelength detecting. Regular shape similar to ideal Gaussian curve provides the best accuracy of center wavelength detecting. Comparison of tested sensor processing characteristics obtained from spectra denoised with using wavelet transform with the same decomposition levels as in previous example is shown in figure 5.

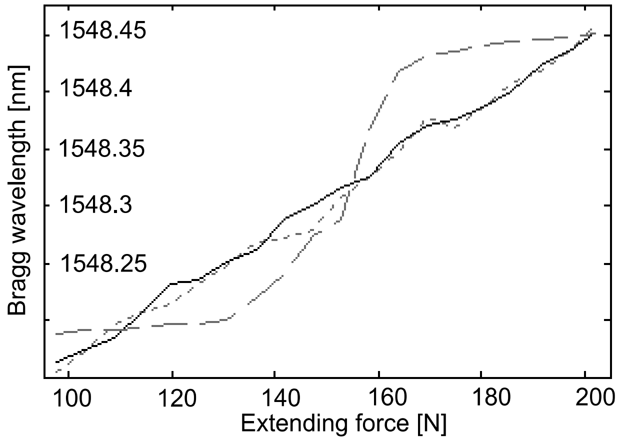

Fig. 5. Force to wavelength shift processing characteristics traced from spectra denoised with different decomposition levels

Line styles in figure 5 are the same as in figure 4, line styles matches to the same decomposition levels. Processing characteristics calculated from spectra denoised by wavelet transform with different decomposition levels shows that the best linearity and smoothness of plot is obtained with setting 5 as decomposition level.

Table 2 contain statistical data of strain-to-wavelength processing characteristics obtained from noisy spectra denoised by using wavelet transform with values 3, 4, 5, 6, 7 as decomposition level.

Table 2. Statistical data comparison of strain-to-wavelength processing charateristics

Decomposition level	Wavelength detecting alg.	Standard deviation	Line correlation index
3	Maximum	3,0446	0,9959
	Centroid	2,6504	0,9969
4	Maximum	1,8258	0,9985
	Centroid	1,6945	0,9987
5	Maximum	2,0508	0,9981
	Centroid	1,8656	0,9985
6	Maximum	6,2149	0,9827
	Centroid	5,5464	0,9863
7	Maximum	10,8408	0,9464

	Centroid	10,7614	0,9472

Comparison of standard deviation and linear correlation index of calculated processing characteristics placed in table 2 shows, that the best linearity is obtained for characteristic traced from spectra denoised by wavelet transform with decomposition level 4. Application value 5 also provides good statistical parameters of processing characteristic. Calculation results also shows, that application of centroid algorithm to detect Bragg wavelength in every case provides better lower standard deviation and higher linear correlation index then application maximum.

Linear regression model obtain from spectra measured from FBG illuminated by SLED high powered source is used as reference. Model calculated from spectra denoised by wavelet with decomposition level 4 is compared with reference model in figure 6. In both characteristics centroid was used to detect Bragg wavelength from spectra.

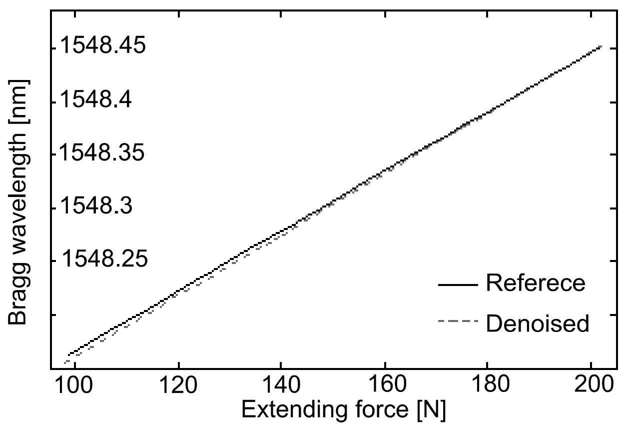

Fig. 6. Linear models of reference and calculated sensor processing characteristics

Models plotted in figure below, shows that processing characteristic calculated from spectra denoised by wavelet with proper decomposition level has very similar angle of scope as reference. Using this technique to denoising FBG spectra causes no systematic error and no shift in sensor processing characteristic.

Conclusions

Digital signal processing algorithms have been used to improve the measurement accuracy of fiber Bragg grating strain sensor illuminated by low powered, broadband source of light. Inherency of strong noise in measured spectrum has great influence in tracing processing characteristic of tested sensor. Executed experiment proved, that application of appropriate Bragg wavelength detection algorithm and denoising algorithm could insignificantly improve calculating accuracy of sensor characteristics.

Application of wavelet filter to denoising spectra with high influence of noise could insignificantly improve the smoothness of plot. Selection of appropriate wavelet function parameters have great influence on final sensor processing characteristic. This algorithm is causing no systematic errors which could have serious influence on accuracy of determination wavelength shift in function of extending force. Comparison of linear regression models executed from sensor strain-to-wavelength shift processing characteristics shows, that high power source could be replaced by weak broadband light source and digital signal processing algorithms.

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