Data Processing Techniques for Fiber Bragg Grating (FBG) Reflectivity Characteristics Measurements

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Abstract. *The paper deals with general overview of signal processing techniques for reflectance characteristics of fiber sensors based on FBG technology. Firstly basic principle of FBG measurement is introduced with the stress on characterization and profile of obtained data. Different types of interpolation approximation algorithms are described, tested and compared on real data obtained from spectrum analyzer unit. Developed software for processing is introduced and discussed from the point of usage in different applications with dynamic or static FBG measurements.*

Keywords: Fiber Bragg Grating, Fiber Optic Sensor, Reflectance Characteristic, Interpolation, Interrogation

1. Introduction

In many modern civil engineering projects often more sophisticated materials are used. Especially the term of “energy efficient building” or “green building” are often introduced as a future of modern buildings [1]. With this attitude a lot of problems appear for architects and building constructors according to new materials used and tools for proper structure environment monitoring. Wooden beams are also preferred to replace the steel supports in constructions like houses and small buildings. With wood implementation into buildings monitoring of dilatation, shrinking, temperature, moisture etc. comes in handy. For that purposes optical fiber sensors (OFS) could be used. OFS have many advantages like multiplexing, signal immunity to electro - magnetic interference (EMI), usage of only one signaling data fiber, etc. One type of sensors are fiber Bragg gratings [2].

The structure of uniform FBG consists of dielectric elements with different index of refraction. Grating sensors implemented or bonded on different materials can be used for measuring physical fields like mechanical [3] or thermal stress [4]. The main principle of FBG monitoring is sensing the Bragg grating central wavelength which is given by equation:

$$\lambda_b = 2 n_{eff} \Lambda \tag{1}$$

Where Λ is space period of grating and n_{eff} is effective index of refraction of fiber core. The uniform FBG structure is shown in Fig. 1 a). For measuring reflectivity characteristics broadband optical source like super-luminescent diode (SLD) is need. The light interferes with FBG structure and narrow spectrum light is reflected towards the SLD. The reflective spectrum has Gaussian character. The reflected optical signal is guided through optical circulator to optical spectrum analyser (OSA) and processed. When influence of measured physical field modulates the FBG structure the frequency position of reflectance characteristic changes (Fig. 1 b)).

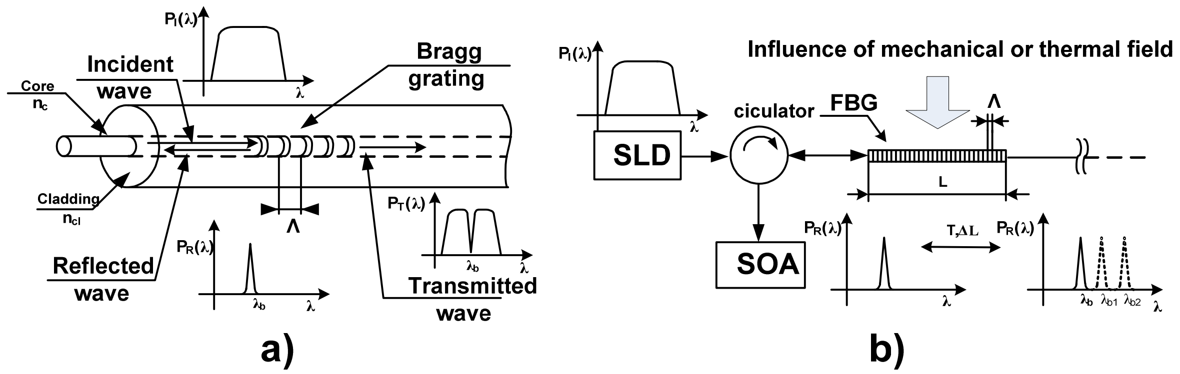

Fig. 1. FBG structure (a), basic measuring apparatus of reflectance characteristics (b).

As it was stated in equation 1the influence on effective refractive index or grating periodicity causes the change in central Bragg wavelength. But the changes in these variables are cross sensitive because any mechanical or thermal influence changes the density of optical material and also the periodicity dimension of the grating [4]. This bounded influence can be described by equation:

$$\Delta\lambda_b = \Delta\lambda_{\Delta\varepsilon} + \Delta\lambda_{\Delta T} \tag{2}$$

It has two contributors to the resulting FBG wavelength shift which could be substituted also with corresponding strain changes $\Delta\varepsilon$ and temperature ΔT [4]. To be more detailed one can write equation 2 in the expanded form:

$$\Delta\lambda_b = 2\left[\Lambda\frac{\partial n_{eff}}{\partial\varepsilon} + n_{eff}\frac{\partial\Lambda}{\partial\varepsilon}\right]\Delta\varepsilon + 2\left[\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right]\Delta T \tag{3}$$

The first addend in the equation (3) represents the change due to FBG elongation - strain $\Delta\varepsilon$ and the second one the FBG thermal change ΔT, during thermal stress. The change in refractive index due to strain partial derivative ($\partial n_{eff}/\partial\varepsilon$) represents the photo-elastic and ($\partial n_{eff}/\partial T$) the thermo-optic coefficient. Change in Bragg central wavelength due to the strain application $\Delta\varepsilon$ is described by statement:

$$\Delta\lambda_{\Delta\varepsilon} = \lambda_b(1-\rho)\Delta\varepsilon \tag{4}$$

where ρ is photo-elastic coefficient for fused silica material equal to 0.22 [5]. On the other hand thermal changes ΔT are specified according to:

$$\Delta\lambda_{\Delta T} = \lambda_b(\alpha+\zeta)\Delta T \tag{5}$$

where α is thermal elongation coefficient with typical value 0.55 x 10^{-6} ºC^{-1} [6] and ζ thermo-optic coefficient with approx. value 6.67 x 10^{-6} ºC^{-1} [7].

2. Signal processing techniques

As stated in chapter 1 for accurate physical quantity estimation (strain or temperature) the value $\Delta\lambda_b$ is needed. Due to the fact that reflectance characteristics of FBG structure is not ideal or proportional to Gaussian curve additional signal processing is needed. Simplest way how to estimate the $\Delta\lambda_b$ parameter is to look for local maximum in FBG reflectance characteristics. More accurate method is the calculation of reflectance centroid or Gaussian polynomial fitting. Detailed description could be found in [8]. Graphical demonstration of mentioned methods are shown in Fig.2.

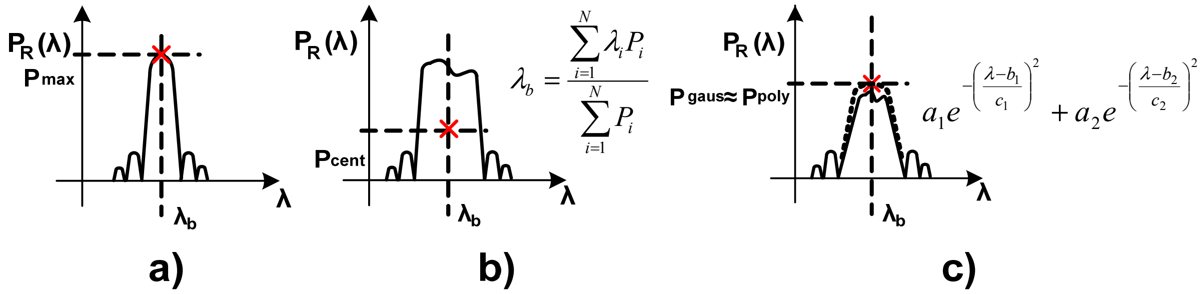

Fig. 2. Signal processing techniques for $\Delta\lambda_b$ estimation: a) maximum detection, b) centroid, c) Gaussian approximation.

To test mentioned methods processing software was created. Test data were obtained from temperature dependence measurement on commercially available uniform high reflectance FBG structure with thermal sensitivity equal to 11 pm/˚C [9]. For heating purposes fiber oven was used. The tested temperatures were t = 25.0, 27.5, 33.1, 41.5, 49.2, 57.9, 72.2, 81.3, 89.8 and 104.1˚C respectively. Temperature was measured with PT100 sensor and given as reference data. For spectral measurement of reflectance FBG characteristic OSA was used with resolution of ± 50pm in 6 nm span bandwidth from 1548 nm to 1554 nm. As broadband light source super-luminescent diode was used. The raw data obtained from OSA is plotted in Fig. 3 a). From graph it is clear that $\Delta\lambda_b$ is increasing with temperature grow. Before signal processing software was used the amplitudes with lower levels than 10 µW were substituted with 0 W (noise cut). After noise cut procedure $\Delta\lambda_b$ was estimated for each temperature with maximum, centroid and Gaussian approximation technique respectively (Fig. 3. b). From obtained $\Delta\lambda_b$ values temperature was calculated and compared with PT100 reference data (Fig. 3. c).

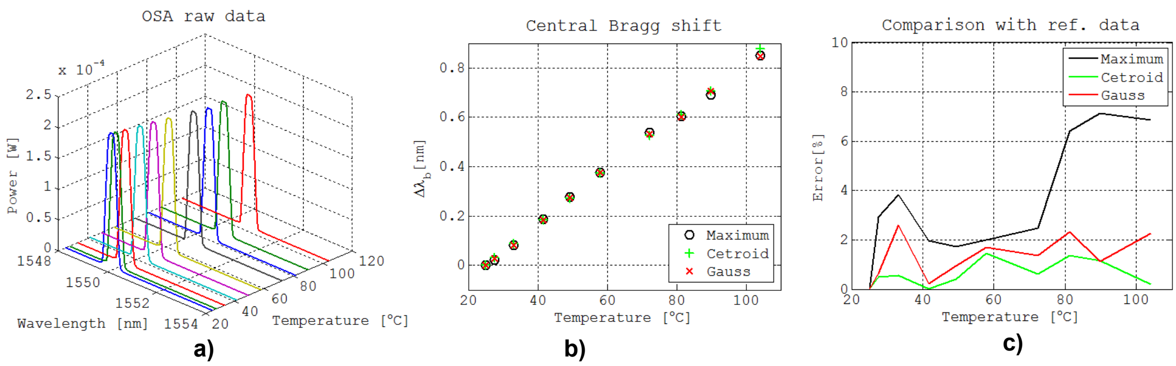

Fig. 3. Measured results: a) raw data, b) $\Delta\lambda_b$ calculation c) data error

The results show that with use of maximum detection algorithm highest error occurred. Especially in the area above 70˚C. Centroid detection had an error below 1.5 % and was also processed with the fastest response in comparison to Gaussian fitting. Therefore one could state that for dynamic and real time measurements centroid method is more suitable than more time consuming polynomial fitting method.

3. Conclusions

In the beginning of the article general overview of uniform FBG structure sensors is brought. The mechanism of sensing and measuring is stated.

In the signal processing techniques chapter three methods for $\Delta\lambda_b$ estimation are introduced and tested. The used experimental data were obtained during heating of the FBG structure. Data comparison shows good correlation between processing techniques in range up to 70˚C. The tested methods especially centroid calculation algorithm is suitable for future planned semi distributed – point sensing application based on FBG.

Usage of FBGs sensors in structure health monitoring application could have a major impact on prevention of overloading conditions and therefore collapsing of the civil engineering buildings. It also could be used as an indicator of inner material properties via monitoring parameters like temperature, moisture and dilatation.

Acknowledgements

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