Efficient Detection of Multiple FBG Wavelength Peaks using Matched Filtering Technique

Sunil Kumar (skp.narayan@gmail.com)
Birla Institute of Technology

Research Article

Keywords: Fiber Bragg grating, matched filtering, cross-correlation

Posted Date: September 23rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-899312/v1

Version of Record: A version of this preprint was published at Optical and Quantum Electronics on January 4th, 2022. See the published version at https://doi.org/10.1007/s11082-021-03460-3.

Efficient Detection of Multiple FBG Wavelength Peaks using Matched Filtering Technique

Sunil Kumar[1], Somnath sengupta[2]
Department of Electronics and Communication Engineering,
BIT Mesra, Ranchi, Jharkhand, India

Abstract

We propose an efficient technique for FBG peak detection based on matched filtering technique. The matched filtering process is based on resonance point estimation between a standard reference spectral signal and a reflected spectrum of FBG. The desired peak wavelength and corresponding peak intensity are predicted by determining ~~of~~ the cross-correlation between the FBG signal and ~~3rd~~ derivative of the reference signal. The peak wavelength and intensity are found from the zero-crossing points of the cross-correlation function. The Mexican-hat wavelet function is chosen as the reference spectral signal due to its narrow shape. The proposed algorithm can suitably be used for multiple peak detection when several FBGs are cascaded and if the FBG signal is weak and noisy.

Key words- Fiber Bragg grating , matched filtering, cross-correlation

1. Introduction

The fiber Bragg grating (FBG) based sensors have wide applications in engineering, medical, civil and military etc. due to its small size, low weight, immunity to electromagnetic interference and ease of multiplexing [1-4]. The ~~basic~~ traditional electrical sensors are nowadays being replaced by FBG sensors due to its ability to sense multiple physical parameters like temperature, strain, humidity, and flow rate etc simultaneously [5-6]. Several FBGs can be multiplexed in an optical fiber with the help of wavelength division multiplexing (WDM) and enabling online health monitoring of large structures [7-9]. However, the key task is to demodulate the FBG peak wavelength from the reflection spectrum. The optical spectrum analyser (OSA) is generally

used to identify the peak, but the drawback is that the peaks cannot be dynamically measured. To measure the wavelength shift of FBG peak due to application of measurand, the spectral data can be collected using OSA or spectrometer and then some signal processing technique may suitably be applied. This would provide efficient and dynamic measurement of FBG peak wavelength. In this context several research works have been carried out. For single peak detection, the statistical techniques like centroid detection [10], polynomial curve fitting, direct peak method [11], Gaussian non-linear method [12] etc. have been reported [13]. For the multiple-peak detection of FBG based sensors the signal processing techniques such as Hilbert transform [14],segmentation based continuous wavelets transform [15], cross correlation with Hilbert transform [16], invariant moments retrieval method [17], centroid localization algorithm [18] have been demonstrated. In these methods, the drawback is that they fail to detect true peaks if the peaks are very narrow and weak. The low intensity peak may be present if the FBG signal is noisy or degraded. Recently radio frequency based FBG demodulation technique is developed [19]. Although this is real-time based technique, but the problem is that it needs large number of components or devices. Thus, there is a requirement of developing an effective signal processing technique which would be applied on the FBG sensor signal for determination of peaks out of the reflection spectrum which may be narrow, weak, or noisy in nature.

In this paper, the multiple FBG-peak detection technique is proposed using match filtering technique. The match filtering technique method is based on finding the cross-correlation between a reference spectral signal and the FBG-sensor signal. The peak wavelength and intensity are found from the zero-crossing points of the cross-correlation function. The Mexican-hat wavelet function is chosen as the reference spectral signal due to its narrow shape. The proposed algorithm can suitably be used for multiple peak detection when several FBGs are cascaded. This algorithm will work well if the FBG signal is weak and contains narrow peaks.

2. Principle of Algorithm

When a boradband light is incident on FBG, a wavlength called Bragg wavelngth is reflected from it. It is given by,

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

where, n_{eff} is the effective refractive index of funadamnetal core mode and Λ is the grating period. Due to any perturbation e.g. strain or temperature, the wavelength is shifted. The amount of shift of wavelength is proportional to applied measurand. Thus in general, a single FBG, may be used for measuring a single physical parameter. However, multiple parameters can also be measured if different FBGs are cascaded in series.

The proposed FBG peak detection method is based on the technique of mathced filtering. In this technique, a reference spectral signal (e.g. Gaussian peak model) is chosen and then matched with the reflected FBG Signal which is may be shifted due parameters strain and tempretature. The reference signal is centered at a particular wavlength, which may not match with the FBG peak wavelength.

In order to explain the algorithim, we consider a Gaussian spectral signal as our signal of interest and a Mexican-Hat wavelet function as the reference signal. The Gaussian spectral signal is chosen as it resembles to an reflected FBG signal and the Mexican-Hat wavelet is chosen because of its narrow spectral band.

The Gaussian spectral signal can be written as [12],

$$\mathrm{R}\,(\lambda) = e^{-4*ln2\left(\frac{\lambda-\lambda_B}{\Delta\lambda_B}\right)^2} \tag{2}$$

where, λ_B is the central wavelength, and $\Delta\lambda_B$ is the 3-dB bandwidth. It is plotted in Fig.1. The wavelength range is chosen from 1542 nm-1544 nm and the central peak is located at 1543 nm.

The reference signal or Mexican-Hat wavelet function, can be described by [20],

$$\Psi(\lambda) = [1-\left(\frac{\left(\lambda-\lambda_{B_{ref}}\right)}{\Delta\lambda_{B_{ref}}}\right)^2]e^{\left(\frac{\left(\lambda-\lambda_{B_{ref}}\right)}{\Delta\lambda_{B_{ref}}}\right)^2} \tag{3}$$

Where $\lambda_{B_{ref}}$ is central wavelength of reference signal.

It is also plotted in Figure-(2) with the same wavlength range as of Figure(1). The $\lambda_{B_{ref}}$ may be chosen as the same value between the used FBG-peak wavelengths range.

The matched filtering is a process for detecting the unknown peak of a signal in spectral domain. It is based on the correlation of the reference signal with the FBG signal. In this method it is necessary that the peak of the reference signal needs be aligned with the peak of FBG signal. This is done by applying the least-square method on the first derivatives of the reference and FBG signals. It can be mathematically expressed as:

$$\mathrm{F}\,(\lambda_\tau, \alpha) = \int_{-\infty}^{\infty}[R'(\lambda) - \alpha\Psi'(\lambda+\lambda_\tau)]^2 d\lambda \tag{5}$$

Where, λ_τ is the delay variable and represents peak location and α represents the height or magnitude of the unknown peak.

The Eq.(5) is minimized by applying derivative with respect to λ_τ and α, on it. It will yield two parameters, C (λ_τ) and α (λ_τ), which are described as in Eq. (6) and Eq. (7).

$$C(\lambda_\tau) = \int_{-\infty}^{\infty} \mathrm{R}\,(\lambda)\Psi'''(\lambda' + \lambda_\tau)d\lambda \tag{6}$$

Where, $\lambda' = \lambda - \lambda_{B_{ref}}$, λ is the wavelength range for reference signal same as FBG

$$\alpha(\lambda_\tau) = \frac{\int_{-\infty}^{\infty} \mathrm{R}\,(\lambda)\Psi''(\lambda'+\lambda_\tau)\,\mathrm{d}\lambda_i}{\int_{-\infty}^{\infty}[\Psi'(\lambda)]^2\mathrm{d}\lambda} \tag{7}$$

The parameter $C(\lambda_\tau)$ results in from the cross-correlation between R (λ) and 3rd derivative of Ψ (λ). It would provide the zero-crossing points. The zero-crossing point is the point at which, the first derivative of F (λ_τ, α) with respect to λ_τ is zero. Thus, to calculate these zero crossing points, we use the following relations:

$$C(\lambda_\tau) = 0 \tag{8}$$

$$\int_{-\infty}^{\infty} \mathrm{R}\,(\lambda)\Psi'''(\lambda' + \lambda_\tau)d\lambda = 0 \tag{9}$$

$$\int_{-\infty}^{\infty} e^{-4*ln2(\frac{\lambda-\lambda_B}{\Delta\lambda_B})^2}.c^{-8}.(\lambda^5 - A_1\lambda^4 + A_2\lambda^3 + A_3\lambda^2 + A_4\lambda - A_5)e^{-\frac{1}{2}(\frac{\lambda-l}{\Delta\lambda_{B_{ref}}})^2}\,d\lambda = 0 \tag{10}$$

$l = \lambda_{B_{ref}} - \lambda_\tau$ And the parameters A_1 , A_2 , A_3, A_4 and A_5 of Eq. (10) are simply the coefficients due to differentiation as given in Appendix-1. By evaluating the integration of Eq. (10), and equating with zero, we can find the zero crossing points, which exists at

$$\lambda_\tau = \lambda_{B_{ref}} \tag{11}$$

Next, to find the desired wavelength peak, we would calculate $\alpha(\lambda_\tau)$ given in Eq. (7) as follows

$$,\alpha(\lambda_\tau) = \frac{\int_{-\infty}^{\infty} e^{-4*ln2(\frac{\lambda-\lambda_B}{\Delta\lambda_B})^2}.c^{-8}(\lambda^4 - B_1\lambda^3 + B_2\lambda^2 + B_3\lambda + B_4)e^{-\frac{1}{2}(\frac{\lambda-l}{\Delta\lambda_{B_{ref}}})^2}\,d\lambda}{\int_{-\infty}^{\infty}\left[(\lambda-\lambda_{B_{ref}})(\lambda^2 - C_1\lambda - C_2)e^{-\frac{1}{2}(\frac{\lambda-\lambda_{B_{ref}}}{\Delta\lambda_{B_{ref}}})^2}\right]^2\mathrm{d}\lambda} \tag{12}$$

The parameters B_1,B_2, B_3, B_4, C_1 and C_2 of Eq. (12) are mentioned in Appendix.1. Now, if the Eq. (11) is substituted in Eq. (12), we see that the value of α (λ_τ) is maximum at $\lambda_{B_{ref}}$. Hence, we can say that the exact peak wavelength exists at $\lambda_{B_{ref}}$, which is the desired peak of the FBG signal. This mathematical concept has been explained graphically in Figure.3. The nature of reflectivity of a single FBG is plotted in Figure.3a with central peak located at a certain wavelength 1543 nm, and this peak wavelength is to be determined by using the proposed matched filtering method. The Figure.3b describes the cross-correlation between FBG signal and 3rd derivative of reference signal, $C(\lambda_\tau)$ i.e. as mentioned in Eq.(6).In this graph, there are multiple zero-crossing points located λ_{τ_1} , λ_{τ_2} and λ_{τ_3} out of which, there exists one true peak wavelength at which the intensity response, α (λ_τ) as given in Eq.(7) is found positive and maximum, which is plotted in Figure.3c. From the figure, it is seen that, it occurs at $\lambda_{\tau_2} = \lambda_{B_{ref}}$ = 1543 nm. This the desired FBG peak wavelength.

Next, we would implement the proposed peak detection algorithm for identifying multiple FBG peaks present in a reflection spectrum. For different FBG peaks, the Eq. (6) and Eq. (7) can be modified as,

$$\mathrm{C}\left(\lambda_{\tau_i}\right) = \int_{-\infty}^{\infty}\sum_{i=1}^{k} R_i\,(\lambda_i)\,\Psi_i'''\ \lambda_i' +\ \lambda_{\tau_i})\,\mathrm{d}\lambda \tag{13}$$

$$\alpha(\lambda_{\tau_i}) = \sum_{i=1}^{k}\frac{\int_{-\infty}^{\infty} R_i\,(\lambda_i)\,\Psi_i''(\lambda_i' +\ \lambda_{\tau_i})\ \mathrm{d}\lambda}{\int_{-\infty}^{\infty}[\Psi_i'(\lambda_i)]^2\mathrm{d}\lambda} \tag{14}$$

Where $\quad R_i\,(\lambda_i) = e^{-K(\frac{\lambda_i-\lambda_{B_i}}{\Delta\lambda_{B_i}})^2}$ (15)

$$\Psi_i(\lambda_i) = [1 - \left(\frac{\lambda_i - \lambda_{B_{ref_i}}}{\Delta\lambda_{B_{ref_i}}}\right)^2]e^{-K(\frac{\lambda_i - \lambda_{B_{ref\_i}}}{\Delta\lambda_{B_{ref\_i}}})^2} \tag{16}$$

Also $\lambda_i' = \lambda_i - \lambda_{B_{ref,i}}$

And $\lambda_{B1}, \lambda_{B2}, \lambda_{B3}, \ldots\ldots\ldots\ldots\ldots, \lambda_{Bk}$ are the multiple FBG peaks.

From eq.13, as explained earlier that, by equating C (λ_{τ_i}) with zero we will get the zero-crossing wavelength points and from the maximum value of $\alpha(\lambda_{\tau_i})$ of eq.14, we will get the desired FBG peaks. In our case we have considered three FBG peaks located at $\lambda_{B1}, \lambda_{B2}$ and λ_{B3} .The process of proposed peak detection for those peaks is explained graphically in Figure.4. The reflectivity comprising of three FBGs is plotted in Figure.4a with central peaks located at wavelengths 1543 nm, 1545 nm, and 1547 nm. The reference FBG signal is considered as the earlier one mentioned in Figure2. However, while applying all mathematical operations, each time the reference signal is shifted to original wavelength peaks of FBGs. The cross-correlation given in Eq. (13) is thus calculated and plotted in Figure4 (b). From this figure, the zero-crossing points can be determined as it was done earlier. The true FBG peaks can similarly be found by determining$\alpha(\lambda_{\tau_i})$, as given in Eq.(14). It has been plotted in Figure4(c).

From the fig.4c, it is seen that the intensity are maximum at $\lambda_{1\tau_2}, \lambda_{2\tau_2}$ and $\lambda_{3\tau_2}$ and based on the relations, $\boldsymbol{\lambda_{1\tau_2}} = \lambda_{B_{ref,1}}, \boldsymbol{\lambda_{2\tau_2}} = \lambda_{B_{ref,2}}$ and $\boldsymbol{\lambda_{3\tau_2}} = \lambda_{B_{ref,3}}$,the desired multiple peaks are found at 1543 nm, 1545 nm, and 1547 nm.

3. Peak detection of Simulated FBG-reflection spectrum

In this section, we have applied the proposed matched filtering technique of peak detection on a simulated FBG spectrum which consists of multiple peaks. The reflection spectrum of a single FBG is described by couple mode theory [17] as:

$$R(\lambda) = \frac{sinh^2(\sqrt{k^2 - s^2}\mathrm{L})}{cosh^2(\sqrt{k^2 - s^2}\mathrm{L}) - \frac{s^2}{k^2}} \tag{17}$$

Where d=detuning, k=ac coupling coefficient, S= dc coupling coefficient and
s= dc self-coupling coefficient

$$S = \frac{2\pi}{\lambda} * dn_{eff} \quad , \ \mathrm{d} = 2\mathrm{n}\pi(\frac{1}{\lambda} - \frac{1}{\lambda_B}) \ , \quad k = \frac{2\pi}{\lambda} * v * dn_{eff}, \ \text{and} \quad \mathrm{s} = \mathrm{S} + \mathrm{d}.$$

Now considering there are three FBGs connected in series and the total reflection spectrum consisting of those FBG peaks may be written as:

$$R_{total}(\lambda) = \sum_{i=1}^{3} R_i(\lambda) \tag{18}$$

Where R_1 (λ), R_2(λ) and R_3 (λ) are the reflected spectrum of three FBGs i.e. FBG-1, FBG-2, and FBG-3. These are equally spaced over the wavelength range from 1542 nm to 1548 nm. The central peaks of the three FBGs, FBG-1, FBG-2, and FBG-3 are located at 1543 nm, 1545 nm, and 1547 nm, respectively. This has been plotted in Figure 5(a).

The reference signal is chosen as Mexican hat wavelet function as described in Eq.[3] with wavelength range from 1542 nm to 1548 nm, same as the wavelength range of total FBG spectrum as given in Eq.(18). However, the central peak has been shifted to a particular original-FBG peak wavelength each time, while applying the matched filtering algorithm.

To find the zero-crossing points, we have determined the cross-correlation between simulated spectrum of FBG signal and the 3rd derivative of reference signal as discussed in earlier section. This is plotted in Figure5 (b). This provides the zero-crossing points at different wavelengths for each segment of FBG spectrum. In each segment, there are three zero crossing points, out of which there are two false peaks and one true peak. Now, to find the true peak position in each segment, the value $\alpha(\lambda_{\tau_i})$ is calculated and plotted in Figure5(c). It can be seen that, $\alpha(\lambda_{\tau_i})$ is maximum at $\lambda_{1\tau_2}$ in wavelength range 1542 nm -1544 nm, $\lambda_{2\tau_2}$ in 1544 nm -1546 nm and $\lambda_{3\tau_2}$ in 1546 nm -1548 nm. On the other hand, $\alpha(\lambda_{\tau_i})$ is negative and minimum at two zero crossing points in each wavelength range mentioned, which represents the false peaks. Thus, the true peak wavelengths are found as $\lambda_{1\tau_2} = 1543.002$ nm , $\lambda_{2\tau_2} = 1545.0015$ nm and $\lambda_{3\tau_2} = 1547.0017$ nm. These wavelength peaks almost match with the FBG peaks initially assumed to exist at 1543 nm, 1545 nm, and 1547 nm with some deviation. However, the deviation or error can be lowered if the computational step is increased.

From figure 6(a), we can see that, the peak position of FBG is shifted, thereafter we apply the proposed peak detection technique and the zero-crossing point at 1543.5nm for FBG1,1545.5nm for FBG2 and 1547.5nm for FBG3 is predicted and the response is plotted in figure 6(b), also the intensity is calculated at these zero-crossing points and we find the intensity is maximum which is shown in figure 6(c). Hence, based on the above result the shift in peak wavelength is 0.5nm and the proposed algorithm is verified by simulation work.

4. Experimental Setup and Result

The proposed algorithm matched filtering for peak detection of multi FBG is verified experimentally. The experimental setup for peak detection has been designed shown in figure 7. The setup contains two FBG which are connected in a cascaded form with the range of FBG1 is 1548nm to 1552nm, and FBG2 is 1552nm to 1556nm with the central peak of FBG1 and FBG2 is 1549.5nm and 1554.4nm. The broadband light source(denseLight Semiconductors, DL-BX9-CS524A), Y-Coupler, Optical spectrum analyzer set as 0.01nm resolution, and computer device.

The broadband light source is passed through terminal-1 of 3 port Y-coupler and the light emerges at terminal-2 and it passes through the cascaded FBG. Some of the light spectra are reflected at a particular wavelength which is entered again at the terminal-2 of Y Coupler and emerges at port 3. The reflected signal at terminal-3 is collected as spectral data and saved in the computer which is connected to an optical spectrum analyzer(OSA) through a GPIB cable for signal processing.

The normalized response of experimental data is plotted in figure 8(a). The proposed algorithm matched filtering is applied in experimental spectral data and the zero-crossing points are calculated by using the eq.(13) and its response is plotted in figure(8b). The position of the zero-crossing point is measured at 1549.5nm for FBG1 and 1554.4nm for FBG2, the intensity $\alpha(\lambda_{\tau_i})$ is calculated using eq.(14) to verify the correct prediction of zero-crossing point. The calculated intensity response is plotted in figure(8c) and seen the maximum intensity is measured at the same zero-crossing points 1549.5nm for FBG1 and 1554.4nm for FBG2.So, based on the concept of matched filtering the exact peak wavelengths are measured,and the proposed algorithm-matched filtering techniques are successfully verified by theoretically and experimentally.

Conclusion

The algorithm for multiple FBG-peak detection using matched filtering technique is developed and simulated. The algorithm is based on finding the cross-correlation between a reference spectral signal and the FBG-sensor signal. The peak wavelength and intensity are found from the zero-crossing points of the cross-correlation function. The proposed algorithm yields good accuracy. However, the limitation is that the reference signal needs to formulated according to the characteristics or central peaks of the FBGs used. Thus, an apriori knowledge of FBGs is required to formulate the reference signal. The change in the wavelength peaks due to application of measurand is determined suitably by the proposed technique. The work is also implemented experimentally for single and multiple FBG peak detection. This algorithm will work well if the FBG signal is weak and contains narrow peaks.

Declarations

- **Availability of data and material –** Applicable(attached in supplementry file).
- **Competing Interests-**This reseach work is algorithm based , there is no competing of interests.
- **Funding-** Not Applicable.
- **Author's contributions-** In the manuscript **'Efficient Detection of Multiple FBG Wavelength Peaks using Matched Filtering Technique'** we have contributed as, the author 'SK' carried out the study all the parameters which are used in matched filtering peak detection technique, the design of peak detection algorithm, and the result analysis. The drafting and manuscript writing is carried out by SS.
- **Code availability-** Not Applicable.

- **Acknowledgements-** Not Applicable.

References

[1] Qi, Yuefeng, et al. "Research on temperature and humidity sensing characteristics of cascaded LPFG-FBG." *Optik* 188 (2019): 19-26.

[2] M. Zhu, H. Murayama, D. Wada, K. Kageyama, Dependence of measurement accuracy on the birefringence of PANDA fiber Bragg gratings in distributed simultaneous strain and temperature sensing, Opt. Express 25 (4) (2017) 4000–4017.

[3] C. Rodrigues, C. Félix, A. Lage, J. Figueiras, Development of a long-term monitoring system based on FBG sensors applied to concrete bridges, Eng. Struct. 32 (8) (2010) 1993–2002.

[4] V.R. Pachava, S. Kamineni, S.S. Madhuvarasu, V.R. Mamidi, Fiber Bragg gratingbased hydraulic pressure sensor with enhanced resolution, Opt. Eng. 54 (9)(2015) 6.

[5] A. Li, Y. Wang, Q. Hu, W. Shieh, Few-mode fiber based optical senses, Opt. Express 23 (2) (2015) 1139– 1150.

[6] D. Yelin, D. Oron, S. Thiberge, E. Moses, Y. Silberberg, Multiphoton plasmon-resonance microscopy, Opt.Express 11 (12) (2003) 1385–1391.

[7] J. Habel, T. Boilard, J.S. Freniere, F. Trepanier, M. Bernier, Femtosecond FBG written through the coating for sensing applications, Sensors 17 (11) (2017) 11.

[8] H. Jiang, J. Chen, T. Liu, W. Huang, A novel wavelength detection technique of overlapping spectra in the serial WDM FBG sensor network, Sens. Actuat. A Phys.198 (2013) 31–34.

[9] K.T.V. Grattan, T. Sun, Fiber optic sensor technology: an overview, Sens. Actuat. A 82 (1) (2003) 40–61.

[10] Trita, Andrea, et al. "Simultaneous interrogation of multiple fiber Bragg grating sensors using an arrayed waveguide grating filter fabricated in SOI platform." *IEEE Photonics Journal* 7.6 (2015): 1-11.

[11] Bodendorfer, Thomas, et al. "Comparison of different peak detection algorithms with regards to spectrometic fiber Bragg grating interrogation systems." *2009 International Symposium on Optomechatronic Technologies.* IEEE, 2009.

[12] Wang, Peng, et al. "Research on peak-detection algorithm for high-precision demodulation system of fiber Bragg grating." *International Journal of Hybrid Information Technology* 7.6 (2014): 337-344.

[13] Z.J. Chen, J. Bai, Z. Tang, W.U.X.H. Zhao, J.J. Zhang, Optimization and comparison of the peak-detection algorithms for the reflection spectrum of fiber bragg grating,Acta Photon. Sin. 5 (4) (2015) 323–334.

[14] Liu F, Tong X, Zhang C, Deng C, Xiong Q, Zheng Z, Wang P. Multi-peak detection algorithm based on the Hilbert transform for optical FBG sensing. Optical Fiber Technology. 2018 Nov 1;45:47-52..

[15] Ding, Peng, Junbin Huang, and Jinsong Tang. "Multi-peak FBG reflection spectrum segmentation based on continuous wavelet transformation." Optical Fiber Technology 50 (2019): 250-255.

[16] Theodosiou, Antreas, Michael Komodromos, and Kyriacos Kalli. "Accurate and fast demodulation algorithm for multipeak FBG reflection spectra using a combination of cross correlation and Hilbert transformation." Journal of Lightwave Technology 35.18 (2017): 3956-3962.

[17] Guo, Yu, et al. "Accurate demodulation algorithm for multi-peak FBG sensor based on invariant moments retrieval." Optical Fiber Technology 54 (2020): 102129.

[18] Yu, Junsong, et al. "Impact localization for composite plate based on detrended fluctuation analysis and centroid localization algorithm using FBG sensors." Optik 167 (2018): 25-36.

[19] Guo, Yu, et al. "FBG wavelength demodulation based on bandwidth of radio frequency signals." Optics Communications 454 (2020): 124478.

[20] Data Analysis and Signal Processing in Chromatography By A. Felinger chapter-8

[21] Huang WP. Coupled-mode theory for optical waveguides: an overview. JOSA A. 1994 Mar 1;11(3):963-83.

[22] Erdogan T. Fiber grating spectra. Journal of lightwave technology. 1997 Aug;15(8):1277-94.

[23] Qin, Zhang-jian, et al. "Peak center and area estimation in gamma-ray energy spectra using a Mexican-hat wavelet" Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 858 (2017): 22-29.

List of Figure

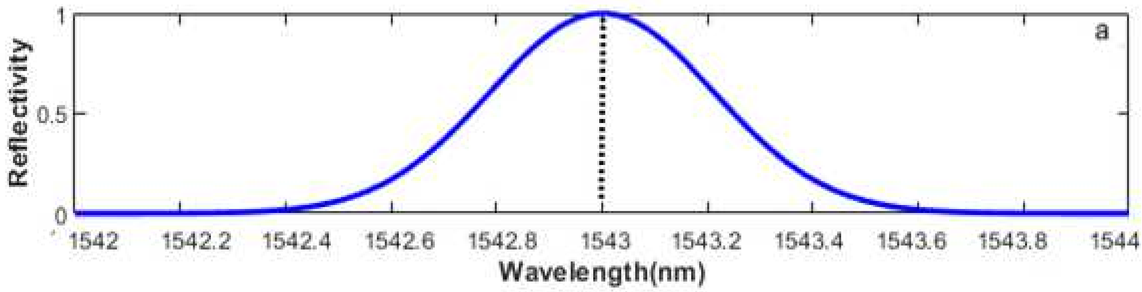

Figure (1) Gaussian model spectrum

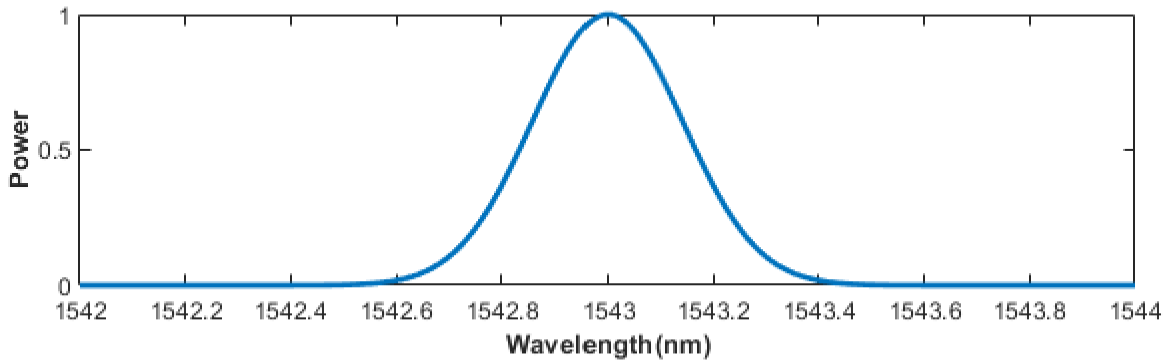

Figure (2). Reference signal as Mexican-Hat wavelets function.

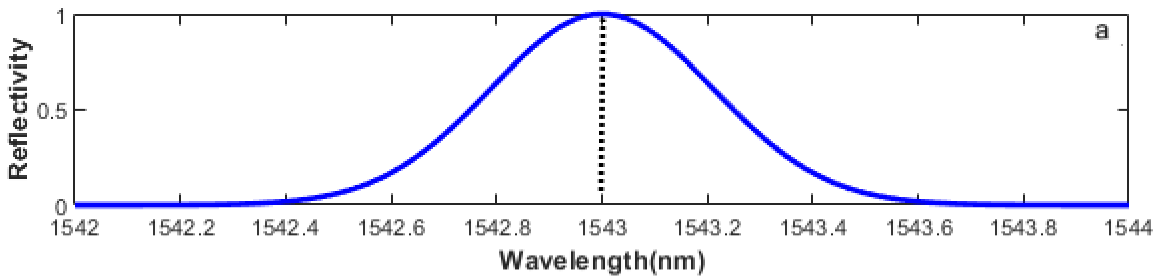

Figure 3(a) an approximated FBG reflected spectrum R (λ)   as given in Eq.2

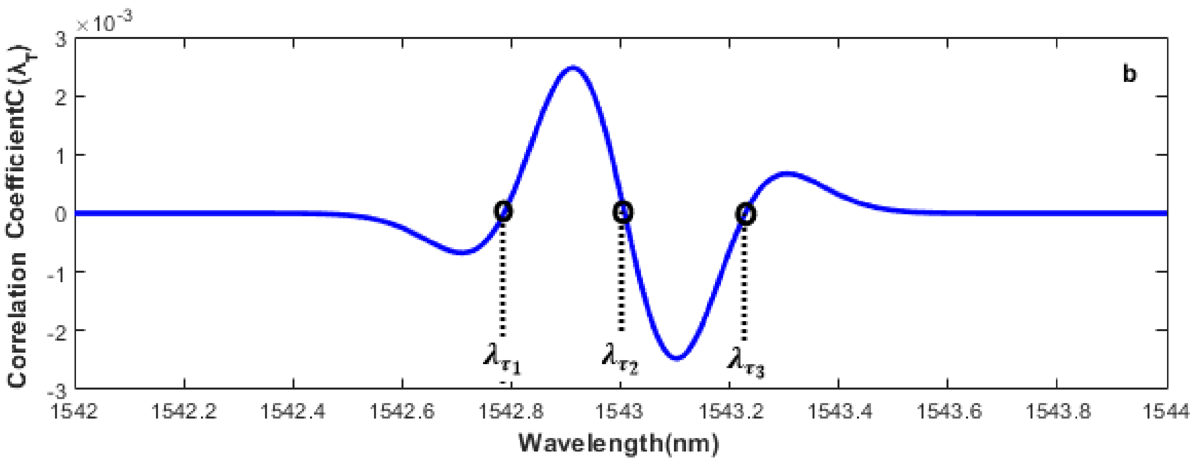

Figure 3(b) Cross-correlation between FBG-signal and 3rd derivative of reference signal as given in Eq. (6)

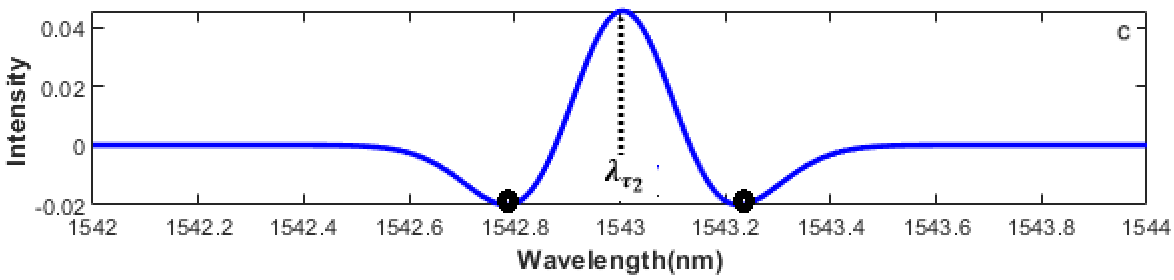

Figure 3(c) Correlation between reference signal and FBG signal as given in Eq. (7).

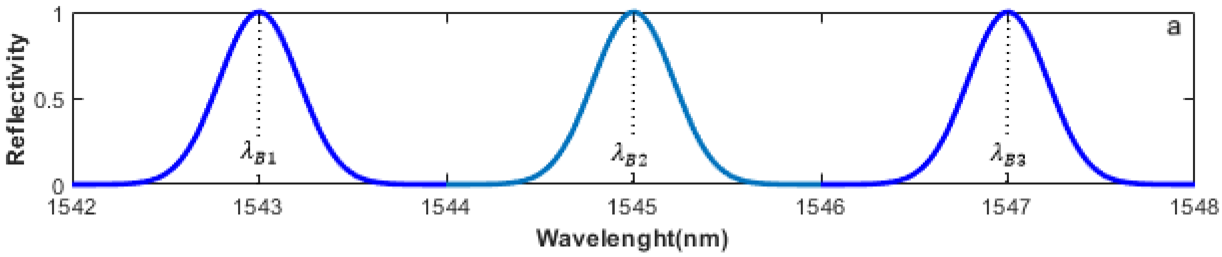

Figure4(a) An approximated 3-FBG reflected spectrum R (λ_i) as given in Eq.15

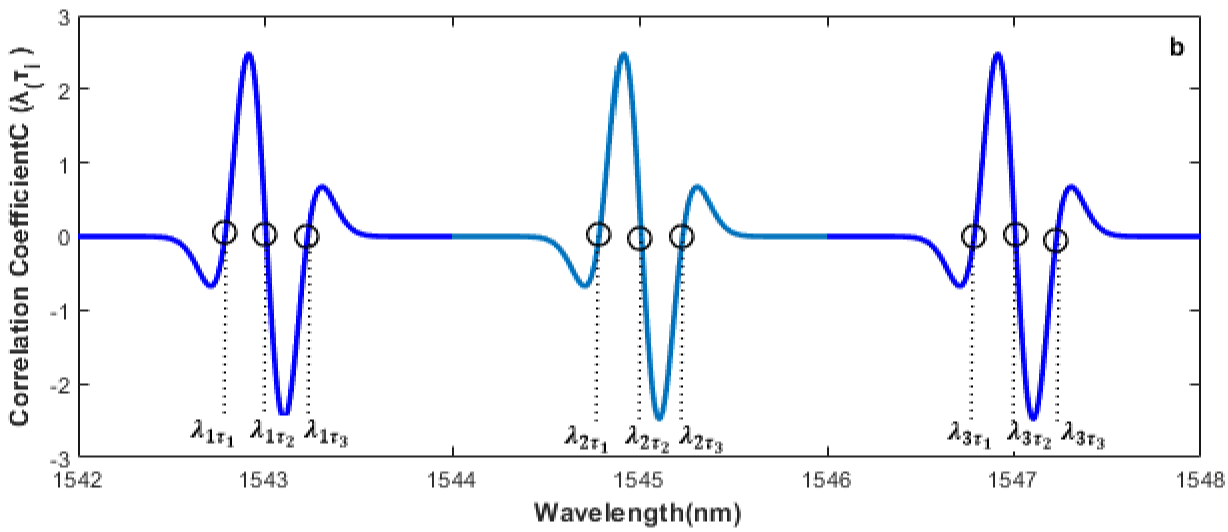

Figure4(b) Cross-correlation between FBG-signal and 3rd derivative of reference signal as given in Eq.13

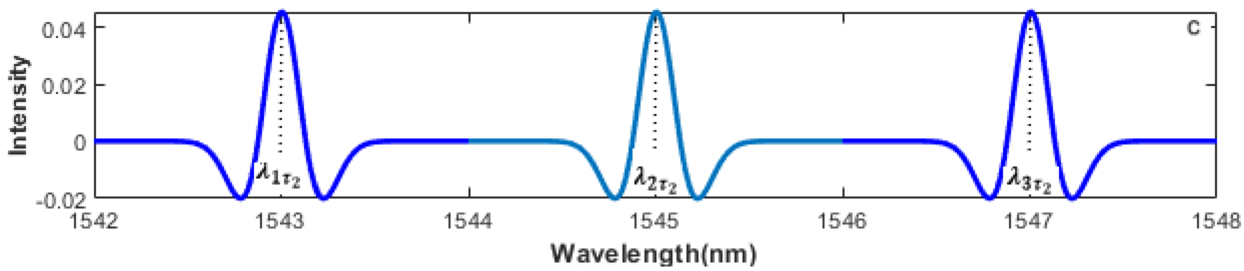

Figure4(c) the Cross-correlation between Reference signal and 3-FBG described in Eq.14.

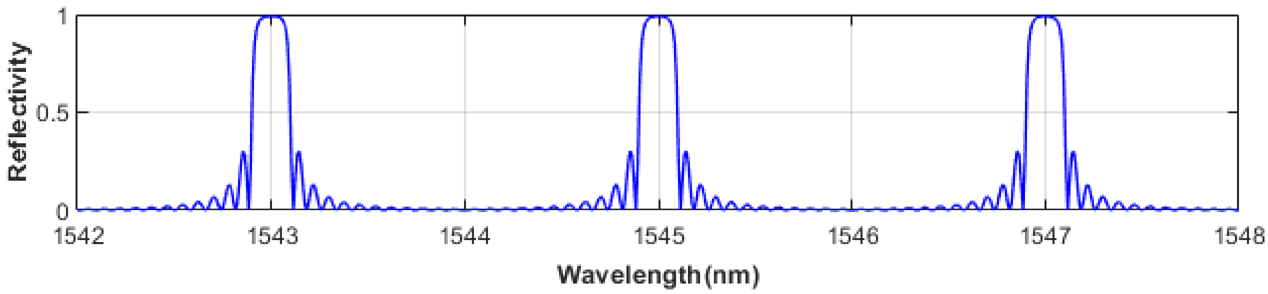

Figure5 (a). Simulated spectrum response of three FBG.

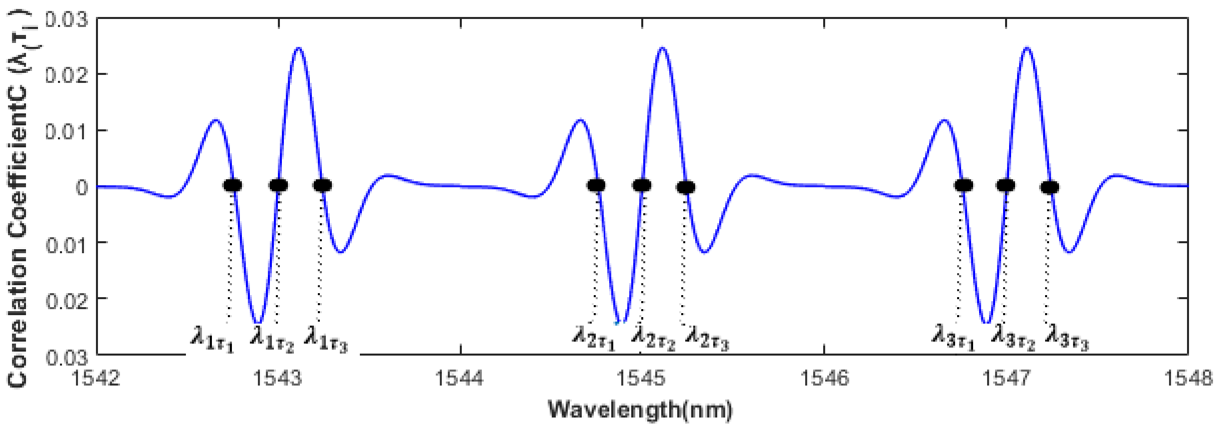

Figure5 (b) Cross correlation between simulated spectrum response of FBG and 3rd derivative of reference signal

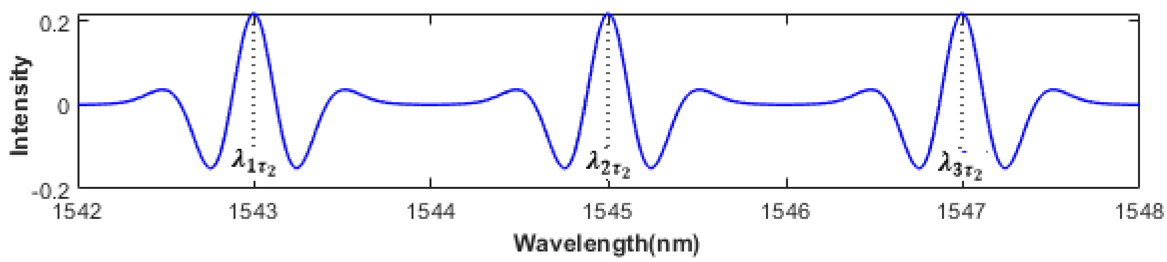

Figure5(c) Intensity Response between simulated response data of FBG and reference signal

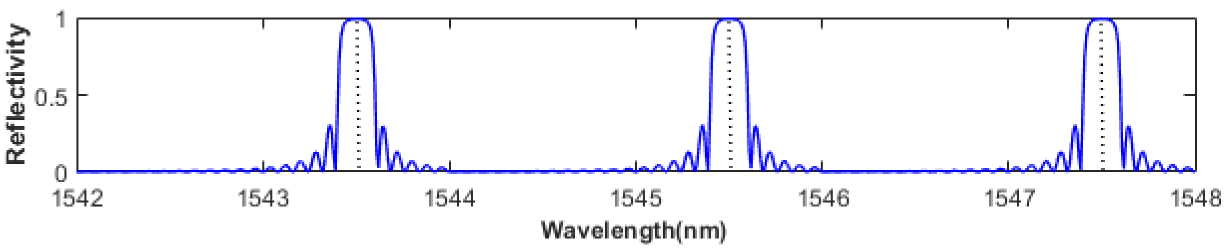

Figure6 (a). shifted Simulated spectrum response of three FBG.

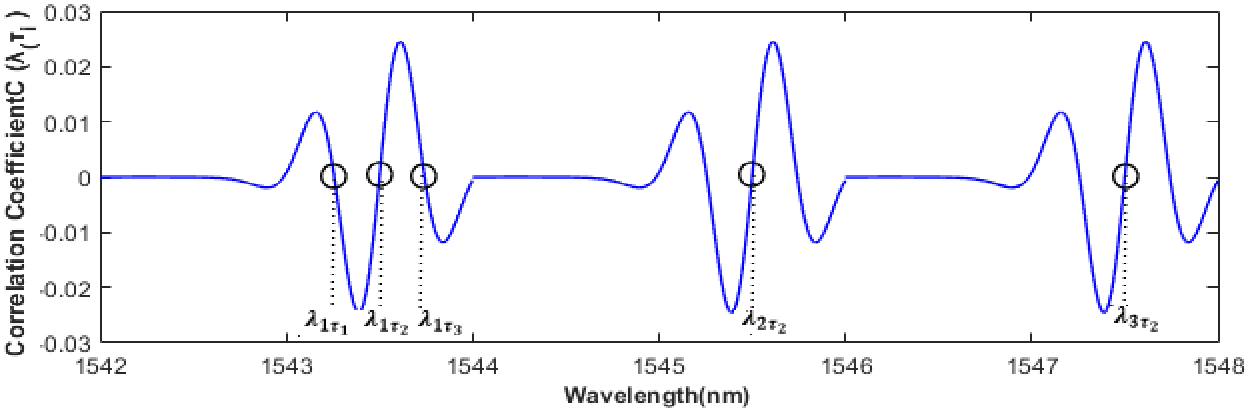

Figure6(b) Zero-Crossing Point calculation after peak is shifted

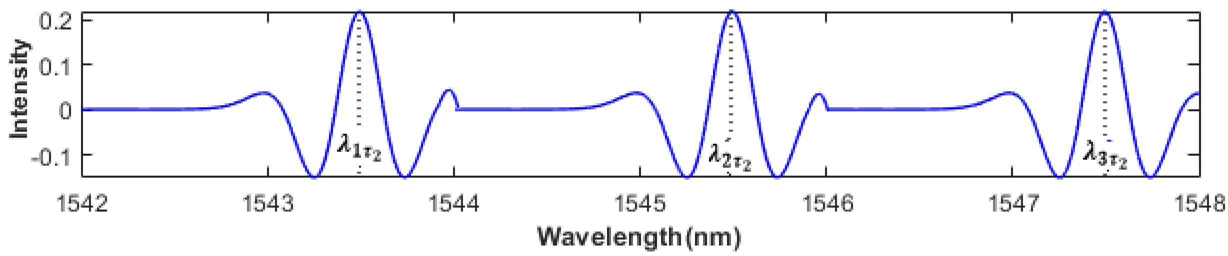

Figure6(c) Maximum Intensity prediction after peak shifting

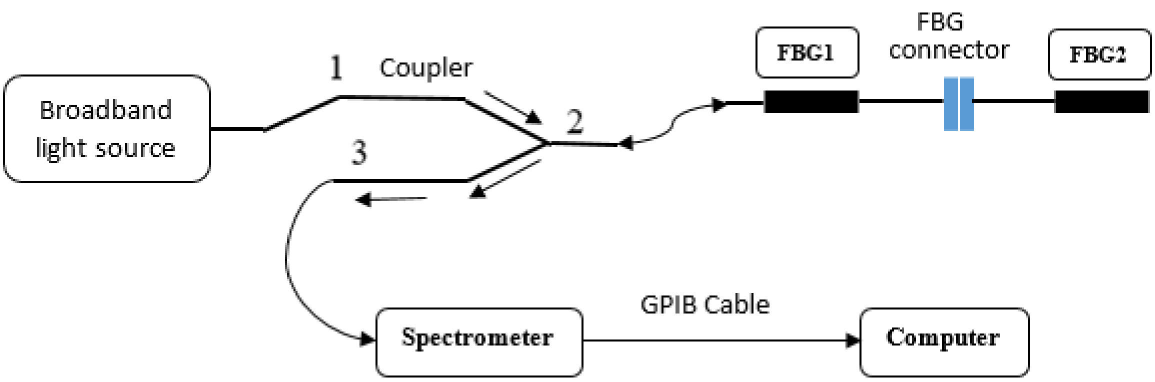

Figure 7. Experimental setup for measurement of FBG peaks

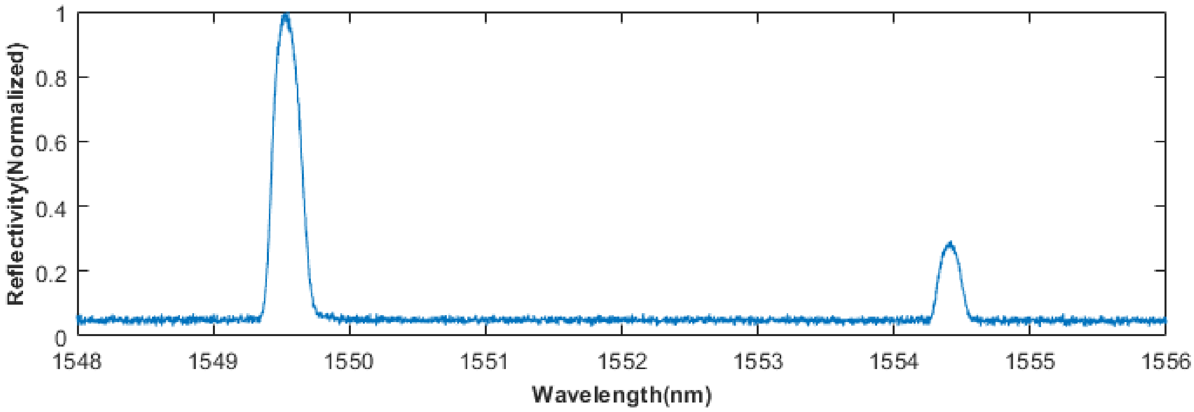

Figure.8(a) Experimental reflected response of two FBG

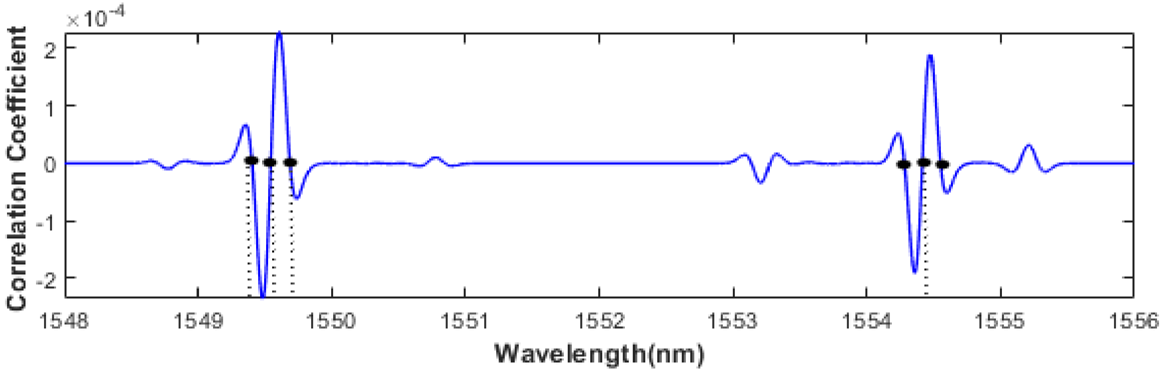

Figure.8(b) Cross correlation between FBG reflected spectrum and 3rd derivative of reference signal

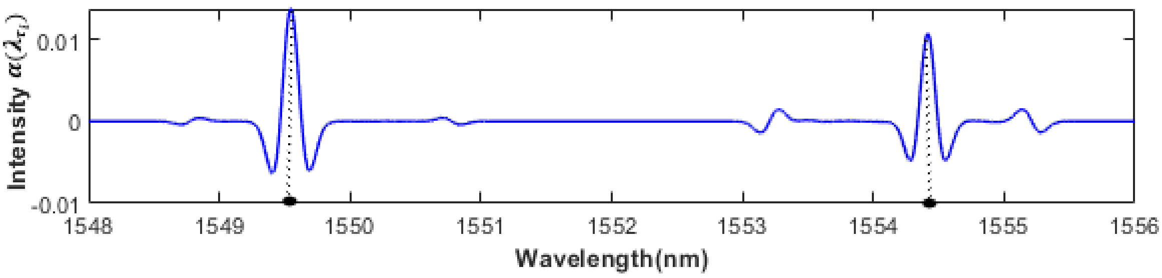

Figure.8(c) Intensity Response between experimental response of FBG and reference signal

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- supplementaryfile.docx