Efficient detection of multiple FBG wavelength peaks using matched filtering technique

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Abstract
We propose an efficient method 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 the cross-correlation between the FBG signal and 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 method has been experimentally verified for isolated as well as overlapped FBG spectrum. 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.

Keywords 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 (Qi et al. 2019; Zhu et al. 2017; Rodrigues et al. 2010; Pachava et al. 2015). The 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 (Li et al. 2015; Yelin et al. 2003). 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 (Habel et al. 2017; Jiang et al. 2013; Grattan and Sun 2003). 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 (Trita et al. 2015), polynomial curve fitting, direct peak method (Bodendorfer et al. 2009), Gaussian non-linear method (Wang et al. 2014) etc. have been reported (Chen et al. 2015). For the multiple-peak detection of FBG based sensors the signal processing techniques such as Hilbert transform (Liu et al. 2018), segmentation based continuous wavelets transform (Ding et al. 2019), cross correlation with Hilbert transform (Theodosiou et al. 2017), invariant moments retrieval method (Guo et al. 2020a), and centroid localization algorithm (Yu et al. 2018) 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 (Guo et al. 2020b). Although this is real-time based technique, 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 method 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 method has been experimentally verified and had has good accuracy. 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, overlapped and contains narrow peaks.

2 Principle of algorithm

When a broadband light is incident on FBG, a wavelength called Bragg wavelength is reflected from it. It is given by,

\[ \lambda_B = 2n_{eff}\Lambda \]  

(1)

where \( n_{eff} \) is the effective refractive index of fundamental core mode and \( \Lambda \) 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 matched 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 temperature. The reference signal is centred at a particular wavelength, which may not match with the FBG peak wavelength.

In order to explain the algorithm, 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. The Mexican-Hat wavelet
is chosen because of its narrow spectral band as it is nothing but the derived version (2nd derivative) of a simple Gaussian function.

The Gaussian spectral signal can be written as (Wang et al. 2014),

$$R(\lambda) = e^{-\frac{4 \ln 2}{\Delta \lambda_B} \left( \frac{\lambda - \lambda_B}{\Delta \lambda_B} \right)^2}$$  \hspace{1cm} (2)

where $\lambda_B$ 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 to 1544 nm and the central peak is located at 1543 nm.

The reference signal or Mexican-Hat wavelet function, can be described by Felinger (1998),

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

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

It is also plotted in Fig. 2 with the same wavelength range as of Fig. 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:
\[
F(\lambda_r, \alpha) = \int_{-\infty}^{\infty} \left[ R'(\lambda) - a\Psi'(\lambda + \lambda_r) \right]^2 d\lambda \tag{4}
\]

where \(\lambda_r\) is the delay variable and represents peak location and \(\alpha\) represents the height or magnitude of the unknown peak.

The Eq. (4) is minimized by applying derivative with respect to \(\lambda_r\) and \(\alpha\), on it. It will yield two parameters, \(C(\lambda_r)\) and \(\alpha(\lambda_r)\), which are described as in Eqs. (5) and (6).

\[
C(\lambda_r) = \int_{-\infty}^{\infty} R(\lambda)\Psi''(\lambda' + \lambda_r) d\lambda \tag{5}
\]

where \(\lambda' = \lambda - \lambda_{\text{ref}}\), \(\lambda\) is the wavelength range for reference signal same as FBG

\[
\alpha(\lambda_r) = \frac{\int_{-\infty}^{\infty} R(\lambda)\Psi''(\lambda' + \lambda_r) d\lambda_i}{\int_{-\infty}^{\infty} (\Psi''(\lambda))^2 d\lambda} \tag{6}
\]

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

\[
C(\lambda_r) = 0 \tag{7}
\]

\[
\int_{-\infty}^{\infty} R(\lambda)\Psi''(\lambda' + \lambda_r) d\lambda = 0 \tag{8}
\]

\[
\int_{-\infty}^{\infty} e^{-4\ln 2 \left( \frac{\lambda - \lambda_{\text{ref}}}{\lambda_{\text{ref}}} \right)^2} \cdot c^{-8} \cdot (\lambda^5 - A_1 \lambda^4 + A_2 \lambda^3 + A_3 \lambda^2 + A_4 \lambda - A_5) e^{-\frac{1}{2} \left( \frac{\lambda - \lambda_{\text{ref}}}{\lambda_{\text{ref}}} \right)^2} d\lambda = 0 \tag{9}
\]

\[
l = \lambda_{\text{ref}} - \lambda_r \text{ And the parameters } A_1, A_2, A_3, A_4 \text{ and } A_5 \text{ of Eq. (9) are simply the coefficients due to differentiation as given in Appendix 1. By evaluating the integration of Eq. (9), and equating with zero, we can find the zero crossing points, which exists at }
\]

\[
\lambda_r = \lambda_{\text{ref}} \tag{10}
\]

Next, to find the desired wavelength peak, we would calculate \(\alpha(\lambda_r)\) given in Eq. (6) as follows.

\[
\alpha(\lambda_r) = \frac{\int_{-\infty}^{\infty} e^{-4\ln 2 \left( \frac{\lambda - \lambda_{\text{ref}}}{\lambda_{\text{ref}}} \right)^2} \cdot c^{-8} \cdot (\lambda^4 - B_1 \lambda^3 + B_2 \lambda^2 + B_3 \lambda + B_4) e^{-\frac{1}{2} \left( \frac{\lambda - \lambda_{\text{ref}}}{\lambda_{\text{ref}}} \right)^2} d\lambda}{\int_{-\infty}^{\infty} \left( \lambda - \lambda_{\text{ref}} \right) \left( \lambda^2 - C_1 \lambda - C_2 \right) e^{-\frac{1}{2} \left( \frac{\lambda - \lambda_{\text{ref}}}{\lambda_{\text{ref}}} \right)^2} d\lambda} \tag{11}
\]

The parameters \(B_1, B_2, B_3, B_4, C_1\) and \(C_2\) of Eq. (11) are mentioned in Appendix-1. Now, if the Eq. (10) is substituted in Eq. (11), we see that the value of \(\alpha(\lambda_r)\) is maximum at \(\lambda_{\text{ref}}\). Hence, we can say that the exact peak wavelength exists at \(\lambda_{\text{ref}}\), which is the desired peak of the FBG signal. This mathematical concept has been explained graphically in Fig. 3.
The nature of reflectivity of a single FBG is plotted in Fig. 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 Fig. 3b describes the cross-correlation between FBG-signal and 3rd derivative of reference signal, \( C(\lambda_\tau) \) i.e. as mentioned in Eq. (5). In this graph, there are multiple zero-crossing points located \( \lambda_{r1}, \lambda_{r2} \) and \( \lambda_{r3} \) out of which, there exists one true peak wavelength at which the intensity response, \( \alpha(\lambda_e) \) as given in Eq. (6) is found positive and maximum, which is plotted in Fig. 3c. From the figure, it is seen that, it occurs at \( \lambda_{r2} = \lambda_{Bref} = 1543 \) 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 Eqs. (5) and (6) can be modified as,

\[
C(\lambda_{e_i}) = \int_{-\infty}^{\infty} \sum_{i=1}^{k} R_i(\lambda_i) \Psi''''(\lambda_i + \lambda_{e_i}) \, d\lambda \\
\alpha(\lambda_{e_i}) = \sum_{i=1}^{k} \frac{\int_{-\infty}^{\infty} R_i(\lambda_i) \Psi''''(\lambda_i + \lambda_{e_i}) \, d\lambda}{\int_{-\infty}^{\infty} |\Psi'(\lambda_i)|^2 \, d\lambda}
\]

where

\[
R_i(\lambda_i) = e^{-K \left( \frac{\lambda_i - \lambda_{r_i}}{\Delta \lambda_{r_i}} \right)^2}
\]
\[
\Psi'_i(\lambda_i) = \left| 1 - \left( \frac{\lambda_i - \lambda_{B_{ref,i}}}{\Delta \lambda_{B_{ref,i}}} \right) \right|^2 e^{-K\left(\frac{\lambda_i - \lambda_{B_{ref,i}}}{\Delta \lambda_{B_{ref,i}}}\right)^2}
\]  
(15)

also, \( \lambda'_i = \lambda_i - \lambda_{B_{ref,i}} \) and \( \lambda_{B1}, \lambda_{B2}, \lambda_{B3}, \ldots, \lambda_{Bk} \) are the multiple FBG peaks.

From Eq. (12), as explained earlier that, by equating \( C(\lambda_i) \) with zero we will get the zero-crossing wavelength points and from the maximum value of \( \alpha(\lambda_i) \) of Eq. (13), we will get the desired FBG peaks. In our case we have considered three FBG peaks located at \( \lambda_{B1}, \lambda_{B2}, \lambda_{B3}, \ldots \). The process of proposed peak detection for those peaks is explained graphically in Fig. 4. The reflectivity comprising of three FBGs is plotted in Fig. 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 Fig. 2. 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. (12) is thus calculated and plotted in Fig. 4b. 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 \( \alpha(\lambda_i) \), as given in Eq. (13). It has been plotted in Fig. 4c.

From the Fig. 4c, it is seen that the intensity are maximum at \( \lambda_{1r_1}, \lambda_{2r_2}, \) and \( \lambda_{3r_3} \) and based on the relations, \( \lambda_{1r_1} = \lambda_{B_{ref,1}}, \lambda_{2r_2} = \lambda_{B_{ref,2}} \), and \( \lambda_{3r_3} = \lambda_{B_{ref,3}} \), the desired multiple peaks are found at 1543 nm, 1545 nm, and 1547 nm.

![Fig. 4](image-url) Illustration of multiple-FBG peak detection using matched filtering technique, a an approximated 3-FBG reflected spectrum \( R(\lambda_i) \) as given in Eq. (14), b cross-correlation between FBG-signal and 3rd derivative of reference signal as given in Eq. (12), c intensity response \( \alpha(\lambda_i) \) as described in Eq. (13)
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 (Guo et al. 2020a) as:

$$R(\lambda) = \frac{\sinh^2 \left( \sqrt{k^2 - s^2}L \right)}{\cosh^2 \left( \sqrt{k^2 - s^2}L \right) - \frac{s^2}{k^2}}$$  \hspace{1cm} (16)

where $d =$ detuning, $k =$ ac coupling coefficient, $S =$ dc coupling coefficient and $s =$ dc self-coupling coefficient $S = \frac{2\pi}{d} * d_{\text{eff}}$, $d = 2n\pi \left( \frac{1}{\lambda} - \frac{1}{\lambda_{a}} \right)$, $k = \frac{2\pi}{d} \times \nu \times d_{\text{eff}}$, and $s = S + d$.

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

$$R_{\text{total}}(\lambda) = \sum_{i=1}^{3} R_i(\lambda)$$  \hspace{1cm} (17)

where $R_1(\lambda)$, $R_2(\lambda)$ and $R_3(\lambda)$ 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 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 Fig. 5a.

![Fig. 5](image-url) Simulation of multiple-FBG peak detection using matched filtering technique, a Simulated spectrum of three FBGs, b Cross-correlation between simulated spectral data of FBG and 3rd derivative of reference signal, c intensity response $a(\lambda_\nu)$ as in Eq. (13)
The reference signal is chosen as Mexican-hat wavelet function as described in Eq. (3) with wavelength range from 1542 to 1548 nm, same as the wavelength range of total FBG spectrum as given in Eq. (17). 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 Fig. 5b. 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 $a(l_i)$ is calculated and plotted in Fig. 5c. It can be seen that, $a(l_i)$ is maximum at $l_{1_{t_2}}$ in wavelength range 1542–1544 nm, $l_{2_{t_2}}$ in 1544–1546 nm and $l_{3_{t_2}}$ in 1546–1548 nm. On the other hand, $a(l_i)$ 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 $l_{1_{t_2}} = 1543.002$ nm, $l_{2_{t_2}} = 1545.0015$ nm and $l_{3_{t_2}} = 1547.0017$ 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.

Next, we have verified our algorithm for detecting the FBG peaks when they get shifted under any circumstances. It has been demonstrated in Fig. 6. Here, we consider that three FBG peaks (same as previous case) get shifted by an equal amount say 0.5 nm. In Fig. 6a, we can see that, the peak positions of FBG are shifted. After applying the proposed peak detection technique, the zero-crossing points have been calculated. The corresponding intensity graph is plotted as done previously and the true peaks are obtained at 1543.5 nm for FBG-1, 1545.5 nm for FBG-2 and 1547.5 nm for FBG-3, as shown in Fig. 6c. This shows that, the proposed algorithm is able to detect the shifts in FBG peaks, which may be equal or different.

### 4 Experimental results and discussion

The proposed algorithm matched filtering for peak detection of multi FBG is verified experimentally. The experimental setup for peak detection is shown in Fig. 7. The setup contains two FBGs which are connected in a cascaded form with the range of FBG-1 is 1548 nm to 1552 nm, and FBG-2 is 1552 nm to 1556 nm with the central peaks of FBG-1 and FBG-2 are 1549.5 nm and 1554.4 nm respectively.

The broadband light source (DenseLight Semiconductors, DL-BX9-CS524A) is passed through terminal-1 of 3 port Y-coupler and the light emerges at terminal-2 and it passes through the cascaded FBGs. The reflected light spectra from FBGs, centered at particular wavelengths enters 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 analyser (OSA) through a GPIB cable for signal processing.

The normalized response of experimental data is plotted in Fig. 8a. The proposed algorithm is applied on the experimental spectral data and the zero-crossing points are calculated by using the Eq. (12) and its response is plotted in Fig. 8b. The position of the zero-crossing points are measured at 1549.5 nm for FBG-1 and 1554.4 nm for FBG-2, and the intensity $a(l_i)$ is calculated using Eq. (13) to verify the correct prediction of zero-crossing points. The calculated intensity response is plotted in Fig. 8c and it is seen that,
the maximum intensity occurs at the same zero-crossing points i.e. 1549.5 nm for FBG-1 and 1554.4 nm for FBG-2.

**4.1 FBG peak detection for overlapped spectra**

The proposed peak detection algorithm using matched filtering technique is verified experimentally to identify the peaks in case of overlapped spectra. We have considered two FBGs having peak wavelengths at 1549.33 nm and 1549.47 nm with 3-dB
bandwidth around 0.3 nm as plotted in Fig. 9a. It is seen that they partially overlap to each other. Using the procedure described earlier, the zero-crossing points have been calculated and are marked by dark circles on the graph mentioned in Fig. 9b. The corresponding intensities at those points have been calculated as shown in Fig. 9c. The wavelength points having maximum intensity are found out, which yield the desired peak wavelengths as 1549.33 nm and 1549.47 nm.

Thus, it is seen that, the proposed FBG-peak detection using matched filtering technique works well for detection of wavelength peaks out of a composite spectrum. It has the ability to detect the noisy or weak spectral signals and also to estimate the height of the peaks from the parameter $\alpha(\lambda_\tau)$, as given in Eq. (6). The performance of this method has been measured by calculating some statistical parameters e.g. mean, standard deviation, and Root Mean Square Error (RMSE) etc. These are also compared with other peak detection techniques as shown in Table 1. It is seen that from the table that, the proposed method provides the mean and standard deviation of 0.091 pm and 0.045 pm.
respectively, which are less as compared to other methods. The 3-dB bandwidth of the FBG signals processed is 0.3 nm, which is almost the same for all techniques. The RMSE is found to be least as 0.34 pm compared to other methods. These show that the peak detection has higher accuracy.

5 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 be formulated according to the characteristics or central peaks of the FBGs used. Thus, an a priori 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.
| Reference no.       | FGB peak detection methods based on                                      | 3-dB bandwidth of FBG signal considered (nm) | Mean (pm) | Standard deviation (pm) | RMSE (pm) |
|--------------------|---------------------------------------------------------------------------|---------------------------------------------|-----------|-------------------------|-----------|
| Liu et al. (2018)  | Hilbert transform                                                         | 0.212                                       | 5.80      | 3.37                    | –         |
| Ding et al. (2019) | Continuous wavelet transformation and Hilbert transform                   | 0.4                                         | –         | –                       | 7.5       |
| Guo et al. (2020a) | Invariants moment interval                                                | 0.3                                         | 0.19      | 0.13                    | 0.5       |
| Chen et al. (2016) | Self-adaptive peak detection method                                       | 0.5                                         | –         | 0.12                    | –         |
| Xu et al. (2020)   | The Levenberg method                                                      | –                                           | 3.6       | –                       | –         |
| –                  | Matched filtering (present work)                                          | 0.3                                         | 0.091     | 0.045                   | 0.34      |
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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.

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Code availability Not applicable.

Declarations

Conflict of interests This research work is algorithm based, there is no competing of interests.

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