Optical Strain Gauge Signal Processing

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Abstract:** (Fiber Bragg Grating (FBG) sensors are becoming more popular in the sensing applications where high precision is required. Fiber Bragg Grating is a periodic variation of refractive index in an optic fiber. Basically FBG is a wavelength selective filter for the optical signals. Filter frequency is based on the pitch length of the grating .Due to strain, the pitch length changes, which in turn changes the peak wavelength of the reflected spectrum. From the center wavelength shift, strain can be computed. Due to temperature , there is an indirect strain inducement in the fiber which can alter the peak wavelength in an indirect way .By computing the change in peak wavelength shift , temperature can also be measured .In this work, noise filtering was carried out with different filters like Butterworth LPF, Gaussian Filter and wavelet de-noising technique. After each filtering, Gaussian fitting technique was used to calculate the peak wavelength of the reflected spectrum since the reflected spectrum resembles with Gaussian distribution. It was observed that Wavelet de-noising associated with Gaussian fitting is more better in terms of peak wavelength shift after filtering .Studied the effect of temperature by applying constant strain at different temperatures in a digitally controlled oven .Observed that peak wavelength is same for a particular temperature at different instances while thermal cycling was carried out . A bonded sensor was tested to find the correlation between signals at different temperatures and found that the signal spectrum is highly correlated at different temperatures and thereby came to a conclusion that existing wavelet de-noising technique with Gaussian fitting can be used reliably for measuring the central wavelength shift.

***Keywords:** Gaussian fitting, Gaussian distribution, Fiber Bragg Grating, Optical Spectral Analyzer*

I. INTRODUCTION

Optical Fiber Sensors (OFS) became more popular after the invention of the practical optical fiber by the Corning Glass works in 1970 [23]. In our work, we are more focused in to special type of Optical sensors called Fiber Bragg Grating sensors, popularly known as FBG. Fiber Bragg Grating sensors are manufactured by changing the refractive index of a particular portion of the Fiber core by various processes. Normally single mode fibers are used for the construction of FBG sensors. Fiber Bragg Gratings sensors are widely used in Industries where accuracy is an important thing. FBG sensors can be used in Reusable launch vehicles in Space technology because of its high accuracy and reliability. It can measure both temperature and strain directly. The most important thing is that multiple FBG sensors can be fabricated in a single Fiber, which can be used to measure the distributed temperature profile of a surface. By means of having special coatings, FBGs can be used in both cryogenic as well as very high temperatures. FBG Sensors are free from Electromagnetic interference, which make them capable of measuring strain and temperature at places like electromagnetic interference is more. The accuracy of the FBG based strain gauges are more as compare with conventional sensors. It can measure an accuracy of p$^{\varepsilon}$ range, which is highly useful to analyze the strain impact on the structures of reusable launch vehicles where precision requirement is more as compare with other industrial applications.

A. Main Challenges

The challenges in FBG sensors are based on the optical signal processing related issues. A constant light source mechanism is always required to supply the light energy as input .A perfect filter should be designed to remove the noise without having much shift in peak wavelength since peak wavelength shift is the reference for calculating the strain and temperature. Unwanted peak wavelength shift can contribute to wrong measurement and that should be avoided as much as possible .Care should be taken while placing the fiber sensor on a surface where strain, temperature or both have to be measured .Fixing of sensor to the surface should be properly done in order to have the accurate reading .An additional sensor should be used to calculate the temperature influence while measuring the strain of an object in a temperature varying environment. In a temperature varying environment, the actual strain is calculated by deducting the influence of thermally induced strain.

II. LITERATURE REVIEW

Optical fiber is simply a circular wave guide [12] [13] which can be used to convey signal in the form of light. It consists of mainly two cylindrical parts, the outer one is called as Cladding and the inner one is called as Core. The Refractive index of outer cladding is slightly less as compare with inner core. Basically the main constituent of optical fiber construction is silica doped with materials like GeO_2 . The dopant materials are responsible for its refractive index profile changes. Acrylate coating [19] is provided over the cladding to protect the fiber from rough surfaces. A Polyethylene sheath is also used to encase the fiber within a strength material such as Kevlar or steel strands. As per the Snell’s law, light can only travel through core since it is having higher refractive index than the outer cladding.

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The refractive index of Core (n_1) is higher than the refractive index of cladding (n_2). The basic principle behind the transmission of light through the optical fiber is Snell's law [17] [18].
If the light entering into the fiber with an angle more than Critical angle, then the light reflects back to the incident plane . This phenomenon is called as Total Internal Reflection which leads the propagation of light along the core.
One of the most commonly used and broadly deployed optical sensors is the Fiber Bragg Grating (FBG) [13], which reflects a wavelength of light that shifts in response to variations in temperature and/or strain[9] [10]. A fiber Bragg grating (FBG) is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index profile of the fiber core, which generates a wavelength-specific dielectric mirror.

This is the basic idea behind the sensors based on Fiber Bragg Grating. In our experiments, we used FBG sensors to measure the strain and we tried to find out the intervention of temperature in the FBG sensor .We studied the thermal characteristics of FBG sensor at various temperatures and observed that the shift in peak wavelength is a function of temperature and the bonding material. We used both Butterworth Low pass filter and Gaussian filtering technique to eliminate the high frequency noise, and found Gaussian Filtering [15] [20] is far better than Butterworth low pass filter in case of peak wavelength finding.

III. PROPOSED METHODOLOGY

Functional Units of experimental set-up consists of the Functional Units of experimental set-up consists of the sensor imprinted on the fiber core, 3 port Circulator, Optical Spectral Analyzer and SLED light source. The reflected spectrum through the third port of the circulator is captured by the OSA. The OSA stored data is processes by MATLAB software. Particular codes were prepared to calculate the peak wavelength of the reflected spectrum after Gauss fitting. Modifications were done in the basic software code to analyze thermal impact on sensor at various temperatures.

A FBG based optical sensor was placed in a thermal chamber to fix the temperature as 25 degree centigrade and then light source is connected to one end through a circulator .A three port circulator was used in this experiment .Light source is fed to the Port 1 and the light comes out of Port 2 is fed to the FBG sensor.

The reflected signal from the sensor comes back to the same Port 2, which goes out of Port 3. An Optical Spectral analyzer is connected to the Port 3 to measure the signal strength in dB scale .The same signal is processed using both Butterworth low pass filter and Gaussian filter technique independently and followed with Gaussian fitting to find out the peak wave length .From the analysis it is observed that Gaussian filter is far better as compare with Butterworth low pass filter .In Gaussian filter there was a 0.16 nm average shift in Gaussian filter with consistency.

The optical signal reflected by the Fiber Grating has been extracted using the Optical spectral analyzer. The Optical spectral Analyzer data represents the power versus frequency parameters and in text form So it should be converted into corresponding wavelength versus power and thereafter it is copied into an excel sheet for further signal processing using MATLAB Software. Butterworth low pass filter and Gaussian filtering techniques were used to filter the signal .In both the cases Gaussian fitting was used to fit the signal since the reflected signal has Gaussian nature. Built in functions were used to find out the peak signal before and after filtering in both Butterworth filtering and Gaussian filtering technique. Experiments were repeated at different temperatures and came to a conclusion that Gaussian filtering is far better as compare with Gaussian filter in terms of center frequency shift and consistency.

A. Reflectance Spectrum of the FBG

The simulation of the mathematical formula of the reflectance spectrum was carried out by using the MATLAB SIMULINK tool. The simulated output was almost similar to the expected reflection spectrum [2].

$$B_{i(\lambda)} = b_i \exp\left[-4\,(\ln 2)\,\frac{(\lambda - bi)^2}{\Delta\lambda_{bi}{}^2}\right] + b_{oi}$$

The above formula represents the reflected spectrum. $B_{i(\lambda)}$ is the reflectance spectrum, b_i is the peak value and $\Delta\lambda_{bi}$ is the FWHM value of the reflected spectrum[2] [3]. Reflectance spectrum of the FBG enters the second port of the circulator and leaving out through the third port of the circulator connected to the OSA .The OSA stores data text in format and can be copied using USB drive for further processing. The reflected spectrum is noise filtered before calculating the central wavelength. In this work, Butterworth LPF, Gaussian filter and wavelet de-noising techniques were used.

A. Filter Selection and Gaussian Fitting

First of all, FBG sensor was selected based on our requirement .In this thesis work, single FBG and double FBG sensors were used. Both sensors are used separately .SLED light source was used to feed the light to the sensor as input through a circulator. A three port circulator was used in this work .Light source was connected to the first port of circulator. The light comes out of the second port was connected to the FBG sensor .The reflected light from the FBG sensor comes back to the same second port. The reflected light in the second port is transmitted towards the third port. Third port was connected to the Optical spectral analyzer. The reflected spectrum can be observed in the OSA screen. By applying pressure on the sensor, the reflected spectrum changes. By that we can ensure the working of both sensor and OSA.

The reflected spectrum is stored inside the OSA in text format which can be copied using a USB storage. The copied data is in the form of power versus as frequency. The frequency can be converted into corresponding wavelength by means of dividing the speed of light by its corresponding frequency.

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All these activities are done in Microsoft excel for the simplicity. The Microsoft -excel stored data (reflectance spectrum) is filtered using MATLAB software.

By Using MATLAB software, different filters are implemented for the noise cancellation.

Butterworth Filter was tried first and then the Gaussian Filter techniques. Gaussian technique was observed as better one in terms of consistency in wavelength shift due to filtering. Butterworth LPF filter shows a wavelength shift of 0.07 nm .Gaussian Filter shows a wavelength shift of 0.16 nm whereas no sudden transition because of the smoothness in the transfer function .So rest of the experiments were carried out using Gaussian filtering only [16].

Gaussian fitting was used to calculate the peak wavelength of the reflectance spectrum since the reflectance spectrum is having a Gaussian distribution similarity. After several trial and error, came to a conclusion that Gauss 7 is the best fit for the reflectance spectrum.

IV. TEST PROCEDURE

First of all the peak wavelength measurement was done on the normal set up without any external load. It was observed that the peak wavelength was shifting even in very small external movement. The observation was done on the continuous capturing mode of the OSA. Later a constant strain was given and observed the peak wavelength shift .The experiment was repeated at different temperatures and analyzed the thermal influence in the sensor. Temperature variation was done by making use of a digitally controlled oven. In this work, a temperature range of 10 degree Celsius to 70 degree Celsius was applied. Readings were taken at a gap of 10 degrees from the 10 degrees to 70 degrees range .Initial temperature was 10 degree Celsius and then brought it down to 15 degree Celsius and then 10 degree Celsius as the lowest temperature .From 10 degree Celsius it was increased to 70 degree Celsius in a step by step interval. Each and every temperature step, readings were taken to calculate the peak wavelength of the reflected spectrum. During the thermal cycling , 3 readings were taken at 25 degree Celsius since thermal cycling started at 25 degree Celsius and then brought back to 10 degree Celsius and raised it to 70 Degree Celsius and again brought back to initial 25 degree Celsius .There were a minimum of two readings at each temperature step excluding the lower temperature 10 degree Celsius and Upper most temperature 70 degree Celsius .From The peak wavelength calculation , It was observed that there is no residual effect due to thermal cycling. The same experiment was repeated on bonded sensor also. The bonded sensor shows a little wider spectrum, but the peak wavelength shift is same as that of the normal sensor. The bonded sensor was observed with load and without load. The readings were taken in both conditions and plotted .It was observed that the sensor with load is showing a constant difference as compare with the sensor without load. That constant difference is based on the strain induced due to applied load. In both the cases the sensors are showing linearity with respect to temperature variation. After recording the test data, various analysis techniques were carried out to find out the accuracy and consistency of the data. Cross correlation coefficient of reflected spectrum at different temperatures were calculated using MATLAB built-in functions. It was observed that reflectance spectrums at various temperature are highly correlated. The rate of change of strain at various temperatures with respect to measurement at 25 degree Celsius was also calculated. The rate of change of strain of the loaded sensor is less as compare with the sensor without load.

B. Calculating the Centre Wavelength of the Reflected Spectrum

Reflected spectrum has been extracted by thy Optical Spectrum Analyzer (JDSU T-BIRD 6000). The extracted data was in text format and in frequency domain. Text data was transformed from frequency domain to wavelength domain and the transformed data was saved in Excel format for the further process. The extracted data underwent filtering .The data was filtered by Gaussian filter and then peak wavelength was calculated using Gaussian fitting before and after filtering. Gaussian fitting was used because of the resemblance of the shape of the reflected spectrum and Gaussian distribution. The below figures show the difference in center wavelength before and after filtering .Before filtering, the peak wavelength was measured as 1526.2859 nm. But the peak wavelength measured after Gaussian filtering was 4526.4459 nm with a wavelength shift of 0.16 nm .

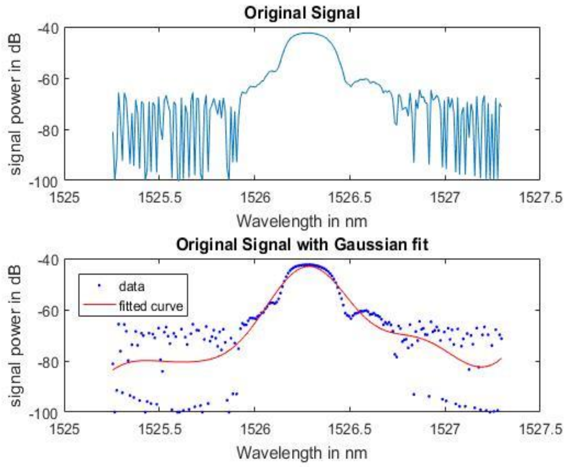

Fig 1. Original Signal before and after Gaussian Fitting

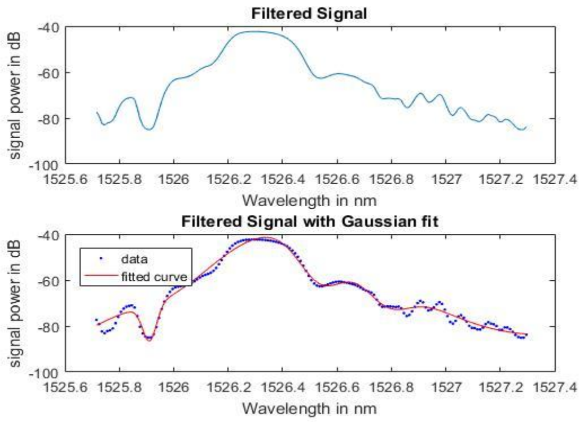

Fig 2. Butterworth Filtered Signal before and After Gaussian Fitting

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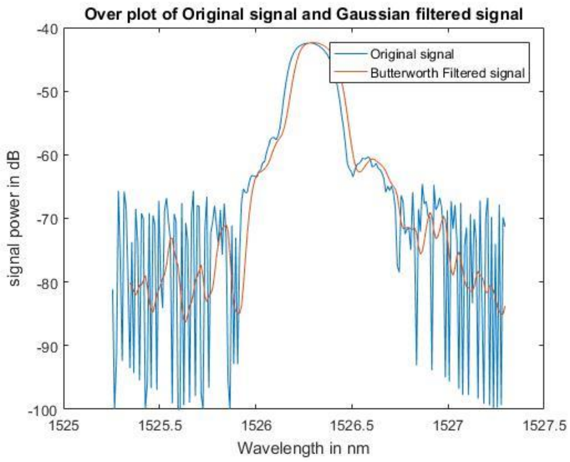

Fig 3. Over Plot of Original signal and Butterworth Filtered Signal

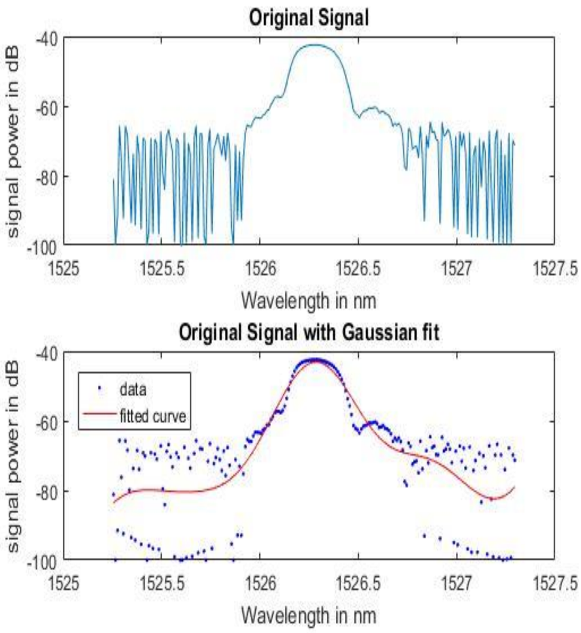

Fig 4. Original signal before and after Gaussian Fitting

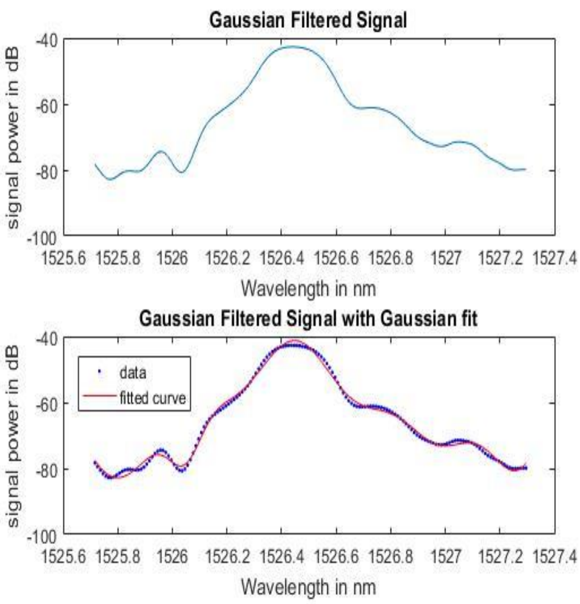

Fig 5. Gaussian filtered signal before and after Gaussian Fitting

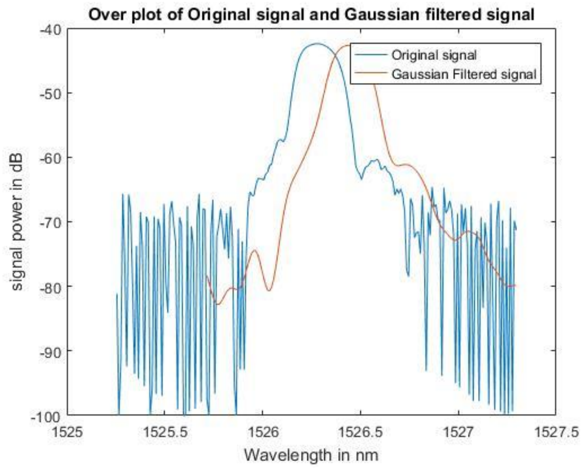

Fig 6. Over Plot of Original Signal and Gaussian Filtered Signal

C. Strain Deviation with Temperature

Strain deviation versus temperature has been calculated by applying controlled temperature. Theoretically the strain should vary in accordance with the temperature variation. initially FBG sensor was placed inside the thermal chamber and set the temperature to 10^0 C and measured the peak wavelength in order to calculate the strain as compare with 25^0 C .Then the temperature was kept on raising 10^0 C at each time and taken the corresponding wavelength shift and there by the strain variation till 70^0 C . After taking the above measurements, an external load is applied to give an external strain .Then the thermal chamber is again set to 10^0 C and calculated the centre wavelength shift in order to calculate the strain. Then the temperature again kept on raising 10^0 C at each instant and calculated the corresponding peak wavelength of the reflected spectrum in order to find out the strain .It has been observed that the change in strain with respect to temperature is linear.

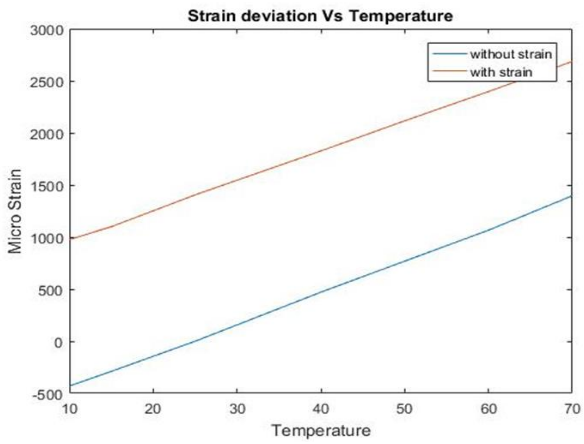

Fig 7 Strain Deviation Vs Temperature on Sensor with Strain and Without Strain

Thermal response of the sensor was observed by varying the temperature from 10 degree Celsius to 70 degree and then brought it back to 10 degree Celsius again with a step of 10 degrees at each point.

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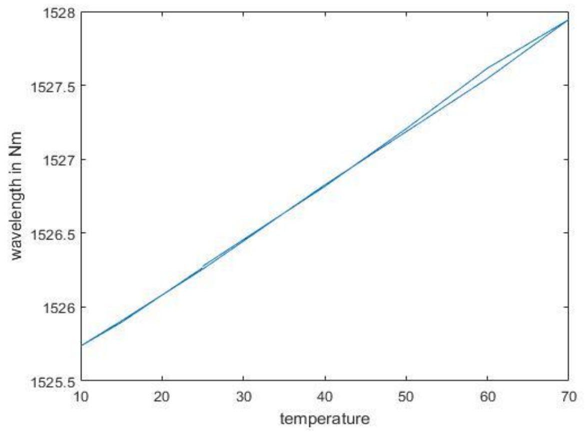

Fig 8 Wavelength vs Temperature Plot

It has been understood from fig 8 that there is not much change in the central wavelength even after thermal cycling. The rise in wavelength is linear with respect to temperature and there is not much residual effect due to temperature.

V. CONCLUSION AND FUTURE SCOPE

In this thesis work, the mathematical formula of the reflected spectrum of the FBG has been simulated and verified .Butterworth Low pass filter and Gaussian filter were applied to filter out the noise components present in the reflected spectrum. Gaussian fitting was used to find out the peak wavelength since the reflected spectrum has a Gaussian distribution. It has been understood that Gaussian filtering along with Gaussian fitting would be a perfect mechanism to find out the peak wavelength of the FBG Reflected spectrum in order to calculate the strain and temperature. Influence of temperature on optical strain gauge was proven experimentally. There is not much temperature residual effect in wavelength shift even after multiple thermal cycling. Future scope of this project is in the areas where accuracy requirement is more, especially in the aerospace industry. In this work, primary focus was in one dimensional applications to find out the longitudinal strain where as it can be used to calculate the two dimensional and three dimensional strain with proper mathematical tools and sensors. The temperature withstanding capacity of the sensor can be enhanced by making use of proper dopants in the optical fiber. Accuracy can again be improved by providing noise filter with less wavelength shift.

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Table 1. Central Wavelength Before and After at Different Filters

	Peak wavelength before filtering	Peak wavelength after filtering	Difference in wavelength
Sensor with Butterworth LPF	1526.2859 nm	1526.3559 nm	0.07 nm
Sensor with Gaussian Filter	1526.2859 nm	1526.4459 nm	0.16 nm

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