WAVELENGTH DIVISION MULTIPLEXED FBG SENSORS FOR THE SIMULTANEOUS MEASUREMENT OF STRAIN, WEIGHT AND TEMPERATURE

7.1 Introduction

FBGs have great potential for a wide range of sensing applications. They are widely used for measurements of different physical quantities like strain, temperature, pressure, flow, displacement etc. [1-6]. FBG sensors are also used in structural health monitoring [7-9]. Compared to other fiber sensors, FBG sensors have many advantages like insensitivity to fluctuations, multiplexing, distributed sensing etc. [10]. The signal obtained from a FBG sensor is encoded
directly in wavelength domain hence the source intensity fluctuations will not affect the measurements. The FBG sensors are widely used in distributed measurements of different parameters [11-14].

In the present investigation, we demonstrate a wavelength division multiplexed FBG sensor for the simultaneous measurement of strain, weight and temperature. Three FBG sensors are connected in series on a standard SMF 28 communication fiber leaving about 25 meters of fiber in between. The FBG is glued on to a cantilever structure using a fast setting epoxy for measuring strain. Standard weights are loaded on the structure for creating strain. The electrical strain gauges are also employed to monitor the strain on the structure. For mass measurement, a 2000g load cell structure is used. The FBG is pasted on the structure using a fast setting epoxy. The standard weights of 100g are added and the reflected spectrum is observed. A temperature controlled water bath is used for the measurement of temperature. The FBG is immersed in the water bath and the temperature is monitored using a digital thermometer. In order to study the temperature drift of strain, the cantilever structure is kept in a chamber and an IR lamp is used for heating. Initially the study of strain and mass are carried out at 22°C. The study demonstrates the capability of simultaneous measurement of strain, mass and temperature. The study of drift in strain measurement at different temperatures is also carried out.
7.2 FBG sensor Multiplexing Techniques

In many applications a large numbers of sensors have to be used for distributed measurement of parameters. The FBG sensors are simple, intrinsic sensing elements that can be written to a single fiber and also the output can be monitored through a single fiber. Hence it can find many applications in distributed sensing. Both Time division multiplexing (TDM) [15, 16] and wavelength division multiplexing (WDM) [17] can be used for distributed sensing.

7.2.1 Time division multiplexing (TDM)

In time division multiplexing of FBG sensors the return pulses between the adjacent FBGs are recovered, with the two pulses separated by a distance equal to the round trip time between the gratings. Using a phase sensitive detection scheme, FBG sensors can be multiplexed using time division addressing. Pulses are launched from a broad band source into a fiber having the FBG sensor array, with different peak reflection wavelengths along the fiber length. The input pulse width has to be equal to or less than the round trip time between the two gratings. The return pulse reflections from each grating are then separated in time at the output. The reflected pulses are fed through a Mach-Zehnder interferometer that acts as the wavelength shift detector. Individual sensor pulses can be demultiplexed using an electronic circuit capable of gating out a single pulse within the pulse train signal, allowing the phase detection methods to be used to recover sensor information from each sensor channel.


7.2.2 Wavelength Division Multiplexing (WDM)

The straightforward multiplexing techniques for FBG sensors is WDM. More over it uses optical power more efficiently [18]. The WDM technique is based on the spectral slicing of an available source spectrum. Each FBG sensor is encoded with a unique wavelength along a single fiber. Since the FBGs are operating in the wavelength domain, the physical spacing between FBG sensors can be as short as desired to give accurate distributed information of measurands. FBG arrays written along a single fiber are illuminated by a broadband source and the optical signals reflected from the FBG sensor array are fed in to a wavelength detection scheme. A parallel topology is also used for connecting the sensors in WDM. A 1X N fiber power splitter and couplers are used for probing the sensors from the broadband source. More FBG sensors can lead to a larger power penalty. In the present study 3 FBGs are written on a single fiber illuminated by a broadband source. Reflected spectrum is analysed using OSA. The resonant wavelengths of FBGs are selected in such a way that they do not interfere.

7.3 Theory

Bragg wavelength shift due to temperature accounts for temperature dependence of the refractive index of silica and thermal expansion of glass. Major contribution is due to temperature dependence of the refractive index of silica. The shift in Bragg wavelength can be expressed as [19]
\[ \Delta \lambda_B = \left( \frac{1}{\lambda} \left( \frac{\delta \lambda}{\delta T} \right) + \frac{1}{n} \left( \frac{\delta n}{\delta T} \right) \right) \lambda_B \Delta T \]  

(7.4)

The first term relates to thermal expansion of fiber and second term to the temperature dependence of refractive index.

The reflected spectrum of a FBG is given by [20].

\[ R(\lambda) = R_B \exp \left[ -4\ln 2 \left( \frac{\lambda - \lambda_B}{\sigma_B} \right)^2 \right] \]  

(7.5)

where \( R_B \) is the reflectivity, \( \sigma_B \) is FWHM of the FBG.

The reflected spectrum from ‘N’ FBG sensor array is given by

\[
    R_n(\lambda) = R_B \exp \left[ -4\ln 2 \left( \frac{\lambda - \lambda_{B0}}{\sigma_{B0}} \right)^2 \right]
    + R_{B1} \exp \left[ -4\ln 2 \left( \frac{\lambda - \lambda_{B1}}{\sigma_{B1}} \right)^2 \right]
    + R_{B2} \exp \left[ -4\ln 2 \left( \frac{\lambda - \lambda_{B2}}{\sigma_{B2}} \right)^2 \right]
    + \ldots \ldots \ldots \ldots R_{BN} \exp \left[ -4\ln 2 \left( \frac{\lambda - \lambda_{BN}}{\sigma_{BN}} \right)^2 \right]
\]

7.4 Experimental details

![Figure 7.1 Experimental set up for distributed sensing](image)
The experimental set-up shown in Figure 7.1 has a white light source ([Yokogawa] AQ 4305), and an optical spectrum analyzer ([Yokogawa] AQ 6319). The fiber has a diameter of 125 micron and a numerical aperture of 0.14. The core and the cladding refractive indices are 1.463 and 1.456 respectively. FBGs with center wavelengths at 1549.75nm and 1551.75nm are used for strain and weight measurements respectively. The FBG employed has a grating length of 13 mm with a reflectivity of 90%. For temperature measurement, central wavelength is 1555nm with a grating length of 10mm and reflectivity of 80%. The white light source is connected to the port 1 of circulator and port 2 of circulator is connected to the FBGs which are connected in series leaving 25m fiber in between. Port 3 of circulator is connected to OSA for the Bragg reflected signal associated with strain, weight, and temperature.

In order to study strain, a cantilever structure is made using a spring steel of 4mm thickness and length and breadth of 20cm and 5cm respectively. The FBG of 1549.75nm is pasted to the cantilever structure with a fast setting epoxy. The electrical strain gauges are also pasted to the structure for monitoring the strain. The strain is applied in the range of 0-1000μstrains. The reflected spectrum is observed for every 100μstrain. The structure is placed on a vibration-free table and sufficient time is given to avoid the loading transients. The reflected spectrum is also monitored during unloading for checking hysteresis of measurement.
For measuring weight, the FBG is pasted to a 2000g double beam cantilever load cell. The standard weights of 100g are added and the reflected spectrum is noted. In order to check the hysteresis of measurement the reflected spectrum is also observed during unloading. Temperature controlled water bath is used for measuring the temperature. The temperature is also monitored using a digital thermometer. The FBG is immersed in the water bath. The temperature is varied from 22°C to 100°C. The reflected spectrum is monitored for every 10°C rise. The water bath is allowed to cool naturally and reflected spectra are recorded to check the hysteresis of the measurement.

7.5 Results and Discussion

![Simulated Reflected spectrum of distributed sensing.](image)
Figure 7.2 shows the reflected spectrum obtained by simulating the distributed study. The simulation was carried out with a broadband source and giving the FBG parameters discussed in section 7.5. The measured results are depicted in figure 7.3. The centre wavelengths of the FBG are selected in such a way that they do not interfere. The 1549.75 nm is used for the strain measurement and 1551.75 nm is employed for mass measurement. These two FBGs are identical except for the Bragg reflected wavelength as shown. The FBG with 1555 nm as the centre wavelength has a reflectivity of 80%. Hence the power reflected is less. The detailed study of strain, mass and temperature are presented below.
7.5.1 Strain

![Back reflected spectrum corresponding strain measurement.](image1)

**Figure 7.4** Back reflected spectrum corresponding strain measurement.

![Wavelength shift for 0 to 1000µ strain](image2)

**Figure 7.5** Wavelength shift for 0 to 1000µ strain

The standard weights are added to study the strain on the cantilever structure. The strain is monitored using electrical strain gauges as well. 0 to 1000µ strain is applied on the structure at a step of 100µ strain.
each. The temperature during the experiment is maintained at 22°C. The reflected spectrum corresponding to strain measurement is as shown in figure 7.4. It is observed that the wavelength is shifted from 1549.2 nm to 1551.1 nm at the leading edge of the reflected spectrum. The wavelength variation for 0 to 1000 µstrain is plotted in figure 7.5.

7.5.2 Weight

The reflected spectrum for the weight measurement is shown in figure 7.6. Standard weights of 100 grams are added and the reflected spectrum is observed. The temperature during the experiment is maintained at 22°C. In the reflected spectrum, the wavelength varied from 1551.392 nm to 1551.808 nm for 0 g to 2000 g at the leading edge of the spectrum. The shift in wavelength with respect to mass is linear and it is plotted in figure 7.7. The reflected spectrum is monitored during the unloading of the structure and hysteresis is found negligible.

![Figure 7.6 Reflected spectrum for 0 to 2000g](image)
Section 7.5.3 Temperature

For the temperature measurement, the FBG is immersed in a water bath. The temperature is controlled and varied from 22 to 100°C. During measurement the temperature is monitored using a digital thermometer and reflected spectrum is monitored for every 1°C rise in temperature. The reflected spectrum of FBG for 22-100°C is shown in figure 7.8. The wavelength is shifted from 1555.416nm to 1556.106nm at the leading edge of the spectrum. The wavelength shift with respect to temperature is found linear and it is plotted in figure 7.9.
7.6 Conclusion

A distributed sensor capable of simultaneous measurement of strain, weight, and temperature is developed. The strain measurement
is carried out in the range of 0 to 1000 μ strains. From the reflected spectrum, wavelength shift is found linear. The sensitivity of strain measurement is 0.83 pm/μ strain. The mass measurement is carried out for 0 to 2000g at 22°C. In the reflected spectrum, wavelength shift is found linear and free of hysteresis. The sensitivity of measurement is 0.2pm/g. The measurement of temperature is carried out from 22 to 100°C. The sensitivity is found to be 10 pm/°C. The temperature sensing FBG can be used as a reference for other measurements to compensate for temperature drift.

Reference


[16] Bo Dong, Shiya He, Shuyang Hu, Dawei Tian, Junfeng Lv, and Qida Zhao, Time-Division Multiplexing Fiber Grating


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