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A methodologically development of quasi distributed sensor capable of simultaneous measurement of strain, weight, and temperature

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Abstract
In this study, the wavelength division multiplexed FBG sensors are simulated using a MATLAB Tool for the measurement of strain, weight and temperature. The experiment is carried out using three FBG sensors connected in series on a standard SMF 28 communication fiber leaving about 25 meters of fiber in between. A broad band source and an optical spectrum analyzer are used to study the reflected spectrum. 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 applying strain. The electrical strain gauges are also employed to monitor the strain on the structure. For weight measurement, a 2000 g load cell structure is used. The FBG is pasted on the structure using a fast setting epoxy. The standard weights of 100 g are added and the reflected spectrum is observed. A temperature controlled water bath is used for the measurement of temperature.

Keywords: Multiplexed FBG sensors, strain, weight and temperature

Introduction
FBGs have great potential for a wide range of sensing applications. They are widely used for quasi distributed measurements of different physical quantities like strain, temperature, pressure, flow, displacement etc [1–6]. FBG sensors are also used in structural health monitoring [7, 8]. The fiber optical sensors have many advantages over the conventional electrical sensors like small in size, real time measurements, fast response, immunity to electromagnetic waves etc. [14]. Compared to other fiber sensors, FBG sensors have many advantages like insensitivity to fluctuations, multiplexing, distributed sensing etc. [10]. The signal obtained from an FBG sensor is encoded directly in wavelength domain hence the source intensity fluctuations will not affect the measurements.

In this study, the wavelength division multiplexed FBG sensors are simulated using a MATLAB Tool for the measurement of strain, weight and temperature. The experiment is carried out using three FBG sensors connected in series on a standard SMF 28 communication fiber leaving about 25 meters of fiber in between. A broad band source and an optical spectrum analyzer are used to study the reflected spectrum. 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 applying strain.

The electrical strain gauges are also employed to monitor the strain on the structure. For weight measurement, a 2000 g load cell structure is used. The FBG is pasted on the structure using a fast setting epoxy. The standard weights of 100 g 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 wooden chamber and an IR lamb is used for heating. Initially the study of strain and weight are carried out at 22 °C. In this study we have demonstrated the simultaneous measurement of strain, weight and temperature. The results are compared with the simulated responses. The study of drift in strain measurement at different temperatures is also carried out.

Theory
According to Bragg's law $\lambda_B = 2n_{eff}\Lambda$

where, 'λ_B' is the Bragg wavelength, 'n_{eff}' is the effective refractive index of the fiber core and 'Λ' Bragg grating period.

The strain and weight measurements are based on the physical elongation of optical fiber corresponding to change in grating pitch and the change in the refractive index of the fiber due to photo elastic effect. At constant temperature it can be expressed as:

$$\Delta\lambda_B = (1 - p_e)\lambda_B\epsilon$$

where, 'ϵ' is the applied strain and 'p_e', the effective photo elastic coefficient and it is expressed as:

$$p_e = \left(\frac{n^2}{2}\right)[P_{12} - \mu(P_{11} + P_{12})]$$

'P_{ij} 'is the Pockel's coefficients of the strain optic tensor and 'μ' is the Poisson's ratio of the optical fiber.

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 [11].

$$\Delta\lambda_B = [\frac{1}{\Lambda}(\frac{\delta\Lambda}{\delta T}) + \frac{1}{n}(\frac{\delta n}{\delta T})]\lambda_B\Delta T$$

The first term relates to thermal expansion of fiber and second term to the temperature dependence of refractive index. The reflected spectrum of FBG is given by [12].

$$R(\lambda) = R_B \exp\left[-4ln2\left(\frac{\lambda - \lambda_B}{\sigma_B}\right)^2\right]$$

where, R_B is the reflectivity, σ_B is FWHM of the FBG.

Experimental Details

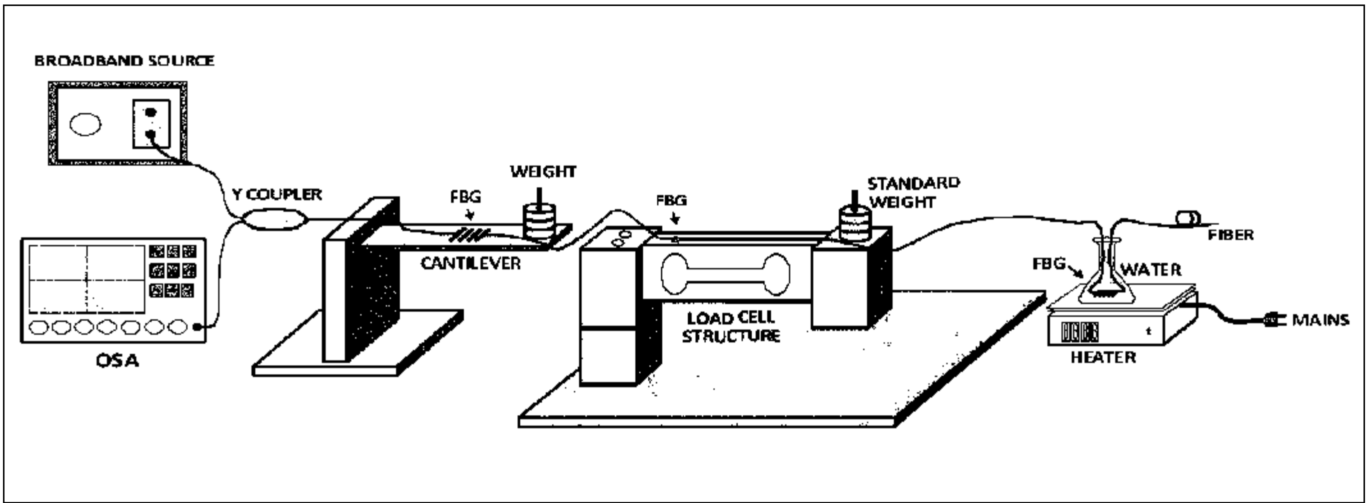

Fig 1: Experimental Set up for Distributed Sensing.

The experimental set-up (Figure 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 1549.75 and 1551.75 nm 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, central wavelength is 1555 nm with a grating length of 10 mm and reflectivity of 80%. The white light source is connected to one input of a 'Y' coupler and the other input of the coupler is connected to the OSA for the Bragg reflected signal. On the other end of the coupler the FBGs are connected in series leaving 25 m fiber in between. Reflected spectrum associated with different strain, weight, and temperature are noted using the spectrum analyzer. In order to study strain a cantilever structure is made in a spring steel of 4 mm thickness and length and breadth of 20 and 5 cm, respectively. The FBG of 1549.75 nm 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 0–1000 μ strains. The reflected spectrum is observed for every 100 μ strain. 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.

For measuring weight, the FBG is pasted to a 2000 g double beam cantilever load cell. The standard weights of 100 g 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 to 100 °C. The reflected spectrum is monitored for every 10 °C rise. The water bath is allowed to cool naturally and reflected spectrums are noted to check the hysteresis of the measurement.

Results and Discussion

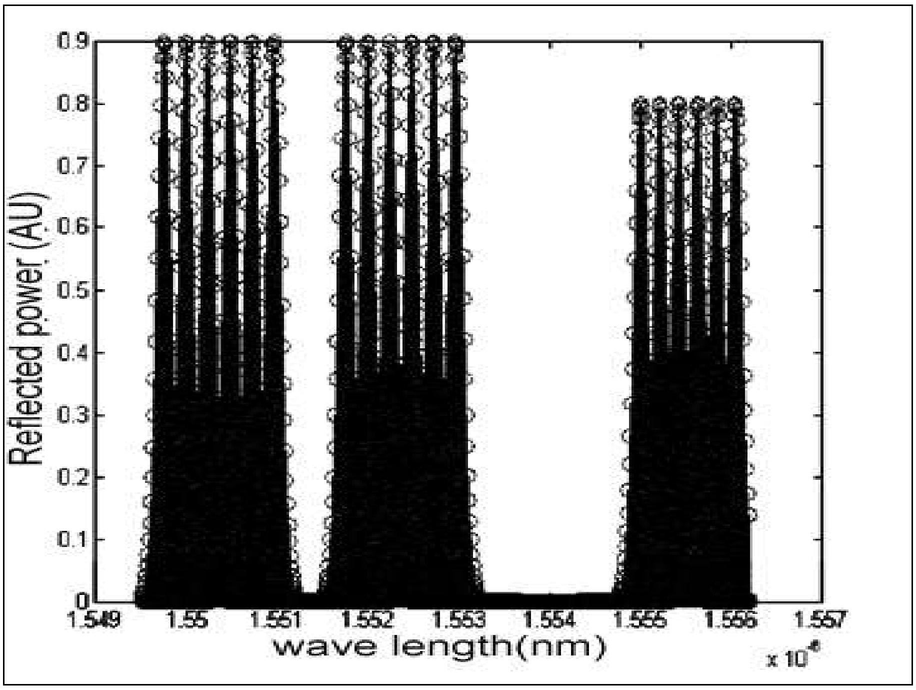

Fig 2: Simulated Result for Distributed Sensing using MATLAB Tool.

Figure 2 shows the simulated reflected spectrum during distributed sensing of strain, weight and temperature. The center wavelengths of the FBG are selected in such a way that they do not interfere. The FBGs for strain and weight are identical except for the Bragg reflected wavelength. The FBG for temperature sensing has a reflectivity of 80%.Hence the power reflected is less. The Reflected spectrum for strain, weight and temperature during the experimental study is shown in Figure 3. The analysis of strain, weight and temperature measurements are discussed in detail below.

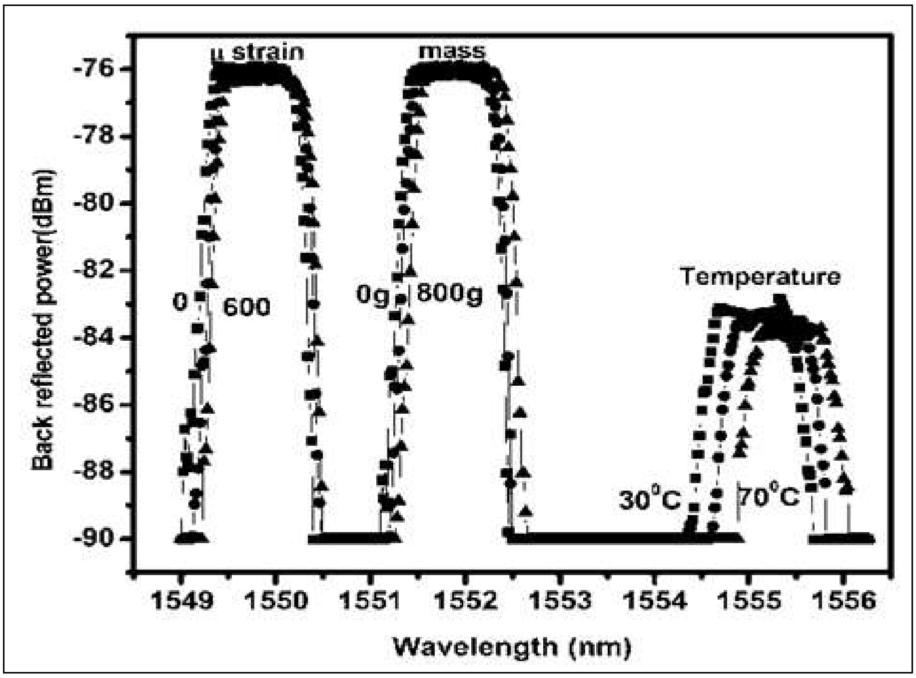

Fig 3: Reflected Spectrum during Distributed Sensing

Strain

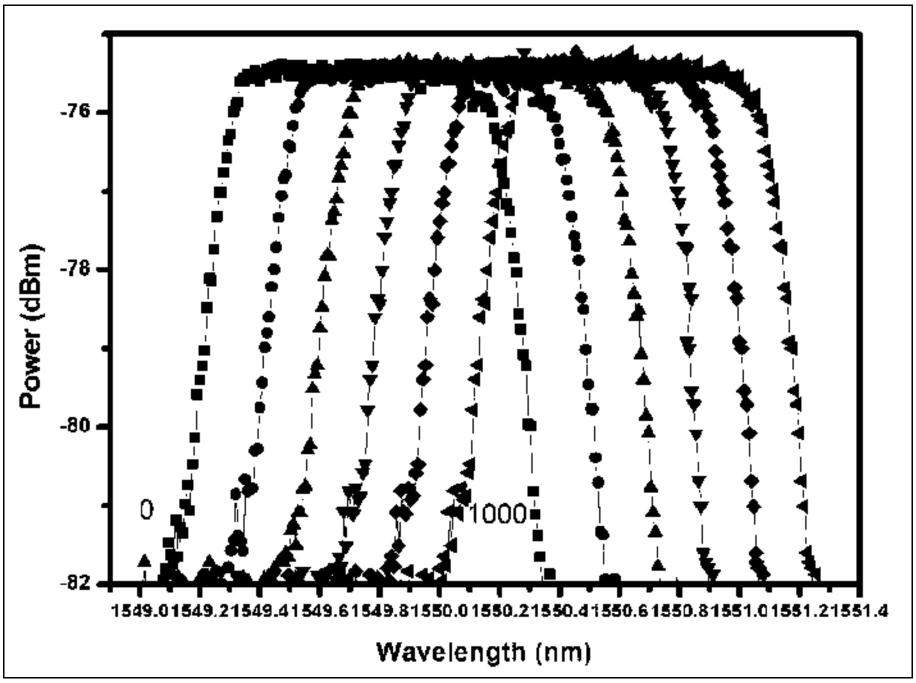

Fig 4: Reflected Power for Strain Measurement.

The strain measurement is simulated using MATLAB Tool and the results are comparable with actual measurements. Simulation for strain at different temperatures is carried out and the results are also compared. 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 1000 μ strain is applied on the structure. The temperature of the structure during the experiment is 22 °C. The reflected spectrum is as shown in Figure 4. During unloading, the reflected spectrum is noted to check the hysteresis and it is observed that measurement is free of hysteresis. In order to check the temperature drift of the measurement, the strain sensing setup is housed in a wooden chamber and an Infrared lamb is used for heating. The temperature inside the chamber is monitored using a digital thermometer. The measurements are repeated for 30, 35 and 40 °C. The wavelength shift with respect to applied strain at different temperatures is simulated and it is shown in Figure 5. The actual measurement results are shown in Figure 6 and it is comparable with the actual results.

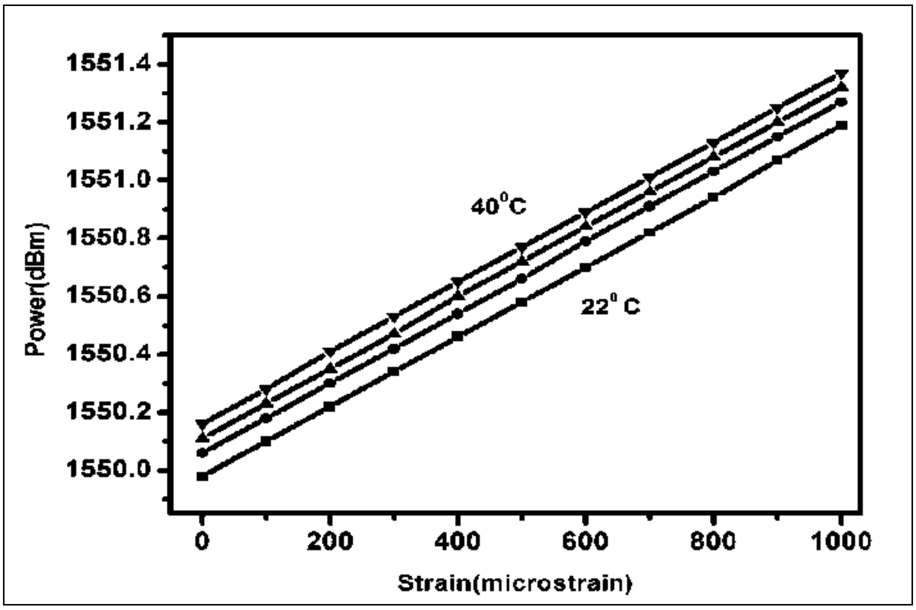

Fig 5: Simulated Strain at Different Temperatures.

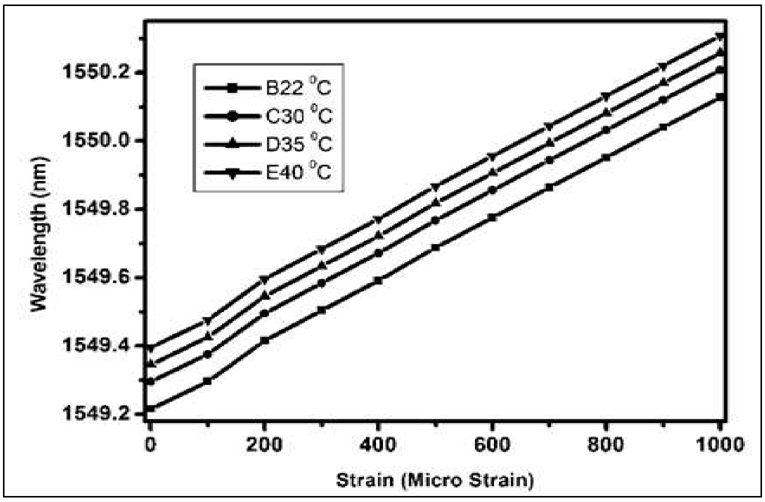

Fig 6: Shift in Wavelength for the 0 to 1000 µ Strain at Different Temperatures.

Weight

The reflected spectrum during the weight measurement is shown in Figure 7. Standard weights of 100 grams are added and the reflection spectrum is studied. The temperature during the experiment is 22 °C. In the reflected spectrum, the wavelength varied from 1551.392 to 1551.808 nm for 0–2000 g at the leading edge of the reflected spectrum. Simulated result and the actual shift in wavelength during measurement are shown in Figure 8. The wavelength shift with respect to weight is linear and it is comparable with the simulated results. The reflected spectrum is monitored during unloading of the structure and hysteresis is found negligible.

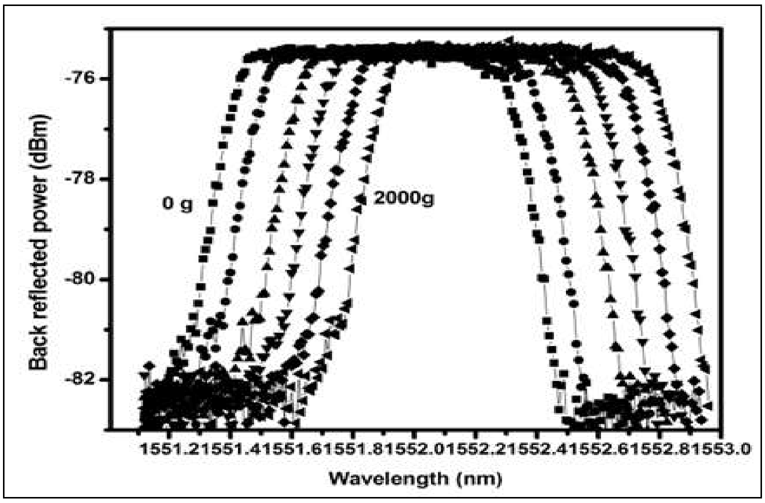

Fig. 7: Reflected Power for 0 to 2000 g.

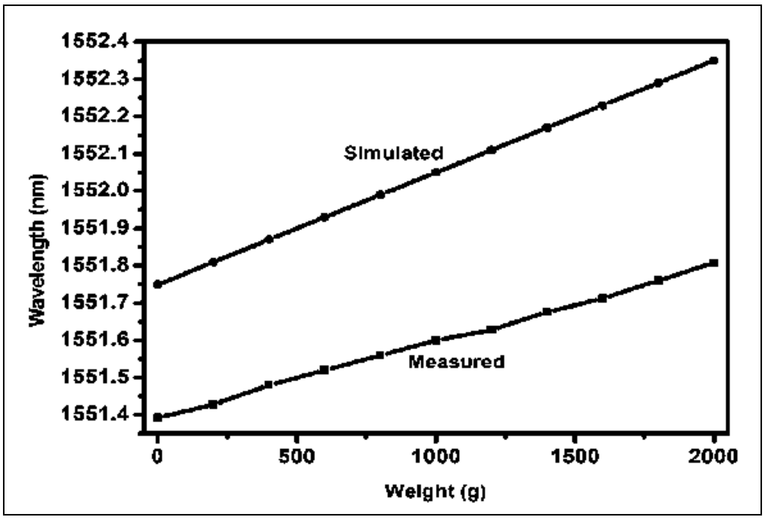

Fig 8: Simulated and Measured Wavelength Shift for the Weight 0 to 2000 g.

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 the measurement the temperature is monitored using a digital thermometer and reflected spectrum is monitored for every 10 °C rise in temperature. The reflected spectrum of FBG for 22–100 °C is shown in Figure 9. The wavelength shifted from 1555.416 to 1556.106 nm at the leading edge of the reflected spectrum. The water bath is allowed to cool naturally and the reflected spectrum is monitored. It is observed that the hysteresis is negligible. The simulated wavelength shift and actual shift during measurement is plotted in Figure 10. The wavelength shift with respect to temperature is found linear and free of hysteresis.

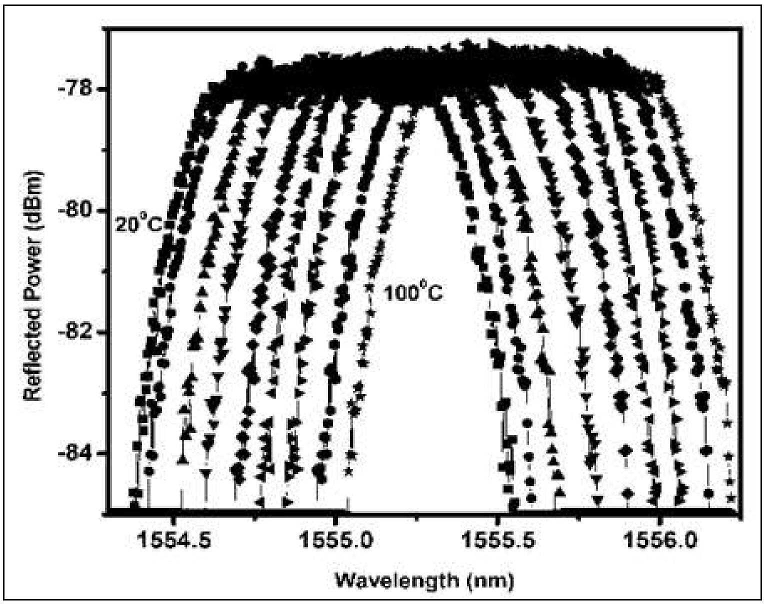

Fig 9: Reflected Power for 22 to 10 °C.

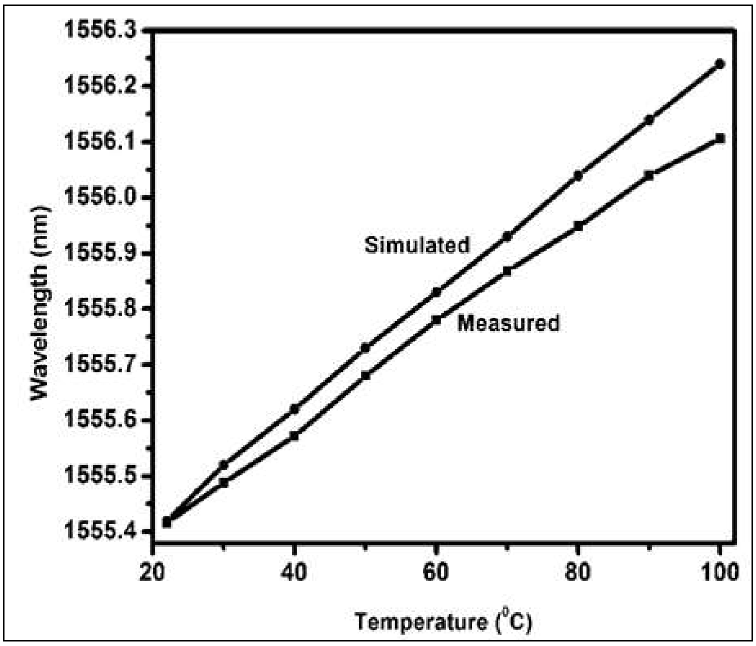

Fig 10: Simulated and Measured Wavelength Shift for a Temperature of 22 to 100 °C.

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. The simulated results and actual shift in wavelength are linear. The hysteresis of the measurement is negligible. The temperature of the strain measurement setup is varied and the wavelength shift with respect to strain at 22 to 40 °C is found linear. There is a temperature drift of 10 pm/ °C and sensitivity of strain measurement is 0.92 pm/µ strain. Simulated results for strain measurement at different temperatures are comparable with experimental results. The weight measurement is carried out for 0 to 2000 g at 22 °C. In the reflected spectrum, wavelength shift is found linear and free of hysteresis. The sensitivity of measurement is 0.2 pm/g. simulated response of the FBG for weight measurement is compared with actual results. The measurement of temperature is carried out from 22 to 100 °C. The sensitivity is found 10 pm/ °C. Response of FBG for different temperatures is also simulated and is compared with experimental results. The temperature measurement FBG can be used as a reference for other measurements and necessary corrections can be carried out in strain and weight measurement.

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