FBG-Baesd Soft Probe for Measurement of Temperature Using Strain Decoupling Technique

Maria Eduarda Benfica Gonçalves[1,2*], Gabriel Rosa Alves[1,2], Rafael Andrade Vieira[1,2], Milena Ventura Castro Meira[1,2,3], Jessica Guerreiro Santos Ramalho[1,2], Valéria Loureiro da Silva[1,2]

[1]SENAI CIMATEC University; [2]Optics and Photonics Engineering Laboratory; [3]Physics Institute, Federal University of Bahia; Salvador, Bahia, Brazil

This study explores the use of Fiber Bragg Grating (FBG) sensors encapsulated in stainless steel for precise temperature measurements in a soft probe applicati on. Encapsulation enhances temperature sensitivity while minimizing strain interference, a common challenge in FBG sensor applications. Experimental results showed minimal wavelength shifts and temperature errors, demonstrating the effectiveness of the metallic capillary in decoupling strain effects from temperature measurements. The calibration curve confirmed high temperature sensitivity and low strain sensitivity. This method offers a reliable solution for precise temperature measurements in environments where strain can introduce measurement noise.
Keywords: Optical Fiber. FBG Decoupling. Sensors Packaging.

In recent years, optical fiber sensors have received significant attention due to their remarkable sensitivity, versatility, and durability. In explosive environments, where electronic sensors are often impractical or dangerous, they are a promising alternative.

Optical fibers are thin strands of glass or plastic that transmit light from one end to the other, primarily used in telecommunications. However, their unique properties also make them ideal for a wide range of sensing applications.

The use of optical fibers in sensing relies on the principle that changes in the external environment can alter the properties of light traveling through the fiber [1]. This alteration can be detected and analyzed to provide precise measurements of the desired parameters. These sensors have been utilized for monitoring sleep [2], breathing [3], and measuring various physical parameters, including vibration [4,5], strain [4], and temperature [6], making them indispensable in numerous industries. There are multiple types of optical fiber sensors, including macrobending sensors, OTDR (Optical Time-Domain Reflectometry), OFDR (Optical Frequency-Domain Reflectometry), and FBG (Fiber Bragg Grating). This work's objective is to develop a soft probe temperature sensor using a packaged FBG.

Received on 11 March 2025; revised 26 May 2025.
Address for correspondence: Raúl Bernardino Oliveira. Avenida Nestor de Melo Pita, 535 - Centro. Amargosa, Bahia, Brazil. Zipcode: 45300000. E-mail: raul07oliveira06@gmail.com.

J Bioeng. Tech. Health 2025;8(3):276-280

Fiber Bragg Grating (FBG)

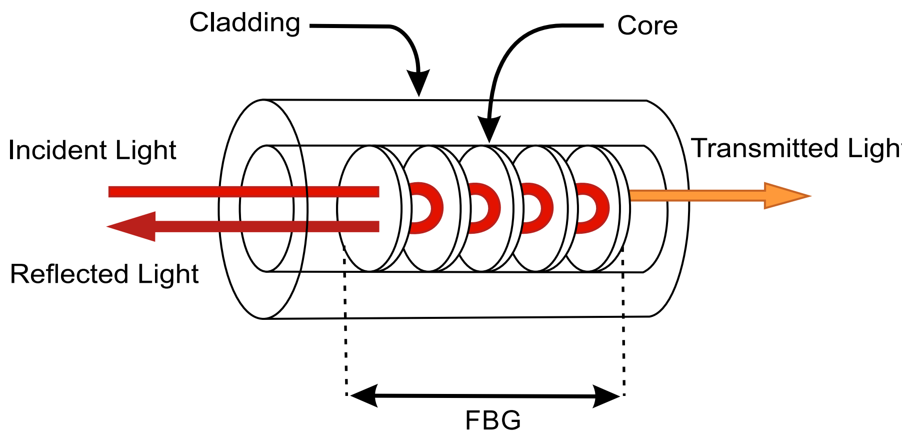
The Fiber Bragg Grating (FBG) is a type of optical fiber with a periodic modulation of the refractive index in its core, which reflects a specific wavelength of light related to the grating period. This allows for the measurement of strain and temperature when the fiber undergoes stretching or compression [7,8]. The core advantage of FBG sensors lies in their multiplexing ability, enabling the monitoring of various points along a single fiber optic cable.

Mathematically, the Bragg wavelength (λB) is determined by the equation:

$$\lambda B = 2 n_{eff} \Lambda$$

Where n_{eff} is the effective refractive index of the fiber core and Λ is the grating period, which is the distance between consecutive grating planes in the fiber. Changes in temperature and strain affect both neff and Λ, leading to a shift in the Bragg wavelength. Specifically, an increase in temperature causes thermal expansion of the fiber and changes

Figure 1. Light reflection inside the FBG optical fiber.



in the refractive index due to thermo-optic effects, increasing λB.

Similarly, applied strain stretches the fiber, increasing Λ and altering neff, which also shifts λB.

Typically, FBG sensors are used as fixed sensors for continuous monitoring of physical and chemical parameters. The development of a probe-type FBG temperature sensor is significant for applications that require point investigations and localized temperature measurements in scenarios where detailed thermal profiling is necessary, such as in medical diagnostics, materials science experiments, and specific industrial processes.

However, one of the main challenges in using FBG sensors as temperature sensors, where contact with an object or surface is required, is the coupling between strain and temperature. When FBG sensors are used in environments where both temperature and mechanical strain vary, the sensor's output can become convoluted, making it difficult to isolate the contributions of each factor. This cross-sensitivity can introduce errors and noise, undermining the sensor's reliability. To mitigate this, effective encapsulation techniques have been developed [9-12]. Packaging the FBG in a metallic capillary presents an effective solution. The metal tube, serving as housing for the FBG sensor, acts to decouple the strains due to contact with the sensing surface and the sensor structure deformations from the FBG temperature sensor. In this work, we explored a stainless-steel encapsulation technique to improve performance and reduce strain interference in an FBG temperature sensor probe.

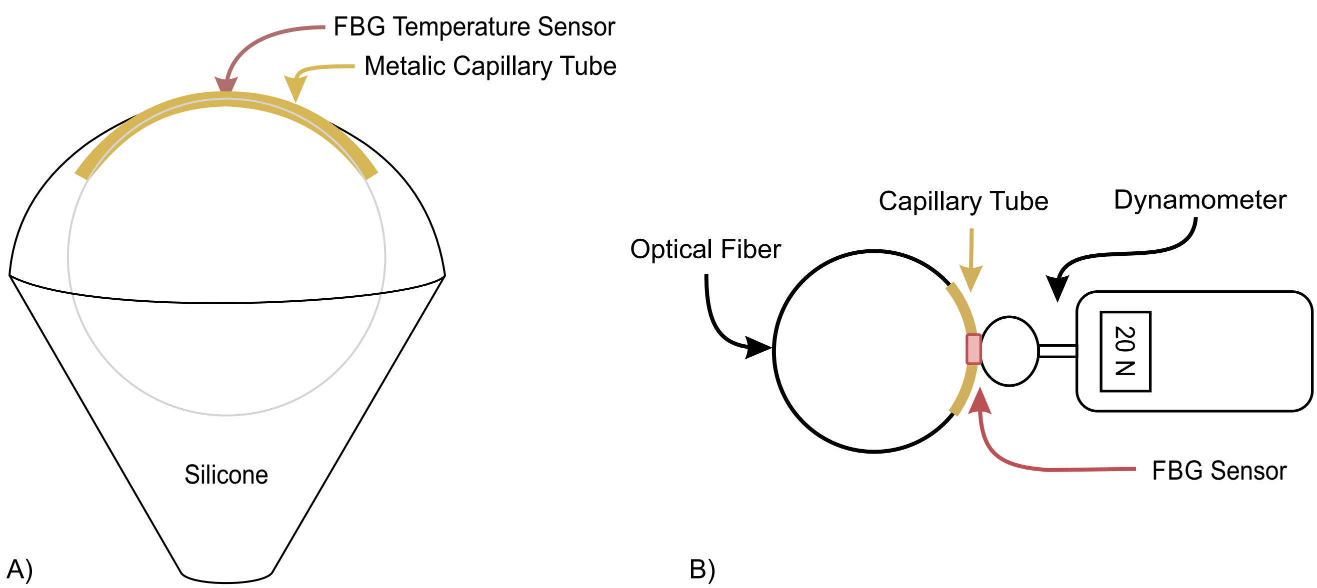
Materials and Methods

The soft probe was constructed using silicone, as depicted in Figure 2a. A stainless-steel capillary, with a 0.5 mm diameter and a length of 25 mm, was employed to encapsulate the bare FBG with the center wavelength of 1550 nm. This encapsulation served dual purposes: it protected the FBG from bending-induced strain and enhanced its thermal sensitivity.

To integrate the encapsulated FBG with the probe, a round plastic structure was used to form a fiber coil during the silicone pouring process. This configuration ensures that the silicone probe functions effectively as a contact temperature sensor, providing reliable and accurate temperature measurements in various application scenarios. To evaluate the degree of isolation of encapsulated FBG from strain, a translational stage was used to press the silicone sensor against a dynamometer with a disc at its end, as shown in Figure 2b. The reflection spectrum was monitored as the force increased from 0 to 18 N in 2 N increments; the spectra were recorded after 10 seconds of stabilization at each force step.

The temperature response of packaged FBG was obtained by placing the soft probe in contact with water on a heating table and

Figure 2. A. Diagram representation of the temperature FBG sensor. B. Schematic representation of test setup.



varying the temperature from 22°C to 100°C. The calibration curve correlating temperature with the transmitted wavelength was created using a thermocouple connected to a multimeter. The tip of the thermocouple was placed in water that had been heated to a specific temperature. The temperature was recorded using a multimeter, while the wavelength was measured with an FBG Interrogator. These measurements were then correlated to make the sensor's calibration curve.

Results and Discussion

The temperature response of the FBG sensor, illustrated in Figure 3, exhibits a linear behavior. The slope of the curve obtained through linear fitting demonstrates that the device's sensitivity is 12 pm/°C. This linearity confirms the sensor's ability to provide consistent and accurate temperature readings.

The reflection spectrum of the encapsulated FBG probe sensor was analyzed as a function of applied force within the investigated range. From this data, a graph was generated depicting the variation of the Bragg wavelength relative to the applied force (Figure 4). This graph shows that an applied force of up to 18 N causes a maximum error of 0.013 nm, which corresponds to approximately 1.1 °C of temperature error. The linear fit of the force test results indicated that the mean sensitivity of the soft probe to strain was 0.2 pm/N, demonstrating the effectiveness of our fiber packaging technique in minimizing strain interference in temperature measurements.

Comparatively, the sensitivity of our soft probe FBG temperature sensor is of the same order of magnitude as that of the sensors described in other works [11,12]. However, our packaging method offers significant advantages in terms of simplicity, asset and personnel safety, and cost-effectiveness.

Conclusion

This work demonstrated the efficacy of utilizing Fiber Bragg Grating (FBG) sensors encapsulated in stainless steel for accurate temperature measurements in a soft probe application. The results indicate that the encapsulation significantly enhances the sensor's sensitivity to temperature while effectively minimizing interference from strain.

The primary challenge addressed was the coupling between strain and temperature, which can compromise measurement accuracy. By housing

Figure 3. Calibration curve of the FBG-based temperature sensor correlating the wavelength shift variation with the temperature measured.

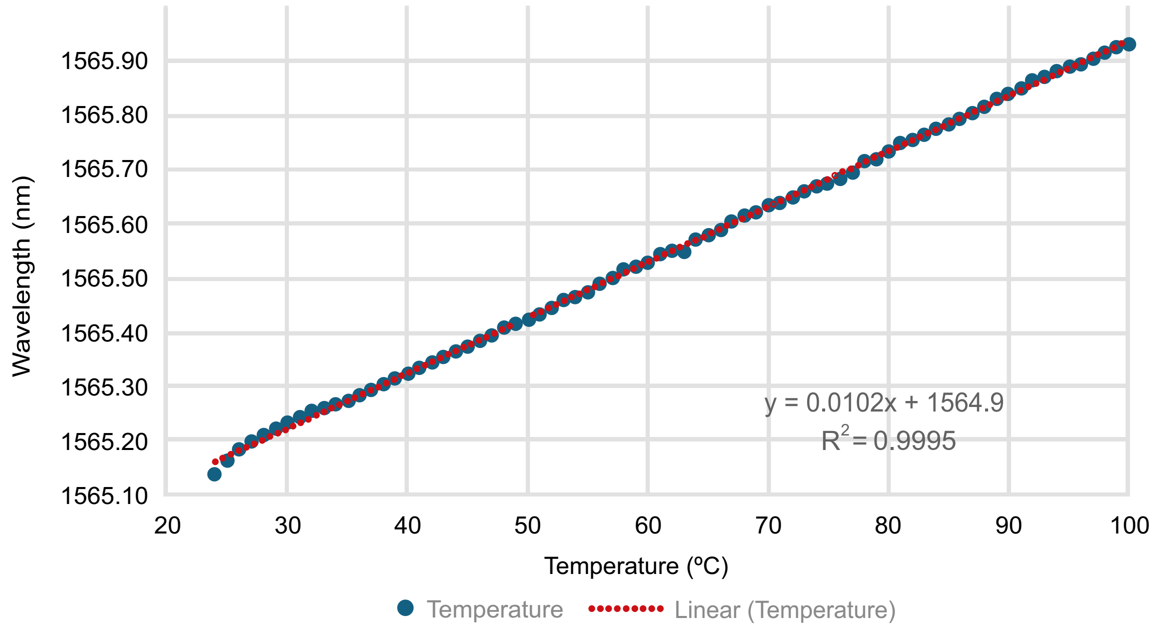
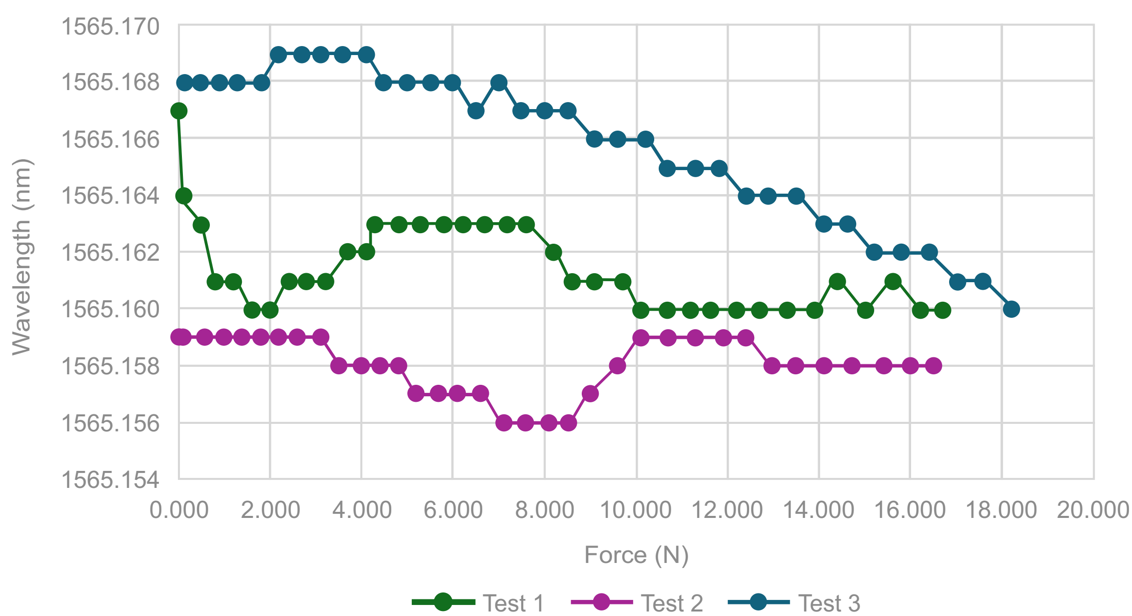


Figure 4. Wavelength shift variation as a function of applied force.



the FBG sensor within a metallic capillary, it was possible to decouple the strain effects from temperature measurements. The results showed minimal variations, with wavelength shifts of less than 1 nm and temperature errors of around 1°C, even under applied forces of up to 18 N.

The calibration curve, with an angular coefficient of 12,0pm/°C, highlighted the sensor's high temperature sensitivity. Additionally, the low strain sensitivity, indicated by an angular coefficient of 0,2pm/N, confirmed the effectiveness of the metallic capillary in decoupling strain from temperature.

These findings underscore the potential of stainless-steel encapsulation as a viable solution for enhancing the performance of soft probe FBG sensors in environments where accurate point investigations and thermal profiling are critical.

The successful decoupling of strain and temperature not only improves measurement accuracy but also broadens the applicability of FBG sensors in various scientific and industrial domains.

Acknowledgments

The authors would like to acknowledge Shell, the project Softrobots, and ANP for making this work possible.

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