Elastomeric-coated FBGs for point-of-care diagnostics

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Malhar A. Nagar[1*], *Giovanni* Mingoia[1,2], and *Davide* Janner[1]

[1]Dipartimento di Scienza Applicata e Tecnologia (DISAT), Politecnico di Torino, Turin, Italy
[2]Fondazione LINKS-Leading Innovation and Knowledge for Society, Turin, Italy

Abstract. This study deploys the application of Fiber Bragg Gratings (FBGs) in physiological pressure monitoring by integrating an elastomeric, biocompatible coating ranging from 300-500μm, designed to improve sensor functionality for in-vivo pressure monitoring applications. FBGs are favored for their sensitivity, immunity to electromagnetic interference, and compact size, making them ideal for embedding within medical devices such as catheters and guidewires. However, their use has been limited by low inherent pressure sensitivity (3.14 pm/MPa) and the impracticality of thicker coatings described in previous studies. Our approach demonstrates that this unique coating not only boosts the pressure sensitivity significantly—surpassing 1.63 orders of magnitude (43.10 times)—but also enhances the signal-to-noise ratio of the optical signal. These advancements enable potential applications in high-resolution manometry, gastrointestinal pressure monitoring, intracranial and intracoronary blood pressure measurements, marking a significant step forward in medical diagnostics and monitoring.

1. Introduction

In the biomedical field, monitoring physiological pressures is pivotal, particularly for diagnosing and treating critical health conditions [1]. Key pressure indices, such as instantaneous wave-Free Ratio (iFR), intracranial pressure (ICP), gastrointestinal pressure, and intracolonic pressure, provide essential metrics for clinicians that enable the assessment of the severity of various diseases. iFR is crucial for evaluating coronary artery diseases, ICP is vital for understanding traumatic brain injuries, gastrointestinal pressure helps diagnose motility disorders of the esophagus and gastrointestinal tract, and intracolonic pressure is instrumental in monitoring diverticular diseases. Accurate measurement and interpretation of these pressures enable precise medical interventions, thereby improving patient outcomes [2-5].

Optical fiber sensors (OFS), particularly Fiber Bragg Gratings (FBGs), are increasingly used for these applications due to their biocompatibility, high sensitivity-specificity, immunity to electromagnetic interference, multiplexing capabilities, and miniaturisation capabilities, which makes them ideal for integration into minimally invasive devices like catheters and guidewires (635 μm and 355.6 μm) [1, 6, 7]. However, practical application of FBGs is limited by its low-pressure sensitivity ($\frac{\Delta\lambda_B}{P}$ = 3.14 pm/MPa i.e., 0.42 fm/mmHg) and the impracticality of thick coatings (>1mm) used in previous studies, compromising device compatibility and size [8, 9]. To address this issue, elastomeric biocompatible coating is engineered with enhanced sensitivity and signal to noise ratio (SNR) which is compatible with dimensions of pressure devices.

2. Research methodology

FBGs function as wavelength-selective filters at the Bragg wavelength (λ_B) in optical domain, where they couple the forward-propagating mode to the backward-propagating mode through periodic perturbations in the fiber core's refractive index. The pressure transduction mechanism can be enhanced by utilizing elastomeric coating having lower Young's modulus (E=870 kPa) and higher Poisson's ratio (μ=0.45) than standard FBG (79 GPa and 0.17) (Fig.1) [10, 11].

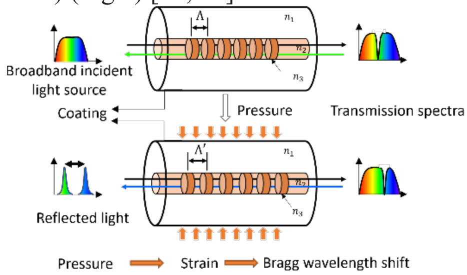


Fig.1. Transduction mechanism: elastomeric-coated FBG pressure sensing (n_i's - refractive indices and Λ – grating length)

The longitudinal strain sensitivity and lateral pressure sensitivity of FBG are given by equations (1) and (2) [9].

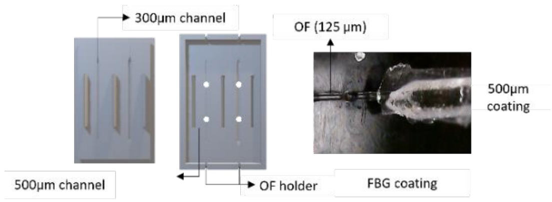
$$\frac{\Delta\lambda_B}{\lambda_B} = (1-p_e)\epsilon \quad (1)$$

$$\frac{\Delta\lambda_B}{P} = (1-p_e)(\frac{2\mu}{E_{eff}})\lambda_B \quad (2)$$

[*] Corresponding author: malhar.nagar@polito.it

Where $\Delta\lambda_B$, ϵ, Eeff denotes Bragg wavelength shift, longitudinal strain and effective Young's modulus.

The FBG coating was done around an FBG length of 3 mm using customized 3D-printed injection molding (Fig.2). We selected a specific resin for the mold fabrication to ensure high tolerance. We consistently achieved a coating thickness ranging from 300 – 500 µm through meticulous post-processing and surface treatments.



a) b)

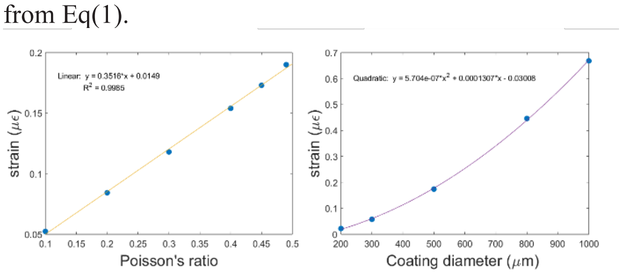
Fig.2. a) Customised 3D-printed two-part mold b) Sample 500 µm FBG coating.

Theoretical simulations were performed using ANSYS Mechanical to conduct static structural analysis on a standard FBG coated with elastomer. Subsequently, an experimental test bench was developed to evaluate the pressure sensitivity of these FBGs under static conditions. The FBG was embedded within a temperature-controlled, custom-made microfluidic channel with a 1mm diameter to mitigate temperature-induced cross-sensitivity. Static fluid pressures ranging from 0 to 450 mmHg were applied using a microfluidic pressure controller acting as a pressure pump.

3. Results

3.1 Theoretical simulation

Results indicated that the pressure-induced strain increases with a higher Poisson's ratio and larger coating diameter. At a constant pressure of 1000 Pa, the strains recorded for 300 µm and 500 µm coatings were 0.057 µϵ and 0.174 µϵ, respectively. Their pressure sensitivities were 69.240pm/MPa and 208.800pm/MPa, respectively, from Eq(1).



a) b)

Fig.3. FEM structural analysis - the impact of a) Poisson's ratio and b) Coating diameter on strain at 1000Pa (7.5mmHg).

3.2 Experimental findings

The strain sensitivity was observed to be 135.585 pm/MPa (i.e., 0.018pm/mmHg). This pressure sensitivity represents a 431-fold increase over the baseline sensitivity of standard FBGs while having a coating under 500 µm, which can be easily integrated with medical devices used for interventional procedures. Additionally, individual pressure plots demonstrated enhancement in SNR.

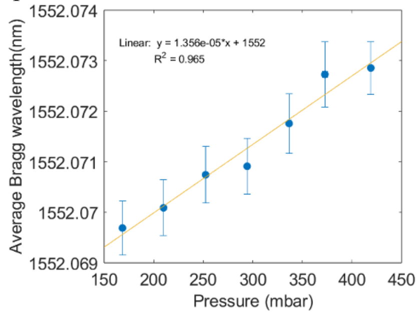


Fig.4. Pressure sensitivity plot.

4. Conclusion

This study demonstrated a substantial increase in FBG pressure sensitivity, enhancing it by 1.63 orders of magnitude (43.10 times) by applying a single-layer, biocompatible elastomeric coating, achieved without the need for extrinsic pressure diaphragms or additional packaging. A customized 3D-printed mold maintained the coating thickness between 300 and 500 µm. This coating not only improved the transduction mechanism but also the SNR. However, the experimental sensitivity was lower than theoretical predictions, likely due to the non-uniform nature of the coating and its adhesion to the OF. This sensor shows considerable promise for diagnostic applications, including intracoronary blood pressure monitoring, gastrointestinal pressure management, and high-resolution manometry, offering enhanced diagnostic and prognostic capabilities for medical treatment.

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