

Modified optical fiber sensors for intravital monitoring

Original

Modified optical fiber sensors for intravital monitoring / Nagar, Malhar; Lai, Marco; Janner, Davide. - (2023). (Intervento presentato al convegno European Conferences on Biomedical Optics tenutosi a Munich (DEU) nel 25-30 JUNE 2023) [10.1117/12.2669431].

Availability:

This version is available at: 11583/2981195 since: 2023-08-22T19:17:30Z

Publisher:

SPIE

Published

DOI:10.1117/12.2669431

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

SPIE postprint/Author's Accepted Manuscript e/o postprint versione editoriale/Version of Record con

Copyright 2023 Society of PhotoOptical Instrumentation Engineers (SPIE). One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this publication for a fee or for commercial purposes, and modification of the contents of the publication are prohibited.

(Article begins on next page)

PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Modified optical fiber sensors for intravital monitoring

Malhar Nagar, Marco Lai, Davide Janner

Malhar A. Nagar, Marco Lai, Davide Janner, "Modified optical fiber sensors for intravital monitoring," Proc. SPIE 12627, Translational Biophotonics: Diagnostics and Therapeutics III, 126272U (11 August 2023); doi: 10.1117/12.2669431

SPIE.

Event: European Conferences on Biomedical Optics, 2023, Munich, Germany

Modified optical fiber sensors for intravital monitoring

Malhar A. Nagar^a, Marco Lai^b, Davide Janner^a

^aPolitecnico di Torino, Department of Applied Science and Technology (DISAT), Turin, Italy

^bPhilips research, High Tech Campus Eindhoven, Eindhoven, Netherlands

ABSTRACT

Sensing using optical fibers is quite an established technology and is increasingly used in the field of bio-medical sensing applications owing to its small size, light weight, immunity towards electromagnetic interference, biocompatibility, sensitivity, and the ease with which it can be integrated with standard catheters leading to a designated point of inspection. Fiber Bragg gratings (FBGs), due to their ease of multiplexing, inherent sensitivity towards strain, and thereby pressure, can be suitably designed to make a novel pressure sensor for diagnosing and monitoring angiogenesis in brain tumors and for assessing vascular lesions inside coronary arteries. However, standard FBGs have a poor pressure sensitivity of 4pm/MPa (0.5fm/mmHg), which is insufficient to detect a few mmHg blood pressure changes.

By utilizing the mechanical properties of modified FBGs with an elastomeric material coating, it is possible to improve the transduction mechanism of effectively translating pressure to strain and increase the resolution and sensitivity by two orders of magnitude (53.4 times) compared to standard FBGs. These modified FBGs could then be used to monitor respective pressure indices, i.e., Intracranial Pressure (ICP) and Instantaneous wave-free Ratio (iFR), by integrating them with catheters or endoscopes and using appropriate signal-processing algorithms. Moreover, a simulation of the modification of the blood vessel flow with respect to the secondary vessel formation is done to study the impact of different blood vessel formations during angiogenesis on pressure, thereby co-relating flow patterns to angiogenesis.

Keywords: Optical fiber pressure sensor, Fiber Bragg Gratings, Instantaneous Wave-free Ratio, Intracranial pressure, Angiogenesis, Pressure sensitivity

1. INTRODUCTION

Brain tumors are abnormal cells in the brain that are either benign or malignant. When primary tumors in the brain grow beyond 1-2mm, they disrupt the functionality and structure of the blood-brain barrier [1], leading to life-threatening neurological disorders. Thus, an early diagnosis is vital for a better prognosis and therapy. Tumor cells grow more quickly than normal cells and can invade areas farther from blood vessels. As a result, they need more oxygen, nutrients, and blood supply to expand, which is accomplished via the growth of new blood vessels from already-existing ones (angiogenesis) [2]. The new blood vessels are leaky and highly permeable, which increases interstitial fluid pressure and, subsequently ICP. The normal mean ICP pressure range for adults is 7–15 mmHg, though readings over 20 mmHg need to be addressed immediately [3]. ICP is measured using a variety of invasive (ventricular catheter, lumbar puncture) and non-invasive (transcranial doppler) techniques. Still, the unmet need is to have a minimally invasive method that uses a pressure sensor for measuring the pressure index due to the high risk of invasive procedures and the unreliability of non-invasive methods.

As fiber technology for sensing is more advanced in cardiovascular applications, the optical fiber pressure sensor would first be tested for assessing vascular lesions using iFR guided strategy and then translated for diagnosing angiogenesis in cancers. In this technique, an optical fiber sensor is integrated with a pressure guide wire and inserted inside the blood vessel. A manual pullback of the guidewire is done to determine iFR (Figure 1(a)), thereby determining the severity of vascular lesions (e.g., stenosis). Surgical intervention is done only when the iFR value is less than 0.89 [4].

2. RESEARCH METHODOLOGY

Fiber Bragg gratings (FBGs), owing to their wavelength-encoded nature, ease of interrogation, less susceptibility towards signal corruption, and linear dependence on pressure are ideal to design a novel optical fiber pressure sensor for measuring ICP, and iFR pressure indices. FBG has a periodic modulation of refractive index in the fiber core, which at Bragg wavelength (λ_B) couples forward propagating mode to backward propagating mode, thereby acting as a spectral filter. Any environmental perturbation in the vicinity of fiber due to external pressure gets translated as the strain, which changes the grating period (Λ) and effective refractive index (n_{eff}) of the fiber core, thereby shifting the Bragg wavelength in the

reflection spectrum (Figure 1(b)) [5]. For standard silica glass fibers at 1550nm, strain sensitivity ($k_c = \frac{\Delta\lambda_B}{\epsilon}$) is 1.2pm/ $\mu\epsilon$, and pressure sensitivity ($\frac{\Delta\lambda_B}{P}$) is 4pm/MPa (or 0.5fm/mmHg) [6]. Therefore, to detect 1mmHg pressure, sub-femtometer accuracy of the Bragg wavelength shift is needed. However, with existing interrogation techniques, only pico-meter wavelength shifts and, at most sub-pm wavelength shifts can be detected accurately with clever read-out techniques [7].

In this work, we study the impact of the FBG parameters and the mechanical properties of the surrounding environment with respect to a potential increase in sensitivity. In particular, materials with lower Young's modulus and higher Poisson's ratio can effectively translate pressure to strain, producing Bragg wavelength shifts of pm or sub-pm range and being detected with adequate SNR with appropriate signal processing algorithms.

$$\lambda_B = 2n_{eff} \Lambda \tag{1}$$

$$\Delta\lambda_P = \lambda_B \left[-\frac{(1-2\nu)}{E} + \frac{n_{eff}^2}{2E} (1-2\nu) (2P_{12} + P_{11}) \right] \Delta P \tag{2}$$

$\Delta\lambda_P$: change in Bragg wavelength due to pressure; P_{11}, P_{12} : components of strain optic tensor

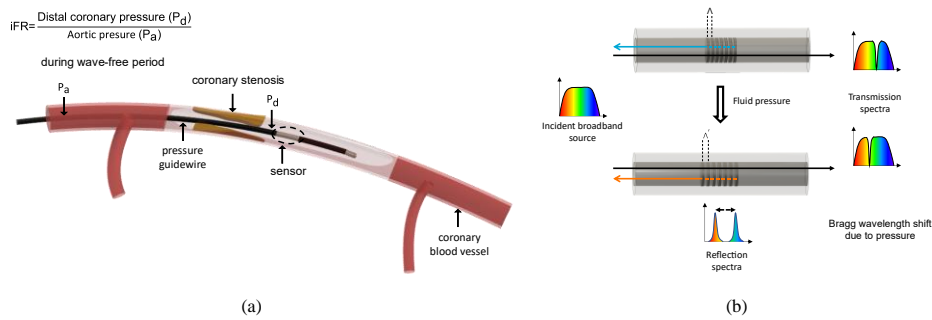


Figure 1. (a) iFR pullback technique for assessment of vascular lesions (b) FBG sensing principle

3. PRELIMINARY RESULTS

Using the finite element method in ANSYS, static strain analysis of standard fibers with fiber diameters of 125 μm and 80 μm is performed, and it is compared with that of an elastomeric material coating. The results revealed that just reducing the size of bare optical fiber from 125 μm to 80 μm hardly changes the sensitivity. However, it increases by an order of magnitude (16 times) when an optical fiber of 125 μm diameter is coated with a polymer compared to a bare optical fiber with the same diameter. Moreover, there is a further enhancement in sensitivity by orders of magnitude (53.4 times) if the diameter of the coated fiber is reduced to 80 μm (Figure 2(a), (b), and Table 1). The linear relationship between applied pressure and strain was also confirmed during the analysis. The chosen material also had lower thermal expansion and thermo-optic coefficient than silica, which effectively reduces the temperature cross-sensitivity of FBG.

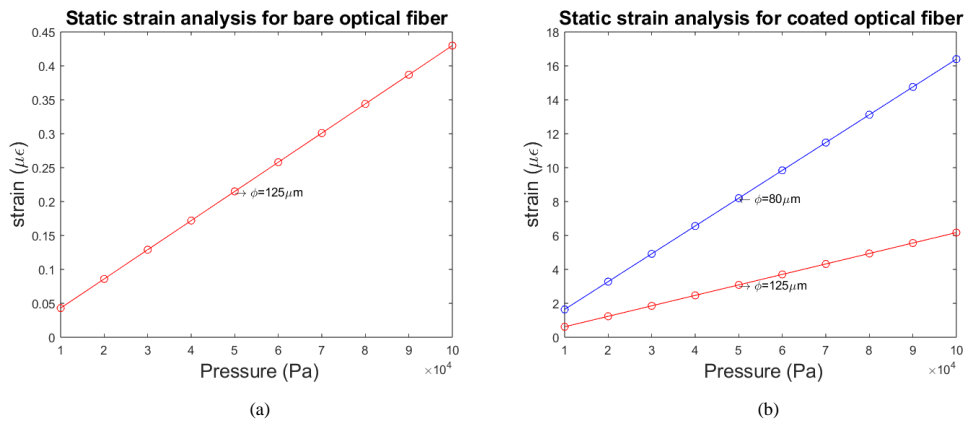


Figure 2. Static strain analysis using finite element method for (a) bare optical fiber and (b) elastomeric coated optical fiber (125 μm and 80 μm) with suitable diameter

Table1. Enhancement of sensitivity of bare fiber and coated fiber for different fiber diameters

Optical fiber diameter (μm)	Sensitivity ($\mu\epsilon/\text{mmHg}$)	
	Bare optical fiber	Coated optical fiber
125	0.0005	0.0080
80	0.0005	0.0267

Additionally, it is observed that when the diameter of the coated material increases, the effective strain on the fiber along the axial direction—which results in the Bragg wavelength shift—increases. However, due to the size of the pressure guide wire, i.e., $350\mu\text{m}$ - $500\mu\text{m}$ [4], the diameter of the coated material cannot be extended indefinitely, and thus the optimum diameter for required sensitivity was found accordingly (Figure 3).

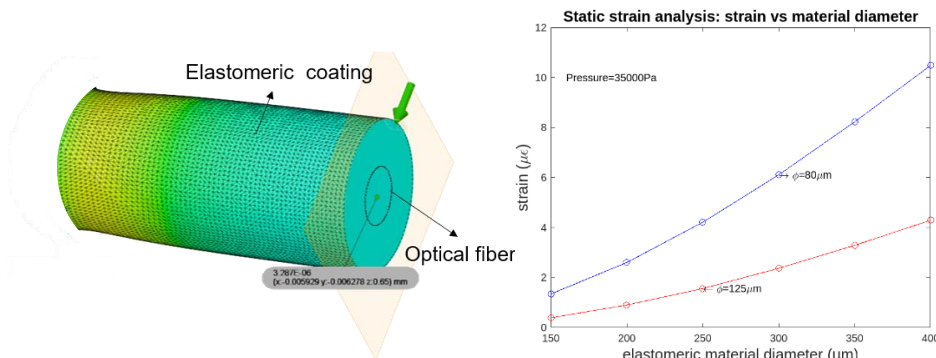


Figure 3. Static strain analysis of optical fiber: strain response with respect to material diameter under fixed pressure of 35000Pa

To study the impact of new blood vessel formations during angiogenesis on pressure, a phasic blood flow simulation is studied on an artery model (Figure 4) to detect bifurcating vessels via pressure sensing at the bifurcation site. Blood is approximated as an incompressible Newtonian fluid with a density of $1.06\text{g}/\text{cm}^3$ and a dynamic viscosity of $0.04\text{dynes}/\text{cm}^2$ [8].

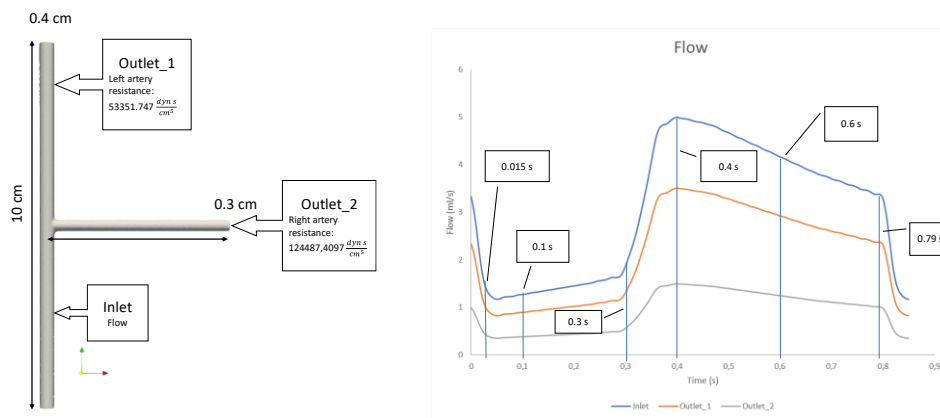


Figure 4. Phasic blood flow in the left artery with a branch

Pressure fluctuations were observed at the centerline of the left artery, and it follows a similar trend across the entire cardiac cycle, as shown in Figure 5. This approach can be used as a preliminary step to establish a correlation between pressure profile and blood flow inside blood vessels at cancer sites, which can be useful to monitor angiogenesis and thus can give an idea about the progression of cancer.

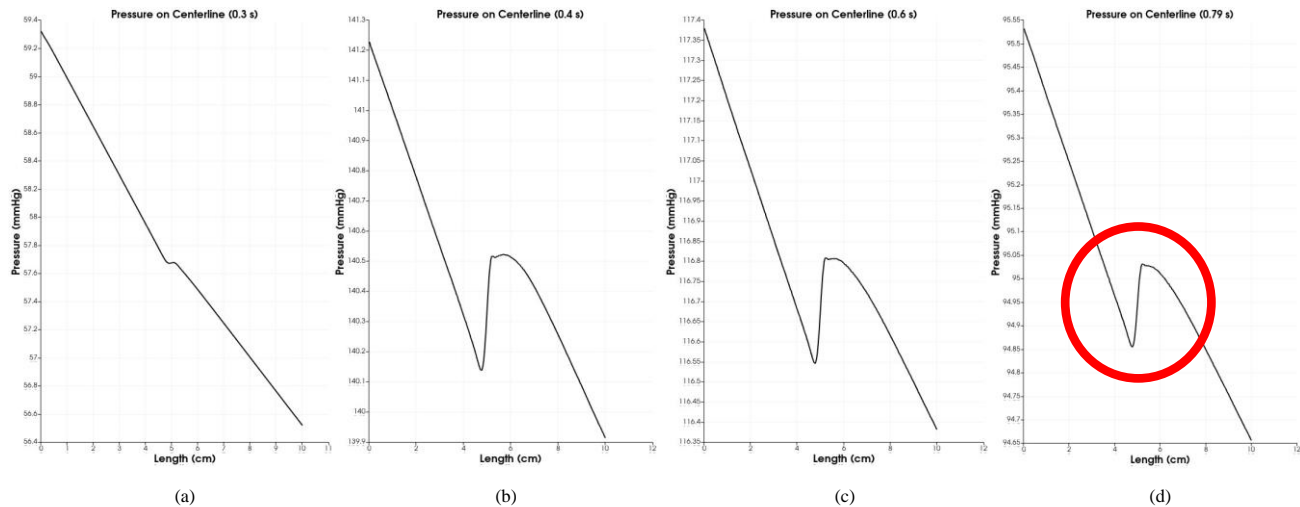


Figure 5. Pressure along the centerline of an artery during an entire cardiac cycle of 0.8s

4. DISCUSSION

Currently, a pressure guide wire is used in conjunction with a piezoresistive sensor (electrical sensor), MEMS-based, or Fabry-Perot (FP)-based optical fiber sensor to monitor pressure indices. Optical fiber sensors are preferred over electrical sensors mainly due to their inertness, small size, and sensitivity [9]. Among various optical fiber sensors, FP sensors are the most sensitive but have complex interrogation and detection procedures and are expensive. In contrast, FBGs have benefits such as linear dependence on pressure, absolute measurement capabilities with straightforward demodulation techniques, and cost-effectiveness while being less sensitive than FP [10]. These modified FBGs with thick coating can enhance resolution and only shortcoming, i.e., the pressure sensitivity of FBGs, making them ideal for monitoring pressure indices like iFR and ICP during interventional procedures.

5. ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860185.

6. REFERENCES

- [1] R. K. Jain, E. di Tomaso, D. G. Duda, J. S. Loeffler, A. G. Sorensen, and T. T. Batchelor, "Angiogenesis in brain tumours," *Nature Reviews Neuroscience*, vol. 8, no. 8, pp. 610–622, Aug. 2007, doi: 10.1038/nrn2175.
- [2] M. Rajabi and S. A. Mousa, "The role of angiogenesis in cancer treatment," *Biomedicines*, vol. 5, no. 2. MDPI AG, Jun. 01, 2017, doi: 0.3390/biomedicines5020034.
- [3] P. Roriz, O. Frazão, A. B. Lobo-Ribeiro, J. L. Santos, and J. A. Simões, "Review of fiber-optic pressure sensors for biomedical and biomechanical applications," *Journal of Biomedical Optics*, vol. 18, no. 5, p. 050903, May 2013, doi: 10.1117/1.jbo.18.5.050903.
- [4] Nijjer, S. S., Chb, M., Sen, S., et al., "Pre-Angioplasty Instantaneous Wave-Free Ratio Pullback Provides Virtual Intervention and Predicts Hemodynamic Outcome for Serial Lesions and Diffuse Coronary Artery Disease," *JAAC: Cardiovascular interventions*, vol. 7, no. 12, p. 1386-1396, Dec 2014, doi: 10.1016/j.jcin.2014.06.015.
- [5] Carlo Massaroni et al., "Medical smart textiles based on fiber optic technology: an overview," *Journal of Functional Biomaterials*, vol 6, p. 204-221, April 9, doi: 10.3390/jfb6020204.
- [6] L. Schenato et al., "Highly Sensitive FBG Pressure Sensor Based on a 3D-Printed Transducer," *Journal of Lightwave Technology*, vol. 37, no. 18, p. 4784–4790, Sep. 2019, doi: 10.1109/JLT.2019.2919917.
- [7] D. Tosi, "Improved KLT Algorithm for High-Precision Wavelength Tracking of Optical Fiber Bragg Grating Sensors," *Journal of Sensors*, vol. 2017, 2017, doi: 10.1155/2017/5412825.
- [8] H. J. Kim, I. E. Vignon-Clementel, et al., "Patient-specific modeling of blood flow and pressure in human coronary arteries," *Annals of Biomedical Engineering*, vol. 38, no. 10, p. 3195–3209, Oct. 2010, doi: 10.1007/s10439-010-0083-6.

- [9] S. Poeggel, D. Tosi, D. Duraibabu, et al., "Optical fibre pressure sensors in medical applications," *Sensors* (Switzerland), vol. 15, no. 7. MDPI AG, pp. 17115–17148, Jul. 15, 2015. doi:10.3390/s150717115.
- [10] R. Correia, S. James, S. W. Lee, S. P. Morgan, and S. Korposh, "Biomedical application of optical fibre sensors," *Journal of Optics* (United Kingdom), vol. 20, no. 7. IOP Publishing Ltd, Jul. 01, 2018. doi: 10.1088/2040 8986/aac68d.