Modified optical fiber sensors for intravital monitoring

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.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

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

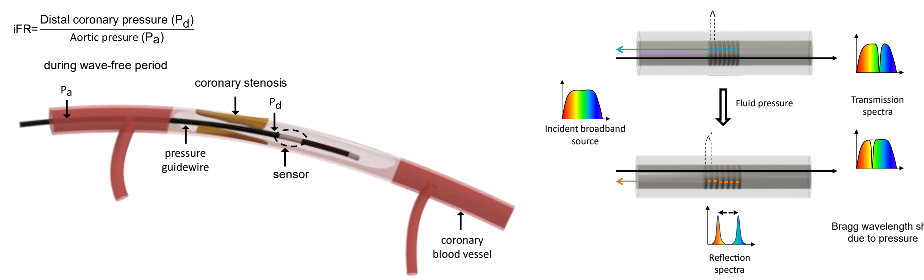
reflection spectrum (Figure 1(b)) [5]. For standard silica glass fibers at 1550nm, strain sensitivity ($k_\varepsilon=\frac{\Delta\lambda_B}{\varepsilon}$) is 1.2pm/με, and pressure sensitivity ($\frac{\Delta\lambda_B}{P}$) is 4pm/MPa (or 0.5fm/mmHg) [6]. Therefore, to detect 1mmHg pressure, sub-femtometer 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.

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

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

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

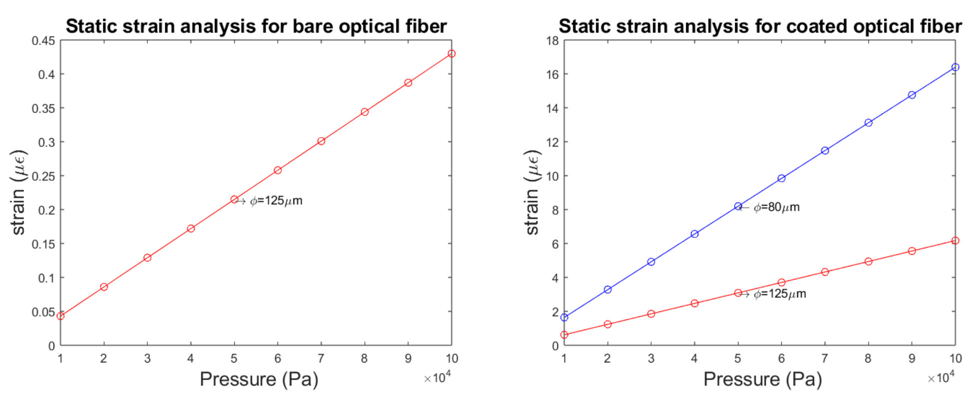


(a) (b)

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 125μm and 80μm 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 125μm to 80μm hardly changes the sensitivity. However, it increases by an order of magnitude (16 times) when an optical fiber of 125μm 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 80μm (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.



(a) (b)

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

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

Optical fiber diameter (μm)	Sensitivity (με/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., 350μm-500μm [4], the diameter of the coated material cannot be extended indefinitely, and thus the optimum diameter for required sensitivity was found accordingly (Figure 3).

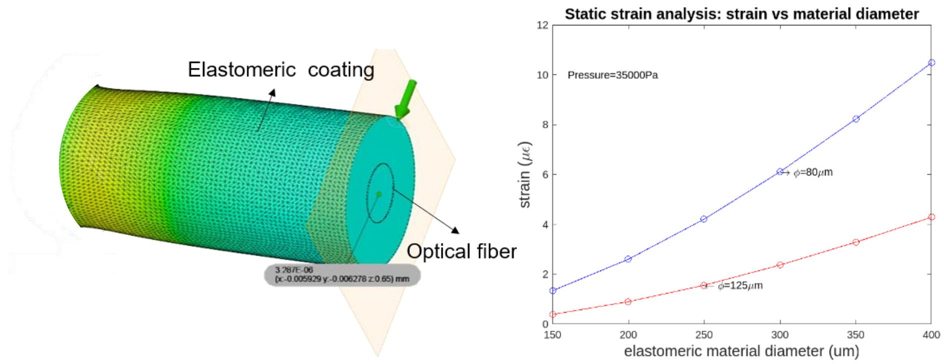


Figure 3. Static strain analysis of optical fiber: strain response with respect to material diameter under fixed pressure of 35000Pa

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 $1.06 g/cm^3$ and a dynamic viscosity of $0.04 dynes/cm^2$[8].

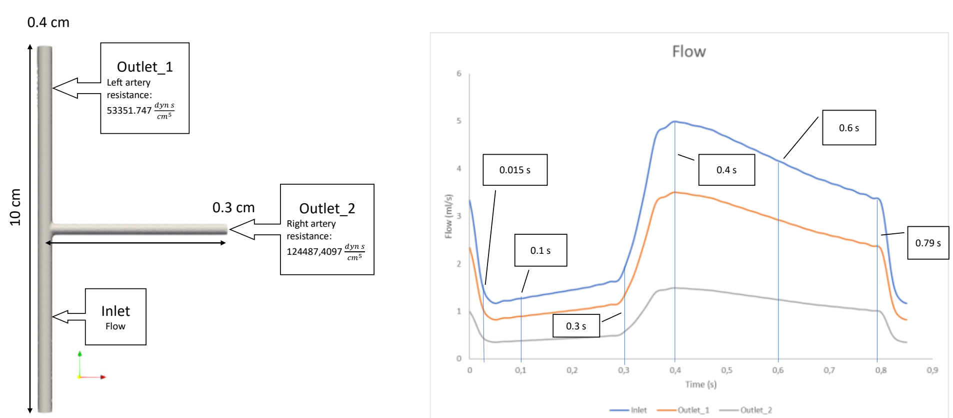
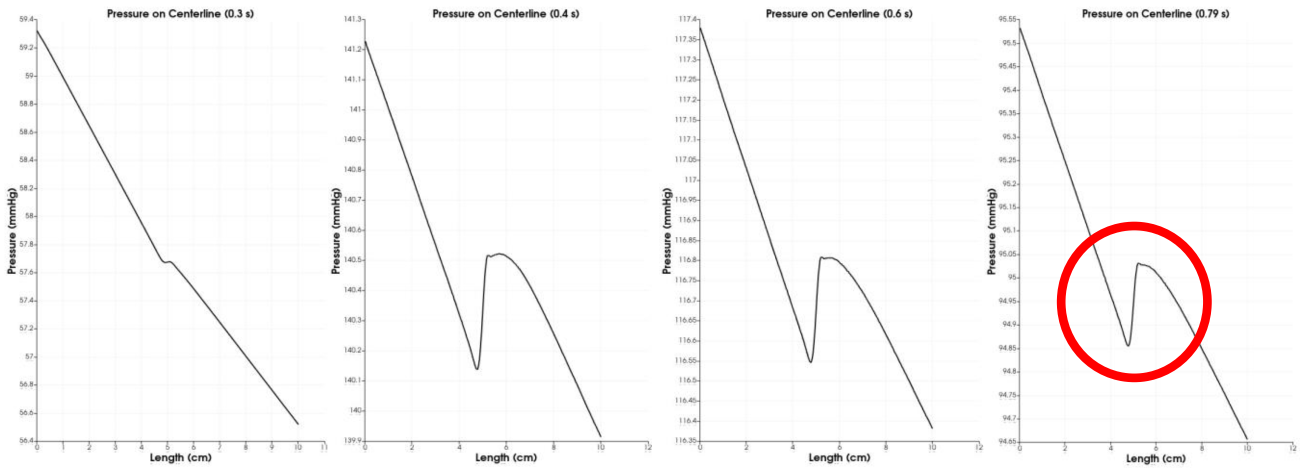


Figure 4. Phasic blood flow in the left artery with a branch

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.



(a) (b) (c) (d)

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 Sklodowska-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.