Doctoral Dissertation
Doctoral Program in Material Science and Engineering (37th Cycle)

Fiber Bragg Grating-Based Sensors: Advanced Techniques in Coating and Interrogation for Biomedical Applications

Customized sub-mm coatings, Dual-comb sensing and Biomedical phantom designs

Malhar Anupamratanshanker Nagar

* * * * * *

Supervisors
Prof. Davide Janner, Supervisor
Dr. Jean Schleipen, Co-Supervisor

Doctoral Examination Committee:
Dr. Francesco Chiavaioli, Referee, Institute of Applied Physics CNR-IFAC
Prof. Joris Lousteau, Referee, University of Politecnico di Milano

Politecnico di Torino
April 28, 2025

I hereby declare that, the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

……………………………….....

Malhar A. Nagar

Turin, April 28, 2025

Abstract

Fiber Bragg Grating (FBG) technology has emerged as a powerful platform for real-time monitoring of pressure, strain, and other physical parameters in both industrial and biomedical domains. It offers a uniquely compact, immune-to-EMI platform for multiparameter sensing, yet conventional gratings lack the pressure sensitivity (~ 0.4 fm/mmHg) and sub-picometre resolution demanded by emerging minimally invasive diagnostics. This research addresses these challenges through four key innovations: (1) Coating-based pressure sensitivity enhancement, (2) Dual Optical Frequency Comb (DOFC) Interrogation, (3) Simple signal processing algorithms, and (4) Biomedical phantom development for validation.

First, femtosecond (fs)-written gratings were encapsulated in sub-millimetre, biocompatible silicone layers applied with 3D-printed injection moulds, boosting static pressure responsivity by a factor of ~ 40 and 150 while maintaining catheter-scale outer diameters. Second, a dual optical frequency-comb (DOFC) interrogator based on injection-locked gain-switched lasers was devised. This interrogation scheme provided a 0.32 με resolution for standard fs-written FBGs and 85 nε for fs-written π-phase-shifted gratings, together with sub-picometre baseline stability over two-minute acquisitions. The dynamic strain sensing capabilities were further validated by successfully tracking sinusoidal strain perturbations at 3 Hz with amplitudes as small as 1 nm (3.57 nε) and 5 nm (17.85 nε). Thirdly, an array of signal processing techniques is proposed and optimized to accurately extract minuscule shifts in the FBG reflection and transmission spectra. Methods such as spline fitting, FFT-Gaussian fitting, and inverted Gaussian fitting are systematically applied and benchmarked against commercial interrogators, revealing superior accuracy in detecting critical sensor outputs. These techniques not only extend linearity to nano-strain increments but also triples the detection Figure-of-Merit at nano-strain levels relative to commercial interrogators.

To translate these advances toward clinical reality, two complementary phantom platforms were constructed. A mechanically compliant, silicone-embedded arterial model was developed which reproduces physiological wall stiffness and accommodates tumour-mimicking inclusions, enabling quasi-static calibration of coated FBG under precisely metered loads. In parallel, an optically scattering, Lipofundin-filled pulsatile phantom equipped with Mylar optical window, integrated intracranial-pressure catheters, and peristaltic flow control was fabricated to study how externally injected pressure distorts blood-flow-index (BFI) waveforms captured by diffuse correlation spectroscopy. Although only initial proof-of-concept trials have been completed, these phantoms establish a rigorous, dual-modality test-bed.

Collectively, these advances establish a coherent framework - polymer-enhanced FBG transducers, ultra-high-resolution dual-comb read-out, and physiologically relevant testbeds that pushes optical-fibre sensing toward clinical reality. The integrated platform can be potentially extensible to a broad spectrum of biomedical pressure-sensing tasks, such as from minimally invasive haemodynamic mapping of coronary and cerebrovascular lesions to fully non-invasive wearables and smart-textile systems for continuous cardiorespiratory monitoring.