Integrated Photonic Interrogation of Extrinsic Fabry–Perot Fiber Sensors for Absolute Distance Metrology in Geophysical Applications

Keywords: integrated photonics, Fabry-Perot Interferometer, optoelectronics, Optical Metrology, Signal Processing

Description of research project

Context:

Absolute optical metrology enables unambiguous and traceable measurement of length, distance, and geometry with nanometric precision. It is a key enabling technology in applications such as LiDAR systems, precision positioning, surface profilometry, and advanced manufacturing. Unlike relative measurement techniques, absolute metrology preserves measurement consistency across time, which is essential for long-term monitoring scenarios where system interruptions (e.g., power loss or resets) can otherwise introduce ambiguity or cumulative error.

Optical interferometry is one of the most mature and powerful approaches for high-precision absolute metrology. Its fundamental principle relies on the encoding of displacement information into the optical phase or frequency of a coherent optical field. Among existing techniques, phase-shifting interferometry (PSI) and frequency-modulated continuous-wave (FMCW) interferometry are widely used.

In PSI, controlled phase variations, typically induced through wavelength tuning or electro-optic phase modulation, are used to retrieve displacement with nanometric sensitivity. In FMCW interferometry, a linear frequency sweep of the laser source is employed, and the optical path difference is extracted from the beat frequency between reference and delayed signals, enabling direct absolute distance retrieval.

These interferometric approaches are increasingly applied to geophysical instrumentation for monitoring ground deformation along active faults. Such measurements are essential to understand earthquake mechanics and improve seismic risk assessment. However, current geodetic techniques typically provide millimetric resolution (≈0.5–2 mm), which is insufficient to reliably detect small-amplitude aseismic deformation phenomena such as slow slip events (SSEs), often considered precursors to large earthquakes.

State of the Art and Scientific Background

Recent developments in opto-geophysical instrumentation have demonstrated the potential of fiber-optic interferometric sensors for high-resolution geophysical monitoring. In particular, extrinsic fiber Fabry–Perot interferometers (EFFPI), developed within our laboratory, have shown the ability to measure nanometric displacements induced by seismic and tectonic activities.

These systems offer several advantages:

- high displacement sensitivity (nm-scale),
- immunity to electromagnetic interference,
- suitability for remote and harsh environments,
- compatibility with long-term deployment.

However, achieving **absolute distance metrology with sub-micrometric resolution, long-term stability, and large dynamic range** remains a major scientific and technological challenge. Existing systems often rely on external references (e.g., gas cells or frequency combs), which limit compactness and field deployability.

Objectives:

This PhD project aims to develop a **fiber-optic sensing system for absolute distance metrology**, based on an Extrinsic Fiber Fabry–Perot Interferometer (EFFPI), with direct application to geophysical instrumentation.

The specific objectives are:

- achieve **submicrometer-scale resolution** over a wide dynamic range for absolute distance measurements
- achieve **nanometer-scale resolution** over a wide dynamic range for relative displacement measurements

- ensure **long-term stability and low drift**, compatible with geophysical monitoring requirements
- develop a **compact and integrated photonic interrogation system** to replace conventional bulk optical references
- enable integration of the sensor into **field-deployable geophysical instruments**
- extend applicability to **precision optical metrology beyond geophysics**

A key innovation of this work is the development of **silicon nitride photonic integrated circuits (PICs)** to implement a compact and robust interrogation architecture for:

- absolute distance measurement, replacing conventional gas-cell-based references.
- relative displacement measurement by locking the laser, replacing conventional gas-cell-based references

The proposed sensor system will be fully characterized in terms of resolution, dynamic range, and long-term stability, prior to its integration into geophysical instruments. These instruments will then be validated through field testing at dedicated sites before deployment.

Proposed Approach and Scientific Innovation

The project builds on previous laboratory developments (ANR LASERTILT, ANR XSTRAIN, ANR LINES, FUI MIRZA) in high-performance opto-geophysical instrumentation.

The proposed system exploits the optical phase response of a laser diode (LD) interrogating the EFFPI sensor. Absolute distance information will be retrieved through controlled modulation of the laser source:

- injection current modulation,
- and/or temperature tuning,

which induce deterministic phase variations of the optical field. These variations are processed using **synchronous demodulation techniques** to extract absolute distance information.

A central innovation of this work is the development of **silicon nitride (SiN) photonic integrated circuits (PICs)** for sensor interrogation.

This approach will:

- replace bulky free-space optical components,
- eliminate dependence on gas-cell frequency references,
- enable compact, stable, and scalable interrogation modules,
- improve robustness for field deployment.

The PIC will implement:

- laser stabilization and locking functions,
- phase demodulation architecture,

  and integrated optical signal processing.

Work Environment

The PhD will be conducted at **LAAS-CNRS**, within the Optical Sensors and Intelligent Integrated Systems team (ENSEEIHT site). The project will benefit from access to a cleanroom facility for photonic integrated circuit fabrication and characterization.

Collaborations will include:

- Laboratory of Geology (ENS Paris)
- Field test sites for geophysical validation

Collaborations: University of Glasgow, UK (PIC model refinement)

Supervision: Dr H. C. Seat and Dr O. Bernal (co-supervisor)

Contact: Dr H. C. Seat, LAAS-CNRS/ENSEEIHT-Toulouse INP (email: hcseat@laas.fr)