CORA Cork Open Research Archive
Cartlann Taighde Oscailte Chorcaí

Title	Ultra-sensitive refractive index sensing using a hybrid photonic crystal external cavity laser and the optical heterodyne technique
Authors	Oliveira, Taynara;Iadanza, Simone;Vorobev, A. S.;Kotlyar, Maria V.;O'Faolain, Liam
Publication date	2025-04-17
Original Citation	Oliveira, T.A., Iadanza, S., Vorobev, A.S., Kotlyar, M.V. and O'Faolain, L. (2025) 'Ultra-sensitive refractive index sensing using a hybrid photonic crystal external cavity laser and the optical heterodyne technique', IEEE Silicon Photonics Conference (SiPhotonics), London, England 14-17 April, pp. 1-2.
Type of publication	Conference item
Rights	© 2025, IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.
Download date	2026-11-01 19:35:42
Item downloaded from	https://hdl.handle.net/10468/17804

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Ultra-sensitive refractive index sensing using a Hybrid photonic crystal external cavity laser and the optical heterodyne technique

T.A. Oliveira[1,2], **S. Iadanza**[1,2,3], **A.S. Vorobev**[1,2], **Maria V. Kotlyar**[1,2], **L. O'Faolain**[1,2]

1. Centre for Advanced Photonics and Process Analysis, Munster Technological University, T12 T66T Bishopstown, Cork, Ireland

2. Tyndall National Institute, T12 PX46 Cork, Ireland

3. Laboratory of Nano and Quantum Technologies, Paul Scherrer Institut, 5232, Villigen, Switzerland

lofaolain@gmail.com

Abstract **- This study presents a breakthrough in refractive index sensing by combining a silicon nitride 1D photonic crystal cavity in a hybrid external cavity laser with the optical heterodyne technique. Achieving ~10^{-7} RIU detection limit, which represents 400x improvement in detection capability over existing high-sensitivity devices.**

Keywords - Photonic Crystal Cavity (PhC), hybrid laser, heterodyne, detection limit (DL).

I. INTRODUCTION

In recent years, numerous optical sensors have been developed to detect various analytes in real-time with high sensitivity and compact design. Optical sensors for chemical or biological molecules are generally categorized into two detection modes: label-free and label-based. Label-based sensors require additional tagging molecules, such as fluorophores and others, which sometimes have undesirable side effects. In contrast, label-free sensors rely on detecting the intrinsic physical properties of analytes, such as refractive index (RI), which means their performance is influenced by sample concentration rather than volume, allowing for detection down to the parts-per-billion (ppb) level and potentially down to femtolitre sample volumes [1]. Such detection limits are crucial for monitoring extremely low concentrations of harmful substances, like viral pathogens in water sources. Given the advantages these sensors offer in biomedical research, healthcare, and environmental monitoring, many photonic devices have been explored as label-free optical sensors, with micro-ring resonators (MMRs) and photonic crystal (PhC) cavities being among the most commonly studied.

Silicon photonic sensors are particularly advantageous for refractive index sensing due to their sensitivity to shifts in resonant wavelength caused by changes in the refractive index of the cladding material, whether through bulk variations or the binding of target analytes. In drinking water distribution systems, for example, Mach-Zehnder interferometers are used for RI measurements to assess water quality. Since any dissolved substance alters the water's refractive index, this method can monitor all chemical changes without the need for specific targeting, unlike sensors that identify only specific

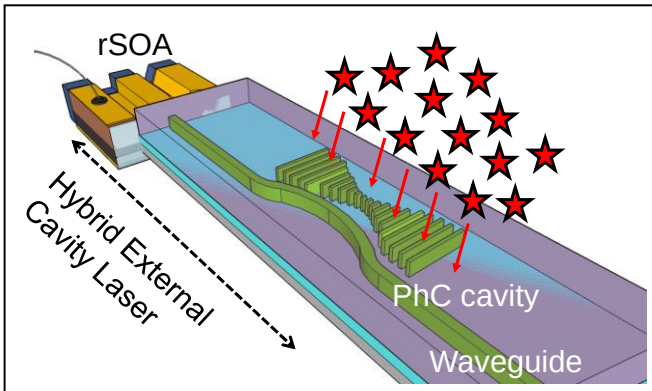


Figure 1 - Schematic of the Photonic Crystal Hybrid external cavity laser using RI sensing of gas mixtures.

contaminants. Therefore, RI sensing enables continuous monitoring and provides early alerts regarding potential issues within the distribution network [2]. The performance of RI sensors is determined by their detection limit (DL), which indicates the smallest detectable change in RI. The DL is influenced by both the sensor's sensitivity to RI changes and its resolution, which depends on the resonator Q-factor and the precision with which wavelength shifts can be measured. Typical silicon MRRs achieve detection limits around $1x10^{-6}$ RIU, corresponding to concentrations in the parts-per-million (ppm) range. However, parts-per-billion sensitivity is often required to detect trace contaminants. While considerable efforts have focused on improving detection limits by optimizing the resonator Q-factor and mode overlap, less attention has been given to advancing sensor readout techniques.

By integrating photonic crystal resonant mirrors with III-V gain chips, we recently developed a novel type of hybrid external cavity laser [3]. We demonstrated the use of this device as an RI sensor by measuring shifts in the lasing wavelength when exposed to different surrounding materials, offering new insights into RI sensor sensitivity to create a Hybrid Laser RI sensor (HLS). In the present work, we use an optical heterodyne technique to measure lasing wavelength shifts in the HLS, directly linked to refractive index changes, achieving an

improvement of approximately 400x in the intrinsic detection limit (iDL) [4] compared to existing high-sensitivity devices.

II. Sensing Principle

The heterodyne technique involves mixing two laser beams with slightly different frequencies, with one acting as a reference called the local oscillator (LO) and the other as the signal of interest (HLS, in this case). The superposition and interference of the laser frequencies generate a beat frequency that falls within the RF bandwidth of the photodetector in use. In our setup, the LO is fixed by a reference tunable laser, while the signal of interest is the HLS lasing frequency. By monitoring the beat frequency, we can detect shifts in the HLS frequency caused by RI changes in the sensor's surrounding environment. These RI variations shift the resonance frequency of the PhC cavity, altering the HLS lasing frequency and, consequently, the beat frequency. Since heterodyne measurement can detect laser wavelength changes comparable to the laser's linewidth (1.6 MHz), it is orders of magnitude more precise than spectrometers and passive-based configurations.

III. Example Results

To precisely vary the cladding refractive index of the HLS, we used a mass flow controller (MFC-SEC-4400) to mix N_2 and CO_2 gases, with RIs ranging from 1.00029442 (100% N_2) to 1.00043822 (100% CO_2). The HLS was placed inside a flow chamber to regulate the gas flow, and an in-line commercial CO_2 sensor (SprintIR®-W 100% CO_2) measured concentration values. Temperature sensors were incorporated to control and characterize the cooling effect of the gases, which minimally affects sensor response. Figure 2 shows an example result where pulses of 100% CO_2 are introduced. As CO_2 concentration increases, red shifts in the beat signal are observed. These results are promising, demonstrating that the HLS in a heterodyne configuration enhances detection of small RI changes by over an order of magnitude compared to the standalone HLS. With a measurement sensitivity of 10006 GHz/RI (R^2 = 0.9943), we estimate a detection limit of ~1.59×10^{-7} RIU—significantly surpassing the high-sensitivity sensor with a DL of 6.86×10^{-5} RIU reported in [5] and offering 10000 times greater resolution than passive PhC cavity measurements alone.

IV. Summary

We have introduced a novel approach to RI sensing based on the optical heterodyne method and RI-sensitive hybrid lasers, achieving over an order of magnitude improvement in detection limit compared to traditional passive optical resonators. One key factor determining detection limits is the quality factor of resonators. Higher Q-factors typically enhance sensor sensitivity; however, there is a trade-off: the sensor mode must interact with the sample, increasing losses and potentially reducing the Q-factor. Our sensor partially overcomes this trade-off by introducing gain—where the sensitivity is determined by the PhC resonator, and the linewidth is governed by the overall laser cavity. This configuration allows our laser-based RI sensor to perform highly sensitive measurements even in lossy environments. Future work will focus on integrating the lasers onto a single chip using techniques such as transfer printing [6]. Further enhancements in laser linewidth [7] and measurement stability [8] are anticipated to dramatically improve detection limits, with the potential for fully integrated RI sensor chips achieving detection limits as low as 10^{-9} RIU or better.

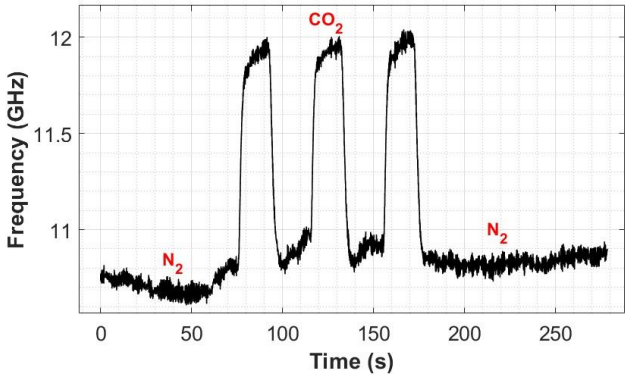


Figure 2 - Example measurement of the beat frequency. Pulse of CO_2 are introduced to the gas chamber enclosing HLS.

Acknowledgments

This work has received funding from the Science Foundation Ireland (SFI) project ID SFI12/RC/2276_P2 (IPIC), METASPECS 21/FFP-A/10002 and 16/ERCS/3838, and by the Horizon 2020 ERC-POC-899774.

References

[1] X. Fan, I. M. White, S. I. Shopova, H. Zhu, J. D. Suter, and Y. Sun, ''Sensitive optical biosensors for unlabeled targets: a review,'' Analytica Chimica Acta, vol. 620, pp. 8–26, 2008.

[2] F. Williamson, J. van den Broeke, T. Koster, M. K. Koerkamp, J. W. Verhoef, J. Hoogterp, E. Trietsch, and B. R. de Graaf, "Online water quality monitoring in the distribution network," Water Practice and Technology 9(4), 575–585 (2014).

[3] S. Iadanza, J. H. Mendoza-Castro, T. Oliveira, S. M. Butler, A. Tedesco, G. Giannino, B. Lendl, M. Grande, and L. O'Faolain, "High-Q asymmetrically cladded silicon nitride 1D photonic crystals cavities and hybrid external cavity lasers for sensing in air and liquids," Nanophotonics 11, 4183–4196 (2022).

[4] E. Luan, H. Shoman, D. M. Ratner, K. C. Cheung, and L. Chrostowski, "Silicon Photonic Biosensors Using Label-Free Detection," Sensors 18(10), (2018).

[5] Lu, K.; Huang, B.; Lv, X.; Zhang, Z.; Ma, Z. Ultrasensitive Silicon Photonic Refractive Index Sensor Based on Hybrid Double Slot Subwavelength Grating Microring Resonator. Sensors 2024, 24, 1929. https://doi.org/10.3390/s24061929

[6] R. Loi, S. Iadanza, B. Roycroft, J. O'Callaghan, L. Liu, K. Thomas, A. Gocalinska, E. Pelucchi, A. Farrell, S. Kelleher, R. F. Gul, A. J. Trindade, D. Gomez, L. O'Faolain, and B. Corbett, "Edge-Coupling of O-Band InP Etched-Facet Lasers to Polymer Waveguides on SOI by Micro-Transfer-Printing," IEEE Journal of Quantum Electronics 56(1), 6400108 (2020).

[7] C. Xiang, P. A. Morton, and J. E. Bowers, "Ultra-narrow linewidth laser based on a semiconductor gain chip and extended Si3N4 Bragg grating," Opt. Lett. 44(15), 3825–3828 (2019).

[8] A. P. Bakoz, A. A. Liles, A. A. Gonzalez-Fernandez, T. Habruseva, C. Hu, E. A. Viktorov, S. P. Hegarty, and L. O'Faolain, "Wavelength stability in a hybrid photonic crystal laser through controlled nonlinear absorptive heating in the reflector," Light: Science and Applications **7**, 39 (2018).