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Refractive Index Sensing using the optical heterodyne method and Photonic crystal hybrid laser

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Abstract: We have demonstrated a new approach to refractive index sensing based on the optical heterodyne method and a refractive index sensitive hybrid laser. We achieved over an order of magnitude improvement in the detection limit relative to the RI measurement based on a passive optical resonator. © 2024 The Author(s)

1. Introduction

Monitoring a substance's refractive index is a powerful method of optical sensing as many contaminants and processes affect the refractive index. The response of an optical resonator is linked to the refractive index of the materials of which it is composed, and for example, many research groups use silicon ring resonators and which detects the small change in resonant wavelength that is induced when material is deposited on the ring [1]. The surface of the ring is functionalized with a range of antigens that are specific to different target compounds. And when samples are run over the chip, macromolecules will bond to the surface changing the resonance wavelength. OptiQua uses Mach Zehnder interferometer based refractive index (RI) measurements to monitor the dynamics of water quality in drinking water distribution networks. The RI is a generic indicator of water quality as any substance that is dissolved in water will change the water's refractive index [2]. Monitoring the RI allows all chemical changes to be tracked regardless of the type, unlike other sensors, each of which are sensitive to only a small subset of possible contaminants. RI sensing can therefore provide event monitoring giving early warning of problems in the network.

The detection limit (DL) is the key measure of the performance of an RI sensor and determines the smallest change in refractive index that a sensor can detect. The DL is a function of both the RI sensitivity, which is the magnitude in shift of the resonant wavelength versus the change in RI of the sample, and of the sensor resolution, which characterizes the smallest possible spectral shift that can be accurately measured [3]. The sensitivity depends on the fraction of the optical mode that interacts with the sample. The sensor resolution depends on precision with which an extremum in the transmission spectrum can be tracked, which will be proportional to Q-factor of the resonator. Typical values for the detection limit are on the order of $1x10^{-6}$ RIU for silicon micro-ring-based sensors, which generally corresponds to concentrations in the parts per million (ppm) range, and is limited by the linewidth of the resonance. While these are powerful techniques, parts per billion sensitivities are required to detect many trace substances and contaminants.

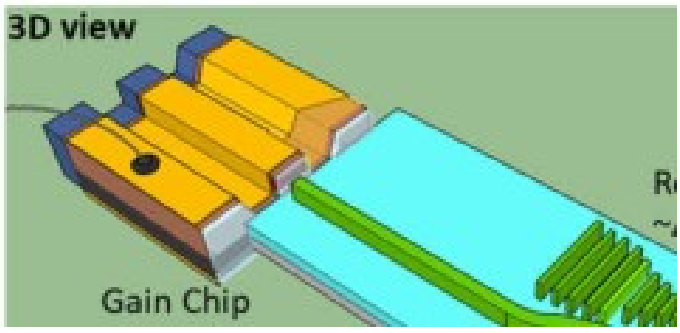

Figure 1 Schematic of the RI sensitive Photonic Crystal Hybrid external cavity laser

We have recently demonstrated a new family or photonic crystal hybrid external cavity (HECL) [4], shown schematically in Figure 1. The laser comprises a III-V gain chip and a silicon nitride based one-dimensional photonic crystal (PhC) which acts as a resonant mirror that sets the operating wavelength. Side mode suppression ratio greater than 40 dB, threshold currents< 20 mA and wall plug efficiencies of almost 10% have been achieved. Much of the mode supported by the 1D PhC exists in the top cladding material (in this case, the air or water of the sample) meaning the lasing wavelength is affected by the sample's refractive index giving a sensitivity of approx. 140nm/RIU [5]. To take advantage of the ultra-narrow linewidth of the lasing line, we have developed a new refractive index sensing technique that is based on optical heterodyne detection. The signal from the refractive

index sensitive HECL is combined with a reference laser on a photodiode and the beat note monitoring giving a system that is orders of magnitude more sensitive than current approaches.

2. Experimental results

The HECL comprises a silicon nitride 1D PhC cavity butt-coupling III-V gain chip, with the dimensions of the SiN waveguide chosen to the area of the gain chip waveguide mode as to maximize optical coupling between the two components. The SiN PhC provides wavelength-selective feedback and the HECL lases at Ph resonance wavelength of the HECL.

To controllably and precisely change the cladding refractive index, we used a controlled mixture of N2 and CO2, which has a refractive index between 1.00029442 (pure N2) and 1.00043822 (pure CO2). The HECL was positioned in a flow chamber with a gas mixer, along with an inline electrochemical sensor as monitor.

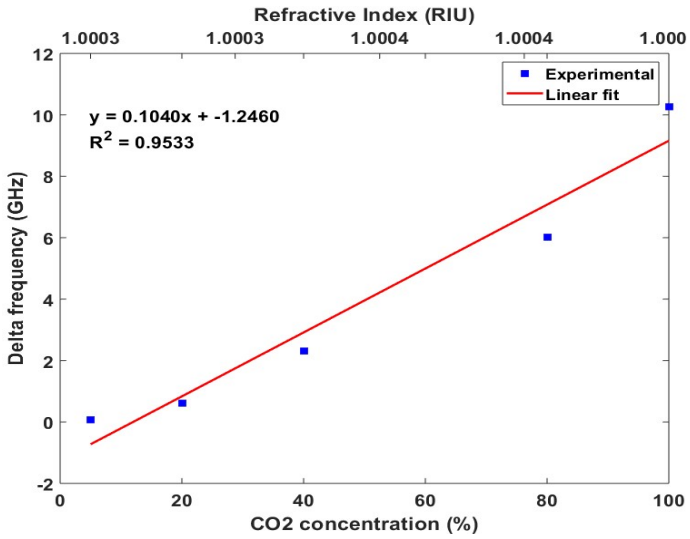

Figure 2 The measured beat frequency as a function of CO2 concentration.

The output of the hybrid laser is now mixed with that of the fixed tunable laser source (TLS) and the output signal (beat intensity) is captured on the 35 GHz photodetector oscilloscope and we measure the beat frequency shift against different cladding refractive indexes.

To controllably change the cladding refractive index, we used a Mass Flow Controlled (SEC-4400) to mix N2 and CO2 gas, which has a refractive index between 1.00029442 (100% N2) and 1.00043822 (100% CO2). The HECL was positioned in a flow chamber to better control the gas flow. Before the gas reached the chamber, in line, we used a commercial CO2 sensor to determine the CO2 concentrations. As the concentration changes, the beat signal red shifts as expected (see Figure). The first calibration curve for this measurement was calculated. To further improve the response linearity in future measurements a flow study will proceed, and with the right settings a better stabilization of the flow inside the chamber can be achieved. For example, a faster modulation of the gas would avoid other drifts on the measurements. The measurements are promising, showing that the HECL in the heterodyne configuration can improve the detection of small changes of RI rather than using the HECL alone. According to the sensitivity of this measurement (72345GHz/RIU), the minimum measurable shift in frequency ~30MHz, we determine the detection limit to be $4x10^{-7}$ RIU, which is substantially better than the $6.6x10^{-5}$ RIU obtained in [5] and 2500 times better the detection limit of the PhC cavity obtained using a passive measurement.

3. Conclusions

We have demonstrated a new approach to refractive index sensing based on the optical heterodyne method and a refractive index sensitive hybrid lasers. We have achieved over an order of magnitude improvement in the detection limit relative to the RI measurement based on a passive optical resonator. Further improvements in the linewidth of the lasers and the stability of the measurements will lead to further dramatic improvements in the detection limit. The technique lends itself to integration [6] promising fully self-contained RI sensor chips with detection limits of 10^{-9} and better.

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