Refractive Index Sensing using Photonic Crystal Hybrid External Cavity Laser

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ABSTRACT: In this work, we show demonstrate a photonic crystal hybid external cavity laser (HECL) that can be used for refractive index sensing applications. To demonstrate its potential for integration we present the first demonstration of a fully integrated hybrid external cavity laser (HECL) in edge-coupling configuration by means of micro-transfer printing. The HECL is able to achieve single-mode regime over a wide range of driving currents with SMSR in the range of 40 dB. This platform provides a RI sensor characterized its compactness, simplicity of fabrication, compatibility with high throughput integration processes.

Keywords: photonic integrated circuits, hybrid external cavity laser, photonic crystal, silicon photonics, silicon nitride,

1. INTRODUCTION

Monitoring a substance's refractive index is a powerful method of optical sensing as any 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 the literature reports many different types for refractive index sensors based on ring resonators[i] and photonic crystals[ii]. The surface of the sensing component can be functionalised with a range of antigens that are specific to different target compounds giving specificity. Importantly, the refractive index of a substance is a volume independent quantity and the signal is not proportional to the sample volume, unlike intensity/fluorescence/ absorption-based sensors, which makes RI monitoring a very promising platform for high performance miniaturised sensing. In particular, the CMOS microelectronics industry offers silicon platforms that allow the realization of of high volume low-cost silicon photonics circuits for optical sensing[iii],[iv]. Specifically, Silicon-on-Insulator (SOI) and silicon nitride (SiN) platforms with buried 2+ µm thick SiO_2 on bulk silicon offer very good light confinement in compact Si and SiN waveguides due to the high refractive index contrast with SiO_2 providing very high performance devices.

Most RI sensors make use of external tunable lasers, while useful for laboratory use such configurations are not very attractive for field deployment of portable, robust sensors. In these case, an on-chip realization of the light source is vital. The lack of light sources in silicon, due to the indirect band-gap of the material, leads to the employment of InP-based materials in silicon photonic integrated circuits as these direct-band-gap materials provide the highest performances in light amplification, modulation and detection[v]. One of the most efficient approaches to insert the light emitted by InP gain materials into the SOI and SiN waveguides is the edge-coupling, which provides broad band, polarization-agnostic low coupling losses of less than 1 dB[vi]. Direct growth of InP-based materials on silicon is extremely challenging, due to lattice constant mismatches and compatibility issues. To face this problem, other integration techniques have been demonstrated through die/wafer bonding[vii] [5-12], which also unlocks hybrid external cavity laser configurations[viii]. However, the die/wafer bonding approach is associated to a great waste of expensive material (i.e., InP), hence high cost. This issue can be completely removed by means of Micro Transfer Printing (µTP), which offers high-throughput, parallel and scalable transfer of devices or dies of material in the desired locations on any platform, with sub-micron accuracy and no waste of III-V material associated. Integration on silicon photonics of InP-based Fabry-Perot and DFB lasers and LEDs through µTP have been recently demonstrated[ix],[x].

In this work we report on a Photonic Crystal Hybrid External Cavity Laser, which is based on the combination of a silicon nitride 1D PhC cavity and III-V gain chip, To maximize optical coupling between the two components, the bus waveguide is designed with dimensions that match the area of the rSOA waveguide mode. This butt coupling approach has the advantage of designing, fabricating, testing, and optimizing the two components separately, ensuring optimal performance of both components. The SiN PhC works as a wavelength-selective feedback thus controlling the wavelength of the HECL. Since part of mode supported by the PhC cavity exists in the cladding material, the lasing wavelength is a function cladding refractive index (RI), making the laser a very precise RI sensor with high sensitivities[xi]. We demonstrate the first heterogeneous integration of reflective semiconductor optical amplifiers on SiN by µTP and their edge-coupling to SU8 polymer waveguides, in turn coupled to SiN waveguides and wavelength selective mirrors (optical resonators) in HECL configuration. The approach allows a very accurate engineering of the alignment between InP RSOAs and polymer waveguides, relaxing alignment tolerances typically needed to realise such a laser.

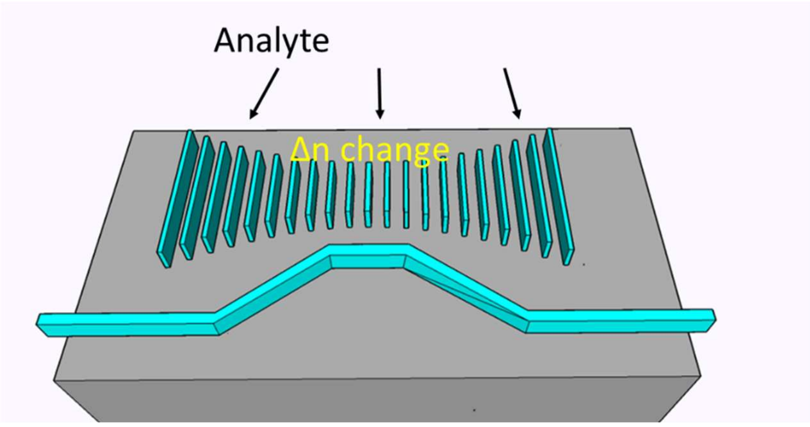

Figure 1 Schematic of the silicon nitride 1D photonic crystal

2. Refractive Index Sensing

The silicon nitride resonator is of the stack mode-gap type consisting in a periodic array of SiN rectangular blocks on silicon dioxide separated by the upper cladding material. The block width is parabolically tapered creating a defect in the photonic bandgap (PBG) giving a Gaussian-shaped electric field distribution along the cavity (the so called "gentle confinement technique), potentially reaching q-factors up to $7x10^8$. The resonator can be optimised for different operating environments by adjusting the etching profile, allowing very high optical performances (Q-factors over 10_5) also in the case of asymmetrically cladded resonators.

A substantial fraction of the mode of the 1D silicon nitride photonic crystal interacts with upper cladding material (which can be gas or liquid) and the resonance wavelength is affected by the sample's refractive index. By immerising the resonator in solutions with different refractive indices, we determine the the sensitivity to be approx. 140nm/RIU and the detection limit to be $1.1x10^{-3}$ RIU

To realise the HECL, we combine a gain chip with the 1D PhC and operate in the resonant mirror configuration [xii,xiii], in which light at the resonance wavelength couples evanescently into the resonator mode and then is outcoupled in the backward propagating direction. This component provides feedback in to the gain chip resulting in lasing at the resonance wavelength. The lasing wavelength shows a wavelength shift with different upper cladding refractive index conditions, and achieves a similar sensitivity. However, as the linewidth of the laser is much narrower than that of resonance of the PhC resonator, the detection limit of the HECL is improved by a factor of ~16 to 6.6*10-5 RIU. This value is limited by the resolution of the Optical Spectrometer Analyser and is far from the ultimate detection limit of this system.

3. Integration using uTransfer Printing

The etched-facet InP RSOAs were undercut and released from their substrate and heterogeneously integrated by µTP on silicon chips with SiN waveguides defined using electron beam lithography (EBL) amd dry etching. The chips included trenches in the SiN to accommodate the SU8 tapers, SiN waveguides and SiN optical resonators [18] to be incorporated 2i5h the polymer waveguides for the mode conversion. The lateral alignment of the emitting facet of the RSOAs was ensured by µTP accuracies, lower than 0.5 µm. A very high adhesion yield of the printed devices (>90%) was achieved thanks to the use of a <10 nm thin vapour coated BCB layer. After the printing, 500 µm long SU8 polymer tapers (3 µm wide base, 0.2 µm wide tip) were defined on top of the SiO_2 in the SiN trenches and SiN tapered waveguides, to be used as spot-size converters in evanescent coupling configuration, via EBL. The alignment accuracy between the SU8 and SiN structures was in the

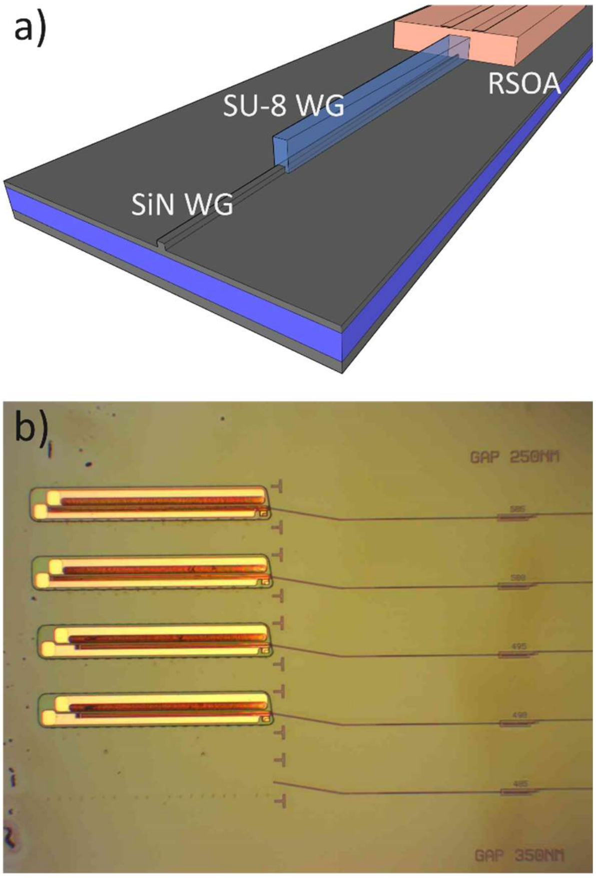

Figure 2 a) Schematics of the coupling between the transfer-printed RSOA and SU8 polymer waveguide and tapers to push light into the SiN waveguide, b) Optical microscope image of the chip showing the transfer-printed RSOA onto the SiN, coupled to SU8 polymer wav range of 20 nm. The schematics of the integrated HECL is shown in Fig. 2a.

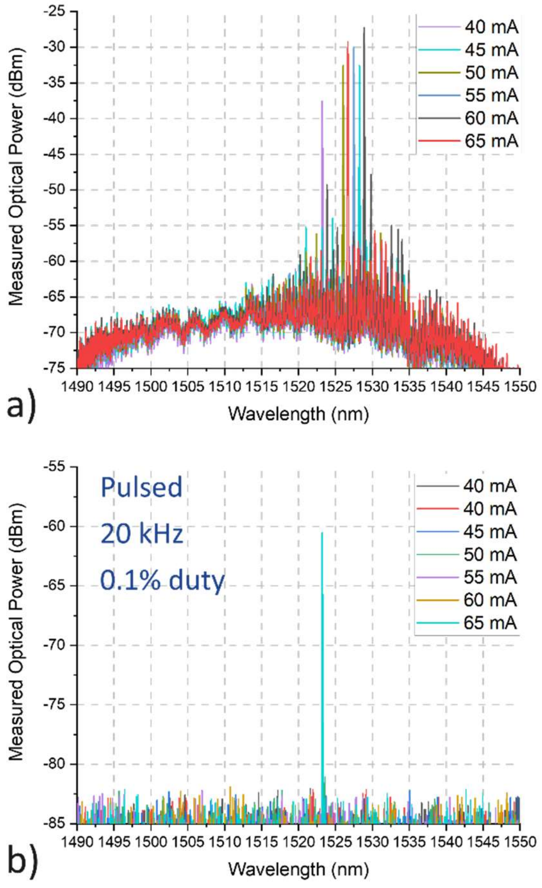

Figure 3 a) Single-mode lasing spectra of one of the measured HECL ad different driving currents in CW, b) Single-mode lasing spectra of the HECL in (a) with pulsed driving currents (20 kHz and 0.1% duty cycle).

Electrical and optical characterization of the fully integrated HECLs based on µTP RSOAs coupled to SiN optical resonators was performed after transfer-printing to evaluate the laser operation. Fig. 2 shows the measured lasing spectra of one of the measured HECL in both continuous wave (CW) and pulsed (20 kHz, 0.1% duty cycle) operation, respectively in Fig.2a and Fig. 2b. The HECL exhibits single-mode lasing operation, with SMSR in the range of 30-40 dB, from 40 mA of driving currents to 65 mA, with variations in lasing wavelength due to heating of the RSOA,. The same single-mode lasing operation is also demonstrated in pulsed regime, in which the heating contribution is greatly reduced, and the lasing wavelength is stabilised over the full driving current range investigated.

4. CONCLUSIONS

In this work, we have demonstrated an new type of Hybrid External Cavity Laser which can be used a self contained refractive index sensor. There are substantial advantages with respect to traditional PIC based refractive index sensors, due to the very narrow linewidth exhibited by the HECL.

We have demonstrated the possibility to fully integrate HECLs (with all their independent optimisation advantages) via means of µTP, without the need of expensive and time-consuming active alignment, unlocking the possibilities of low-cost and high-volume manufacture.

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