Modelling of asymmetric slot racetracks for improved bio-sensors performance

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***Abstract*—This paper presents a study on asymmetric slot waveguide resonators to be used as sensing elements in Laboratory on a chip (LOC). They combine slot waveguide high sensitivity and advantages, with improved resonator performance due to enhanced mode matching in racetrack bends. Depending on target bio-molecules, asymmetric slot resonators are very promising for small molecule sensing (dimensions < 200nm), maximizing their interaction with the optical field used for sensing.**

Keywords—slot waveguides; ring resonator sensors; silicon photonics; biosensors; Lab on a Chip (LOC)

I. Introduction

Integrated optical sensors are currently a hot topic in reaserch [1], since they can completely revolutionize biological and clinical diagnosis tools as well as pharmaceutical and personalized medical treatment fields [2]. These sensors can be designed such that they can exploit current silicon techonology, thus they can be produced on low-cost, tiny chips, which integrate together with all required electro/optics/microfluidic components. The final result is having stand-alone analysis chips (LOCs) [3], able to completely handle fluids and reagents, as well as to use optical signals for interrogating hundreds of multiplexed sensors and to drive and controll all chip components using the electronic cicuits on the chip itself.

Several optical sensing mechanisms have been proposed so far, e.g. sensors based on refractive index change, intensity change, interferometry, absorption, surface plasmon resonance [4], some of which have been commercialized [5]. But they are still far from actual integration, since analysis chips are part of a bulky equipment, which should be operted by trained technicians. On the other hand, waveguide based optical sensors are very easy to be integrated on silicon photonics chip, and if used in resonant configurations [6], can have small footprints (of the order of few hundreds of microns), and they can be easily multiplexed to have high data throughput. Indeed, each resonator can be tuned (e.g. by matching biomolecule characteristics) or functionalized in order to sense different target bio-molecules, thus allowing the possibility of having a sample screening just using a tiny amount of the biological fluid under test.

II. Motivations

Many SOI sensor configurations have been proposed, such as strip [7] and slot waveguide ring resonators [8], disk resonators [9], photonic crystals [10], and Bragg gratings [11]. Their sensing mechanism is based on revealing refractive index changes (in *bulk sensing*, the change is caused by bulk solution concentration changes while in *surface sensing*, by molecular binding events on sensor functionalized surface) in the waveguide top cladding. Due to the change in cladding properties, the modal effective index (n_{eff}) of propagating light in the sensor varies. In turns, in waveguide resonators this variation results in a shift of resonance wavelength (λ_{res}). It is worth noting that over device cross-section, the overlap between the electric field intensity and the change in cladding properties is proportional to n_{eff} variation [12]. This relation makes slot waveguides particularly suitable for sensing, since the electric field is forced by two high-index parallel silicon strips, separated by a small gap (of the order of 100-200 nm wide), to travel in the small gap [13], which, in the case of bio-sensors, is filled by the fluidic solution (Fig 1a)). It has been demonstrated that using slot waveguides in racetrack configuration (Fig.1 b)), can produce sensitive sensors, with sensitivity of the order 260 nm/RIU [14]. Nonetheless, they limit of detection (ILOD, definition in ref [14]) is limited by a low resonator quality factor (Q), due to high losses in the light path.

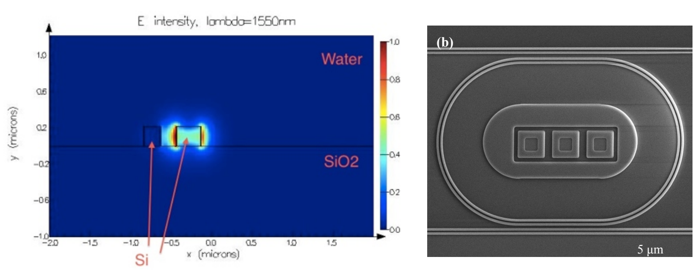

Fig.1: (a) Electric field intensity on an asymmetric slot cross-section, water top cladding. (b) SEM imagine of a previously fabricated symmetric slot racetrack

These losses are mainly due to sidewall roughness of slot walls that could be improved by successive improvements of technological processes, and to an elevated mode mismatch in slot-waveguide based bends. The detrimental effect caused by this last kind of loss is pointed out also by results achieved with slot Bragg (straight) resonators, which presents high sensitivity combined with moderately elevated Q, thus a very low ILOD, with an improvement of sensitivity, with respect to strip Braggs, of about 6 times [14]. Nonetheless, Bragg resonators are not as compact as racetrack or disk resonators, plus they are not very suitable for cascading and multiplexing, since transmitted light is very poor.

III. Methods

Asymmetric slot resonators were simulated using an eigenmode solver (Lumerical MODE Solutions), and then data gathered from MODE (e.g. effective index, propagation loss, water absorption, mode mismatch, coupling loss) were used with a dedicated Matlab code to evaluate resonator parameters, such as Q factor and free spectral range (FSR). Designed rings will be fabricated exploiting eBeam lithography (EBL) on Silicon on insulator (SOI) chips. EBL provides a low-cost, fast turn-around, foundry-compatible fabrication alternative that has been optimized to produce low-loss silicon photonic components. After fabrication the chip will be tested using our automated setup, shown in Fig.2.

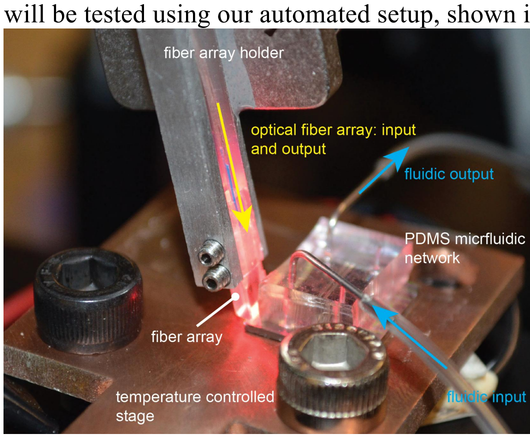

Fig.2: Fiber array is used to bring light from a tunable laser source (operating in 1460 nm to 1580 nm wavelength range), and to collect the sensor output light. The chip is immobilized on the motorized stage using vacuum, and PDMS channels are reversibly bonded to chip surface to allow fluids flow.

IV. Results and Discussion

We have studied the effect of having an asymmetric slot on bend loss, in order to understand if having a not symmetric slot is effectively beneficial for mode mismatch.

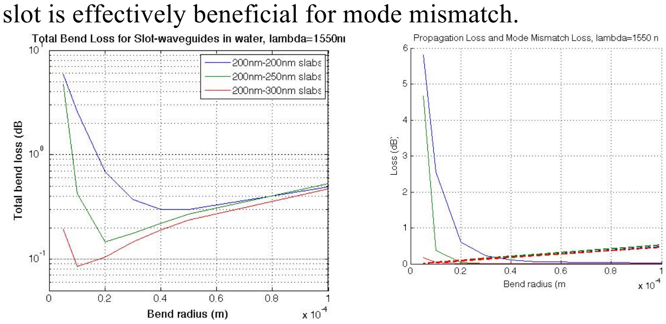

Fig.3: (left) Total bend loss for different bend radii, for different slot waveguide geometries; (right) Contributions to bend losses: continuous line are for mode mismatch loss, dotted line are for propagation loss in the bend. Legend color is equal for both figures.

In Figure 3, we reported the effect of varying the width of one of the two silicon strips that made up the slot. One side is kept constant to a width of 200nm, while the other is varied from 200nm width to 300nm. The gap in the middle is 200 nm and strip height is 220 nm (like in standard SOI chips). The figure on left side is the total loss for a 90 degrees bend, while the right one shows the contribution of propagation loss in the bend (dotted lines) and the effect of mode mismatch loss (continuous lines). It is possible to observe that in the symmetric slot (blue lines, in both figures) waveguides loss per bend is very high, in particular for smaller radii, and the main contribution to bend loss is given by the mode mismatch loss. This loss is strongly decreased (from almost 6 dB per bend to less than 0.5 dB) in the slot waveguide with strips 200nm-300nm wide (most asymmetric case). For larger radii the dominant contribution to total loss is given by propagation loss, which includes water absorption from the top cladding. Achieved loss values for asymmetric slot are closer to bend loss value of strip waveguide in water (0.015 dB for R=10μm to 0.11 dB for R=100 μm, 90 degrees bends), thus higher resonator quality factor is expected (of the order of 10^4) and as a consequence improved bio-sensing performance.

In conclusion, preliminary studies show that asymmetric slot racetrack can be very promising in terms of achieving sensitive and accurate bio-sensors, potentially easy to be multiplexed on the same bus.

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