Recent Advances in Modeling Silicon Photonic Sensors

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Nowadays, the interest in Silicon Photonics has been fastly increasing for a number of applications, including sensing. In this work some recent advances in modeling and design of silicon photonic sensors are briefly reviewed. Modeling and optimization of silicon on insulator slot waveguides are presented, showing improvements with respect to other guiding structures. Moreover, some other integrated optical sensors are modelled and designed for detecting physical quantities with high sensitivity, including angular velocity in gyros and electromagnetic field. The devices under investigation are based on either linear or non linear effects, such as plasma dispersion and Raman gain.

Introduction

In the last years silicon is likely become a very important platform for Nanophotonics. In fact, the compatibility with silicon integrated circuits manufacturing, as well as its low cost, full integration of electronic and photonic devices, high index contrast and immunity to electromagnetic interferences, are fundamental reasons for the interest in Silicon Photonics. As a transmission medium, silicon has also much higher nonlinear effects than the commonly used silicon dioxide, in particular Kerr and Raman effects.
By this technology, different nanophotonic guiding structures can be fabricated, showing an increasing performance in terms of waveguide sensitivity, going from rib to wire to slot waveguides, as sketched in Fig. 1.

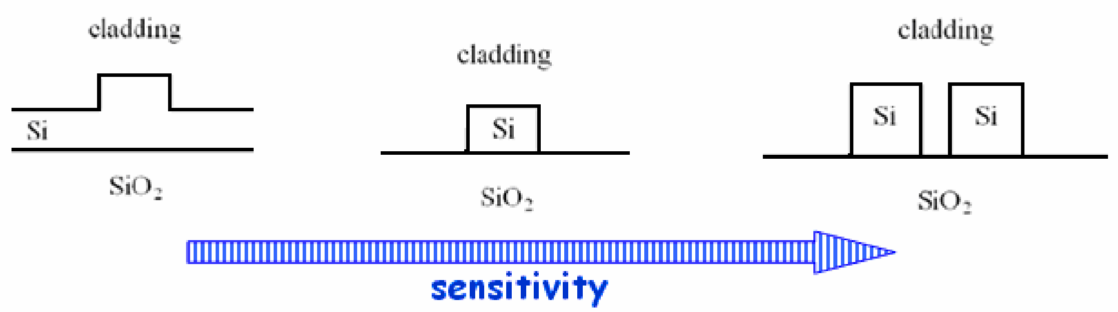

Fig. 1. Different silicon-on-insulator (SOI) waveguides for increasing sensitivity.

Here the waveguide sensitivity is defined as the change of mode effective index as a function of refractive index cover change (in a label-free detection scheme), i.e.:

$$S_w = \frac{\partial n_{eff}}{\partial n_c}$$

In next section a number of sensing schemes are shown in silicon, as well as their potential for sensing. Architectures have been modelled and designed with various numerical techniques, including finite element method, beam propagation method, nonlinear coupled-mode theory.

Silicon photonic sensors

A first approach can be seen in Fig. 2, where a grating etched on a SOI rib waveguide is designed for liquid sensing [1]. The shift in analyte concentration affects the guiding structure overlay RI and, consequently, the mode effective index. This change in effective index produces a wavelength shift in the grating reflectivity spectrum, allowing to perform the concentration measurement (e.g., glucose in blood).

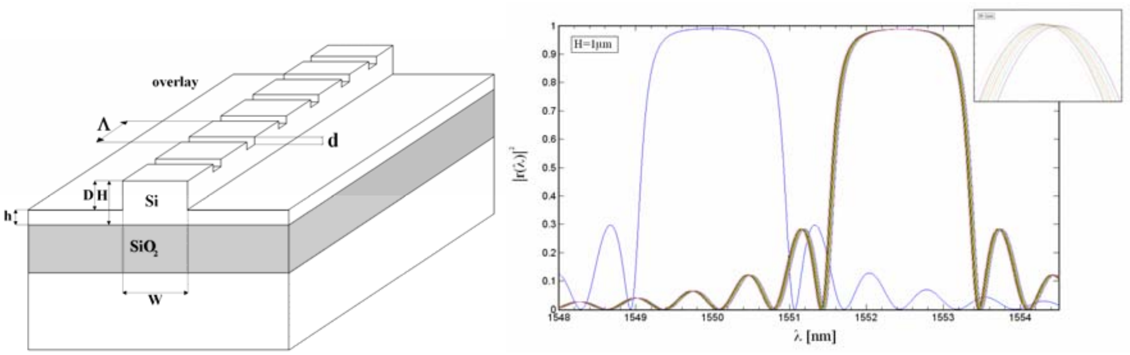

Fig. 2. SOI grating photonic sensor and relevant reflectivity spectra.

By this approach, a sensitivity in terms of wavelength shift under Bragg condition is expected as $S = \partial\lambda_{\max}/\partial n_c = S_w \Lambda/m$, where $\Lambda = 270$ nm is the grating period and m is the grating order. A maximum value of $S^{\max} = 33$ nm/RIU and a detection limit of 10^{-4} RIU have been found, by considering first-order grating (m = 1), 173 µm long and 10 nm deep. Third-order gratings (m = 3) could be also used, but with lower sensitivity.
Ammonia sensing can be performed by using a resonant microring (radius of 3 µm) excited by an external SOI wire waveguide, as in Fig. 3 [2].

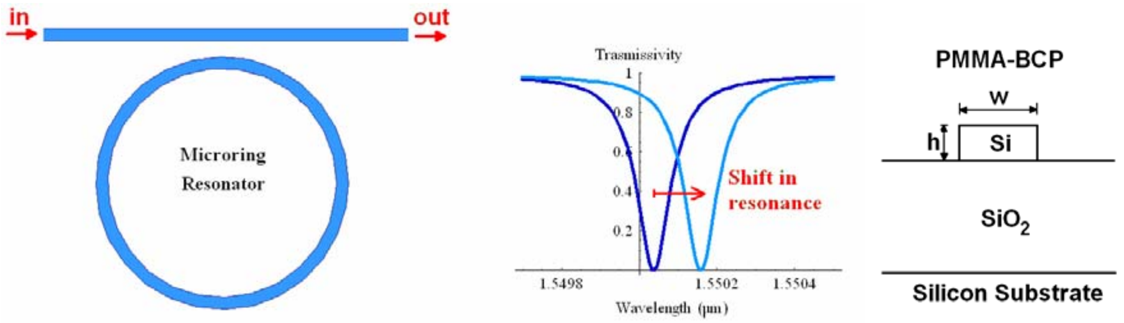

Fig. 3. Ammonia sensing by a microring resonator using a silicon wire and PMMA-BCP cover.

If the cover is an organic material as PMMA where polymeric bromocresol purple (BCP) is included, its refractive index will change with ammonia concentration in the surrounding environment. This change produces a shift in microring resonance wavelength, as $S = \partial\lambda_{res}/\partial n_c = S_w\,\lambda_0/n_{eff}$ (see Fig. 3). In our design, a minimum detectable change in cover medium refractive index of 8×10^{-5} and a sensor overall sensitivity of 140 nm/RIU are expected.
Guiding structures of increasing importance are the slot waveguides, whose characteristic electric field distributions are sketched in Fig. 4 for quasi-TE and quasi-TM modes, using again SOI technology. Both surface and homogeneous sensing can be

achieved by this approach, depending on the presence or not of a sensible molecular adlayer (see Fig. 4).

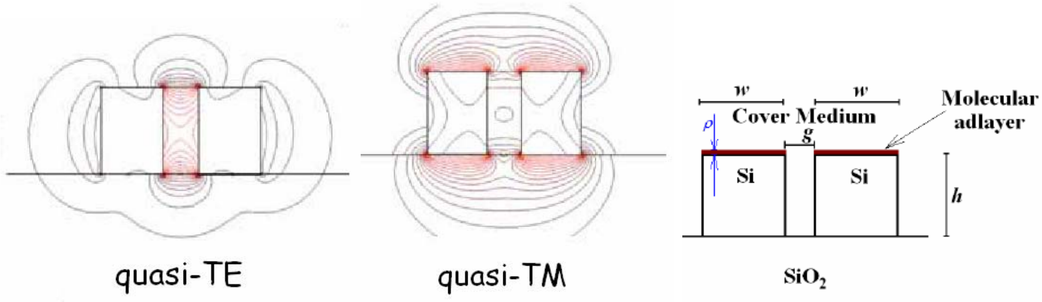

Fig. 4. Electric field distributions for quasi-TE and quasi-TM modes, and SOI slot for surface sensing.

Slot waveguides can allow important performance in terms of sensitivity. Values $S^{\max} \sim 4.6\times10^{-4}\,\mathrm{nm}^{-1}$ for surface and $S^{\max} > 1$ for homogeneous sensing have been demonstrated [3] in optimized structures (slot gap width 100nm, wire width 180nm, slot height 324nm), giving an overall sensitivity of about 1000 nm/RIU, i.e. at least one order of magnitude better than in the previous case.

Electromagnetic field (EMF) sensing has been also investigated by modeling a new approach of high sensitivity sensor [4]. The architecture is shown in Fig. 5 and consists of two coupled optical microcavities, one Fabry-Perot between two waveguide gratings and one microdisk resonator (radius of 150 µm).

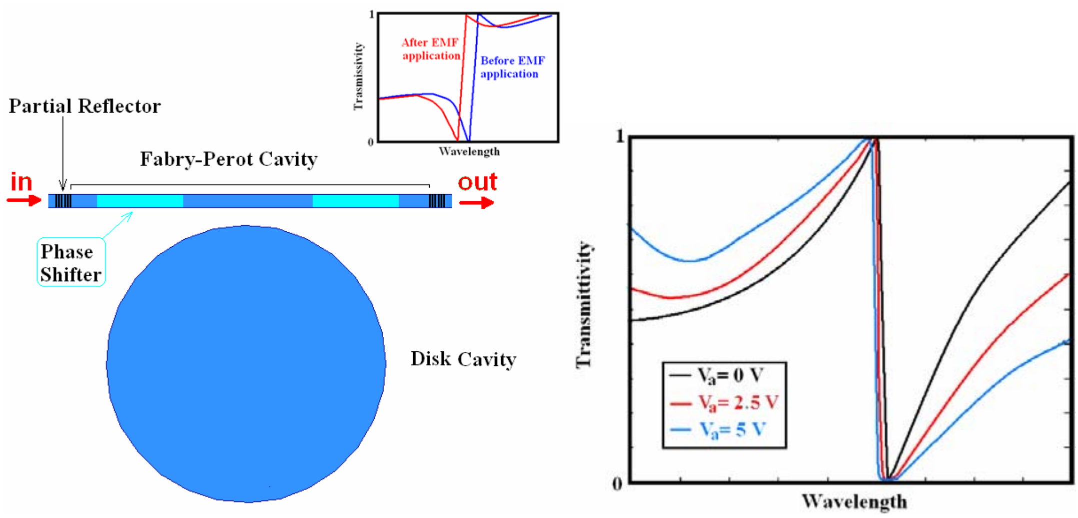

Fig. 5. Architecture of electric field photonic sensor and its transmittivity spectra.

Phase shifting, depending on electric field picked up by the antenna connected to phase shifters electrodes, produces a phase change in propagating optical signal due to plasma dispersion effect in a MOS structure. This induced phase change produces a shift in coupled cavities transmission spectrum, according to a Fano resonance, which is detected at the output with high sensitivity. Wavelength or amplitude interrogation schemes are so possible, as in Fig. 6, where the cross section of MOS-based SOI waveguide is also shown. A minimum voltage of 60 mV can be detected with a bandwidth of 500 MHz.

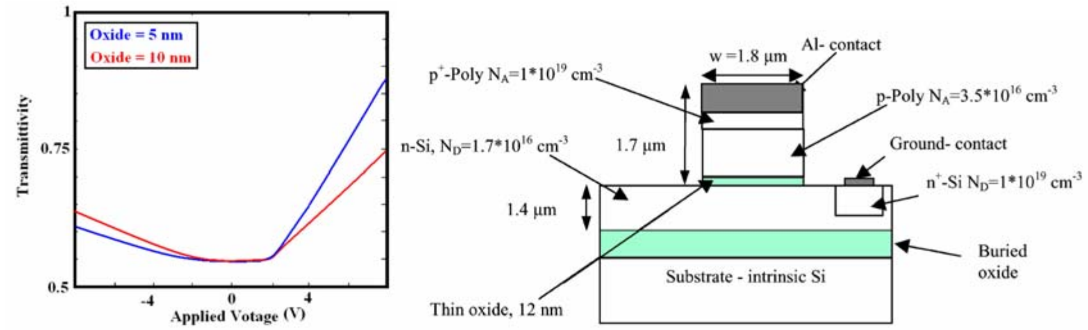

Fig. 6. Sensor amplitude interrogation and MOS-based SOI waveguide cross section.

Finally, Fig. 7 shows the architecture of a photonic sensor for detecting angular velocity in gyro applications [5]. It is based on a resonant racetrack excited by two lasers, P1 and P2, through directional couplers C1 and C2. The wavelength shift, as induced by the angular velocity under measurement, is detected by PD1 and PD2.
Raman effect can be excited, so increasing the sensitivity by monitoring the shift at two different wavelengths. A minimum detectable angular rate of about 300 °/h has been found. In the architecture, two optical isolators, I1 and I2, and two thermo-optic modulators, M1 and M2, for controlling lock-in effect are also included.

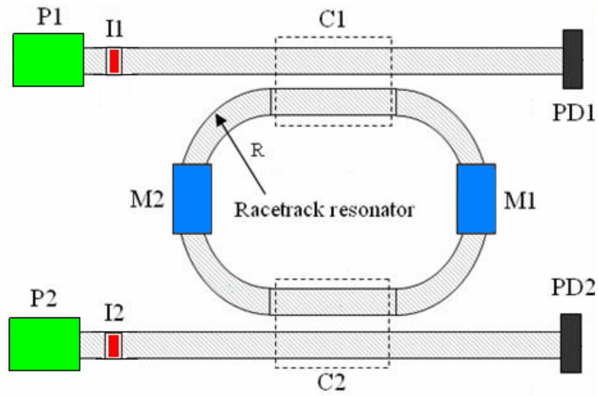

Fig. 7. Architecture of a Raman angular velocity photonic sensor.

References

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