Investigation of a p-i-n Dual-Cavity E-Field Photonic Sensor

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Abstract—**Photonic sensors are widely used for the measurements of broadband electromagnetic fields because they are constructed with dielectric materials, thus inducing minimal perturbation of the electric field under investigation and being mostly independent of electromagnetic interference. In this paper, the modeling and design of a high sensitivity electric field sensor, based on a whispering-gallery-mode resonator coupled with a Fabry-Perot cavity in silicon-on-insulator (SOI) technology, is presented. The sensing element consists of a p-i-n diode with a forward bias, implemented in an optical rib waveguide. A comparative study is performed between three waveguides with different transverse dimensions, in terms of propagation losses and effective mode index variation as a function of measuring electric field. Finally, the transmission spectrum of the complete sensor has been evaluated and a comparison between the results for each structure has been carried out. The study has been performed by a multiphysics simulation tool based on the finite element method (FEM).**

Keywords-component; Photonic Sensors; Resonators; SOI Technology; p-i-n diode; Finite Element Method.

I. ARCHITECTURE OF ELECTRIC-FIELD PHOTONIC SENSOR

The general structure of the sensor in SOI technology is presented in Fig. 1. It is well known that a simple ring (or disk) resonator has a symmetric transmission spectrum with a Lorentzian line shape, acting as a notch filter with a zero transmission at resonance.

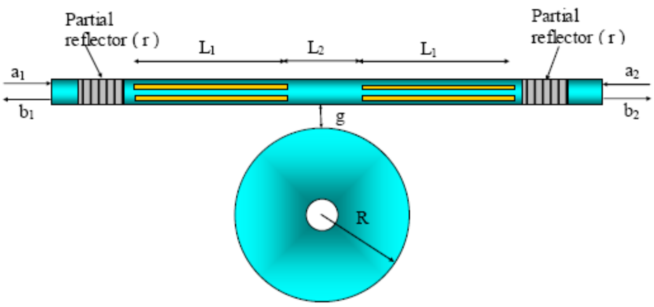

Figure 1. Scheme of dual-cavity electric field sensor.

The presence of a Fabry-Perot cavity between two reflectors (gratings) and coupled with the resonator, induces an asymmetric Fano-resonance line shape, with higher slope between the zero and the unity transmission in comparison with that of the isolated disk (or ring) resonator. This slope enhancement should provide a greatly improved sensitivity of the whole architecture [1]. In absence of electric field, the optical mode propagates in the center of the waveguide without any perturbation. When an electric field is measured, the voltage applied at the electrodes shown in Fig. 1, proportional to the measuring electric field, induces a variation in the refractive index of the waveguide as well as in the absorption coefficient of the material via the plasma dispersion effect. This is achieved with a selective doping of the SOI-rib structure as a p-i-n diode. In this work a heavily doped p^+ region is assumed on top of the rib and two n^+ regions are placed on both sides of the slab region [2], as sketched in Fig. 2. A Gaussian doping profile with peak of 10^{18} cm^{-3} for both p^+ and n^+ regions is considered. When a voltage is applied, free electrons and holes are injected in the rib waveguide center, and the change in carrier concentration induces the variation of both refractive index and absorption coefficient [3].

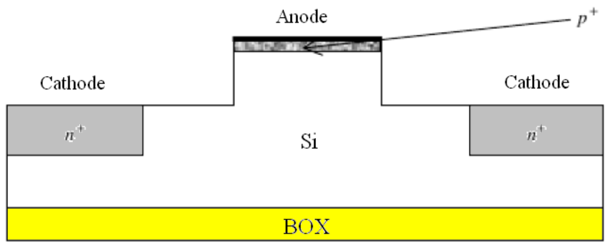

Figure 2. Cross section of sensor p-i-n straight rib waveguide.

The change in refractive index and absorption coefficient induce a change in the real and imaginary parts of effective mode index, with the final result that the transmission spectrum of the device will be modified as a function of unknown electric field. Measuring the output optical power of the sensor (amplitude interrogation), or its wavelength shift (wavelength interrogation), an estimation of electric field intensity can be provided. In both cases, a high sensitivity to the applied voltage is expected, due to the enhanced transmission spectrum slope.

II. Simulation of E-field Photonic Sensor

Finite element method (FEM) simulations have been performed for three straight rib waveguides with different transverse dimensions. The parameters of SOI-rib waveguides are the rib width W = 4μm, 1.8μm, 0.4μm, the core total height H = 6.5 μm, 3.1μm, 0.5μm, and the etching depth D, that measures the difference between total height and slab height, with D = 3.2μm, 1.7μm and 0.35μm, respectively. The simulations have been carried out in an integrated multi physic electro-optical domain [4], by varying the voltage applied to the electrodes in the [0 ÷ 4V] range, for quasi-TE mode.

The results of the simulations show that the real part of the effective mode index is constant for applied voltages less than 0.7V, i.e. the threshold voltage for the diode. If the voltage is further increased, the effective index starts decreasing, with an almost linear dependence with the applied voltage. The imaginary part of the effective mode index has a opposite behavior, being constant for V < 0.7V and then increasing with the voltage. For the smallest waveguide, the index dependence on applied voltage is slightly sublinear and the curve tends to saturate. It was found that the value of both real and imaginary parts (related to the propagation loss) of effective index decrease with decreasing the waveguide dimensions, as well as the index sensitivity versus the applied voltage. Then, the sensitivity in smallest waveguide is an order of magnitude smaller than that in the biggest one. The large and middle structures have a fairly similar behavior with small differences in the parameter values.

The next step in the simulations was to measure the differences in the transmission spectra for the three structures. As an example, Fig. 3 shows a comparison between transmission spectra obtained in large waveguide-based sensor, for three values of the applied voltage, 1.455V, 1.46V and 1.465V.

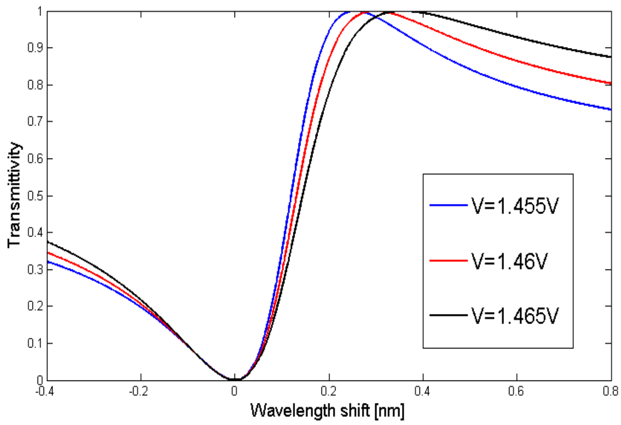

Figure 3. Transmissivity spectrum versus applied voltage for the large rib waveguide-based sensor: Va=1.455V (blue line); Va=1.46V (red line); Va=1.465V (black line).

It was found for each structure that both asymmetry and slope of the spectrum increase with increasing the reflection coefficient of the two reflectors of Fabry-Perot cavity, shown in Fig. 1. The simulations have also shown that the spectrum slope decreases for larger applied voltages. This suggests that it is more useful to choice a voltage bias point close to 1.5V value, in order to improve the overall sensitivity of the sensor. The three curves in Fig. 3 show the shift of transmission spectrum peak as a function of the applied voltage, which can be appropriately measured in terms of the Δλ/ΔV ratio, taking into account the minimum voltage change that the sensor can detect as a wavelength shift. Of course, the larger the ratio, the better the sensitivity. Table I shows a summary of the results found for the three structures for an applied voltage of 1.46V, assuming a reflection coefficient r = 0.5, disk radius R=150μm and lengths L_1 = 0.85mm and L_2 = 100μm for metallized and not-metallized regions, respectively. These results show that larger structures perform better than the smaller ones in terms of sensitivity. On the other hand, the smaller structure has better performance in terms of propagation loss. The comparison has been performed with constant longitudinal length for the three structures. This aspect suggests that, due to the moderate propagation loss of the smaller waveguide, it should be possible, in principle, to improve its sensitivity by increasing the longitudinal dimension L_1.

Table I. Comparison of three p-i-n rib structures.

Parameter	*Large rib structure*	*Micro rib structure*	*Sub-micron rib structure*
n_{eff}	3.469	3.449	2.834
$\lvert\Delta n_{eff}\rvert$	1.87×10^{-3}	1.22×10^{-3}	2.05×10^{-4}
α [dB/cm]	36.14	23.36	2.78
dn_{eff}/dV [V^{-1}]	0.00266	0.00166	0.000257
$\Delta\lambda/\Delta V$ [nm/V]	9.02	0.71	0.06
ΔV [mV]	5	10	100

III. Conclusions

The design of a high sensitivity photonic E-field sensor is proposed and examined by FEM using a commercial software tool. Results demonstrate that this sensor is capable of detecting voltage variations as small as 5 mV by using p-i-n diodes in large rib structures instead of complex metal-oxide-semiconductor structures. The potential of the dual-cavity architecture is significant and it could be further improved. The proposed sensor is based upon SOI technology, therefore this device is a potential candidate for integration in large opto-electronic signal processing systems.

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