Silicon-on-Insulator Slot Waveguides for Integrated Optical Sensing

Francesco Dell'Olio and Vittorio M. N. Passaro
Politecnico di Bari, Dipartimento di Elettrotecnica ed Elettronica, via Edoardo Orabona n. 4, 70125 Bari, Italy
(e-mail: passaro@deemail.poliba.it)

Abstract: *Silicon-on-Insulator slot waveguides for highly sensitive and compact photonic integrated sensors are theoretically proposed and discussed in this paper. Slot guiding structure sensitivity has been investigated by 3D Finite Element Method and results are compared with those related to rib or wire sub-micrometer silicon waveguides.*

Introduction

In recent years, there is a growing interest for highly sensitive optical sensors in different areas such as process control, medical diagnostics, environmental monitoring and biotechnology. In this framework, integrated optical sensors have attracted considerable attention because of their immunity to electromagnetic interference, high sensitivity, good compactness and robustness and high compatibility with fiber networks [1].

Different kinds of guided-wave optical sensors have been proposed, such as those based on directional couplers [2], Mach-Zehnder interferometers [3], Bragg gratings [4], and microring resonators [5]. In these sensors the shift of a chemical/physical quantity to be sensed affects the propagating mode effective index, which is measured in different ways, according with sensor architecture. The effective index change is usually produced by a change of cover medium refractive index. Measurement sensitivity depends on the distribution of evanescent optical field in the cover medium, so one of the most important design task is the waveguide optimization in order to maximize its sensitivity.

CMOS-compatible technologies are widely used for fabrication of integrated optical sensors because of their low cost and possibility to monolithically integrate photonic and electronic devices. Recently sub-micrometer silicon wire waveguides [6], realized using Silicon-on-Insulator (SOI) technology, have been demonstrated as very attractive for evanescent field integrated optical sensors because they exhibit a sensitivity significantly greater than that assured by other kinds of guiding structures, such as rib waveguides in silicon oxinitride (SiON), polymeric materials or silica [7]. Adopting a Si-wire waveguide, a highly sensitive microring resonator-based ammonia optical sensor has been proposed [8].

When two Si-wires are very close to each other, it is possible to realize another kind of SOI nanometer guiding structure, usually indicated as SOI slot waveguide [9]. It enables to confine optical power in a narrow low-index gap region between the two high-index Si-wires. A great variety of optical devices can be realized by using slot waveguides, including microring resonators [9], optical modulators [10], electrically pumped light emitting devices [11], directional couplers [12], all-optical logic gates [13] and beam splitters [14]. A Finite Element Method (FEM)-based modal investigation devoted to study slot waveguide geometrical parameter influence on optical power fraction confined in the low-index gap region has been recently performed [15].

However, SOI slot waveguides for integrated optical sensors represent a quite unexplored research field.

In this paper, we demonstrate that SOI slot waveguides (see Fig. 1) exhibit a sensitivity significantly higher than that of other sub-micrometer SOI waveguides. Moreover, we have optimized the slot guiding structure geometrical parameters to maximize its sensitivity to changes of cover medium refractive index. As operating wavelength λ =1550 nm has been assumed.

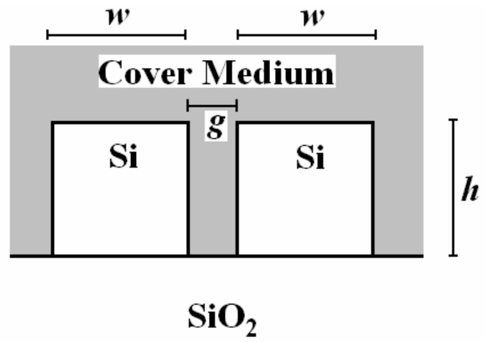

Fig. 1. SOI slot waveguide structure.

Sensitivity Calculation

Slot waveguides sensitivity to changes of cover medium refractive index can be expressed as:

$$S_w = \frac{\partial N}{\partial n_c} \qquad (1)$$

where N is the effective index of mode propagating in the guiding structure and n_c is the cover medium refractive index.

According with variational theorem for dielectric waveguides, we can write:

$$S_w = \left.\frac{\partial N}{\partial n_c}\right|_{n_c = n_c^0} = 2c\, n_c^0 \iint_C |\mathbf{E}|^2 dxdy \qquad (2)$$

where c is speed of light in vacuum, C indicates cover medium region, n_c^0 is the unperturbed value of cover medium refractive index and **E** is the normalized electric field of optical mode propagating in the slot structure.

From Eq. (2), it is evident that waveguide sensitivity depends on the optical field confinement factor in the cover medium. As defined in Eq. (1), it can be numerically estimated by varying the cover medium refractive index n_c in a narrow range and finding the relevant change of effective index N. To determine effective index N, the rigorous numerical approach based on 3D full-vectorial FEM has been applied.

Slot waveguide sensitivity dependence on Si-wire width w has been investigated, for gap region width g equal to 50 nm, 100 nm and 200 nm and quasi-TE or quasi-TM modes (as in Fig. 2 and Fig. 3, respectively). The Si-wire height is h = 250 nm. As cover medium an aqueous solution containing a chemical substance (as, for example, glucose) whose concentration has to be measured, has been assumed. When analyte concentration in the solution changes, a shift of cover medium refractive index is induced. Cover medium refractive index unperturbed value n_c^0 has been fixed as equal to 1.33 (water), while cover medium variation range was between 1.333 and 1.335.

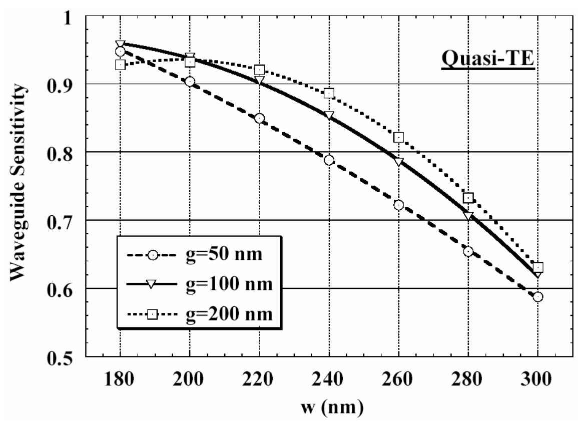

Fig. 2: Slot waveguide sensitivity dependence on *w*, for quasi-TE mode and *g*=50 nm, 100 nm and 150 nm (*h*=250 nm).

From data reported in Fig. 2 and 3, it is evident as quasi-TE mode is significantly more sensitive to cover medium refractive index changes than quasi-TM one. This difference is due to the fact that optical field confinement in the cover is larger for quasi-TE than for quasi-TM mode (see Fig. 4 and 5). For example, optical field confinement factor in the cover medium is equal to 67.31% for quasi-TE and 41.41% for quasi-TM mode, assuming a slot waveguide with *h*=250 nm, *w*= 250 nm and *g*=100 nm.

For quasi-TE mode, slot waveguide sensitivity decreases monotonically when *w* increases either for *g*=50 nm or *g*=100 nm, whereas sensitivity dependence on *w* exhibits a maximum (0.932, corresponding to *w*=200 nm) for *g*=200 nm. However, the maximum sensitivity (0.957) is obtained for *g*=100nm and *w*=180nm. For quasi-TM mode, sensitivity dependence on *w* is monotone for *g*=50 nm and *g*=200 nm and exhibits a maximum (corresponding to *w*=220 nm) for *g*=100 nm. Maximum value (0.518) is obtained for *g*=100 nm and *w* =220 nm.

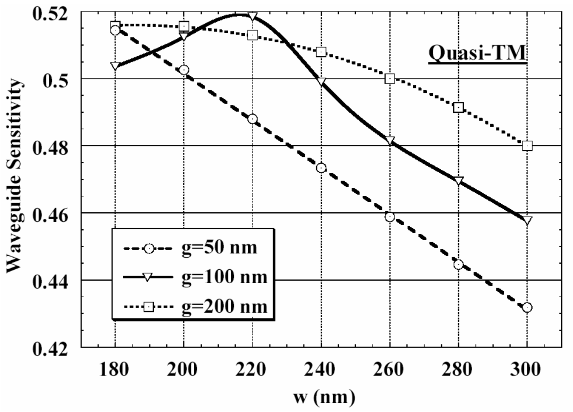

Fig. 3: Slot waveguide sensitivity dependence on *w*, for quasi-TM mode and *g*= 50 nm, 100 nm and 150 nm (*h*=250 nm).

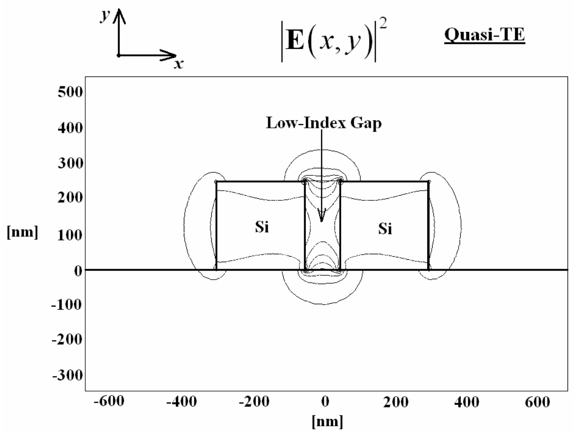

Fig. 4: Squared electric field module for quasi-TE mode (*h*=250 nm, *w*=250 nm, *g*=100 nm, n_c=1.333).

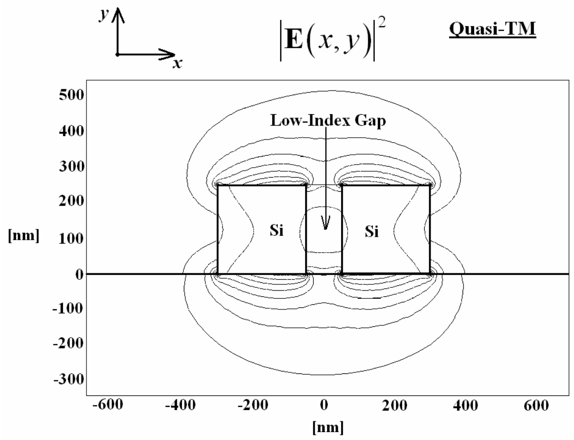

Fig. 5: Squared electric field module for quasi-TM mode (*h*=250 nm, *w*=250 nm, *g*=100 nm, n_c=1.333).

To compare slot waveguides sensitivity with that of other SOI sub-micrometer structures, sensitivity dependence on waveguide width for either SOI rib waveguide (Fig. 6) or Si-wire waveguide (Fig. 7) has been investigated. In both cases we assume a waveguide height equal to 250 nm and an aqueous solution as cover medium (index 1.33). For SOI rib waveguide an etch depth d_{rib} =200 nm has been fixed. Results are shown in Fig. 8 and 9 considering both quasi-TE and quasi-TM modes.

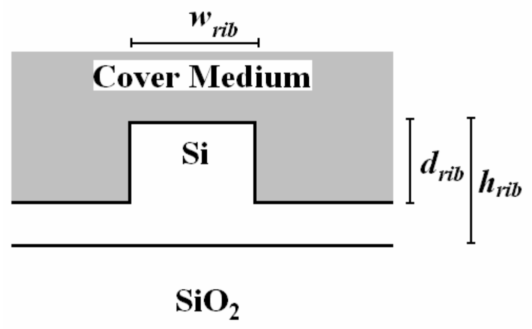

Fig. 6: SOI rib waveguide structure.

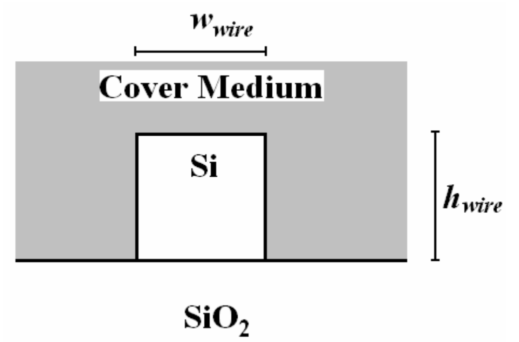

Fig. 7: Si-wire waveguide structure.

For SOI rib waveguide, quasi-TM mode assures a higher sensitivity than quasi-TE one, whereas for Si-wire waveguide, quasi-TM case is more sensitive than quasi-TE one only for w_{wire} >320 nm. Moreover, it is possible to notice that Si-wire waveguide exhibits a higher sensitivity with respect to SOI rib waveguides in all considered cases. Moreover, sensitivities for both SOI rib and Si-wire waveguides are always lower than that assured by a SOI slot waveguide when quasi-TE mode propagates.

To further maximize the SOI slot waveguide sensitivity, we have investigated the influence of h/w ratio. Assuming g = 100 nm, waveguide sensitivity has been calculated versus h/w varying in the range from 1.2 to 1.8, with w = 140 nm, 180 nm and 220 nm, respectively. Quasi-TE (in Fig. 10) and quasi-TM modes (Fig. 11) have been considered.

For quasi-TE mode, sensitivity monotonically increases by increasing h/w, but the relevant slope decreases when w increases. For w=180 nm and h/w=1.8 (i.e. h=324 nm), the maximum sensitivity has been obtained (S_w = 1.0076).

For quasi-TM mode and w=140 nm, sensitivity increases monotonically when h/w increases. For w=180 nm, sensitivity dependence on h/w exhibits a maximum for h/w =1.4. Finally, for w=220 nm, sensitivity monotonically decreases when h/w increases.

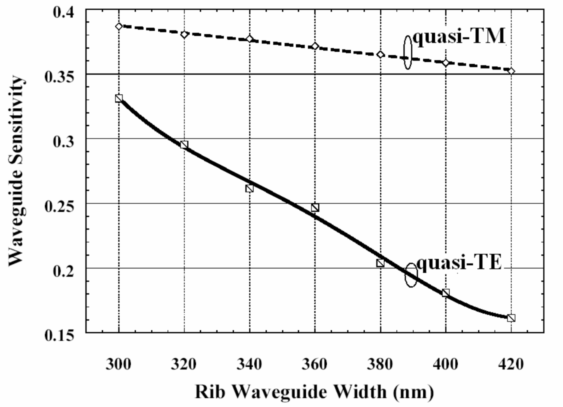

Fig. 8: SOI rib waveguide sensitivity dependence on w_{rib}, for quasi-TE and quasi-TM modes (h_{rib}=250 nm, d_{rib}=200 nm).

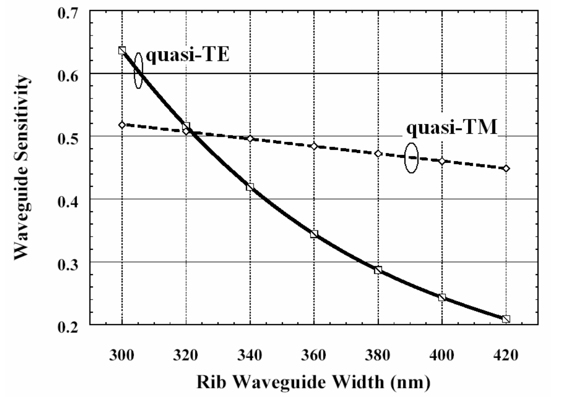

Fig. 9: Si-wire waveguide sensitivity dependence on w_{wire}, for quasi-TE and quasi-TM modes (h_{wire}= 250 nm).

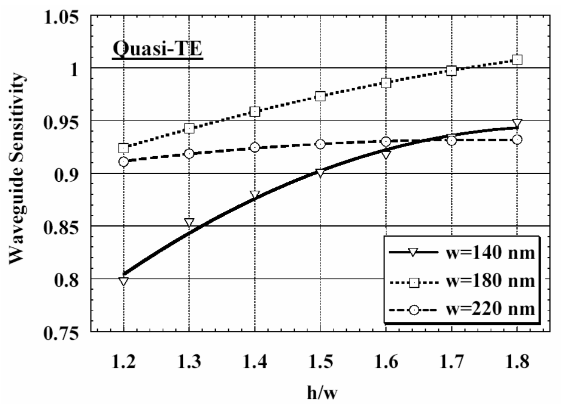

Fig. 10: SOI slot waveguide sensitivity dependence on h/w, for quasi-TE mode and w=140 nm, 180 nm and 220 nm (g=100 nm).

Slot waveguide sensitivity dependence on h/w can be expressed analytically by a quadratic polynomial. Thus we can write:

$$S_w = c_0 + c_1\left(\frac{h}{w}\right) + c_2\left(\frac{h}{w}\right)^2 \quad (3)$$

where c_0, c_1 and c_2 are fitting parameters, whose values are reported in Table 1.

Finally, for w=180 nm, h=324 nm and quasi-TE mode, sensitivity dependence on g has been investigated (see Fig. 12). The maximum sensitivity

(1.0076) has been obtained exactly when g = 100 nm.

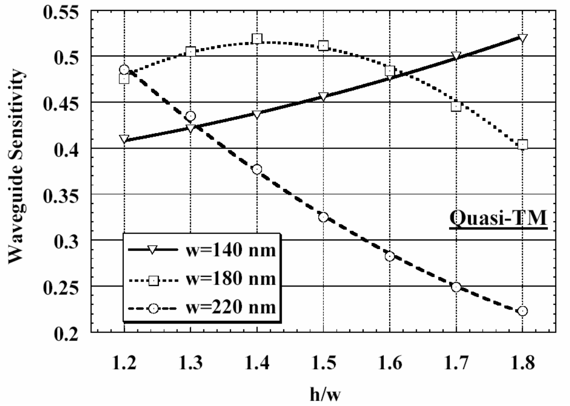

Fig. 11: SOI slot waveguide sensitivity dependence on h/w, for quasi-TM mode and w=140 nm, 180 nm and 220 nm (g=100 nm).

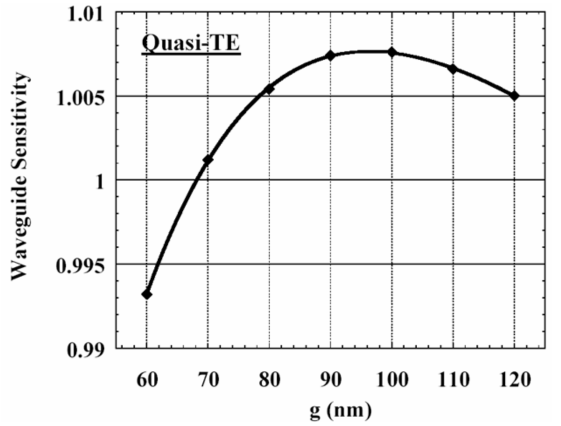

Fig. 12: SOI slot waveguide sensitivity dependence on g, for quasi-TE mode, w=180 nm and h = 324.

Table 1: Fitting parameters related to slot waveguide sensitivity dependence on h/w.

	w	c_0	c_1	c_2
TE	140	-0.161	1.186	-0.318
	180	0.584	0.380	-0.080
	220	0.719	0.244	-0.070
TM	140	0.390	-0.101	0.097
	180	-1.056	2.218	-0.783
	220	1.705	-1.390	0.314

The optimized SOI slot waveguide having h=324 nm, w=180 nm and g=100 nm has been investigated for n_c=1 (air as cover medium) and n_c=1.33 (water as cover medium). Effective index, birefringence, optical field confinement factor in the cover medium and effective index dispersion (defined as the derivative of effective index with respect to wavelength) have been calculated, either for quasi-TE or quasi-TM modes (see Table 2).

Conclusions

Sensitivity of SOI slot waveguide has been optimized in this paper. A set of geometrical parameters permitting to achieve a sensitivity value of 1.0076 has been found. This value is significantly larger (difference around 40%) than that obtainable adopting any Si-wire or SOI rib waveguide.

Moreover, has been proved that slot guiding structures are the most attractive for SOI technological platform in nanometer evanescent field photonic integrated sensors.

Table 2: Parameters of optimized SOI slot waveguide (h=324 nm, w=180 nm, g=100 nm).

Parameter	n_c = 1	n_c = 1.33
Effective index (TE)	1.252891	1.870414
Effective index (TM)	1.578634	1.989995
Birefringence (N_{TM} - N_{TE})	0.737	0.411
Effective index dispersion (TE) [nm^{-1}]	-8.02×10^{-4}	-7.81×10^{-4}
Effective index dispersion (TM) [nm^{-1}]	-1.38×10^{-3}	-1.19×10^{-3}
Confinement factor in cover medium (TE)	70.5%	76.4%
Confinement factor in cover medium (TM)	38.0%	41.2%
Waveguide sensitivity (TE)	-	1.0076
Waveguide sensitivity (TM)	-	0.4040

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