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Optimization of a dual-slot waveguide for a refractive index biosensor

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The present article illustrates the modeling and optimization of a dual-slot waveguide for the application of a refractive index biosensor. The nanometer scale waveguide structure uses the silicon-on-insulator platform for the consideration of higher sensitivity and compactness of a resonator biosensor. The modal analysis is performed using the finite difference method based on full vector eigenmode calculation. The maximum field penetration in the lower index region is found for the quasi-TE mode. The sensitivity is maximized through the optimization of the waveguide dimension by relating effective refractive index with the dispersion of a waveguide. The biosensor showed the maximum calculated sensitivity of 461.327 nm/RIU and a limit-of-detection of 2.601×10^{-6} RIU (where RIU denotes refractive index unit).

Keywords: biosensor, evanescent field, eigenmode, dispersion.

1. Introduction

In the past decade, silicon photonics has been explored extensively for the use of optical biosensors. Photonic devices found applications in drug diagnostics, medicine, homeland security and environmental monitoring [1]. Optical biosensors offer several advantages, compared to the traditional electromechanical sensors, like compact structure, robustness, immunity to electromagnetic interference (EMI). Optical biosensors depend on two methods; the first method is based on fluorescence detection and it is a label based detection technique. This technique is very sensitive but required a complex labeling process that attached the radioactive fluorophores particles directly to the targeted molecule. Hence requires a long time and expertise in making quantitative analysis [2]. On the other hand, the second method is label-free detection. Label-free detectors detect the binding event by attaching the biomolecule to the surface of the optical sensors. Label-free detection is an advantage of the analysis of the biomolecular process in real time by observing the alteration in the optical properties of the sensor [3, 4].

In literature, various optical biosensors based on slab waveguides using metamaterials, photonic crystal cavities, ring resonators, interferometers, and surface plasmon resonance are reported [5–21]. Out of these photonic sensors, those based on a planar waveguide using a silicon-on-insulator (SOI) platform are comparatively favorable due to an ease of integration for a lab-on-chip applications [22]. For planar waveguide biosensors, detection is performed using an evanescent field of the guided wave. In a conventional strip and rip waveguide the modal field dominantly propagates in a high index region causing very low interaction of the field with biomaterial which results in a low sensitivity. The upper surface of a biosensor, also called an upper cladding, for a label-free detection is required to fill with a targeted biomaterial [3–5].

Biosensors based on slot waveguides provide higher sensitivity due to their nature of confinement of the field in a low refractive index region [23]. Target biomaterial present in a slot, which is mediated in between the rails of two high index regions, allows maximum interaction between the biomaterial and the modal field. In this work, a dual-slot waveguide is presented for a biosensing application. The dimension of the waveguide is optimized for maximizing the resonator bulk sensitivity by varying a slot width and center channel width.

2. Theory and modeling of dual-slot waveguide biosensor structure

In the present work, the performance parameter of a biosensor is bulk sensitivity. The bulk or homogenous sensitivity ($\mathrm{d}n_{\mathrm{eff}}/\mathrm{d}n_{\mathrm{c}}$) is calculated as a ratio of change in the effective refractive index of a waveguide to a change in the refractive index of a biomaterial present on the upper cladding surface. In [22], TalebiFard *et al.* considered the effect of dispersion on the shift in resonator wavelength through the consideration of group index n_{g}. The group index is directly related to the effective refractive index of a waveguide [7, 8], hence the dimension of the waveguide is required to be optimized for an optimum value to enhance the resonator bulk sensitivity. The resonator bulk sensitivity S directly related to a $\mathrm{d}n_{\mathrm{eff}}/\mathrm{d}n_{\mathrm{c}}$ and is inversely related to n_{g}, moreover, the value of the resonant wavelength λ_{res} is fixed at 1550 nm and the expression is represented as [22]

$$S = \frac{\lambda_{\mathrm{res}}}{n_{\mathrm{g}}} \frac{\mathrm{d}n_{\mathrm{eff}}}{\mathrm{d}n_{\mathrm{c}}} = \frac{\Delta\lambda_{\mathrm{res}}}{\Delta n_{\mathrm{c}}} \tag{1}$$

The analysis of a dual-slot waveguide is done by using a full-vector 2D eigenmode calculation for the solution of a fundamental quasi-TE mode. The schematic of a cross -section of the waveguide is shown in Fig. 1**a**. The meshing of the waveguide geometry is performed using a finite difference method, then Maxwell's equations are articulated into an eigenvalue problem to evaluate an effective refractive index and a field profile of a mode [24]. The silicon (Si) channels with a refractive index of 3.476 at 1550 nm are designed on the SOI platform. The thickness (GH) of Si channels is 220 nm. The lower cladding material is silicon dioxide ($\mathrm{SiO_2}$) of a refractive index 1.444, and the upper cladding material is filled with water of a refractive index 1.326, as targeted biomate-

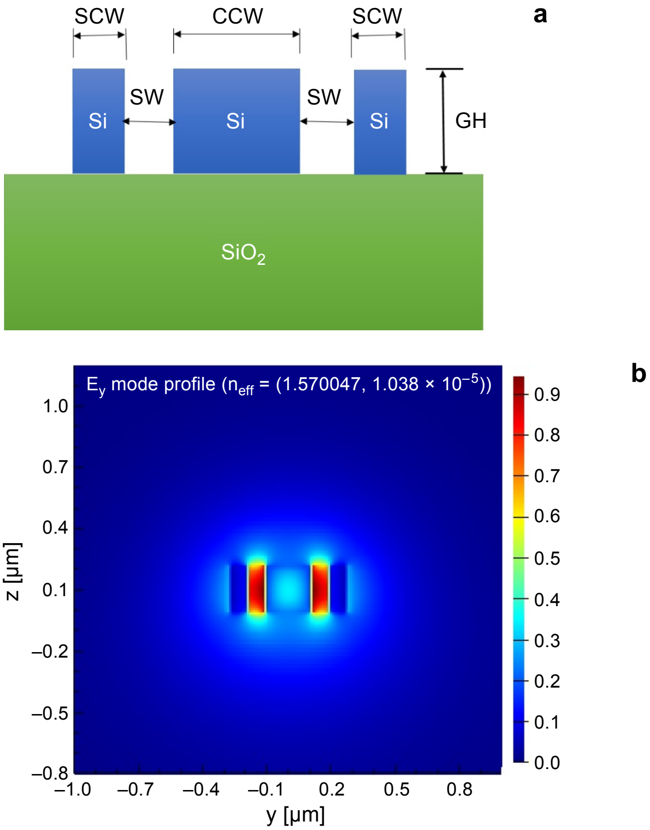

Fig. 1. Cross-section of dual-slot waveguide (**a**), and mode profile of a dual-slot waveguide for a center channel width (CCW) of 220 nm (**b**).

rial [25]. In this configuration of a waveguide, the quasi-TE mode is highly confined in the slot region as compared to a TM mode. The higher confinement enables the increased interaction between the propagated field and the biomaterial present in the waveguide that likely enhances the sensitivity of the biosensor and also detects the small change in the refractive index of a biomaterial. Figure 1**b** shows the modal confinement in a dual-slot waveguide.

The waveguide consists of two side channels of width (SCW) and a center channel of width (CCW). We have assumed the value of SCW is kept constant at 80 nm. The value of the CCW is varied from 200 to 280 nm for variation in slot width (SW) ranging from 60 to 140 nm, to determine the effect of the variations on the effective refractive index.

3. Results and discussion

Effective index and group index are plotted in Fig. 2 for various values of CCW. Figure 2**a** demonstrates the variation of n_{eff} corresponding to a change in CCW. The lower value

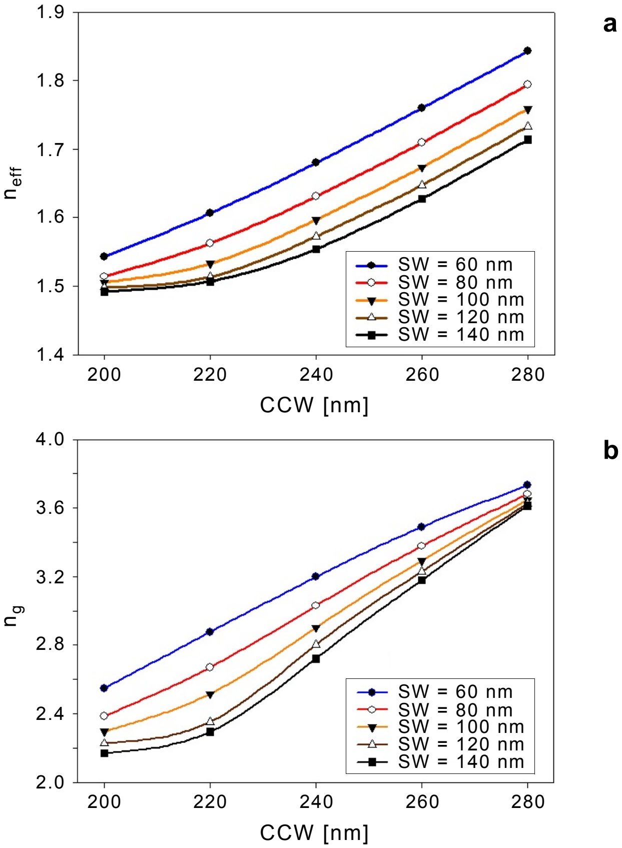

Fig. 2. Change in the effective refractive index as a function of center channel of width (**a**), and change in the group index as a function of center channel of width (**b**).

of the n_{eff} is found for an increase in the value of the SW, that is due to the reduction of the coupling of the mode in the slot region [26, 27]. The value of n_{g} is shown in Fig. 2**b**. It is observed that the value approached a constant value for an increase in CCW, so the sensitivity depends only on the value of $\mathrm{d}n_{\mathrm{eff}}/\mathrm{d}n_{\mathrm{c}}$.

Figure 3 shows the plot of the variation of sensitivity for a change in the CCW. It is observed that the higher value of sensitivity is found for SW = 60 nm that is due to an increase in the confinement of the mode in the slot region, but smaller SW has limitations like difficulty in providing the biomaterial and capillary force in liquid [25]. Also, the fabrication errors, specifically surface roughness, are more prone to a small scale dimension that increases the propagation loss due to an additional scattering loss [24]. Therefore the considered value of maximum sensitivity S is 461.327 nm/RIU for SW = 100 nm. Figure 2 shows that the value of the effective index and group index increases on increasing the dimension of CCW. The increase in the effective index leads

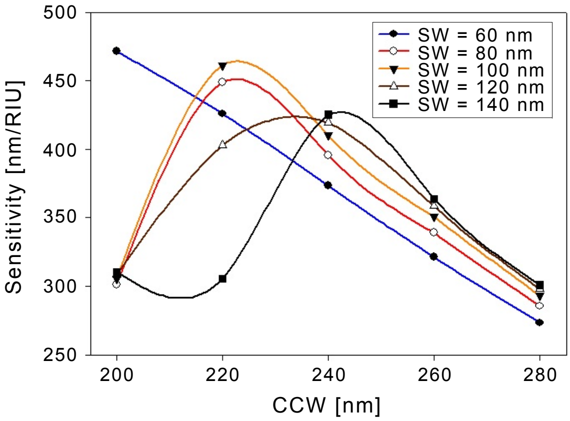

Fig. 3. Sensitivity as a function of center channel of width.

to the fact that the confinement of the mode in the slot region decreases that reduces the sensitivity of the sensor as presented in Fig. 3. The optimized dimension for a CCW is 220 nm for SW of 100 nm.

4. Detection limit of biosensor

Limit-of-detection (LOD) is an important parameter to analyze the performance of the biosensor. LOD is the smallest possible change in the refractive index required for alteration of the resonance wavelength. It is inversely related to the sensitivity of the biosensor, and analytically it is expressed as LOD = σ/S (where σ is smallest resolvable signal and S is the sensitivity) [26]. We have considered a complete system noise by using three standard deviations σ as a measure of sensor resolution [28]

$$\rho = 3\sigma = 1.2 \text{ pm} \tag{2}$$

The LOD from Eq. (2) is 2.601×10^{-6} RIU. The unit of LOD is a refractive index unit (RIU) used for quantification of biosensor performance and required to compare the photonic biosensor from a different structure.

5. Conclusion

We have investigated a dual-slot waveguide for a resonator biosensor. The modal analysis is carried out using the finite difference based full vector eigenmode approach for the evaluation of the quasi-TE mode. The precise optimization method considers the evaluation of the effective refractive index and group index with the help of two parameters that are slot width and center channel width for maximizing the resonator bulk sensitivity. The proposed sensor exhibits a resonator bulk sensitivity of 461.32 nm/RIU and a limit-of-detection of 2.601 × 10^{-6} RIU. The sensor easily found application for lab-on-chip diagnostics due to the advantages such as compactness, higher sensitivity, and compatibility with CMOS fabrication facilities.

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