Design of Slot Waveguide based Directional Coupler for Optical Sensing of low concentration of Ethanol in Water

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***Abstract*—In this study, sensing of low concentration (0-10%) of ethanol in water is presented by refractive index sensing by silicon slot waveguide-based direction coupler. The significance spectral variation and sensitivity is observed to detect low concentration of ethanol in water.**

Keywords—Slot waveguide, directional coupler, optical sensor.

I. INTRODUCTION

Silicon photonics-based devices getting more attention because of its small footprint, high sensitivity, stability, label free sensing, low limit of detection and compatibility with modern CMOS fabrication technology [1]. There are various applications such as optical filter, optical switches, power splitters, logic gates, modulators, and sensors. All mentioned applications are possible by the various type of developed waveguide structures like photonics crystal waveguide, slot waveguide, coupled slot waveguide, Mach-Zehnder interferometers, directional couplers, and ring resonator [2]. All devices are more sensitive towards the various of refractive index which finds the applications in the field of liquid sensing, gas sensing, chemical sensing and bio-sensing [3]. Also, silicon photonics platform opens the pave for high refractive index contrast optical waveguides based on silicon-on-insulator platform. Specifically, slot waveguide based on silicon (~3.48) and silica (~1.48) has attract to modify the existing optical devices with silicon waveguide because of small size in order of micrometre, and strong confinement of light in low refractive index [4]. In slot waveguide, low refractive index material is sandwich by high refractive index material, i.e., silicon (Si), Si_3N_4, TiO_2 etc, and light is confine and propagate in the low refractive index through the electric field discontinuity between low refractive index and high refractive index boundaries. The low index cladding region is influence by the sensing material produce the significance effect on confinement of light. So, slot waveguide structures are become suitable candidate for silicon photonics based refractive index sensor [5].

Previously, optical directional coupler use for optical reciprocal, optical modulation, and optical sensing [6]. In directional coupler, refractive index sensing can be possible through changing the transmittance characteristics with changing coupling characteristic by refractive index variation of cladding material [7]. The replacement of optical waveguide in optical directional coupler can be expand capability of optical sensing through strong light and sensing materials interaction. On the based of sensing materials, it can be liquid sensor, gas sensor, and bio-sensor.

With the variation of the concentration of ethanol in water induce the change of refractive index of sensing slot waveguide. The refractive index of aqueous solution is dependent on concentration of the ethanol with water. The concentration of ethanol concentration change of 1% in solution water induces a refractive index change in solution of order of 10^{-5} [8]. In the direction coupler, the two different asymmetric slot waveguides can be optimized for common effective index (n_{eff}) then optical field confine in the one slot waveguide can couple with another slot waveguide after a coupling length.

The current work explores the possibilities of the slot waveguide-based optical directional coupler for sensing applications. In this analysis, slot waveguides are optimized for phase-matching condition where effective index of both slot waveguide are same at different concentrations of ethanol in water. Further, obtain the spectral variation of phase matching condition with respect of concentration changing from 1.33285 (0%) to 1.33899 (10%). Lastly, the sensitivity of optical sensor is also calculated.

II. SENSING AND DESIGN CONSIDERATION

The proposed waveguide sensor consists of two parallel non-identical silicon slot waveguides over silicon-on-insulator substrate is placed with separation of length d, which is creating directional coupler. In this asymmetrical coupler architecture, one slot waveguide is filled with sensing aqueous solution and another slot waveguide is covered with silicon SiO_2 (~1.45). The cross-sectional view of schematic of a slot waveguide based directional coupler is shown in Fig. 1, where height (h) of silicon waveguides is 300 nm, width (w_{Si}) of the silicon waveguide is 200 nm, and distance (d) between two slot waveguides form their edge is 600 nm. The width of the slot region (distance between the two-silicon waveguide) is different for both slot waveguides as 98 nm for reference slot waveguide cover with SiO_2 (~1.45) and 60 nm for slot waveguide filled with sensing aqueous solution. The sensitivity of directional coupler can be obtained through spectral variation with respect to variation concentration of ethanol in water. The simulation and optimization of slot waveguide based directional coupler is performed by simulation tool COMSOL based on finite element method (FEM).

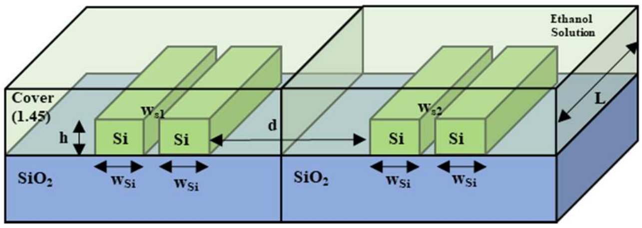

Fig. 1. Cross sectional view of schematic of a slot waveguide based directional coupler sensor

III. Result and Discussion

This characterization of sensor done by obtaining the spectral variation of effective index by changing the concentration of ethanol corresponding to variation in refractive index from 1.33285 to 1.33899. There are two phase-matching condition is obtained at effective index 1.811 for 0% and 1.778 for 10% of ethanol in water. Corresponding to quasi-TE mode coupling between slot waveguides are shown in Fig. 3 and 5 for 0% and 10% levels. With increment in the length of slot waveguide-based direction couple, subsequently optical field is coupled with each other. But, coupling length is chosen for maximum coupling of optical field from one waveguide to another one after travel of coupling length.

Finally, sensing mechanism is working based of shifting in transmittance spectrum induced by sensing aqueous solution from 0-10 %. The shift is linear and corresponding sensitivity is come to be ~10 µm/RIU for small amount of detection of ethanol in water mixture. On the other hand, transmittance is varying in the slot waveguides with the variation of concentration. It can be detected by any commercial optical spectrum analyser.

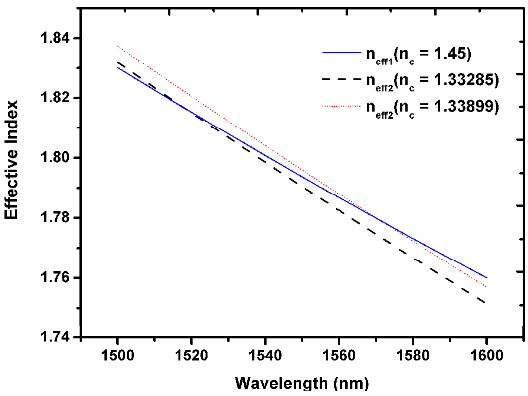

Fig. 2. Spectral variation of n_{eff1} and n_{eff2} with variation of concentration of ethanol in water.

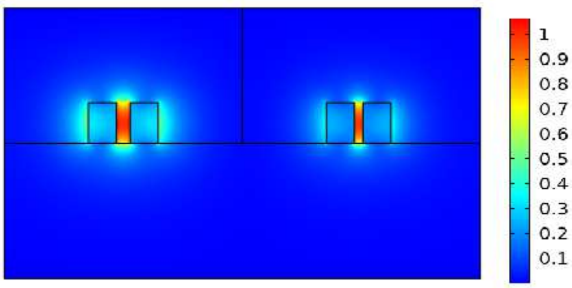

Fig. 3. Optical coupling between waveguides at $n_{eff1} = n_{eff2} = 1.811$ at wavelength (λ) 1512 nm

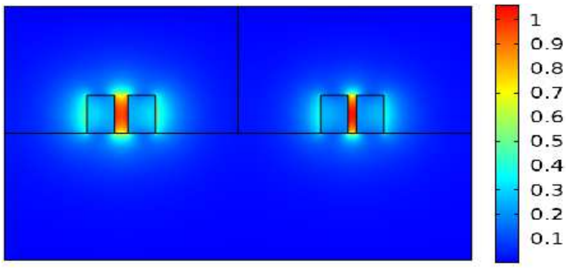

Fig. 4. Optical coupling between waveguides at $n_{eff1} = n_{eff2} = 1.778$ at wavelength (λ) 1572 nm

IV. Conclusion

In this paper, modelling of slot waveguide-based optical direction coupler for aqueous solution sensing of ethanol is demonstrated. This sensor modelling can be predicting the concentration of low ethanol in water in range of 0-10% with the sensitivity of ~10 µm/RIU. Further, it can be optimized for detection of wide range of concentrations of ethanol and water.

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