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Original research article

Refractive index sensor utilizing thermo-optic effect of silicon waveguide

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ABSTRACT

We propose a refractive index sensor based on thermo-optic (TO) effect in directional coupler (DC) with silicon waveguide to detect physiological concentrations of glucose in water. A temperature compensation method is used to realize a refractive index sensor with high sensitivity. The coupling length of the DC with silicon waveguide is calculated by coupled-mode theory. Different silicon width and separation distance of DC have great influence on the sensitivity and resolution to refractive index change of glucose water. Based on simulation results, a sensor with a size of 119.5 μm × 10 μm can be obtained with a resolution of about 1.49×10^{-6} and a sensitivity of 867 K/RIU for glucose concentration less than 1000 mg/dL using highly sensitive detectors with a noise equivalent power (NEP) of picowatt. We also give the equivalent circuit for the refractive index sensor in order to realized opto-electronic integration.

1. Introduction

Refractive index detection is widely researched for a number of applications including monitoring of chemical processes, label-free monitoring of bio-molecular interactions on surfaces and plane-ness detector in precision processing, which promises real-time results and minimal sample preparation with no fluorescent labeling required [1,2]. For an ideal refractive index sensor, it must show a very high sensitivity, quick response, small size, portability and low cost. Many optical methods have been developed to meet these demands, such as photonic crystal structure [3], planar waveguide ring resonator [4], directional coupler (DC) [5], Mach-Zehnder interferometry [6]. However, tiny refractive index detection is difficult in the above methods as it may bring an undetectable physical parameter. Therefore the sensitivity of the sensor will be greatly reduced by use of other technology.

Silicon-on-insulator (SOI) waveguide structures are very promising in the application areas which are characterized by small optical losses over communication wavelengths and fully compatible with CMOS technology and micromechanical devices [7,8]. Silicon is available in large size, good quality and low price, and its technology is highly developed. As silicon's thermo-optic (TO) effect [9] is significantly larger than its electro-optic effect [10], it is an attractive method to modulate the refractive index in SOI waveguides. A number of different silicon-based TO devices have been reported to date.

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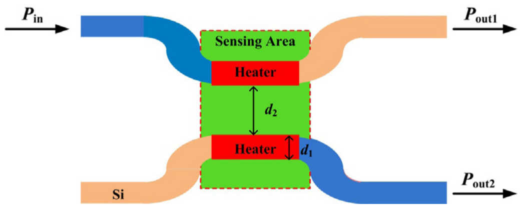

Fig. 1. The schematic diagram of refractive index sensor with a DC structure.

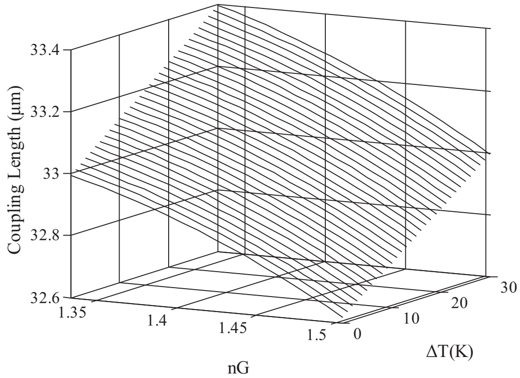

Fig. 2. Coupling length for different sample index and modulation temperature.

In this paper, we propose a refractive index sensor based on TO effect in a DC with silicon waveguide. A temperature compensation method is used to realize a refractive index sensor with high sensitivity. The influences of silicon width and separation distance of DC on the sensitivity and resolution to refractive index change of glucose water are discussed.

2. Sensing mechanism, simulation results and discussion

In a refractive index sensor with a DC structure as shown in Fig. 1, the sample (n_0) to be measured is injected into the sensing area, and the temperature of one silicon (n_1) waveguide can be modulated by the heater. Here we make use of d_1 and d_2 to denote the width of silicon waveguides and the separation distance between them.

The coupling effect of the DC can be analyzed by interference phenomena between the even mode and odd mode, and the electric field in the directional coupler can be approximated by the summation of even mode and odd mode when high-order modes are neglected. The corresponding mode-coupling coefficient of DC is

$$\kappa = \frac{\beta_e - \beta_o}{2} \tag{1}$$

in which we make use of β_e and β_o to denote the propagation constant of the even mode and odd mode, respectively. The coupling length of the five-layer waveguide can be written as

$$L_c = \frac{\pi}{2\kappa} = \frac{\pi}{\beta_e - \beta_o} \tag{2}$$

In this case, the output power can be defined as

$$P_{out1} = \cos^2(\kappa z) P_{in} \tag{3}$$

$$P_{out2} = \sin^2(\kappa z) P_{in} \tag{4}$$

We set the coupling length of the DC as that with water ($n_0 = 1.333$) in sensing area and in this case the incident light is totally coupled into Port 2, which means Pout1 is zero and P_{out2} is maximum. As samples with different glucose concentration bring changes of coupling length in DC, the output of Port 1 (P_{out1}) is nonzero. By accurately modulation the temperature of silicon waveguides with the heater, the refractive index of silicon can be changed. Thus the coupling length can be modulated by the silicon temperature and it is possible to adjust it back to the original value and keep P_{out1} remains zero. We call this phenomenon as the thermal-optic compensation effect in the proposed structure. In this method, a relationship between the refractive index of sample and the modulated temperature can be obtained. Based on the relation between the refractive index and the glucose concentration [8], different modulated temperature determines the glucose concentration in water.

In our sensor, we choose the length of the DC as the coupling length with water in sensing area. The input power will be totally coupled into P_{out2} and the photo-detector cannot detect any power in P_{out1}. In fact the coupling length can be