Design of optical channel waveguide Mach-Zehnder interferometer (MZI) for environmental sensor applications

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Abstract. High sensitivity environmental sensors with a simple and compact structure are required to monitor unwanted pollution such as liquid waste. In this research, a component of environmental sensor based on optical channel waveguide Mach-Zehnder interferometer (MZI) has been designed and also simulated. The materials used in the design were titanium dioxide (TiO₂) as a core and silicon dioxide (SiO₂) with air as cladding. The sensitivity value of the MZI sensor obtained by simulation using computer program was 11 nm/RIU at the angle of 16°. Meanwhile, the obtained fixed length of MZI sensing arm was 4 μm. The proposed design can be used for identifying the existence of liquid material precisely.

1. Introduction

Today, environmental pollution is caused by substances that are extremely dangerous and has reached an alarming level. The environmental damage caused by pollution in the air and water have threatened the sustainability of the living creatures on this earth. Therefore, it required a system for controlling the pollution level. One important component is a sensor with a very high level of sensitivity and selectivity. To meet this need, it is necessary to develop a sensor with the specifications as described above.

Since a few years ago, research and development of sensor components of electronic-based technologies are being replaced by light-based technologies. Optical signals have begun to be applied to the sensors for various needs such as chemical sensors, atmospheric or oceanic with a high level of sensitivity in a compact and simple devices [1-4]. Many types of waveguide sensors have been studied, such as planar waveguide structures, Mach-Zehnder interferometers (MZIs) and silicon micro-ring, for example SMR and MPRR [5-6]. The waveguide ring-resonator-based sensor has several advantages as follow. The shape is small and compact, thus it can be integrated with other components (light source, detector, coupler and so on), and it is easy for mass production [4].

In this paper, the design of the MZI structure for sensor applications environment is reported. The material used were titanium dioxide (TiO₂) as a core, silicon dioxide (SiO₂) and air as cladding with frequency of 180-193 THz. By varying the value of the angle in MZI structure and simulating it using computer program, the optimum value of sensitivity was obtained. The proposed device can be used for identifying difference liquid material precisely.
2. Method and design
The material of waveguide MZI was composed of core TiO$_2$ (n = 2.4) over a layer of SiO$_2$ (n = 1.53). The length of the waveguides sensing ($L$) was 4μm [1] with a thickness ($h$) of 1μm. The MZI waveguide structure is shown in figure 1, assuming the values of the air layer around were varied by n = 1.01, 1.1 and 1.2 as well as the variation of angle at 16° and 20°. The frequency range used was about 180 to 193 THz or equaled to 1666-1554 nm. The result from varying refractive index of the cover medium, MZI output power, theoretically is a function of the phase difference ($\Delta\phi$) which is explained by equation 1:

$$ P = \cos^2\left(\frac{\Delta\phi}{2}\right) $$

$$ \Delta\phi = \frac{2\pi}{\lambda} \times L \times \Delta n_{eff} $$

where $L$ is the length of the sensing pathways. In this study, the length of waveguides was equal and $\Delta n_{eff}$ was the difference in effective refractive index between the two waveguides, namely the path sensing and reference [4].

![Figure 1](image1.jpg)

**Figure 1.** (a) Cross section of MZI. (b) View of 3-D MZI structure. (c) Scheme of MZI [7].

Field distribution of the waveguide was accomplished by transverse electric (TE) or transverse magnetic (TM) mode which was capable of analyzing 2-D waveguides. Because it was not possible to settle directly using these methods, we used the effective index method (EIM) [8].

In this study, the detection was performed when there was a change of refractive index caused by the change of analyte concentration, which was due to the presence of foreign substances. Such changes resulted in a shift in the frequency response.

Changes in the refractive index around the optical device changed the effective refractive index, which was marked by a shift in the output spectrum when the effective refractive index increased. Therefore, the magnitude of this shift was a function of the sensitivity of a sensor that can be expressed by the Free Spectral Range (FSR). FSR is defined as the maximum frequency difference to each other [9].

3. Result and discussion
Measurement technologies of optical sensors are generally based on changes in the effective refractive index. Refractive index changes due to the change in concentration of the analyte or the detection of foreign substances. Optical mode determines the spectral output of a device in term of resonance spectrum or interference fringe. Changes in the refractive index around the optical device will change the effective refractive index of the optical mode that leads to a shift in the output spectrum. Results displayed by bio-chemical sensors can be characterized by absorption, transmission, fluorescence intensity and polarization or reflection.

Another method of optical sensor is to see a shift in the spectrum of wavelengths or frequencies, which is caused by the changes of the refractive index. Such method is used for sensing the surface...
because this mechanism is very sensitive to small changes in the refractive index. Related to this shift, it is important to see the steepness of the spectrum peaks or troughs in the view of a previous spectrum or vice versa.

3.1. Design of MZI for value of angle at 16°

Figure 2 shows the graph of transmission loss as a function of wavelength with the value of angle at 16°. The value of the refractive index of the analyte being tested was 1.2 (air). The shift in frequency response occurred for all frequencies.

Figure 3 shows another graph of wavelength versus transmission loss for the value of angle at 16° in which the refractive index value of the analyte being tested was 1.1. The shift was seen more clearly at the beginning of the frequency range, however there were two peak points where the shifts are very small, i.e. at 1600.931 nm and 1584.2 nm.

Figure 4 is a graph of wavelength vs transmission loss for the value of angle at 16° and the refractive index value of the analyte being tested of 1.01. The shift happened more for all frequency ranges. This was due to the refractive index difference of the core material.

3.2. Design of MZI for value of angle at 20°

Figure 5 shows the graphs of wavelength against transmission loss for analyte that has refractive index of 1.2 and the angle formed at 20°. The shift occurred across all frequencies and seemed to be greater than that of the angle of 16°.
Figure 6 is a graph of the transmission loss as a function of wavelength for the refractive index value of the analyte of 1.1 and the angle formed at 20°. The shift occurred across all frequencies and seemed to be greater than that of the angle at 16°.

Figure 7 is a graph of the wavelength versus transmission loss with a refractive index of the analyte being tested 1.01 on a 20° angle to the core material TiO$_2$. The shift occurred for all wavelengths. In contrast to figure 6, for the core material and the refractive index of this analyte test, the shift does not occur for all frequencies.

The shift of the frequency response seen in the pictures above, namely the environment (air) and analyte, occurred when the analyte reacted with the cover medium, namely air. The analyte was absorbed on the surface of the air so that the reduction occurred. This caused electrons in the core material to get difficulties in passing the energy gap.

The nature of the source of the wavelength used was very influential. When light was passed through a medium, the particles absorbed the light. The amount of absorption was determined by the cosine of the angle of light incidence. The greater absorption angle caused greater reflected light.

The simulation done by varying the angle and refractive indices produced different output power. Damping was even greater with enlargement of the angle formed by the second optical path. From the pictures, visible spectrum shift occurred at a greater value of the refractive index of the test. This
means that the analyte, interference signal and movement of the membrane of other molecules were detected. Shifting value was determined also by the value of the refractive index core. The refractive index of greater core provided a great shifting spectrum [11]. For a sensor, FSR value can be determined directly by determining the frequency difference between two adjacent peaks [10].

3.3. The values of sensor sensitivity

A sensor is considered good if it has properties of high sensitivity and selectivity. The sensitivity of a sensor can be defined as the ratio between the signal difference and changes in the amount of measured signal. The results of the frequency response shift of MZI structure in earlier tests (figure 2-7) can be used to assess the shift of each peak then to obtain the sensor sensitivity values. The resulting sensor sensitivity can be seen in figure 8 and 9.

![Figure 8](image1)

**Figure 8.** Graphs of MZI sensor sensitivity with the value of angle at 16°. The refractive index of TiO$_2$ were (a) 1.2, (b) 1.1 and (c) 1.01.

![Figure 9](image2)

**Figure 9.** Graphs of MZI sensor sensitivity with the value of angle at 20°. The refractive index of TiO$_2$ were (a) 1.2, (b) 1.1 and (c) 1.01.

Figure 8 shows the sensitivity of the MZI sensor. The $n$ value of the analytes tested were 1.2, 1.1 and 1.01. The material used as a core was TiO$_2$ with an angle of MZI structure at 16°. The sensitivity for each MZI structure with the different values of $n$ are 3.9 nm/RIU, 11 nm/RIU and 1.15 nm/RIU. Whereas in figure 9, the sensitivity of MZI sensor structure with an angle value at 20° is shown. The sensitivities value were 3 nm/RIU, 2.8 nm/RIU and 3.36 nm/RIU. From some of these variations, it was concluded that the MZI sensor with 16° angle value has a high value of sensitivity to analyte with $n = 1.1$.

4. Conclusion

The design of the Optical Channel waveguide Mach-Zehnder Interferometer (MZI) was proposed. From the simulation results, we can conclude that Mach-Zehnder Interferometer (MZI) single mode had high sensitivity. Sensor with little attenuation owned by a small angle can be calculated based on the equation 1. Optical path length (L) = 4$\mu$m with a very small angle formed optimal small attenuation of FSR values. The proposed device can be used for precisely identifying different liquid material.
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