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Optical Properties of Hybrid Mach-Zehnder Interferometer for Biochemical Sensor Application

Dedi Irawan

Industrial Engineering, Faculty of Science and Technology
UIN Suska Riau, Pekanbaru 28282 Indonesia
Department of Physics, University of Riau, Pekanbaru 28282 Indonesia

Rado Yendra

Department of Mathematics, Faculty of Science and Technology
UIN Suska Riau, Pekanbaru 28282 Indonesia

Hartono

Department of Mathematical Education, Faculty of Tarbiyah and Education
UIN Suska Riau, Pekanbaru 28282 Indonesia

Okfalisa

Department of Informatics Engineering, Faculty of Science and Technology
UIN Suska Riau, Pekanbaru 28282 Indonesia

Abstract

We reported the optical properties of hybrid Mach-Zehnder Interferometer (MZI) designed by silicon waveguide covered with graphene material in single-atomic layer thickness. Graphene was applied to the specific area of MZI arm in certain length. The upper arm was set as the sensing region and another arm plays an important key as the reference signal. The sensor sensitivity has determined mathematically from the power difference launched at the output ports due to obtain good sensitivity. Our results shows novel optical absorption of graphene on waveguide (hybrid waveguide) applied in MZI arm. The presence of sample, which induces the effective index of the hybrid waveguide, significantly induces the phase of light propagation and the power ratio at the output ports which determines the sensitivity. Finally, we calculated the effect of the distance between the graphene to the core and the specific length of graphene layer on MZI arm.

Keywords: Optical Properties, Hybrid Mach-Zehnder Interferometer, Graphene, Sensitivity

1. Introduction

The use of optical component in communication system and sensing application has been greatly expanded in past two decades. In communication sector the electrical circuit has been transformed to the photonic principle of operation in an optical circuit. Mostly it consist of passive devices such as directional fiber coupler, wavelength division multiplexing (WDM), optical switching, routers, splitters, combiners, ring resonator, and all Mach-Zehnder interferometer (MZI). Other important application was utilizing the optical component for biochemical detection. For example the use of fiber brag gratings (FBG), ring resonator, taper fiber, and MZI in various sensor application such as detecting blood, DNA, Protein, tissue etc [1-7].

Recent years, an integrated optical MZI was used for biosensor based on a fabrication technique of MZI using Ag^{+} -Na ion exchange in a glass substrate [8,14]. The use of sensor was demonstrated to monitor a bimolecular interaction by building up protein multi layers on the sensor surface. The sensor performance then was characterized with respect to bulk supersaturate index and by the formation of multiple protein ad layers using a biotin-avid in-based biochemical system. In Other work, the integrated planar optical waveguide interferometer was also designed for biosensor. The sensor sensitivity was investigated based on the evanescent electromagnetic field of the guided light penetrated slightly into the surrounding material [9].

Graphene becomes a novel material which has been presented in recent years. It promises dual properties of high impact of mechanical and optical characteristic with a potential application [10]. Previous study shows that the simultaneously tuning the graphene sheet size and crosslink mechanisms, an optimal design of graphene based papers can be established with well appreciated mechanical performance. This design concept is reminiscent of many nature materials such as bones and mollusk shells [11, 13]

In this work, we utilized a basic of 2 X 2 MZI by covering the upper arm with graphene material in single atomic layer thickness. The presence of the graphene on waveguide has changed the optical properties of the waveguide namely hybrid region. This region becomes very aggressive and sensitive to the various samples which changes its properties such effective index. This paper also presents the power propagation in the hybrid waveguide of MZI as function of the operational wavelength. The power output ratio is then depicted as function of the absorption coefficient which means that high absorption coefficient produces high power difference at the output terminal of MZI and yields high sensor sensitivity.

2. Design of Hybrid Mach-Zehnder Interferometer

Mach-Zehnder interferometer (MZI) is a great optical device that allows two optical signals interact at two its arms and coupling. The power propagation in the MZI significantly depends on the coupling coefficient which contribute to split and to combine the input signal before and after propagating in the arms area.

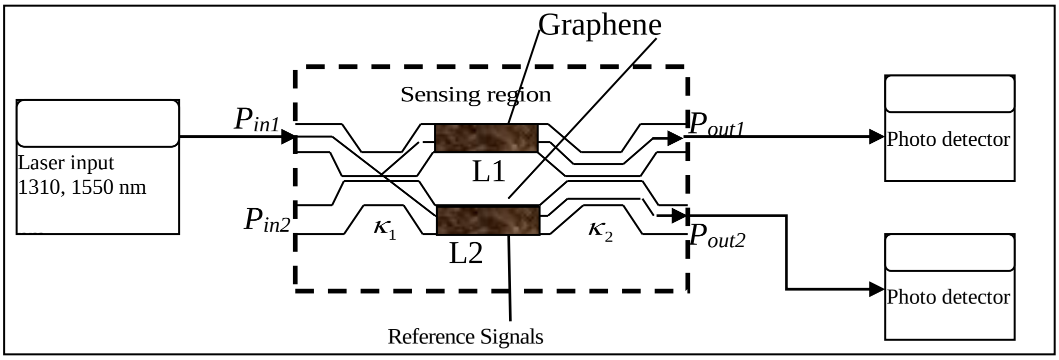


Figure 1. Schematic of hybrid MZI for Biochemical sensor

If the electric field of input port 1 and input port 2 are denoted by E_1 and E_2 respectively, and the electric field amplitudes at the output ports 1 and the output ports 2 are denoted by E_{Out1} and E_{Out2}, the optical propagation of MZI in z -direction is basically expressed in term of the matrix transform as follows [12]:

$$\begin{bmatrix} E_{\text{out1}} \\ E_{\text{out2}} \end{bmatrix} = \begin{bmatrix} -s^2 + c_1{}^2 z^{-1} & -\text{j}cs(1+z^{-1}) \\ -\text{j}cs(1+z^{-1}) & c_2{}^2 - s^2 z^{-1} \end{bmatrix} \begin{bmatrix} E_{\text{in1}} \\ E_{\text{in2}} \end{bmatrix} \tag{1}$$

where $c_1 = \sqrt{1-\kappa_1}$ and $c_2 = \sqrt{1-\kappa_2}$ are the constants of the coupling coefficient of the MZI, and $\text{j}s = -\text{j}\sin(\theta) = -\text{j}\sqrt{\kappa}$. Therefore, the output spectrum at both output ports are $P_{Out1} = |E_{Out1}|^2$ and $P_{Out2} = |E_{Out2}|^2$. The length of two arms and the coupling coefficient play an important key in wide range of application includes passive devices and sensing. In addition, the absorption coefficient is often utilized to control optical switching, in other way it is also utilized to get various range of sensor sensitivity.

Design of MZI as sensing tools by utilizing an arm as the reference, and the other one as the sensing area, the sensitivity which is determined by the power ratio can be mathematically approximated as follow,

$$\frac{P_{\max}}{P_{\min}} = \frac{\exp(-\alpha L_1) + \exp(-\alpha L_2) + 2\exp(-\alpha(L_1 + L_1)/2)}{\exp(-\alpha L_1) + \exp(-\alpha L_2) - 2\exp(-\alpha(L_1 + L_1)/2)}$$
$$= \left(\frac{1 + \exp(\alpha \Delta L_1 / 2)}{1 + \exp(\alpha \Delta L_1 / 2)}\right)^2 \approx \left(\frac{4}{\alpha \Delta L_1}\right)^2 \quad (2)$$

Where $\Delta L = L_1' - L_2$ is the difference sensing-active length.

The interesting phenomenon is to disturb the absorption function of two arms. In this work, we cover the waveguide of two arms by Graphene material with certain length of L_1 and L_2 as shown in Figure 1. By considering the graphene is in single-atomic layer thick, the absorption coefficient can be determined from the inter band transition conductance as $e^2 / 4\varepsilon_0 \hbar c = 2.3\%$ [12]. For a dissipative media per unit area $\langle Q \rangle_S$ such as Graphene on Waveguide (GoW), the optical absorption when propagating inside GoW can be determined as the Ohmic Loss or resistive dissipation as follow [13]

$$\int_S \langle Q \rangle_S \, dr^2 = 1/2 \int_S J_S \cdot E_t dr^2 = \frac{\sigma_0}{2} \int_S |E_t|^2 \, dr^2 \ , \quad (3)$$

where $\sigma_0 = e/4\hbar$ is the AC conductance of the graphene for inter band transition. E_t is the transverse component of electric field and J_S is the induced surface current. In case of optical intensity makes a normal incidence, the approximation given by Equation (3) can be applied to get the absorption coefficient of the $\frac{\langle Q \rangle_S}{I_{Incidence}} = \frac{\sigma_0}{\varepsilon_0 c} = 2.3\%$. In case of GoW with Mach-Zehnder interferometer configuration, the absorption coefficient can be written as $\alpha = -\frac{1}{P(z)} \frac{\partial P(z)}{\partial z}$. Since the absorption in this calculation works for the dissipation area $\langle Q \rangle_S$, Equation (3) is equal to the integration of the dissipation per unit area along the interaction length (graphene layer) L in x direction. It can be mathematically expressed as

$$\frac{1}{P(z)} \int_L \langle Q_S(x) \rangle dL = \frac{\sigma_0}{2P(z)} \int_L |E_t(x, y)|^2 dx \quad (4)$$

Furthermore, the electromagnetic field amplitude, E_x will exponentially decrease as function of L. Now, by assuming the absorption coefficient is also decrease exponentially as function of the distance above the top surface as $\alpha(y) = \alpha_0 e^{-2\gamma y}$, where γ is field decay constant outside the waveguide, the output power of MZI, which its arms covered by graphene in single atomic layer, can be written as follow.

$$P_{Out} = P_{In}/4\left\{\exp(-\alpha L_1) + \exp(-\alpha L_2) + 2\exp\left[-\alpha(L_1 + L_2)\right]\cos(2\pi n_{eff} \, \Delta L/\lambda)\right\} \quad (5)$$

Equation (6) describes the optical power at the output port of MZI which is determined by difference length of GoW at two arms.

3. Results and Discussion

The propagation of light in waveguide is determined by the geometrical structure such as refractive index, waveguide size, material characteristics, absorption coefficient and propagation constant. We found that the graphene layer induce the absorption coefficient of the waveguide. This hybrid type of MZI provides a good sensitivity as sensor device. 1 mW input signal was launched in to input terminal 1 of MZI. This signal will be split by fiber coupler with coupling coefficient equal to 0.5. This coupler will divide the input signals symmetrically in same value. One signal is propagating in the upper arm, and the second signal is propagating in the lower arm. These signals are then combined again by the coupler with coupling coefficient equal to 0.5 before both two signals released at the output ports.

A. Power Transmission

The presence of graphene on waveguide shows that the absorption coefficient was significantly changed the typical of power transmission. Power transmission of the hybrid MZI was simulated in the difference length of graphene material on the waveguide. Figure 2 shows the effect of the graphene to the effective index and the power transmission of the MZI. We confine the length of graphene on the waveguide from L=0 micron to L=80 micron. The power transmission was significantly changed with sinusoidal profile.

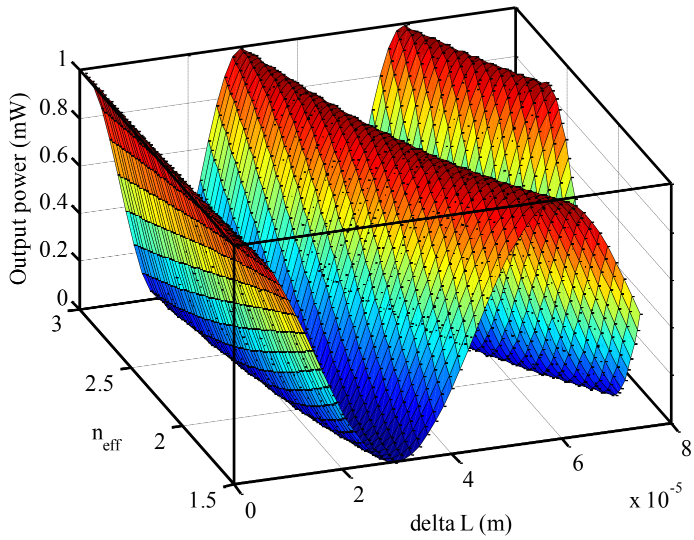
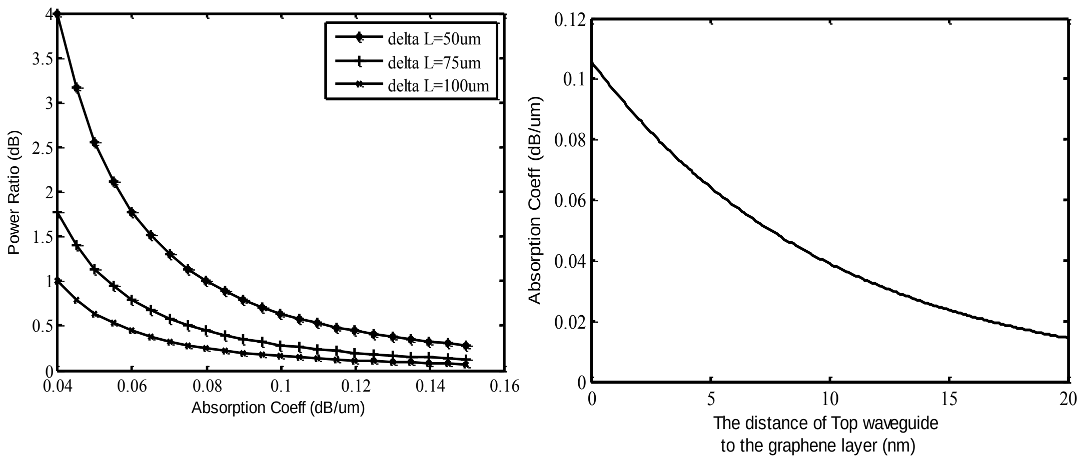


Figure 2. Effect of the length of graphene layer to the power transmission and the effective index.

It can be seen clearly also the effective index was very much depends on the length of graphene on the waveguide. Our result shows that the effective index was exponentially decreased from 3 to 1.5 by increasing the length of graphene layer from 7 micron to 25 micron. We note here that the change of effective index due to length of the graphene layer becomes weaker for higher order of sinusoidal wave. For example to change the effective index from 3 to 1.5 requires the increasing of the length of graphene layer from 40 micron to 67. This properties promise difference range of sensor sensitivity application. In this case the first order (7 micron to 25 micron) has sensitivity higher than second order of effective index change (40 micron to 67 micron).

B. Absorption Coefficient

The absorption coefficient of the hybrid waveguide of MZI not only changes the characteristic of the power transmission, but it also induces the ratio of power released at the output ports. Since the sensor sensitivity determined based on power difference detected at the output ports, it becomes important sensor parameters. Figure 2a shows that power ratio was exponentially decreased as function of the increment of absorption coefficient. This becomes a gold results supported by the effect of difference length of graphene layer on the upper and lower arm. This properties leads to design all MZI device for biochemical sensor in desired sensitivity range by setting length of graphene layer on the waveguide.



(a) (b)

Figure 3. a) Power ratio at output ports change by absorption coefficient. b) Effect of the distance of graphene layer on top of waveguide.

Another important parameter is the distance of graphene layer on the top of waveguide. Since the graphene is distributed on the substrate by using MOCVD methods, this allows some micrometer space between core and the graphene layer. Figure 3b depicts the absoption exponentially decreased for longer distance between them. Certainly, this distance is the second choice to adjust the absorption coefficient in case of difficult to maintain the langth of interaction length of graphene on the waveguide.

C. Sensor Sensitivity.

The sensor sensitivity was successfully determined as function of interaction length of sensing area. It can be seen in Figure 4 the sensitivity profile of the MZI which was determined based on the power difference detected at the output ports due to the presence of sample at the sensing area. We can see that the hybrid MZI, denoted by solid line high, has better sensitivity compared with the conventional Silica waveguide of MZI as given by the dash line. In general, two material still shows a good agreemen, where the most sensitive region depicted in range of interaction length between 0.1 micron and 4 micron. The sensitivity initially increase in high gradient until it reachs maximum value. It then shaply decreased until a limit where the sensitivity remains decreasing gradually. This profile of hybrid MZI promise a good sensor for wide application in biochemistry for sample detection such blood, protein, DNA analysis etc [13,14].

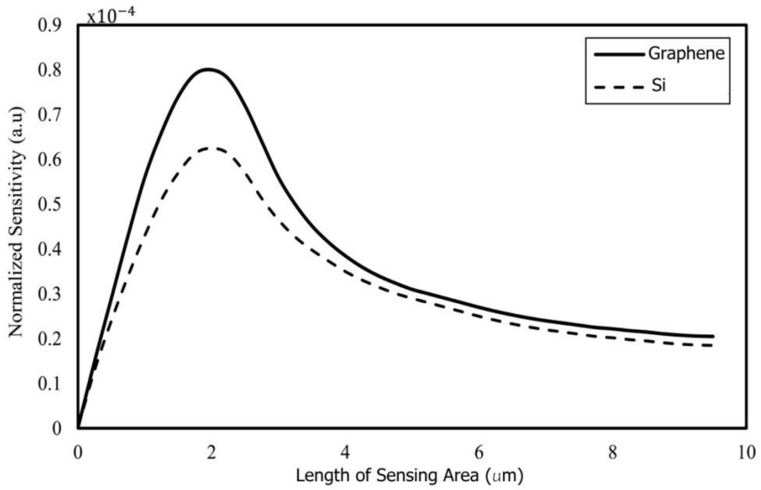


Figure 4. Sensitivity profile of MZI configuration

4. Conclusion

The study of hybrid MZI shows that the effect of graphene layer to the waveguide changes the effective index and absorption coefficient. By covering the waveguide with single atomic layer thick of graphene enhances the absorption coefficient. However, the effective index significantly changed by changing the length of graphene layer on the waveguide. Hybrid MZI promise high sensor sensitivity compared to the conventional silica waveguide which can be controlled by adjusting the length of sensing area. The distance of graphene layer to the cladding also affects the absorption coefficient. The absorption coefficient exponentially decreased as function of the length interaction increment.

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