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TEMPERATURE EFFECT ON REFRACTOMETRIC DOUBLE RING RESONATOR

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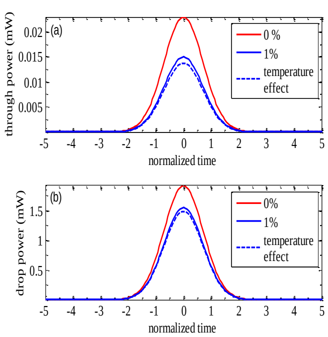
Graphical abstract



Abstract

The effect of temperature on double ring resonator (DRR) glucose sensing is investigate theoretically and proposed. Different from other optical resonator, the pulse laser is used as an input source and the vertical DRR configuration is used. The concept for pulse propagation is based on the split-step Fourier method. Result shows that the detection of glucose is measured by optical losses and the losses at 26°C are 1.86 dB at through and 0.93 dB at drop port, respectively. The performance of glucose sensing on DRR is degraded by temperature. Effect of temperature creates more losses which results total loss of 2.01 dB at through and 1 dB at drop port when temperature increase by 1°C.

Keywords: Optical sensor, optical soliton, temperature sensor, ring resonator

Abstrak

Kesan suhu ke atas dua cincin penyalun (DRR) glukosa penderiaan adalah menyiasat secara teori dan dicadangkan. Berbeza dengan penyalun optik lain, laser denyutan digunakan sebagai sumber masukan dan konfigurasi DRR menegak digunakan. Konsep untuk perambatan denyutan adalah berdasarkan kaedah Fourier berpecah-langkah. Keputusan menunjukkan bahawa pengesanan glukosa diukur dengan kehilangan optik dan kehilangan pada 26°C adalah 1.86dB pada melalui dan 0.93dB pada penurunan liang masing-masing. Prestasi penderiaan glukosa pada DRR merosot akibat suhu dan menyebabkan hilangnya 2.01dB dan 1dB pada liang penurunan apabila suhu meningkat sebanyak 1°C.

Kata kunci: Sensor optik, soliton optik , sensor suhu, cincin resonator

1.0 INTRODUCTION

Insulin is the type of hormone that is required to take up glucose from the blood [1]. Insulin that fails to produce or fails to respond to the glucose creates high blood sugar inside the person body and possible to produce a chronic systemic disease called diabetes mellitus. The diabetes mellitus have two type; type I and type II. Type I diabetes or known as juvenile diabetes is a disease in which the patient body is inability to produce insulin [1].

This type of diabetes cause a risk of complications such as heart disease, kidney disease (nephropathy), and eye disease (retinopathy) 1. Type II diabetes or known as adult diabetes is characterized as noninsulin dependent which the body still produce insulin but some part of cell body resistance to the hormone and fail to take up the glucose appropriately [1]. This type of diabetes cause a risk of complications such as anesthesia and poor wound healing. Both types I and II diabetes mellitus have a same acute effect; hypoglycemia which occur when the glucose level in blood is too low. This disease is too dangerous for the body because make the body feel weak which results shock and even coma and death. Therefore, the prototype for measuring the correct amount of glucose concentration is needed to control glucose level in drinking water for the hypoglycemia patients. Aforementioned research use many technique measurement based on optical method for monitoring glucose level in blood and one of them is the non-invasive optical method with optical coherence tomography [2-4]. This method is much more safe compare with current ''finger-stick'' methods that avoid patient feel pain and increase patient compliance to control blood sugar levels. Opto-fluidic ring resonator is another optical method for monitoring the glucose level and this method is the combination of optical ring resonator architecture with microfluidics [5]. This method compensate the drawbacks of human interstitial fluid (ISF) that offer advantages of high sensitivity and low sample consumption without any extra sample delivery system. Although the device is very sensitive and small, unfortunately, the device sensitivity also disturb by temperature. The change sensitively with temperature in glucose sensor is required to take account because it defect the device performance [6]. Most of group research use continuous laser as an input source and only focus on application for monitoring glucose in blood but neither use the pulse laser as an input source and develop an application for monitoring glucose level in drinking water for hypoglycemia patients.

In this research, the input source is change from continuous laser to pulse laser and the core waveguide material is silicon with cladding doped by silicon dioxide. The microring resonator is designed vertically because to focus the detection only at ring. The DRR configuration is used to get a maximum detection for device. The objective are to develop the prototype theoretically and investigate the effect of temperature to the device sensor.

2.0 THEORETICAL MODELING

The system description is based from Figure 1. The input optical pulse used for this research is described as the Gaussian pulse. The pulse profile is based from [7],

$$E(0,t)=\sqrt{P_o}\exp\left(-\frac{t^2}{2t_o^2}\right). \tag{1}$$

where, the amplitude and pulse width is represented as $\sqrt{P_o}$ and t_o. The Gaussian pulse propagation within DRR is governed by the modified nonlinear Schrödinger equation (NLSE) given by

$$\begin{aligned}&\frac{\partial E}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 E}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 E}{\partial t^3}=i\gamma P_o E\\&-\frac{\alpha_{TPA}}{2}E-\frac{\alpha_{lin}}{2}E-\frac{\alpha_{FCA}}{2}E-\frac{\alpha_G}{2}E\end{aligned} \tag{2}$$

where E, β_2, β_3, and γ represent the amplitude field, group velocity dispersion parameter, third-order dispersion, and nonlinear parameter. The third-order dispersion in Equation (2) is considered negligible because this dispersion only cause a minor effect to the pulse [8, 9]. The terms α_{lin}, α_{FCA}, α_{TPA}, and α_G are the absorptions occur within silicon; linear propagation loss, free carrier absorption (FCA), two photon absorption (TPA), and glucose absorption (GA), respectively. TPA, GA and FCA can be modeled as

$$\alpha_{TPA}=\frac{\gamma\cdot n_{core}\beta_{TPA}P_o}{k\cdot n_2}, \tag{3}$$

$$\alpha_{FCA}=\sigma_{FCA}\left(N_{photon}+N_{thermal}\right), \tag{4}$$

$$\alpha_G=\frac{4\pi}{\lambda}\cdot n_{GR}. \tag{5}$$

Here the terms σ_{FCA}, n_{core}, n_2, N_{photon}, $N_{thermal}$, and k are the FCA cross section, core refractive index, nonlinear refractive index, free-carrier density of photon, free-carrier density of temperature, and vacuum propagation constant. The index ratio, n_{GR}, is the ratio of glucose index, n_G, over total index, n_{tot}. The glucose and total refractive index is given by [10]

$$n_G=0.2015\left(G/100\%\right), \tag{6}$$

$$n_{total}=n_{core}+n_{cladding}. \tag{7}$$

where the G, n_{core}, and $n_{cladding}$ are represented as the percentage of glucose concentration in deionize water, the core waveguide and the cladding waveguide. The total index here is refer to the total of core and cladding refractive index which pulse propagate along these indexes. The free-carrier density of photon is described as

$$N_{photon} = \frac{\beta_{TPA} P_o^{\,2} \tau_{eff}}{2hv_o A_{eff}^{\,2}} \tag{8}$$

The terms τ_{eff}, A_{eff}, P_o, β_{TPA}, and N_{photon} represent the effective carrier recombination lifetime, effective mode area, pulse peak power, TPA coefficient, and photon carrier density. The term hv_o is represented as the single photon energy. The free-carrier density of temperature is given by [11]

$$N_{thermal} = \left(N_c N_v\right)^{1/2} \exp\left(-E_g / 2k_B T_{change}\right), \tag{9}$$

where the operators E_g, k_B, T_{change}, N_c, and N_v are the silicon bandgap energy, Boltzmann constant, temperature change, effective density of states in the conduction and valence band, respectively. The temperature change is defined as the change of the temperature level upon core material which is given by

$$T_{change} = T_o + \Delta T\left(t\right). \tag{10}$$

The T_o is represented as initial temperature and $\Delta T\left(t\right)$ is the changing factor that depend on the size of waveguide width [12],

$$\Delta T\left(t\right) = T_{\max}\left(1 - e\left[\frac{-t}{\tau_T}\right]\right). \tag{11}$$

The T_{max} and τ_T are the maximum temperature increase and thermal time constant is given by

$$\tau_T = \frac{\rho_{Si} C_{Si} W_c^{\,2}}{\kappa_{Si} \pi^2}. \tag{12}$$

The ρ_{Si}, C_{Si}, κ_{Si}, and W_c are the silicon cavity mass density, specific heat, thermal conductivity, and cavity width of sensing ring. The suitable method to solve NLSE is the split-step Fourier method (SSFM). The method is based on splitting the NLSE into two parts and describe the interplay between group-velocity dispersion (GVD) and self-phase modulation (SPM) when a single Gaussian pulse propagate within waveguide. This method is valid to first order and start by splitting NLSE into two parts; dispersion and nonlinear part. The dispersion and nonlinear part is pretended to act independently when pulse propagate along medium. The step of propagation is shown with the dispersion part acts alone and after that the nonlinear part acts alone. The procedure of pulse propagation is repeated until the end of DRR.

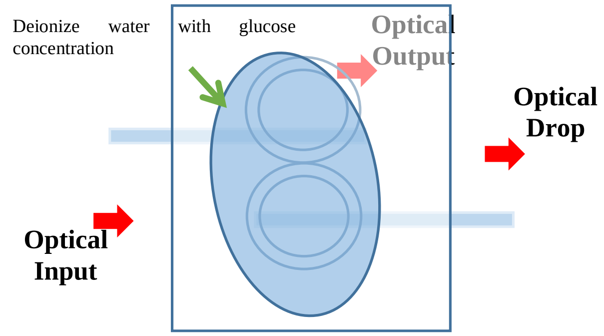


Figure 1 Schematic diagram of vertical double ring resonator glucose sensing

3.0 RESULTS AND DISCUSSION

The DRR glucose sensing consists of vertically coupled microrings is ilustrated in Figure 1. A Gaussian pulse is fed into the input port of DRR. The defect of sensing device on temperature is studied. The optical parameters that used in simulation are presented in Table 1. The pulse propagation within ring circumference is depend on the nonlinear radius and dispersion radius. In this research, the GVD and SPM need to balance these effect for maintaining its power but expose with other losses including linear loss, TPA, and FCA.

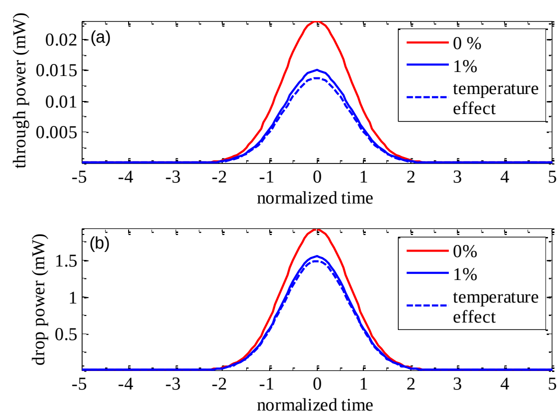


Figure 2 The results of the (a) through and (b) drop power against normalized time with glucose concentration of 0% and 1%. The temperature effect of 32 °C is used

Table 1 Values of the parameters used for simulation of DRR glucose sensing

Parameter name	Symbol	Value
Nonlinear index	n_2	$6 \times 10^{-18}\ \mathrm{m^2/W}$ [14]
TPA coefficient	β_{TPA}	$5 \times 10^{-12}\ \mathrm{m/W}$ [9]
Wavelength	λ	1.55µm
Effective mode area	A_{eff}	$0.13\ \mathrm{\mu m^2}$ [15]
Nonlinear coefficient	γ	$187.0924\ \mathrm{W^{-1}/m}$
FCA cross section	σ_{FCA}	$1.45 \times 10^{-21}\mathrm{m^2}$ [9]
Linear propagation loss	α_{lin}	22 dB/m
Pulse width	t_o	10 ps
first & second ring	$R_{first}\&R_{second}$	10 µm

Parameter name	Symbol	Value
Group velocity dispersion	β_2	$-26.83\ \mathrm{ps^2 mm^{-1}}$
Input peak power	P_o	1 Watt
Core index	n_{core}	3.48 [16]
Cladding index	n_{cladd}	1.32
Coupling coefficient at 1st, 2nd, & 3rd regions	$\kappa_1, \kappa_2, \kappa_3$	0.5
Transmission coefficient at 1st, 2nd, & 3rd regions	t_1, t_2, t_3	0.5
Silicon cavity mass density	ρ_{Si}	$2.33\ \mathrm{g/cm^3}$ [12]
Specific heat	C_{Si}	$0.7\ \mathrm{J/g.K}$ [12]
Thermal conductivity	κ_{Si}	$1.3\ \mathrm{J/cm.s.K}$ [12]
Thermal dissipation time	τ_θ	$1\ \mu\mathrm{s}$ [17]
Deionize water index	$n_{cladding}$	1.3292 [10]

To understand the effect of glucose concentration within deionize water and temperature along a silicon DRR, the effect are shown by power reduction at through and drop port in Figure 2. The power reduction causes by changing in cladding refractive index (deionize water). The change in cladding index produced because the add-up of glucose concentration in deionize water. The add-up of glucose in deionize water is shown by measuring the ratio of glucose index and shows that the increase of ratio describe the increases of glucose concentration in the deionize water. Other effect of power reduction come from losses inside material. The losses is caused by the linear absorption, TPA, and FCA. The linear absorption is mostly causes by the surface roughness and leakage substrate of silicon [13]. The TPA is the absorption process that require two photons energy that larger than silicon band-gap energy to absorb by electron for excitation process from valence band to conduction band. The process is possible for near-infrared wavelength at 1.55 μm because the total photons energy is larger than band-gap energy. The TPA creates electro-hole pair (EHP) in both band and generates additional loss due to photon absorption by electron for excitation process in conduction band. This process called FCA. Another effect of power reduction in DRR is the temperature. The temperature affect the system performance by creating additional loss due to some electrons excitation from valence band to conduction band that giving rise to a concentration of electron in the conduction band. The rise of electron concentration in conduction band create more FCA process that result a distortion to sensing performance.

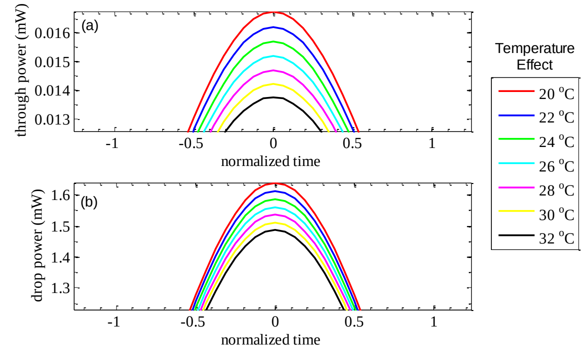


Figure 3 Result of the (a) through and (b) drop power against normalized time with different temperatures. The glucose concentration of 1% is used

The impact of temperature on the system is shown in Figure 3 (a) and (b). The result shows that the power is depleted when increase temperature and generate more power reduction when temperature increase from 20 oC to 32 oC. Higher temperature also create more EHP and generate more FCA. The FCA produce more reduction of the pulse power and degrade the capability for sensing performance. The power reduction causes by glucose and temperature is measured in Figure 4 (a) and (b). When increase the glucose concentration in deionize water from 0% to 1% at temperature level of 26 oC, each output (through and drop port) at DRR produce insertion loss of 1.85 dB at through port and 0.93 dB at drop port. This result is valid only for ideal condition but in reality the result is depend on temperature. The temperature affect the exact loss of glucose concentration in deionize water and if the temperature increase at 1 oC, the losses is increase from 1.85 dB to 2.01 dB at through port. Similar results produce at drop port that losses is increased from 0.93 dB to 1 dB when temperature of 1 oC is increased.

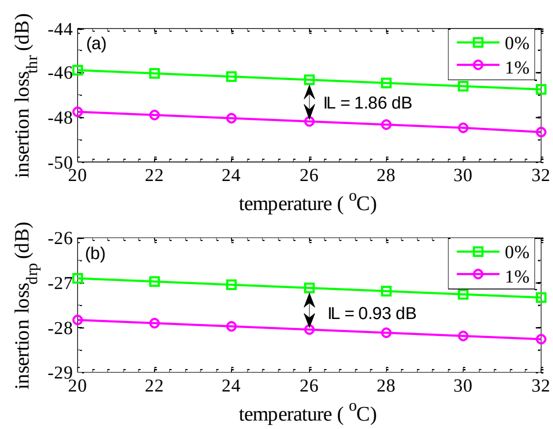


Figure 4 Insertion loss against with different temperature. Insertion loss (IL) for both power are 1.86 dB and 0.93 dB when 1% of glucose insert into the deionize water

4.0 CONCLUSION

In summary, the temperature is enabling to defect the DRR glucose sensor by measuring the power reduction at through and drop port. The increment of glucose concentration in deionize water is based on losses at through and drop port that the losses are 1.85 dB and 0.93 dB at 26 °C. The temperature affect the system performance with increase the losses from 1.85 dB to 2.01 dB at through port and similar results produce at drop port that losses is increased from 0.93 dB to 1 dB. The optimum performance for monitoring of glucose level is achieved at lower temperature.

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