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EFFECT TEMPERATURE IN CHEMICAL SENSING USING TRIPLE STAGE MICRORING RESONATOR

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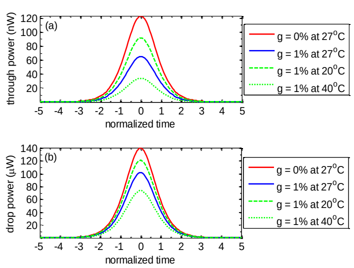
Graphical abstract



Abstract

The split-step Fourier technique is used to study the effect of temperature in triple stage microring resonating sensor (TSMRRS). The optical bright soliton beam is used as the probe pulse into the TSMRRS and the effect of temperature variations on various concentrations of glucose in deionize water is investigated. The detection of glucose is measured by intensity variations of output signals from through and drop ports of TSMRRS. The temperature variations cause an exact intensity reduction of glucose concentration in deionize water when the temperature increased by 1 oC. The performance of TSMRRS glucose sensor is improved for temperature range similar with standard room temperature which shows that TSMRRS is suitable candidate for chemical sensing application.

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

Abstrak

Teknik Fourier pisah-langkah yang digunakan untuk mengkaji kesan suhu pada tiga peringkat cincin mikro bergema penderia (TSMRRS). Optik pancaran soliton yang cerah digunakan sebagai denyutan probe ke dalam TSMRRS dan kesan perubahan suhu pada pelbagai kepekatan glukosa dalam air deionize disiasat. Pengesanan glukosa diukur dengan variasi keamatan isyarat keluaran dari menerusi dan liang penurunan TSMRRS. Variasi suhu menyebabkan pengurangan keamatan sebenar kepekatan glukosa dalam air deionize apabila suhu meningkat sebanyak 1 oC. Prestasi TSMRRS glukosa pengesan adalah lebih baik untuk julat suhu yang sama dengan suhu bilik piawai yang menunjukkan bahawa TSMRRS adalah calon yang sesuai untuk aplikasi penderiaan kimia.

Kata kunci: Penderia optic, optik soliton, penderia suhu; tiga peringkat cincin mikro

1.0 INTRODUCTION

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]. 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]. 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. The prototype for measuring the correct amount of glucose concentration is required 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. Other optical method for monitoring the glucose level such as opto-fluidic ring resonator 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 microring resonator is very sensitive and small, unfortunately, the device sensitivity also disturbed by temperature. The change sensitively with temperature in glucose sensor is required to take account because it defect the device performance [6]. A continuous laser is the most popular source used by researchers 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 of silicon dioxide. The microring resonator is designed vertically because to focus the detection only at ring. The triple stage microring resonating sensor (TSMRRS) 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 input optical pulse used for this research is described as the bright soliton pulse in which popular for biosensor, switching, and slow light[7-10]. The pulse profile is based from [11],

$$E(t) = \sqrt{P_o} sech(t/T_o) \tag{1}$$

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

$$\partial E/\partial z + i\,\beta_2/2\,.\,\partial^2 E/\partial t^2 - \beta_3/6.\,\partial^3 E/\partial t^3 = i\gamma P_o E - \alpha_{TPA}E/2 - \alpha_{FCA}E/2 - \alpha_{lin}E/2 - \alpha_G E/2 \tag{2}$$

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 [11, 12]. The terms α_{lin}, α_{TPA}, α_{FCA}, 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

$$\alpha_{TPA} = \gamma n_{core}\beta_{TPA}P_o/kn_2 \tag{3}$$

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

$$\alpha_G = 4\pi n_{GR}/\lambda \tag{5}$$

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 [13]

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

$$n_{tot} = n_{core} + n_{cladding} \tag{7}$$

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

$$N_{photon} = \beta_{TPA}{P_o}^2\tau_{eff}/2h\nu_o A_{eff} \tag{8}$$

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 $h\nu_o$ is represented as the single photon energy. The free-carrier density of temperature is given by [14]

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

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[15]

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

The is represented as initial temperature and is the changing factor that depend on the size of waveguide width [16],

$$\Delta T(t) = T_{max}(1 - e^{(-t/\tau_T)}) \tag{11}$$

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

$$\tau_T = \rho_{Si} C_{Si} W_c^2 / \kappa_{Si} \pi^2 \qquad (12)$$

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 bright 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 TSMRRS.

3.0 RESULTS AND DISCUSSION

The TSMRRS glucose sensing consists of vertically coupled microrings is ilustrated in Figure 1. A soliton pulse is fed into the input port of TSMRRS. The defect of sensing device on temperature is studied. The optical parameters that used in simulation are presented in Table 1. From 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 [17]. 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 TSMRRS is the temperature. The increasing of temperature effect 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 generate more FCA process that result a distortion to sensing performance. The lower temperature below standard room temperature (in this case the standard room temperature is 27 °C) amplify the pulse power that also create inaccuracy for detecting the glucose concentration. The pulse power is amplified from 64.84 nW into 91.45 nW when decrease temperature from 27 °C to 20 °C at through port. The result is same with drop port which the power is increased from 102 µW to 121.2 µW when decrease the temperature from 27 °C to 20 °C.

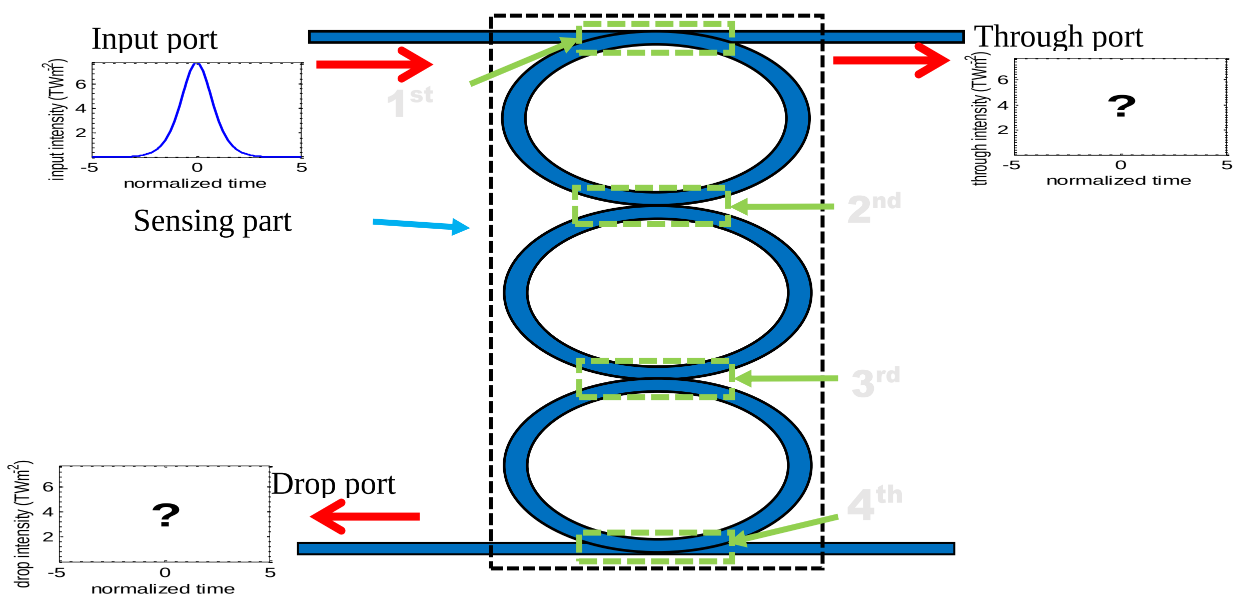


Figure 1 Schematic diagram of vertical triple stage microring resonating sensor. The red arrow describe the pulse propagation along waveguide. The sensing part is showed at black dash box and the 1st , 2nd, 3rd, and 4th are represented as the number of coupling region in vertical triple stage microring resonating sensor

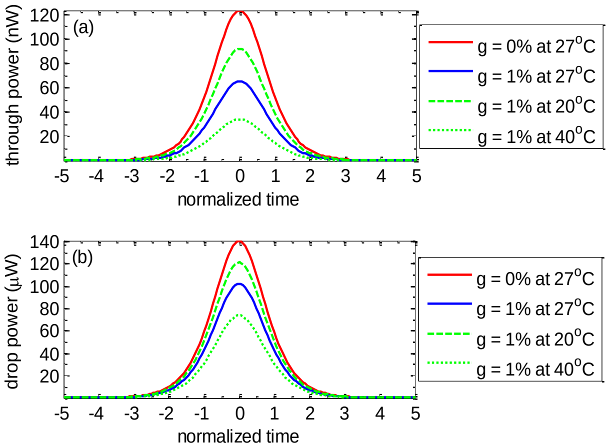


Figure 2 Effect of temperature in glucose sensing. The g is represented as the glucose concentration within deionize water. The fluctuation of temperature distort the accuracy to detect glucose solution within deionize water. The standard room temperature for this case is 27 °C

The impact of temperature on the system is shown in Figure 3(a) and (b). The total transmission is come from an output at through and drop port. The transmission of each port is determined by decibel unit. The result shows that the power is depleted when increase temperature from 27°C to 37°C. 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 at 0% of glucose concentration at through port at increasing of 1°C is 0.216 dB. Similar results produce at drop port with reduce its power of 0.108 dB when temperature increase of 1°C. This results of power reduction are same with 1% of glucose concentration.

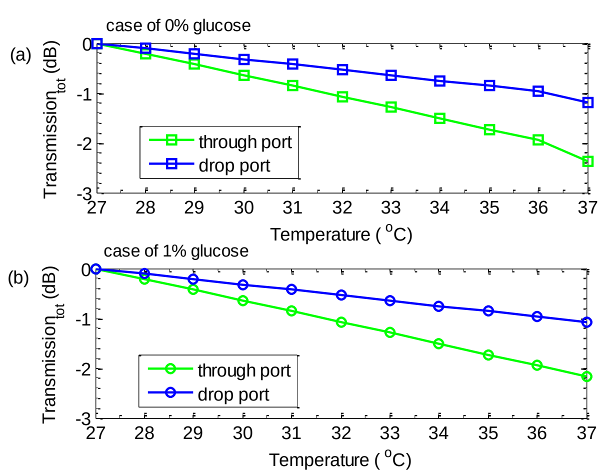


Figure 3 Total transmission against variation of temperature with (a) no glucose concentration and (b) 1% of glucose concentration within deionize water

Table 1 Values of the parameters used for simulation of TSMRRS temperature effect in glucose sensing

Parameter name	Value	Symbols
Nonlinear index	$6 \times 10^{-18}\ \mathrm{m^2/W}$ [18]	n_2
TPA coefficient	$5 \times 10^{-12}\ \mathrm{m/W}$ [11]	β_{TPA}
Wavelength	$1.55\mu\mathrm{m}$	λ
Effective mode area	$0.13\ \mu\mathrm{m}^2$ [19]	A_{eff}
Nonlinear coefficient	$187.0924\ \mathrm{W^{-1}/m}$	γ
FCA cross section	$1.45 \times 10^{-21}\mathrm{m}^2$ [11]	σ_{FCA}
Linear propagation loss	$22\ \mathrm{dB/m}$	α_{lin}
Pulse width	$10\ \mathrm{ps}$	t_o
Waveguide length	$10\ \mathrm{mm}$	L
First, Second, & Third ring	$10\ \mu\mathrm{m}$	R_{first}, R_{second}, $\&R_{third}$
Group velocity dispersion	$-26.83\ \mathrm{ps^2mm^{-1}}$	β_2
Input peak power	1 Watt	P_o
Core index	3.48 [20]	n_{core}
Cladding index	1.32	n_{cladd}
Coupling coefficient at 1st, 2nd, 3rd, & 4th regions	0.5	$\kappa_1, \kappa_2, \kappa_3, \kappa_4$
Up, left, down, & right transmission coefficient	0.5	t_1, t_2, t_3, t_4
Silicon cavity mass density	$2.33\ \mathrm{g/cm^3}$ [16]	ρ_{Si}
Specific heat	$0.7\ \mathrm{J/g.K}$ [16]	C_{Si}
Thermal conductivity	$1.3\ \mathrm{J/cm.s.K}$ [16]	κ_{Si}
Deionize water index	1.3292 [13]	$n_{cladding}$

4.0 CONCLUSION

In summary, the temperature is enabling to defect the TSMRRS glucose sensor by measuring the power reduction at through and drop port. The accurate detection of glucose concentration in deionize water is distorted by the temperature based on power reduction at through and drop port that the losses are 0.216 dB and 0.108 dB when increase the temperature at 1°C. It is found that the effect of temperature defect the accuracy for measuring the changing in glucose concentration. The performance of TSMRRS glucose sensor is improved for temperature range similar with standard room temperature which shows that TSMRRS is suitable candidate for chemical sensing application.

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