UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electronic and Computer Engineering

SILICON PHOTONICS DEVICES BASED ON MICRORING RESONATOR FOR OPTICAL INTERCONNECT SYSTEM

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DECLARATION

I declare that this thesis entitle “Silicon Photonics Devices based on Microring Resonator for Optical Interconnect System” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this report and in my opinion this report is sufficient in terms of scope and quality as a partial fulfillment of Master of Science in Electronic Engineering.

Signature :………………………………………………………..

Supervisor Name : Dr. Hazura binti Haroon

Date :………………………………………………………..

DEDICATION

To my beloved Ibu, Abah, Abg Fikri, Abg Etai, Kak Intan, Anas & Umar, Biela, Aish and Aan.

ABSTRACT

Optical filter that utilizes silicon microring resonator (MRR) has been the promising element for future optical integrated circuits due to its various advantages such as small size, low insertion loss, high Q-factor and so on. This research begins with revision of some related research. The main objective is to model and develop silicon device configuration based on MRR that suitable for Wavelength Division Multiplexer (WDM) systems. The trade-off between those parameters such as ring radius, gap size and width of the core were investigated to study the effect to the MRR performance. The MRR was built by using the wave optic module by COMSOL Multiphysics 5.1. With this simulation, the terms that indicate the performance of MRR which are insertion loss (IL), extinction ratio (ER), free spectral range (FSR) were determined. The optimization work was done by using Taguchi Method where MRR had achieved 5.55% of ER and IL dropped 71.4%. Higher order microrings in the form of series-coupled MRR (SCMRR) and parallel-coupled MRR (PCMRR) were also modeled and investigated to determine the effect of the geometry and number of rings to the performance design. The comparison of single MRR, SCMRR and PCMRR were determined. Via simulation, the single MRR produced FSR of 42.0 nm with IL of 0.5 dB and ER of 25.0 dB. The 5th order of SCMRR produced FSR of 44.5 nm with ER of 11.5 dB and IL of 2.5 dB. Meanwhile, for the 5th order of PCMRR, the FSR was 42.6 nm with ER of 48.0 dB and IL of 0.5 dB. The performance of the developed filter device, PCMRR was tested on a WDM optical network using Optisystem software from Optiwave. It is found that PCMRR was successfully working on the WDM system where 1562 nm was successfully filtered out with 0.5 dB of IL. Besides that, to prove the potential of MRR as a unique element of passive and active devices, (de) multiplexer and sensor based MRR were also studied and presented in this project. The (de) multiplexer based MRR was achieved high FSR, low loss, crosstalk around 20 dB and suitable for working at C-band wavelength. In the meantime, the sensitivity of optical sensor based MRR was analyzed and calculated as $1x10^{-6}$ m/1°C. This result has achieved the sensor performance with low birefringence.

ABSTRAK

Penapis optik yang menggunakan silikon penyalun mikrogegelang (MRR) adalah elemen yang dijanjikan untuk litar bersepadu optik masa depan kerana pelbagai kelebihan seperti saiz kecil, kehilangan sisipan rendah, Q-faktor yang tinggi dan sebagainya. Kajian ini bermula dengan semakan semula beberapa kajian yang berkaitan. Objektif utama adalah untuk mencipta dan membangunkan konfigurasi peranti silikon berdasarkan MRR yang sesuai untuk sistem Pemultipleks Pembahagian Panjang Gelombang (WDM). Hubungkait antara parameter seperti jejari cincin, saiz jurang dan lebar teras telah disiasat untuk mengkaji kesan kepada prestasi MRR. MRR dibina dengan menggunakan modul gelombang optik oleh COMSOL Multiphysics 5.1. Dengan simulasi ini, istilah-istilah yang menunjukkan prestasi MRR seperti kehilangan sisipan (IL), nisbah kepupusan (ER), Julat Spektrum Bebas (FSR) telah ditentukan. Kerja-kerja pengoptimuman telah dilakukan dengan menggunakan Kaedah Taguchi di mana prestasi MRR telah mencapai peningkatan ER sebanyak 5.55% dan IL menurun sebanyak 71.4%. MRR tertib tinggi dalam bentuk MRR sesiri (SCMRR) dan MRR selari (PCMRR) juga telah direkabentuk dan disiasat untuk menentukan kesan geometri dan beberapa mikrogegelang kepada rekabentuk persembahan peranti. Perbandingan tunggal MRR, SCMRR dan PCMRR ditentukan. Melalui simulasi, tunggal MRR menghasilkan FSR sebanyak 42.0 nm dengan IL sebanyak 0.5 dB dan ER sebanyak 25.0 dB. SCMRR menghasilkan FSR sebanyak 44.5 nm dengan ER sebanyak 11.5 dB dan IL sebanyak 2.5 dB. Sementara itu, untuk PCMRR, FSR adalah sebanyak 42.6 nm dengan ER sebanyak 48.0 dB dan IL sebanyak 0.5 dB. Prestasi peranti penapis PCMRR telah diuji pada rangkaian optik WDM dengan menggunakan perisian Optisystem dari Optiwave. Didapati bahawa PCMRR telah berjaya beroperasi pada sistem WDM di mana 1562 nm telah berjaya ditapis dengan IL sebanyak 0.5 dB. Selain itu, untuk membuktikan potensi MRR sebagai elemen yang unik di mana berkebolehan beroperasi sebagai peranti pasif dan aktif, MRR berdasarkan penyahmultipleks dan pengesan juga dikaji dan dibentangkan di dalam projek ini. MRR berdasarkan penyahmultipleks mencapai FSR yang tinggi, kehilangan sisipan yang rendah, cakap silang sekitar 20 dB dan sesuai untuk beroperasi di gelombang jalur-C. Dalam pada itu, sensitiviti optik MRR berdasarkan pengesan dianalisis dan dikira sebanyak $1x10^{-6}$ *m/1°C. Keputusan ini telah mencapai prestasi pengesan dengan dwibiasan yang rendah.*

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λ	-	Wavelength
n_1	-	First-refractive index core
n_2	-	Second- refractive index core
n_3	-	Third- refractive index core
n_{core}	-	Refractive index of core
n_{clad}	-	Refractive index of cladding
κ	-	Amplitude coupling coefficient
a	-	Round-trip amplitude transmission coefficient
ϕ	-	Round-trip phase
r	-	Amplitude transmission coefficient
t	-	Optical field component
Φ	-	Phase shift
m	-	Integer number
R	-	Ring radius
n_{eff}	-	Effective index
λ_o	-	Wavelength of the light propagating in the ring
λ_1	-	The first wavelength of the light propagating in the ring
λ_2	-	The second wavelength of the light propagating in the ring
λ_3	-	The third wavelength of the light propagating in the ring
λ_4	-	The fourth wavelength of the light propagating in the ring
n_g	-	The group index of light

L_{eff}	-	The effective length of microring
τ	-	The field attenuation
κ_1	-	The field coupling coefficient through the couplers at input port
κ_2	-	The field coupling coefficient through the couplers at add-drop port
c	-	The speed of light
Δv	-	The wavelength in frequency term
$\Delta\lambda$	-	The wavelength changes
ΔL	-	The length changes
Δn_{eff}	-	The effective refractive index changes
η	-	The signal-to-noise ratios
y_i	-	The simulation value of ER
ε_z	-	The strain in the z-direction
ε_0	-	The constant
ΔT	-	The temperature change
σ_x	-	The principal stress tensor components along the x
σ_y	-	The principal stress tensor components along the y
σ_z	-	The principal stress tensor components along the z
n_0	-	The refractive index of the material without stress
C_1	-	The first stress-optical constants
C_2	-	The second stress-optical constants
$\boldsymbol{E}$	-	Young's modulus
v	-	Poisson's ratio
p_{11}	-	The stress-optic tensor elements
E	-	The stress-optic tensor elements
r	-	The radius vector

n(r)	-	The index of refraction
β	-	The propagation constant
P	-	The transmission of the input and output coupler
Q	-	The optical delay and the waveguide loss
α	-	The loss per unit length in the microring waveguide
g	-	The distance between the bus waveguide and microring waveguide
N	-	The number of resonators
M_R	-	The transmission for a single MRR
$M_\wedge$	-	The phase propagation from one microring to the next
P	-	The coupler matrix
Q	-	The resonator delay matrix
H	-	The height of SiO_2
h	-	The height of straight and ring waveguides
w	-	The width of the straight
Δ	-	The difference between the maximum and minimum SNR
ρ_f	-	The percentage of most optimal parameters
η_i	-	The SNR value for each experiment
m_{xj}	-	The SNR value of the parameter
W_w	-	The waveguide width
W_R	-	The ring width

LIST OF ABBREVIATION

SoC	-	System-on-chip
ONoC	-	Optical Networks-on-Chip
GNoCPC	-	Generic NoC protocol converter
WDM	-	Wavelength division multiplexer
MRR	-	Microring resonator
FTTH	-	Fiber-to-the-Home
CMOS	-	Complimentary metal-oxide semiconductor
SOI	-	Silicon-on-insulator
SCMRR	-	Series coupled microring resonator
PCMRR	-	Parallel coupled microring resonator
CMT	-	Coupled Mode Theory
FSR	-	Free spectral range
ER	-	Extinction ratio
IL	-	Insertion loss
TMM	-	Transfer matrix mode
ITU	-	International Telecommunication Union
FBG	-	Fiber-bragg grating
AWG	-	Arrayed waveguide grating
VLSI	-	Very large-scale integration
SCISSOR	-	Side-coupled integrated spaced sequence of resonators
CROW	-	Coupled-resonator optical waveguides
HIC	-	High index contrast
WGM	-	Whispering gallery mode

FWHM	-	Full-width-at-half-maximum
F	-	Finesse
MZI	-	Mach-zhender Interferometer
OADM	-	Optical add-drop multiplexer
OOFDM	-	Optical orthogonal frequency division multiplexing
MEMS	-	Micro-electro-mechanical-systems
TE	-	Transverse electric
TM	-	Transverse magnetic
FEM	-	Finite Element Method
OA	-	Orthogonal Arrays
SNR	-	Signal to noise ratio
ANOVA	-	Analysis of variance
GUI	-	Graphic unit interface
CF	-	Control factor
SST	-	Ratio of the sum of square deviation
SSF	-	Sum of square of SNR for each CF
BER	-	Bit error rate
TEC	-	Thermal expansion coefficient
OSA	-	Optical Spectrum Analyzer

LIST OF PUBLICATIONS

The research papers produced and published during the course of this research are as follows:

1. Nadia, A.A., Hazura, H. and Hanim, A.R., 2015. The Potential of Silicon Photonic Devices based on Micro-Ring Resonator. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC), 7*(1), pp.17-20.
2. Nadia, A.A., Hazura, H. and Hanim, A.R., 2016. Compact Optical Filter based on Microring Resonator. *ARPN Journal of Engineering and Applied Sciences, 11*(5), pp.3320-3323.
3. Hazura, H., Hanim, A.R., Nadia, A.A., 2016. Performance Enhancement of Optical Microring Resonator using Taguchi Method Experimental Design. *ARPN Journal of Engineering and Applied Sciences, 11*(5), pp.3212-3216.
4. Haroon, H., Nadia, A.A., Hanim, A.R., Zain, A.M., Othman, S.K. and Salehuddin, F., 2016. Optical Routers based on Microring Resonator for Optical Networks-on-chip. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, *8*(1), pp.41-44.
5. Haroon, H., Aziz, N.N.A., Hanim, A.R., Zain, A.M., Othman, S.K. and Salehuddin, F., 2016. MRR Filter Characterizations in WDM System for Digital Signals Transmissions. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, *8*(1), pp.29-32.

6. Haroon, H., Aziz, N.N.A., Hanim, A.R., Zain, A.M., Othman, S.K. and Salehuddin, F., 2017. Stress-optical Effect Analysis on Silicon-on-Insulator Planar Waveguide. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*. (Under review)
7. Haroon, H., Hanim, A.R., and Aziz, N.N.A., 2017. On the Effectiveness of Taguchi Method in Optimizing the Performance of Parallel Cascaded MRR Array (PCMRRA). *Optoelectronics and Advanced Materials, Rapid Communications, ISI*. (Under review)

CHAPTER 1

INTRODUCTION

1.1 Research Background

Today, the concept of information technology in the modern life experience has become more challenging and demanding where there is an exponential growth in the quantity of the internet network traffic. The appearance of digital electronics, cloud computing and web applications requires huge amount of network traffic, excessive power consumption of voice switching and massive bandwidth demand for data contained in communication network especially data centers (Hamza *et.al,* 2016). Conventional on-chip communication for system-on-chip (SoC) faces several issues such as poor scalability, limited bandwidth and so forth. Therefore, a powerful and efficient data handling is required in order to transmit data in large capacity, faster, more intelligent and less power consuming. The demand for larger capacity of information technology involves technology issues and revolutionary challenges such as miniaturization, interconnection and integration of photonic devices on a nanometer scale. According to a review on optical interconnects for data center networks by Kachris *et.al.* (2012), the authors stated that the optical interconnects have gained attention as a promising solution by offering high throughput, low latency and reduced energy consumption. Estimation for performance, bandwidth requirements and power consumption for the future high performance systems also studied and listed as in Table 1.1. It is noted that even peak performance and bandwidth requirements continue to increase within 4 years, the power consumption is also increasing, but in much slower rate where 2 times in every 4 years but still producing large energy.

Table 1.1 Prediction of performance, bandwidth requirements and power consumption for future systems

Year	Peak Performance (10x/4 years)	Bandwidth requirements (20x/4 years)	Power consumption bound (2x/4 years)
2012	10 PF	1 PB/s	5 MW
2016	100 PF	20 PB/s	10 MW
2020	1000 PF	400 PB/s	20 MW

Optical Networks-on-Chip (ONoC) is seen as a potential emerging key technology in communication industries. ONoC is a promising technology that overcomes several limitations of the bottleneck in traditional electrical interconnects such as inability to support higher data rates, limited bandwidth, poor scalability and higher power consumption. As shown in Figure 1.1, ONoC is mainly consists of three blocks; transmitter, optical router and receiver (Patil *et.al,* 2012). The input signal which is an electrical signal from the generic NoC protocol converter (GNoCPC) converting to optical signal by transmitter port and receiver transform the signal back to an electrical signal.