The Potential of Silicon Photonic Devices based on Micro-Ring Resonator

Nadia A. A., Hazura H., Hanim A. R
Centre for Telecommunications Research Innovations (CETRI)
Faculty of Electronic & Computer Engineering
Universiti Teknikal Malaysia Melaka, Malaysia
nurulnadia0@gmail.com

***Abstract*— Silicon photonic is the theory and application of photonic systems that utilize silicon as an optical medium. The fabrication compatibility with current CMOS processes offer vast development and future improvement of optical devices. By using silicon micro-ring resonator, the requirement of high speed on-chip interconnections can be achieved. This paper gives an overview of the recent research on the potential of silicon photonics based on micro-ring resonator.**

***Index Terms*— Silicon photonic, micro-ring resonator.**

I. Introduction

Recently, silicon photonic has gained significant attention as an essential research field for academicians and engineers. By forming the photonic devices on the silicon medium, light can be guided through the silicon structure [1]. Silicon photonic has been proposed as a technology for optical interconnection when the chip level copper interconnection has reached the limitation [2]. Silicon photonics has become a superior option in the communication network due to many advantages. The compatibility of silicon photonic with CMOS process enables the integration of electronics and photonics devices on the same chip. Silicon-on-insulator (SOI) is formed in thin layers of silicon that are isolated from silicon dioxide. Silicon and silicon dioxide have a great high refractive index difference, offers the strong optical confinement makes it possible to create very densely photonic circuits [3]. SOI also enables increased chip functionality without the high cost of process.

In communication network, on-chip wavelength-division-multiplexed (WDM) systems are one of the main applications. Thus, numerous recent researches has been focused on improving optical filter, optical modulator as well as optical switches in order to meet the requirement of greater bandwidth capacities, higher data-transfer speeds with lower power consumptions in the longer range distance and also smaller dimension that reliable to the WDM systems [4-5]. Micro-ring resonator provides potential solutions to overcome the issues by optimizing the device structure to attain the desired performance. Therefore, this paper focused on the potential of micro-ring resonator as an optical filter, optical modulator and optical switches.

II. Micro-Ring Resonator

In order to fulfill the requirements of photonic network in terms of integration density and power consumption, Qianfan Xu et al. [5] stated that micro-ring resonator is the preferable selection. This is due to the compact size, high quality factor (Q), transparency to off-resonance light and no intrinsic reflection.

Meanwhile, Hazura Haroon et al. [7] highlight the importance of micro-ring resonator as one of the elements for wavelength division multiplexed (WDM) system due to its capabilities of high wavelength selectivity and versatility. Other potentials of micro-ring resonator are also discussed by Xuan Wang et al. [8].

A. Principle of Operation

A study conducted by the authors in [6], [9], [10] and [11], explains a constructions of a micro-ring resonator which consists of a straight waveguide and a ring waveguide. It is typically formed on a silicon-on-insulator (SOI) substrate. Figure 1 shows an example of the layout of a basic micro-ring resonator and coupled micro-ring resonator [11]. The fundamental structure of micro-ring comprises one or two straight waveguides coupled to the circular waveguide, also known as micro-ring, which serves as input port and through port.

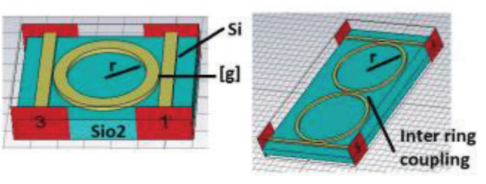

Figure 1: Example of single micro-ring resonator and double coupled micro-ring resonator

Figure 2 shows the schematic diagram and cross-section view of the micro-ring resonator [7]. The coupling condition is dependent to the design parameters such as micro-ring radius (R), refractive index (n), gap size between the ring and straight waveguide (g) and also wavelength of input light (λ). In addition, W and h are the width and height of waveguide, respectively.

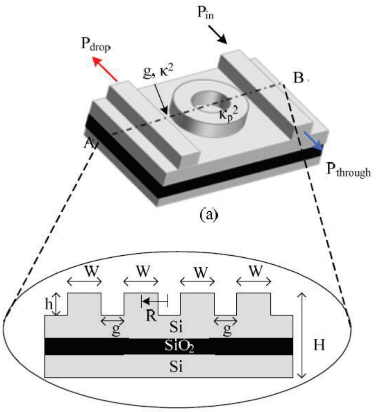

Figure 2: A schematic diagram and cross-section view of micro-ring resonator

A directional coupler theory is often used in micro-ring resonator circuitry to portray the interactions between the straight waveguide and the micro-ring. When two waveguides are cascaded adjacently, a fraction of light will be coupled from one waveguide to another. Therefore, when the light or optical energy is introduced to the input port, resonant wavelengths are possibly transmitted to the through port.

The equation (1) is for the resonant wavelength of the ring. It is given by [12]:

$$\lambda_r = \frac{2\pi R n_{eff}}{m} \tag{1}$$

where R and m is the ring radius and integer, respectively.

Hazura Haroon et al. [13] describe the interaction between light waves in the micro-ring and straight waveguides by coupled mode theory (CMT) using transfer matrix model. Figure depicts the illustrated of the couplers and delay unit from micro-ring resonator.

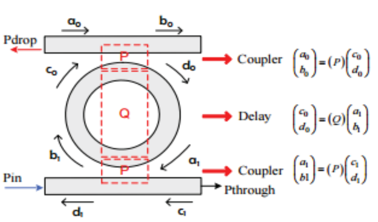

Figure 3: Coupler and delay unit of micro-ring resonator

Referring to the Figure 3, the coupling area between ring and straight waveguide are denoted as P. The following equation (1-9) can calculate by [13]:

$$P = \frac{1}{\kappa}\begin{pmatrix} 1 & t \\ -1 & t^{*} \end{pmatrix} \tag{2}$$

where κ is the normalized coupling coefficient and t is the transmission coefficient. Meanwhile, Q is the optical phase delay and waveguide loss is given by:

$$q = \frac{1}{\kappa}\begin{pmatrix} 0 & e^{i\beta\pi R} \\ e^{i\beta\pi R} & 0 \end{pmatrix} \tag{3}$$

where R and β is the ring radius and propagation constant, respectively. β is given by:

$$\beta = \frac{2\pi}{\lambda_o} n_{eff} - j\frac{\alpha}{2} \tag{4}$$

In equation (5), α is the loss per unit length in the microring, λ_o is the resonant wavelength and n_{eff} is the effective refractive index.

$$\begin{pmatrix} a_o \\ b_o \end{pmatrix} = (PQP)\begin{pmatrix} c_1 \\ d_1 \end{pmatrix} \equiv (M)\begin{pmatrix} c_1 \\ d_1 \end{pmatrix} \equiv \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}\begin{pmatrix} c_1 \\ d_1 \end{pmatrix} \tag{5}$$

By assuming $\kappa = \kappa_{in} = \kappa_{out}$ and only has 1 input, c_1 will be zero, therefore the matrix equation can be simplified as equation (6) and equation (7).

$$|T| = \frac{b_o}{c_o} = \frac{m_{22}}{m_{12}} = \frac{\sqrt{1-\kappa_{in}} - \sqrt{1-\kappa_{out}}\, e^{-i\beta 2\pi R}}{1 - \sqrt{(1-\kappa_{in})(1-\kappa_{out})}\, e^{-i\beta 2\pi R}} \tag{6}$$

$$|D| = \frac{d_1}{a_o} = \frac{1}{m_{12}} = \frac{\sqrt{\kappa_{in}\kappa_{out}}\, e^{-i\beta 2\pi R}}{1 - \sqrt{(1-\kappa_{in})(1-\kappa_{out})}\, e^{-i\beta 2\pi R}} \tag{7}$$

Furthermore, κ can be referring by the equation (8):

$$\kappa = \frac{2\eta^2 \gamma \exp(-\gamma . gap)}{\beta\left(W + \frac{2}{\gamma}\right)(\eta^2 + \gamma^2)} \tag{8}$$

where gap is the distance size between ring and straight waveguide. For η and γ are as following equation (9) and equation (10):

$$\eta = \sqrt{n_{core}^2 k_o^2 - \beta^2} \tag{9}$$

$$\gamma = \sqrt{\beta^2 - n_{core}^2 k_o^2} \tag{10}$$

where $k_o = \frac{2\pi}{\lambda_o}$.

The key performance of micro-ring resonator can be observed by its free spectral range (FSR), quality factor (Q-factor) and the finesse (F). The following equations are specified by [12] for measured these performance.

The calculation for the FSR is agreed by different between two successive peaks or by equation (11):

$$\Delta\lambda = \frac{\lambda_r^2}{2\pi R\, n_g} \tag{11}$$

where n_g is the group index.

To calculate the Q-factor, the 3-dB bandwidth or full width at half maximum (FWHM) must be define first. It can be approximately measured as:

$$\delta\lambda \approx \frac{\kappa^2 \lambda_r^2}{2\pi^2 R n_g} \quad (12)$$

When the micro-ring resonator is on resonance, light intensity in the ring that coupled form the input port can be indicated by Q-factor or finesse. Thus, finesse is given by:

$$F = 2\pi N \quad (13)$$

Where N is the number of round trips light energy in the ring waveguide and the Q-factor is measured by:

$$Q - factor = \frac{\lambda_r}{FWHM} \quad (14)$$

III. Recent Research

Micro-ring resonator is multifunctional elements with many device applications such as optical modulator, optical filter, optical switcher, multiplexer even wavelength selector [13-14].

The whispering galleries phenomenon is an analogy to the concept of micro-ring resonator [18]. In resonance condition which is when the light propagated in the input waveguide and passed through the ring, then it will be coupled to the output waveguide. Only few selected waveguide will be at resonance within the ring, so the micro-ring resonator can functions as a filter. It also can act as switch when two or more ring waveguides can be coupled to each other.

Meanwhile, as shown in Figure 3, Fakhrurrozi et al. [6] illustrate the WDM (Wavelength Division Multiplexing) as a technique of micro-ring resonator. In a single signal, if λ_3 is used, therefore the other wavelength which is $\lambda_1\lambda_2\lambda_4$ will return and act as input to transmit again.

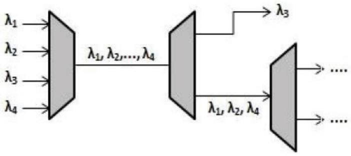

Figure 4: Illustration of micro-ring resonator technique

Several applications are briefly explained below.

A. Micro-ring resonator as a modulator

Optical modulator device is an important component in the communication link. Theoretically, modulation refers to the process to control or manipulate the properties of a material by applying the external electrical field. The existence of the applied voltage changes the refractive index and the speed of light in resulting the maximum possible output.

The first experimental GHz modulator was demonstrated, using majority carriers, which was based on metal-oxide-semiconductor (MOS) capacitor-like structure. Nevertheless, the speed is slow due to carriers recombination as the modulator is switched from ON to OFF state. In order to improvise the speed, pre-emphasis driving signal have been demonstrated by many researchers. When the modulator is forward biased, it injects majority carrier quickly into the region until the required carrier concentration in the waveguide. When the modulator is in the reversed biased, it rapidly sweeps out the carriers [3].

Qianfan Xu et al. [15] deals with the pre-emphasis technique in order to widen the bit rate to 40 Gbps based on electrooptic modulation. The structure consists of a ring resonator embedded in a PIN that fabricated on a SOI substrate. The ring resonator and waveguide were designed with a silicon ridge waveguide of 200nm x 450nm cross section. A slab of 50nm height is used as a platform for carriers injection in the doped region. The P and N doped region were doped with 10^{19} / cm^3 dopant concentrations. The experiment result verified that the bit rate successfully extended to 40 Gbps.

B. Micro-ring resonator as an optical switch

The application of the micro-ring as an optical switch has been demonstrated by Kengo Miura et al. [16]. The work was based on the integration of micro-ring resonator (MRR) and Mach-Zehnder interferometer (MZI) thermo-optic switches as a wavelength selective switch (WSS). WSS is designed for wavelength channel routing for TE mode light waves. MRRs are used as static wavelength filters and routing path will choose by MZI-based thermo-optic. The proposed WSS comprised of a 2x2 ports and four wavelength channels. The cross-sectional dimension of waveguide was 450x220 nm^2 embedded in SiO_2. The curvature radii of MRRs 2.675, 2.700, 2.725 and 2.750 um were selected for channels 1,2,3 and 4, respectively. The channel spacing was 8.75 nm. The gap between the ring waveguide and the busline was 60 nm. The coupling length of 3dB directional couplers used in the MZI switch was specified to be 8 um and MZI arm length was 200 µm. The result showed a change in transmittance was less than 1.7 dB which includes fiber-to-waveguide coupling losses at input and output.

Xuan Wang et al. [8] developed a WSS switch based on a Si micro-ring resonator using thermooptic effect with higher switching speed, less power consumption and more compact size. The authors have demonstrated a compact tunable wavelength switch with ultrawide tunable range (>6.4 nm) which enables multichannel switching. It is a ~40% faster switch with a reduced top cladding thickness of 0.5µm. With the smaller ring diameter, 2 µm radius and ~47 NM FSR, the power consumption improved. The rise-delay times of the device was 10-120 µs, and the fall-delay times of less than 16 µs for a switching range of 0.2-6.4 nm.

In [9], the authors designed the 2x2 optical switch based on silicon-on-insulator (SOI) micro-ring resonator. The device use free carrier dispersion effect in order to tune the refractive index of the micro-ring. The radius was 2 µm. The gap spacing between the bus waveguide and the micro-ring was 100 nm. The rib waveguide height was about 700nm, rib width was 500 nm and slab height was 200 nm. By implanting PN junction at the ring waveguides, the active region of the resonator was formed. The analysis was about the changes of refractive index at a specific drive voltage. It showed the refractive index increases as the applying applied voltage is getting higher. In conclusion the active micro-ring resonator can control the propagation path of the light wave in the switch.

C. Micro-ring resonator as a filter

A study by [7] has proposed a micro-ring resonator based wavelength filter. The design parameter such as size of rings and channels, resonant order, radii of micro-ring and gap size were determined. In addition, free spectral range (FSR), insertion loss and quality factor (Q-factor) was also obtained. The design performance was analyzed and characterized by using FDTD simulation by R-soft. The authors have shown the result and prove that smaller size optical filter provides a good FSR and Q-factor.

Vien Van et al. [17] gives an overview of recent progress in the development of WDM filter based on micro-ring resonator. The authors highlight the new structure of micro-ring filter which is a two-stage micro-ring ladder filter on a SOI platform. The design consists of two parallel cascaded micro-ring doublets connected by a π-phase shift element. The result showed the comparison between measured and theoretical spectral responses of the filter. The design was an advanced integrated optic filter based on parallel cascades of high-order micro-ring networks.

IV. CONCLUSION

In this paper, the potential of the micro-ring resonator as one of the key elements in optical devices development has been reviewed. The study is focused on the diversification functions of the device in which the structure of the device can be altered to suit specific applications. This study is important in order to enhance the performance of optical devices which in turn will improve the overall performance of optical networks.

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