Resonant Frequency Drifting of the Mach-Zehnder Interferometer Coupler Assisted Reflective-Type Microring Resonator

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***Abstract*—We analyze the wavelength drifting of a Mach-Zehnder Interferometer coupler assisted reflective-type microring resonator (RT-MRR) based on the transmission matrix formalism. An experiment is carried out to validate our analysis. The results show that the resonant wavelength of the RT-MRR periodically drifts as a function of the control signal, which helps us to understand the wavelength drifting mechanism and to find solutions to avoid the wavelength drifting effect.**

Keywords*—*resonant wavelength drifting, reflective type microring resonator, silicon photonics

I. Introduction

Microring resonator (MRR) is regarded as a fundamental building block in photonic integrated circuit. Conventional MRR, taking the most widely-used add-drop MRR as an example, consists a resonant cavity, which is realized by a looped waveguide, two tunable couplers and two straight waveguides serve as optical I/Os. Typically, the coupling coefficients of the MRR is tuned by Mach-Zehnder interferometer (MZI) couplers. When a light beam is sent to the MRR from the input port, by adjusting the coupling coefficient of the optical couplers, the light will be coupled into the looped waveguide, circulate in the cavity, and coupled out of the cavity from the through and drop ports. Since different transmission responses can be obtained at the different ports of the MRR, and the transmission response can be adjusted by controlling the coupling coefficients, MRR can be applied into various applications, such as optical filtering, optical sensing, optical logic gate, etc. [1], [2].

However, the conventional MRR intrinsically stimulates a Lorentzian magnitude response with quite narrow bandwidth, which limits the feasibility of the MRR in the wideband applications. To solve this problem, recently, we proposed a novel reflective-type microring resonator (RT-MRR) [3]. By combining the fast and slow light effect, we can obtain a flat-top and wideband intensity (or group delay) response by using only a single resonant cavity, which is very suitable for broadband microwave photonic applications, including flat-top microwave photonic filtering, optical true time delay and beamforming, XNOR/XOR optical logic operation and high-linear electro-optic modulation [4], [5]. To achieve the aforementioned functionalities, the coupling coefficient of the RT-MRR needs to be configured, while the resonant wavelength should keep unchanged. However, since the optical coupler is typically realized by an MZI with a thermal-optic heater in its one arm, the length of the heater attached arm will inevitably change when tuning the voltage applied to the thermal-optic heater. As a result, the length of the resonant cavity will be changed, so the resonant wavelength will be shifted consequently, leading to a degraded performance of the proposed system. Therefore, investigation of the wavelength drifting mechanism is necessary for the applications based on this new kind of RT-MRRs. Although feedback control can compensate for this problem [6], [7], analysis of the mechanism can lead to new solution for effectively mitigating the wavelength drift phenomenon[8].

In this work, we theoretically and experimentally analyzed the resonant wavelength drifting of the MZI coupler assisted RT-MRR. The tuning of the coupling coefficients of the MZI coupler assisted RT-MRR is based on two MZI couplers. Firstly, we analyzed the phase shift effect of the signal-arm phase-shift MZI coupler based on the transmission matrix formalism. Then we applied the model of the MZI coupler to the RT-MRR and obtained an analytical description of the resonant wavelength drifting property of the RT-MRR. Finally, we carried out an experimental measurement of a fabricated RT-MRR. The experiment results agree well with the simulation, which will help us to find solutions to avoid the wavelength drifting effect in future applications.

II. Principle

The schematic of the proposed RT-MRR is shown in Fig. 1. The RT-MRR is similar to an MZI coupler assisted conventional add-drop MRR, but with an extra reflector add to the drop port (port 7 in Fig. 1). With the reflection of the reflector, the light beam injected into the RT-MRR undergoes two procedures successively. Firstly, the light injected from the port 1 (Input) will be coupled into the resonant cavity by the Lower Coupler, circulated along the counter-clockwise direction (colored in blue in Fig. 1), and coupled out of the resonant cavity from port 7. Besides, being reflected by the reflector at port 7, the light will be coupled into the resonant cavity again by the Upper Coupler, circulated along the clockwise direction (colored in red in Fig. 1) and finally coupled from the cavity from port 8. As a result, the response at port 8 will be a superposition of the counter-clockwise and the clockwise responses.

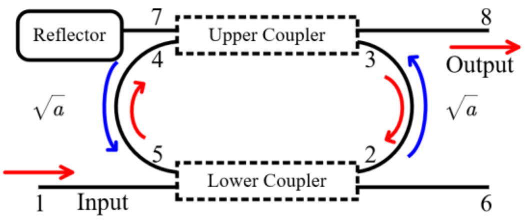

Fig. 1. Model of the MZI coupler assisted RT-MRR

Fig. 2. Schematic of a signal-arm phase-shift MZI coupler

In the mathematical model discussed here, we assume that insert loss is only induced from the bent waveguides 4→5 and 2→3. Based on the transfer matrix formalism, we can yield the transfer function of the proposed RT-MRR as

$$\begin{aligned}|\frac{E_8}{E_1}|^2 &= |\frac{a^{\frac{1}{2}} K_1 K_2 e^{j\frac{\phi}{2}}}{1-a\cdot e^{j\phi}T_1T_2}\cdot\frac{T_2-aT_1e^{j\phi}}{1-ae^{j\phi}T_1T_2}|^2 \\ &= a\cdot|\frac{K_1K_2e^{j\frac{\phi}{2}}\cdot(T_2-aT_1e^{j\phi})}{(1-ae^{j\phi}T_1T_2)^2}|^2\end{aligned} \tag{1}$$

where a and ϕ are the waveguide loss factor and the phase shift of each circulation in the resonant cavity, respectively. T_1 and K_1 refer to the self-coupling and cross-coupling coefficient of the Lower Coupler in Fig. 1, respectively; while T_2 and K_2 refer to the self-coupling and cross-coupling coefficient of the Upper Coupler, respectively.

Based on the resonant condition of the resonant cavity, the RT-MRR will be at the resonant state when

$$\Phi_{\text{Couplers}} + \beta L = 2\pi m, m \in Z \tag{2}$$

where Φ_{Couplers} is the phase shift introduced by the MZI couplers, which will be discussed afterward, L is the length of the bent waveguides and β is the corresponding propagation constant. The resonant wavelength, thereby, is given by

$$\lambda = \frac{2\pi n_{\text{eff}} L}{2\pi m - \Phi_{\text{Couplers}}} \tag{3}$$

To evaluate the phase shift produced by the MZI coupler, a single-arm phase-shift MZI coupler is firstly analyzed.

For a single-arm phase-shift MZI coupler as shown in Fig. 2, when supposing the light traveling in one sense and lossless, the transfer matrix of this MZI coupler can be interpreted through complex number $T(\varphi)$, $K(\varphi)$ and a unitary matrix, which is given by

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} T(\varphi) & K(\varphi) \\ -K^*(\varphi) & T^*(\varphi) \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} \tag{4}$$

where φ is the optical phase shift introduced by the phase shifter as shown in Fig. 2. Therefore, the introduced phase shift when the light is transmitted from port 1 to port 3 is given by

$$\begin{aligned}\Phi_{13}(\varphi) &= \begin{cases} \arctan(\Gamma_1) & \text{if } \Gamma_1 \geqslant 0 \\ \pi + \arctan(\Gamma_1) & \text{if } \Gamma_1 < 0 \end{cases} \\ \text{where } \Gamma_1 &= \frac{-k\sin\varphi}{1-k(1+\cos\varphi)}\end{aligned} \tag{5}$$

where k is the splitting ratio of the directional coupler in the MZI coupler. Similarly, the resulted phase shift when the light goes from port 1 to port 4 can be written as

$$\begin{aligned}\Phi_{14}(\varphi) &= \begin{cases} \arctan(\Gamma_2) & \text{if } \Gamma_2 \geqslant 0 \\ \pi + \arctan(\Gamma_2) & \text{if } \Gamma_2 < 0 \end{cases} \\ \text{where } \Gamma_2 &= \frac{1+\cos\varphi}{\sin\varphi}\end{aligned} \tag{6}$$

Also, the self-coupling coefficient ($|T(\varphi)|^2$) and cross-coupling coefficient ($|K(\varphi)|^2$) of the signal-arm phase-shift MZI coupler can be obtained as

$$\begin{aligned}|T(\varphi)|^2 &= |1-k(1+\cos\varphi)+j\cdot(-k\sin\varphi)|^2 \\ &= 2k(k-1)(\cos\varphi+1)+1\end{aligned} \tag{7}$$

$$|K(\varphi)|^2 = 2k(1-k)(\cos\varphi+1) \tag{8}$$

As can be seen from Eq. (5), the phase shift Φ_{13} is a function of the phase shift φ, so tuning the coupling coefficient by MZI couplers will certainly affect the total phase shift of the resonant cavity, thereby causing the resonant frequency drifting. When applying Eq. (5) to Eq. (3), the resonant wavelength drifting as a function of phase shifts induced by MZI couplers can be given by

$$\lambda(\varphi) = \frac{2\pi n_{\text{eff}} L}{2\pi m - (\Phi_{13}(\varphi_{\text{Upper}}) + \Phi_{13}(\varphi_{\text{Lower}}))} \tag{9}$$

III. EXPERIMENT AND RESULTS

Based on Eq. (9), we simulate the resonant wavelength drifting as a function of the phase shift of MZI couplers, and the simulation result is shown in Fig. 3, The splitting ratio of the directional coupler in the MZI coupler is chosen to be 0.4. In the meanwhile, the effective index n_{eff} is set to be 2 and the length of the bent waveguide is chosen to be 628.3 μm. The loss of the waveguide is not counted; therefore, the waveguide loss factor is set to be 1. The simulation result shows that the wavelength shift is a non-linear function of phase shifts of each MZI coupler. The maximum resonant wavelength offset is achieved when φ_{Upper} and φ_{Lower} are 5.4410, and the minimum resonant wavelength offset is obtained when φ_{Upper} and φ_{Lower} are 0.8410.

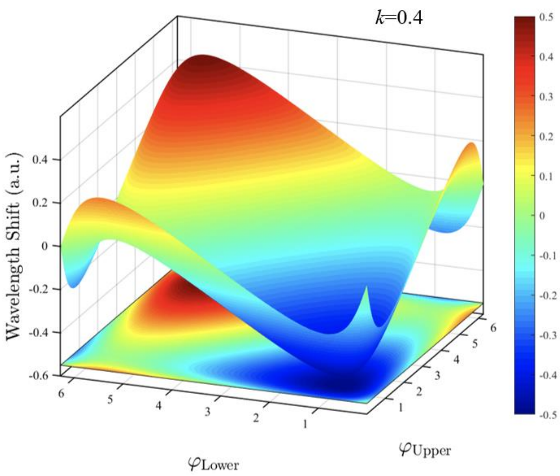

Fig. 3. Relationship between the wavelength drifting and the phase shifts of each MZI coupler,

To verify the analysis, an integrated RT-MRR circuit is fabricated on the TriPleX™ silicon nitride platform. Fig. 4 shows the structure of the fabricated RT-MRR. As shown in Fig. 4, two thermo-optical MZI couplers are employed to adjust the coupling coefficients. For each MZI coupler, a resistive metal-based thermo-optic heater on the top cladding is utilized to tune the effective index, thereby reconfigure the MZI coupler and the coupling coefficients. The length of the ring cavity is 4293.9 μm. The free spectral range (FSR) is 0.3247 nm and the effective index is 1.72.

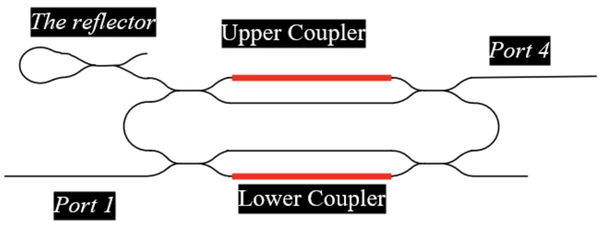

Fig. 4. The structure of the proposed silicon nitride RT-MRR circuit.

To measure the optical intensity response of the RT-MRR, a high-resolution optical spectrum analyzer (APEX AQ6370C, resolution: 0.08 nm) together with an internal swept laser source is used. Besides, a RIGOL programmable DC supply is employed to apply different combinations of the voltages to control the heater of the MZI couplers. Fig. 5 compares the simulation and the measurement results of the resonant wavelength drifting of the RT-MRR when the voltage applied to the upper coupler is fixed at 11 V. The red-dotted curve illustrates the relationship between the voltage applied to the lower MZI coupler and the drifting of the resonant wavelength. Within a certain range from 0 to 13 V, the phase shift increases as the increasing voltage. The simulation result, which is shown as the black solid line, depicts the resonant wavelength drifting when changing the phase shift φ_{Lower}. By increasing the phase shift φ_{Lower}, the resonant wavelength will encounter a redshift until it reaches the maximum value. As can be seen from the analysis above, the experimental resonant wavelength drifting result coincides with the theoretical simulation.

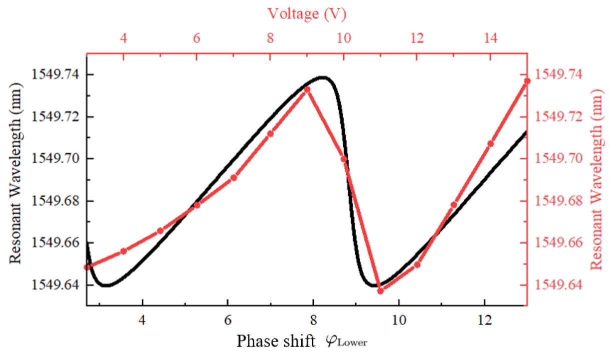

Fig. 5. The resonant wavelength as a function of the phase shift φ_{Lower} (black curve and the bottom axis) and the measured resonant wavelength as the function of the voltage added to the lower heater. The voltage applied to the upper coupler is preserved at 11V. For simulation, $k = 0.4$.

IV. Conclusion

As a compelling building block, the MZI coupler is widely used in tuning the coupler coefficient of the resonant cavity. However, the tunability comes with a price of the instability of resonant wavelength, which may produce an undesirable effect for further applications. In this work, we modeled, evaluated, and measured the resonant wavelength drifting properties of an RT-MRR. Using the transmission matrix formalism, we calculated the effect on the resonant wavelength of the RT-MRR introduced by the MZI couplers. Then, we demonstrated our model using a fabricated RMTRR on the TriPleX™ silicon nitride platform. The analysis of the wavelength drift mechanism will help us to understand the wavelength drifting mechanism and to find solutions to avoid the wavelength drifting effect in future implementations based on the RT-MRR.

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