Resonance Enhancement in Silicon-on-Insulator-Based Two-Ring Mach–Zehnder Interferometer
S. Darmawan, Y. M. Landobasa, P. Dumon, R. Baets, and M. K. Chin

Abstract—We propose and demonstrate a two-ring coupled Mach–Zehnder interferometer (2RMZI) device that exhibits a sharp resonance with background suppression to give both high finesse and modulation depth. The combination of MZI and the two-ring structure leads to more complete destructive interference that effectively removes the unwanted background envelope effect found in the transmission spectrum of a simple two-ring-two-bus (2R2B) system. The projected finesse enhancement of 2R2B relative to one-ring coupled MZI and 2R2B is discussed based on best-fit parameter values that match the fabricated devices.

Index Terms—Guided waves, high-index contrast, integrated optic devices, Mach–Zehnder, microring resonators, photonic wire, silicon-on-insulator (SOI) technology, two-ring configuration.

I. INTRODUCTION

MICRORING resonators are flexible building blocks in photonic integrated circuits for realizing various optical functionalities such as filters, sensors, modulators, and switches. Of particular interest for sensing and switching applications is the microring-based Mach–Zehnder interferometer (MZI) structure where a single-ring is coupled to one arm of the MZI (1RMZI) to give a resonant enhancement of the phase shift in that arm [1]. Recently, the two-ring configuration was proposed by Landobasa in single-bus (2R1B) and double-bus (2R2B) excitation [2], [3]. These structures consist of two mutually coupled rings of possibly different sizes, where only one ring, referred to as the inner ring, is coupled to the bus(es), as shown in the inset of Fig. 1(a). A significant resonance narrowing is predicted and observed [3] when the size of the outer ring is twice that of the inner ring (i.e., \( \gamma = 2 \)), which implies that the outer-ring resonance coincides with the inner-ring antiresonance (refer to the narrow resonance in Fig. 1(b) at \( \delta_1 = \pi \)). In such a case, the two-ring system can effectively localize the light strongly inside the outer ring, giving rise to a sharp resonance with finesse limited only by the intrinsic and coupling losses.

In the two-bus case, the finesse is lower compared to the one-bus because the coupling loss is twice as large, but it has the advantage of having two complementary outputs—through (T) and drop (D)—and hence is useful as an add–drop filter. The drop spectrum of the 2R2B structure over one full spectral range is shown in Fig. 1(b), where \( \delta_1 \) is the inner ring round-trip phase. Note that the sharp narrow resonance at \( \delta_1 = \pi \) (antiresonance in inner ring) corresponds to the strong resonance in the outer ring, while the broad split resonance at \( \delta_1 = 2\pi \) occurs when both rings are resonant. The narrow resonance arises because of the 2\( \pi \) resonant phase response from the outer ring which leads to rapid successive destructive and constructive interference. However, the destructive interference is not complete, resulting in an off-resonant dip that does not go to zero. This background envelope limits the application of such narrow resonances, e.g., for switching, modulation, or sensing. For such applications, the important figures of merit are the finesse and the modulation depth (MD) or the contrast ratio (CR). The latter MD (CR) is given by the difference (ratio) between the on-resonance and off-resonance transmission values, and is reduced by the background envelope.

To alleviate this problem, we propose to excite the 2R1B with an MZI, as shown in Fig. 1(a). By doing so, we obtain...
three advantages: 1) The double-bus excitation is converted into single-bus excitation, giving improved light localization inside the two-ring system. 2) The output is similar to 2R2B as the MZI has both complementary cross and bar outputs. In a balanced MZI, the bar (cross) port is similar to the drop (add) port of the 2R2B. 3) The additional pathway through the MZI, shown as P3 in Fig. 1, together with the two possible pathways P1 and P2 through the 2R1B structure, allows a more complete destructive interference off the antiresonance of Ring 1 thereby giving improved CR, MD, and finesse for the narrow resonance. This is borne out by the simulated spectrum for a balanced, lossless two-ring coupled MZI (2RMZI) as shown in Fig. 1(b), where the background envelope has been significantly suppressed.

In general, however, the MZI itself may not be balanced due to fabrication variations and the presence of rings near one arm. This intrinsic asymmetry may be represented by a phase bias ($\Delta \varphi_B$) in the other arm. The 2RMZI outputs are then given by

$$T_{\text{BAR}} = \frac{|t_1 - \exp(i \Delta \varphi_B)|^2}{2}$$

$$T_{\text{CROSS}} = \frac{|i[t_1 + \exp(i \Delta \varphi_B)]|^2}{2}$$

(1)

where $t_1$ is the complex transmission amplitude of the two-ring structure given in [2] [the phase of $t_1$ is shown in Fig. 1(b)], which depend primarily on the round-trip loss in the rings, the reflectivity between the bus and Ring 1 ($r_1$) and that between Rings 1 and 2 ($r_2$). In the presence of $\Delta \varphi_B$, the output spectra are asymmetric and the narrow resonances look like Fano resonances [4].

II. RESULTS AND DISCUSSION

The 2RMZIs were fabricated in the Electronics and Information Technology Laboratory of the French Atomic Energy Commission (CEA LETI) using a complementary metal–oxide–semiconductor (CMOS)-based 196-nm deep-ultraviolet (UV) process. Fig. 2 shows the 2RMZI and 2R1B devices fabricated in a silicon-on-insulator (SOI) wafer. The SOI consists of 196-nm-thick silicon on a 2-μm-thick buffer oxide layer. The single-mode waveguide has a width of ~450 nm and a measured loss of ~3 dB/cm consistent with [5]. The 3-dB couplers in the MZI are based on multimode interferometers with a width of 3.5 μm and a length of 45 μm. The MZI arms are 200 μm long and are fabricated without any tuning mechanisms. The microring radius is 5 μm for $R_1$ and 10 μm for $R_2$. The coupling between the bus and Ring 1 ($r_1$) and between the rings ($r_2$) are achieved with “race-track” directional couplers with lengths $L_{C1}$ and $L_{C2}$, respectively. The outer ring has two additional straight sections of length of $L_{C3}$. The gap width is ~200 nm. To facilitate fiber input and output coupling each device is fabricated with vertical grating couplers [6]. The fibers are butt-coupled to the grating couplers at 10° from vertical. The device transmission is measured with a broadband amplified spontaneous emission light source (1.41 to 1.62 μm) and an optical spectrum analyzer. A set of three devices with different $L_{C1}$ values were tested, as listed in Table I.

Table I

<table>
<thead>
<tr>
<th>DUT</th>
<th>$\gamma$ (fit)</th>
<th>$L_{C1}$ (μm)</th>
<th>$r_1$(fit)</th>
<th>$L_{C2}$ (μm)</th>
<th>$r_2$(fit)</th>
<th>$a_1$(fit)</th>
<th>$a_2$(fit)</th>
<th>$\Delta \varphi$ (fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>2.000</td>
<td>4</td>
<td>0.86</td>
<td>3</td>
<td>0.90</td>
<td>4.2984</td>
<td>0.995</td>
<td>0.58 μm</td>
</tr>
<tr>
<td>02</td>
<td>2.001</td>
<td>6</td>
<td>0.77</td>
<td>3</td>
<td>0.90</td>
<td>4.272</td>
<td>0.995</td>
<td>0.65 μm</td>
</tr>
<tr>
<td>03</td>
<td>2.000</td>
<td>8</td>
<td>0.65</td>
<td>3</td>
<td>0.90</td>
<td>4.253</td>
<td>0.995</td>
<td>0.61 μm</td>
</tr>
</tbody>
</table>

Fig. 3. Measured spectra of 2RMZI bar (in blue) and cross output (in green) for DUT 01 to 03. The faint bold curves are the experimental results, and the solid curves are the theoretical fit. The red curves represent the theoretical case if the bare-MZI is balanced ($\Delta \varphi_B = 0$). The loss factor is measured as $a_1 \sim 0.995$.

Fig. 2. Fabricated 2RMZI (left) and 2R1B (right) based on SOI. $L_{C1}$ and $L_{C2}$ are lengths of the DC sections of Rings 1 and 2.

Fig. 3. Measured spectra of 2RMZI bar (in blue) and cross output (in green) for DUT 01 to 03. The faint bold curves are the experimental results, and the solid curves are the theoretical fit. The red curves represent the theoretical case if the bare-MZI is balanced ($\Delta \varphi_B = 0$). The loss factor is measured as $a_1 \sim 0.995$.
the corresponding finesse values are ~355, 270, and 199, which give the finesse enhancement factor of ~12.4, 9.5, and 7 times relative to the 1RMZI, and of ~1.5, 1.9, and 2.6 times relative to the 2R2B. Note the opposite trends for 1RMZI and 2R2B in their dependence on $r_1$, as is evident in Fig. 5(b). Compared with 1RMZI, 2RMZI always gives superior finesse. Relative to 2R2B, 2RMZI is superior when $r_1$ is relatively small. In the high-$r_1$ regime, the finesse of 2R2B is as good as 2RMZI because the light is so well localized inside the two-ring system, and it becomes insensitive to whether the lower ring is coupled to one or two buses. In terms of MD, 2RMZI gives better results than 2R2B for the lower $r_1$ values, where the envelope effect dominates and degrades the MD for 2R2B. In the extreme case, the resonance becomes unresolved. On the other hand, for higher $r_1$ values, the 2RMZI is more sensitive to loss due to higher finesse and the MD can be slightly lower than the 2R2B case. This is a natural occurrence in any high-finesse system. As a guideline, $r_1$ should be less than ~0.73 for the 2RMZI to have higher MD than the 2R2B (MD ≥ 0.37), in the case where $r_2 ∼ 0.9$ and $a ∼ 0.995$.

III. CONCLUSION

We have proposed and demonstrated the 2RMZI device to remove the unwanted envelope effect in the transmission of the 2R2B system [7]. The device is realized on SOI using 193-nm CMOS-based deep-UV lithography. By taking account of the MZI phase imbalance, good agreement is obtained between theory and experimental spectra. Overall, the 2RMZI offers higher finesse and MD compared with the 1RMZI and 2R2B counterparts. In this work, a projected finesse up to 355 with MD ∼ 0.19 is realistically achievable by the fabricated 2RMZI devices but only if the fabrication-induced imbalance in the MZI is canceled out either by incorporating width variations in one of the MZI arms or some sort of tuning mechanism (e.g., thermal tuning).

REFERENCES


