An Ultrafast with High Contrast Ratio 1×2 All-optical Switch based on Tri-arm Mach-Zehnder employing All-optical Flip-flop

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Abstract—This paper introduces a novel 1×2 all-optical switch based on Tri-arm Mach-Zehnder (TaMZ) that uses an all-optical flip-flop (AOFF). The proposed switch is analytically modeled and simulation shows a marked improvement in signal on/off contrast ratio (CR) between two outputs over a larger range of control signal power compared to the existing symmetric Mach-Zehnder (SMZ) switches. In addition, TaMZ switch offers both broadcasting and complete switch-off capability, which further enhances the flexibility of the optical switching applications. The paper presents the principle of TaMZ-based switch and investigates the CR performance. It is shown that the CR improvement is more than 10 dB compared to conventional SMZ switch in a control signal power range of 20 dB.

Index Terms—Tri-arm Mach-Zehnder, all-optical flip-flop, control signal, contrast ratio.

I. INTRODUCTION

The rapid increase in the volume of the internet traffic is the major driving force for the deployment of low cost ultrahigh capacity optically-transparent communication networks, which remove the bottleneck imposed by the high-cost and speed-bottleneck of the optical-to-electronic-to-optical conversions at every network nodes [1, 2]. Nowadays, photonic network is designed to achieve not only increased capacity and low operation cost, but also provide greater functionality. Technologies for enhancing functionality of photonic networks include all-optical switching, wavelength conversion and optical signal regeneration. In recent years, we have seen intense research activities in development of all-optical switches as the building blocks for all the above optical functions, such as the terahertz optical asymmetric demultiplexers (TOADs) [3], Mach-Zehnder interferometers (MZ) [4] and the ultrafast non-linear interferometers (UNIs) [5], which are widely studied and practically employed. TOAD is composed of a short interferometer optical fiber loop with a semiconductor optical amplifier (SOA) positioned in a fixed location offset from the loop center. However, its switching performance in ultrahigh-speed applications (>100 Gbps) is limited because of its fixed and asymmetric switching window (SW) profile owing to the fixed SOA location and the counterpropagation effect between the data and control signals within SOA [6]. MZ-based switch overcomes these limitations by using the two identical arms consisting of an identical pair of SOAs each inducing the nonlinearity effect on the propagating data signals when a control signal is injected into both MZ arms. Since both the data and control signals propagate in the same direction within SOAs, the response of MZ switch is as fast as the pulse width and the SW width achieved could be within a few picoseconds range [7]. In addition, MZ switch offers a superior integration capability while consuming low control power energy (< 1 pJ) [8] compared to the TOAD. In UNI switch, the SW is achieved by the phase difference between the two orthogonal polarization components of the data signal provided by the fast nonlinearity of the SOA through its interaction with the second control pulse whenever this presents [9]. However, due to the fiber birefringence and polarization control, UNI offers a poorer integration capability compared to the MZ switch.

Among the proposed MZ-based switches, the symmetric MZ switch is the most promising due to its narrow and rectangular-shaped symmetrical SW profile providing improved timing-jitter-tolerance [7], low power and superior integration capability [8]. A number of 1×2 SMZ switches have been proposed and developed for a number of key applications in all-optical high-speed networks such as OTDM demultiplexer [10], logic gates [11, 12], optical flip-flop [13], wavelength conversion [14], switching [15] and header processing [16, 17]. In the first four applications, achieving a high on/off contrast ratio (CR) between two outputs is not that critical, since only one of the SMZ outputs is used in switching mode, whereas, in the latter applications, where both outputs are used, CR greater than 20 dB is required for proper operation. However, the typical inter-outputs CR for the SMZ switch is relatively low (~10 dB) and sensitive to the controlling scheme and SOA parameter (due to small linewidth enhancement), which consequently results in performance degradation. Therefore, to improve and enhance the performance and applications of SMZ-based switches one needs to augment the CR.

In this paper we presents a novel 1×2 Tri-arm MZ switch that achieves higher CR between two output ports compared to the conventional SMZ by introducing an auxiliary arm coupled to the two existing arms of SMZ switch. In addition, we propose a controlling scheme based on the AOFF, which improves the flatness of switching window gain and the dynamic range of the control signals. The paper is organized as...
follows: after the introduction, Section II characterizes the proposed TaMZ switch and the controlling scheme employing AOFF. Section III presents the inter-output CR. The simulation results and discussions are presented in Section IV. Finally, Section V concludes the findings in the paper.

II. TRI-ARM MACH-ZEHNDER SWITCH

A. Symmetric Mach-Zehnder Switch and Contrast Ratio

A typical SMZ switch comprising of an interferometer with two identical arms, SOAs and a number of 2×2 couplers is depicted in Fig. 1(a). The input data signal is fed into the SMZ input via a 2×2 coupler C₁, which introduces a π/2 phase shift. In the absence of the control signals (CS₁ and CS₂), the SMZ is in the balance state and the data components experience the same gain and phase induced by the SOAs, recombining at the output 2×2 C₀ coupler and emerging from the output port 2 (OP₂) whereas no signal emerges from the output port 1 (OP₁).

However, when in the switching mode both the gain and phase properties of SOA₁ and SOA₂ are changed by the injection of CS₁ and CS₂ (single pulses), delayed by a SW time of T_sw, in the opposite direction to the input signal, respectively, see Fig. 1(b). Thus resulting in an imbalance state in SMZ during T_sw, and consequently the data signal emerging from OP₁ when no signal at the OP₂. The switching window gain SW₁(t) and SW₂(t) of OP₁ and OP₂, respectively, are computed by [18]

\[ SW_1(t) = \frac{1}{2} \left[ G_1(t) + G_2(t) - 2 \sqrt{G_1(t)G_2(t)} \cos(\Delta \phi_{1,2}(t)) \right] \]  

\[ SW_2(t) = \frac{1}{2} \left[ G_1(t) + G_2(t) + 2 \sqrt{G_1(t)G_2(t)} \cos(\Delta \phi_{1,2}(t)) \right] \]  

\[ \Delta \phi_{1,2}(t) = -\frac{1}{2} \alpha_{LEF} \ln \left( \frac{G_1(t)}{G_2(t)} \right) \]  

where \( \alpha_{LEF} \) is the linewidth enhancement factor, \( G_1(t) \) and \( G_2(t) \) are the temporal gain profiles of SOA₁ and SOA₂ and \( \Delta \phi_{1,2}(t) = \phi_1 - \phi_2 \) is the phase difference between \( G_1(t) \) and \( G_2(t) \). For ensuring a constant gain level for SOA₁ during a large T_sw, CS₁ is kept at constant level to thwart the SOA gain recovery [19]. Note that in (1) and (2), the gains \( SW₁ \) and \( SW₂ \) are inversely proportional and in the normal mode (i.e. without CSs) input signal is switched to OP₂.

To evaluate the switching performance during switching period, the following two CRs need investigating: (i) the interoutput \( CR_{OP_{i,j}} \) defined as the power ratio between the switched signal at OP, and non-switched signal at OP_j (\( i, j = 1 \) or 2) when TaMZ is designed to switch data to OP, and (ii) the inter-channel \( CR_{CH} \) defined as the power ratio between the switched and non-switched signals at the \( i^{th} \) output, which are given by:

\[ CR_{OP_{i,j}} = \frac{SW_{\text{ON},i}(t_0 < t < t_0 + T_{sw})}{SW_{\text{OFF},j}(t_0 < t < t_0 + T_{sw})} \]  

\[ CR_{CH} = \frac{SW_{\text{ON},i}(t_0 < t < t_0 + T_{sw})}{SW_{\text{OFF},i}(t \in [t_0 + T_{sw}])} \]  

where \( t_0 \) denotes the start of the switching duration T_sw. In (4), \( CR_{OP_{1,2}} \rightarrow 0 \) when \( \Delta \phi_{1,2}(t) = 0 \), i.e. \( G_1 = G_2 \) whereas \( CR_{OP_{1,2}} \rightarrow \infty \) when \( \Delta \phi_{1,2}(t) = \pi \). However, to achieve a phase difference of \( \pi \) as in (3), the gain difference between \( G_1 \) and \( G_2 \) and \( \alpha_{LEF} \) needs to be high [7], which requires a high-powered control signal and a specific SOA. Figure 2 depicts the graph of CRs against the CS power obtained by simulation with SOA parameters given in Table 1. \( CR_{OP_{1,2}} \) and \( CR_{CH} \) reach the maximum of 12 and 13.5 dB, respectively, which are observed at the optimum CS (single pulse) peak power of 28 dBm and decreasing with the increase/decrease of CS power over a wide range due to the inversely proportional property of (1) and (2). \( CR_{CH} \) is higher \( CR_{CH} \) with a maximum value of 25 dB at optimum CS power of 28 dBm due to insufficient \( \alpha_{LEF} \) for \( \Delta \phi_{1,2} \rightarrow \pi \). In addition, high \( CR_{CH} \) is achieved in a wider range than in \( CR_{CH} \) due to the fact that the denominator in (5) \( \rightarrow 0 \) (depending on the equality of \( G_1 \) and \( G_2 \)) is easier achieved in \( CR_{CH} \) as compared to only the case of \( \Delta \phi_{1,2} \rightarrow \pi \) for maximum \( CR_{CH} \). Note that the decrease in CRs beyond the optimum CS is due to the low gain difference between \( G_1 \) and

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial gain</td>
<td>24 dB</td>
</tr>
<tr>
<td>Laser chip length – ( L_{SOA} )</td>
<td>0.5 x 10^{-3} m</td>
</tr>
<tr>
<td>Active region width</td>
<td>2.5 x 10^{-6} m</td>
</tr>
<tr>
<td>Active region thickness</td>
<td>0.04 x 10^{-6} m</td>
</tr>
<tr>
<td>Spontaneous emission factor – ( n_{sp} )</td>
<td>2 (NF = 6 dB)</td>
</tr>
<tr>
<td>SCH confinement factor – ( \Gamma )</td>
<td>0.56</td>
</tr>
<tr>
<td>MQW linewidth enhancement factor – ( \alpha_{LEF} )</td>
<td>3.0</td>
</tr>
<tr>
<td>Initial carrier density</td>
<td>1 x 10^{-4} m^{3}</td>
</tr>
<tr>
<td>Transparency carrier density – ( N_{t} )</td>
<td>1.5 x 10^{-4} m^{3}</td>
</tr>
<tr>
<td>Group effective index</td>
<td>3.7</td>
</tr>
<tr>
<td>DC bias current – ( I_{b} )</td>
<td>0.15 A</td>
</tr>
</tbody>
</table>

![Figure 1: (a) SMZ switch interferometer configuration and (b) temporal controlling scheme](image1)

![Figure 2: Plots of CR vs. CS powers with T_sw = 0.1 ns](image2)
G₂ and the over saturated SOA gain, thus resulting in reduced input signal amplification. Therefore, employing SMZ with a control pulse as the CS requires a high peak pulse power and a small Tₑ₂ due to relaxation time of SOA gain recovery [7].

Since the SMZ OP₁ offers much better CR compared to the OP₂, it is advantageous to couple two SMZs to form a new 1×2 TaMZ switch with high CRs at both OP₁ and OP₂. In addition, the use of AOFF to generate a constant CS will overcome SOA relaxation time, thus providing the capability of switching a long packet (i.e. a large Tₑ₂). In the following section, TaMZ-based switch with AOFF is derived and analyzed.

B. Tri-arm Mach-Zehnder Switch

The proposed TaMZ-based 1×2-switch block diagram is depicted in Fig. 3(a), with an AOFF, an optical bias signal, an optical broadcast signal and two CSs. The switch operation is illustrated in Fig. 3(b) for both switching and broadcasting. In the normal operation mode with no CSs, a small constant optical bias signal establishes an imbalance state between the upper and the center arms (the upper interferometer) of TaMZ, see Fig. 3(c). Thus, the input signal emerges from the OP₁, but no signal at OP₂ because the lower interferometer (center and lower arms) is balanced. In the switching mode, CS₀ (a single pulse) is applied to the AOFF to generate a constant CS₁ (duration of Tₛ), which is injected to the upper and center arms to swap the current states of the upper and lower interferometers into balance and imbalance state, respectively. Therefore, OP₁ is turned off and the input signal emerges from OP₂. By applying CS₂ (a single pulse) to TaMZ, the SOA₂ gain is saturated such that gain and phase profiles matching that of SOA₃. Therefore the balance state is restored in the lower interferometer and consequently turning off OP₂. At the same time, CS₁ exits both SOA₁ and SOA₂, thus once again turning OP₁ on due to imbalance state in the upper interferometer by the presence of optical bias signal. The optical broadcast signal is in use for broadcasting input signal to both OP₁ and OP₂. In Figs. 3(b) and (c), when both CSs are off while broadcast signal is non-zero, input packet is switched to both OPs because of the imbalance state being set in both upper and lower interferometers. To completely block the input signal emerging at both switch outputs, none of CSs, bias and broadcast signals is applied, thus offering more flexibility in TaMZ switching modes compared to the standard SMZ switch.

In TaMZ configuration, a number of 3-dB attenuators are used to ensure equal power levels at the 2×2 C₀₁ and C₀₂ couplers. Note that the factor β (< 1) at the control input for the upper arm is to ensure power equality for both (bias + βCS₁) and CS₁ signals, thus achieving an ideal balance state in the upper interferometer when CS₁ is applied. Assuming the coupler, combiner and splitter are designed with the transfer functions given in Table II and the input signal has an electrical field Eᵢν [20]. The fields in the upper, center and lower arms after propagating through SOAs are given by

\[
E_U = \frac{1}{\sqrt{2}} g_1 e^{-j\phi_1} (1-\alpha_1) E_{iν}
\]

\[
E_c = j \frac{1}{\sqrt{8}} g_2 e^{-j\phi_2} \left( \alpha_1^{\frac{1}{2}} + \alpha_2^{\frac{1}{2}} \right) E_{iν}
\]

\[
E_L = \frac{1}{\sqrt{2}} g_3 e^{-j\phi_3} \left( 1-\alpha_2 \right) E_{iν}
\]

where g₁ and phase φ₁ are the field gain and phase, respectively, of a SOA₁ complex gain induced on the electrical field of signal propagating through it. α is the coupling factor of 2×2 coupler. From (6) and Fig. 3(c), the output fields at OP₁ and OP₂ are computed as

\[
E_{o_1} = \frac{E_{iν}}{\sqrt{8}} \left[ K_{11} g_1 e^{-j\phi_1} - K_{12} g_2 e^{-j\phi_2} \right]
\]

\[
E_{o_2} = \frac{E_{iν}}{\sqrt{8}} \left[ K_{21} g_3 e^{-j\phi_3} - K_{22} g_2 e^{-j\phi_2} \right]
\]

TABLE II
TRANSFER FUNCTIONS OF 2×2 COUPLER, 2×1 COMBINER AND 1×2 SPLITTER

<table>
<thead>
<tr>
<th>Schematic</th>
<th>( E_{i_1} )</th>
<th>( E_{i_2} )</th>
<th>( E_{o_1} )</th>
<th>( E_{o_2} )</th>
<th>( E_{i_1} )</th>
<th>( E_{i_2} )</th>
<th>( E_{o} )</th>
<th>( E_{o_1} )</th>
<th>( E_{o_2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2×2 coupler</td>
<td>( E_{i_1} )</td>
<td>( E_{i_2} )</td>
<td>( E_{o_1} )</td>
<td>( E_{o_2} )</td>
<td>( E_{i_1} )</td>
<td>( E_{i_2} )</td>
<td>( E_{o} )</td>
<td>( E_{o_1} )</td>
<td>( E_{o_2} )</td>
</tr>
<tr>
<td>Transfer function</td>
<td>( \begin{bmatrix} E_{o_1} \ E_{o_2} \end{bmatrix} = \begin{bmatrix} (1-\alpha) &amp; j \alpha \ j \alpha &amp; (1-\alpha) \end{bmatrix} \begin{bmatrix} E_{i_1} \ E_{i_2} \end{bmatrix} )</td>
<td>( E_{o} = \frac{1}{\sqrt{2}} \left( E_{i_1} + E_{i_2} \right) )</td>
<td>( E_{o_1} = E_{o_2} = \frac{E_{i}}{\sqrt{2}} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>
TABLE III: AOFF TRUE TABLE

<table>
<thead>
<tr>
<th>SET</th>
<th>RESET</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>OFF</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>ON</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>OFF</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Don't care</td>
</tr>
</tbody>
</table>

Figure 4: Generation of CS₁ by a “set”/“reset” AOFF with multiple forward control and feedback-loop

TABLE IV: SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input data bit rate</td>
<td>100 Gbit/s</td>
</tr>
<tr>
<td>Input date pulse power</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Optical wavelength</td>
<td>1554 nm</td>
</tr>
<tr>
<td>Optical pulse width – FWHM</td>
<td>2 ps</td>
</tr>
<tr>
<td>Packet length</td>
<td>2 ns (200 bits)</td>
</tr>
<tr>
<td>Packet guard band</td>
<td>1.5 ns</td>
</tr>
<tr>
<td>Switching window width – Tₛₚ</td>
<td>5.5 ns</td>
</tr>
<tr>
<td>Average optical continuous wave bias signal</td>
<td>– 3 dBm</td>
</tr>
<tr>
<td>Average broadcast signal</td>
<td>– 6 dBm</td>
</tr>
<tr>
<td>Cs₁ pulse power</td>
<td>33 dBm</td>
</tr>
<tr>
<td>Cs₁ power</td>
<td>11.7 dBm</td>
</tr>
<tr>
<td>Cs₁ factor – β</td>
<td>0.98</td>
</tr>
<tr>
<td>Cs₂ pulse-power</td>
<td>25 dBm</td>
</tr>
<tr>
<td>G₁₁-G₁₂ = G₂₁-G₂₂</td>
<td>24 dB</td>
</tr>
<tr>
<td>G₁₁-G₁₂ = G₂₁-G₂₂</td>
<td>19 dB</td>
</tr>
<tr>
<td>G₁₁,CS₁ = G₂₁,CS₁</td>
<td>6 dB</td>
</tr>
<tr>
<td>AOFF splitting factor – γ</td>
<td>0.125</td>
</tr>
<tr>
<td>AOFF Pₛₚ</td>
<td>0 dBm</td>
</tr>
<tr>
<td>AOFF feedback loop delay – Tᴮᴸ</td>
<td>0.2 ns</td>
</tr>
</tbody>
</table>

where the coefficients $K_i$ are computed by

$$K_{i1} = (1 - \alpha_{i1})^{\frac{1}{2}}(1 - \alpha_{o1})^{\frac{1}{2}}; \quad K_{i2} = \frac{1}{2} \left( \alpha_{i1}^{\frac{1}{2}} + \alpha_{i2}^{\frac{1}{2}} \right) \alpha_{o2}^{\frac{1}{2}}$$

$$K_{o1} = (1 - \alpha_{o1})^{\frac{1}{2}}(1 - \alpha_{o2})^{\frac{1}{2}}; \quad K_{o2} = \frac{1}{2} \left( \alpha_{o1}^{\frac{1}{2}} + \alpha_{o2}^{\frac{1}{2}} \right) \alpha_{o2}^{\frac{1}{2}}$$

As result, the SW gains of OP₁ and OP₂ are calculated by

$$SW_1 = \frac{P_{o-1}}{P_{in}} = \left( \frac{E_{o-1}^* E_{o-1}}{E_{in}^* E_{in}} \right) = \frac{1}{8} \left[ K_{i1}^2 G_1 + K_{i2}^2 G_2 - 2 K_{i1} K_{i2} \sqrt{G_1 G_2} \cos \Delta \phi_{i2} \right]$$

$$SW_2 = \frac{P_{o-2}}{P_{in}} = \left( \frac{E_{o-2}^* E_{o-2}}{E_{in}^* E_{in}} \right) = \frac{1}{8} \left[ K_{i1}^2 G_3 + K_{i2}^2 G_2 - 2 K_{i1} K_{i2} \sqrt{G_3 G_2} \cos \Delta \phi_{i2} \right]$$

where $\Delta \phi_{i,j}$ (i, j = 1, 2) is derived from (3) and the power gain $G$ relates to the signal field gain $g$ given by [20]

$$G = g^2$$

Note that in (8) and (9), the on/off states of both outputs are only dependent on the gain-level equalities of $G₁₁$, $G₂₁$ and $G₂₂$. C. All-optical flip-flop

The employing of an ultrafast AOFF in TaMZ switch is to supply a constant CS₁ to maintain a flat gain for the signals at OP₁ and OP₂. There are a number of schemes to realize AOFF as reported in [13, 21-23]. In this paper, an AOFF with a feedback-loop (FBL) and multiple forward controls as in [23] is proposed and offers a fast response, achieving sub-nanoscond latching capability which is independent to the delay associated with FBL.

The AOFF set/reset operation principle is illustrated in Table III where the on/off status of Q output (CS₁) is defined by the excitations of “set” and “reset” pulses (CS₀). Figure 4 shows the schematic diagram of the proposed AOFF, which is composed of an SMZ switch, multiple-control-signal-generating modules including attenuators and delay units, a continuous wave (CW) source and a FBL with a signal propagation delay of $Tᴮᴸ$. The “set” pulse stream Sᵣ excites SOA₁ causing the imbalance in SMZ thus switching the input CW signal to the AOFF output (i.e. Q > 0). A portion of Q signal (in γ %), $Pᴮᴸ$, will be fed back to the upper control port and therefore, maintaining the imbalance state in SMZ. Before the arrival of $Pᴮᴸ$ during an initial transient period due to the loop delay $Tᴮᴸ$, the pulses in Sᵣ continuously maintain SMZ imbalance state, thus avoiding the gain recovery in SOA₁ when the first pulse of Sᵣ exits it. Q is toggled off when a “reset” signal (i.e. a delay version of CS₀) is converted to R and then applied to the lower control port to restore the balance state in SMZ. Since SMZ turns off, $Pᴮᴸ$ still arrives to the upper control port during $Tₛₚ$, therefore, for immediately turning-off, R, needs to have multiple pulse within $Tₛₚ$. The multiple control pulse in Sᵣ and R, ensure the proper operation of AOFF when $Tₛₚ < Tᴮᴸ$.

III. INTER-OUTPUT CONTRAST RATIO PERFORMANCEs

The TaMZ switching “on”/“off” states at the output OPᵣ (8) and (9), depend on the imbalance/balance states between the $i^{th}$ and $(i+1)^{th}$ arms. Note that for high CRs in (4) and (5), the denominators, representing the non-switched signals, should be minimized as much as possible. Assuming the SOAs are the same, in the case of perfect coupler factors $\alpha_{i1} = \alpha_{i2} = \alpha_{o1} =$...
\( \alpha_{02} = 0.5 \) of \( C_{I1}, C_{I2}, C_{O1} \) and \( C_{O2} \), respectively, when TaMZ switches input data to \( \text{OP}_4 \), the ideal \( CR_{\text{OP4}} \rightarrow \infty \). However, in practice, \( \alpha_{0j} \) or \( \alpha_{ij} \) or both may not be equal to 0.5, therefore \( CR_{\text{OP4}} \) will be reduced. This is due to the left-over power at \( \text{OP} \) caused by unevenly split signals in the TaMZ arms and its outputs. The inter-output \( CRs \) of TaMZ with respect to variations of \( K_{ij} \) can be computed from (4) and (5) by

\[
CR_{\text{OP1,2}} = \frac{G_{21} - K_{21} \sqrt{G_{21} G_{2-1}} - 2K_{21} \sqrt{G_{21} G_{2-1}} \cos \Delta \phi_{1,2-1}}{G_{21} + K_{21} \sqrt{G_{21} G_{2-1}} - 2K_{21} \sqrt{G_{21} G_{2-1}} \cos \Delta \phi_{2,3-1}}
\]

\[
CR_{\text{OP2,1}} = \frac{G_{12} - K_{12} \sqrt{G_{12} G_{1-2}} - 2K_{12} \sqrt{G_{12} G_{1-2}} \cos \Delta \phi_{1,2-1}}{G_{12} + K_{12} \sqrt{G_{12} G_{1-2}} - 2K_{12} \sqrt{G_{12} G_{1-2}} \cos \Delta \phi_{2,3-1}}
\]

where \( G_{i2}, G_{jB} \) and \( G_{j,CS1} \) represent the initial SOA gain, SOA gains induced by the Bias and \( CS_1 \), respectively. In the broadcasting mode (i.e. no CSs), \( CR_{\text{OP}} \) is the same for \( \text{OP}_1 \) and \( \text{OP}_2 \) provided the power of the broadcast and bias signals are the same, i.e. \( G_{i2} = G_{jB} = G_{j,CS1} \) where \( G_{j,CS1} \) is the gain induced by the broadcast signal.

IV. RESULTS AND DISCUSSIONS

Investigations of the switch operation and \( CRs \) are carried out by means of numerical calculation and simulation evaluation using the Virtual Photonics Inc. software. The main SOA and switching parameters are given in Tables I and IV, respectively. Figure 5 illustrates the operation of TaMZ switch in switching and broadcasting modes. With no CSs, the 1st input packets are switched to \( \text{OP}_1 \). When an optical Gaussian-shaped pulse \( CS_0 \) is applied, AOFF generates a constant CS \( \text{CS}_1 \) during \( T_{SW} = 5.5 \) ns, which is injected to both \( \text{SOA}_{1,2} \) to switch the 2nd and 3rd input packets to \( \text{OP}_2 \). Note that there is a drop in the carrier densities of both \( \text{SOA}_{1,2} \) during \( T_{SW} \) due to \( \text{CS}_2 \). With \( \text{CS}_2 \) pulse being applied to \( \text{SOA}_2 \) and \( \text{CS}_1 \) exiting both \( \text{SOA}_{1,2} \), TaMZ restores itself to a normal operation mode and switches the 4th input packet to \( \text{OP}_1 \). TaMZ broadcasts the 5th packet to both \( \text{OP}_{1,2} \) on the receiving the broadcast signal and returns to the normal mode in the absence of CSs, thus switching the 6th packet only to \( \text{OP}_1 \). In Fig. 5, the transient time of changing (i.e. SOA carrier density changes) from the normal mode to switching mode is small due to ultrafast response of SOA when interacting with CS [6]. However, restoring back to the normal mode requires more time due to the SOA carrier relaxation time inherited from SOA-based switches. Therefore, a packet guard band is employed to ensure switch’s full gain recovery.
Figure 6 displays the CRs over a range of CS1 power. Within the power range up to 20 dBm, CRs are relatively high and constant at ~20 dB, showing a considerable improvement compared to the SMZ, see Fig. 2. For both CR_{OP1} and CR_{CH1}, the improvement is more than 10 dB. For CR_{CH1}, the value is almost the same with SMZ; however, TaMZ offers a larger range of CS power compared with the SMZ switch. For higher values of CS1 power, CRs drop due to a deeper SOA gain saturation requiring a longer recovery time (~1.5 ns), thus resulting in a higher residual power of non-switched signals. Note that the values of both CR_{OP1,2} and CR_{CH1} drop faster than their counterparts CR_{OP2,1} and CR_{CH2}. This is due to a higher CS1 power will further reduce SOA && K2 gain levels (G_{1,CS1} and G_{2,CS1}) during T\_SW, thus increasing SW2 gain (9) compared to a fixed SW1 gain induced by a constant-power bias signal when no CS1 is applied.

The investigation of the CR_{OP} performance against the variations of the coupling factors of C_{II} and C_{OI} (\alpha_{II} and \alpha_{OI}, respectively), which affects the upper interferometer, is depicted in Fig. 7. In Fig. 7(a), the predicted and simulated results show that the performance of CR_{OP1,2} is degraded by a few dB when \alpha_{II} offset from 0.5. In contrast, CR_{OP2,1} only slightly varied due to the split input power difference between two arms of the lower interferometer being less than that difference in the upper interferometer. Nevertheless, Fig. 7(b) shows the smaller variations in CRs causing by the C_{OI} variation compared to the C_{II} variation. This could be explained from the factor K_{ij} in (7), where the contribution of \alpha_{II} is in K_{II}, K_{12} and K_{22} whereas \alpha_{OI} only influences to K_{11}. The predicted results for CR_{OP1} at \alpha_{II} = 0.5 and CR_{OP2,1} are not shown in Figs. 7(a) and (b), respectively, since they reach infinity corresponding to (11) and (12). It is noticed that the predicted CR_{OP} values are higher than simulated CR_{OPs}, due to the consideration in simulation model of (i) the cross gain modulation (XGM) effect between the counter-propagating CSs and input data results in a small reproduced power emerging at OPs and (ii) the ripples of SOA_{1&2&3} gains causing the left-over power at OPs when being switching-off, whereas in theoretical calculation, XGM is neglected and the gains are assumed equal (see Table IV).

V. CONCLUSIONS

The paper has introduced and characterized the 1x2 Tri-arm Mach-Zehnder switch with an all-optical flip-flop. In TaMZ, the CR performance showed an improvement of more than 10 dB over a wider power range of control signal compared to the conventional SMZ. Introducing an AOFF in controlling scheme has enhanced the TaMZ performance by means of maintaining a constant output gain and providing a large range of switching duration. Investigation of CR performance against the variation of the coupler factor in the TaMZ interferometer has shown that the impairment of the input 2x2 coupler would penalize CR performance larger than the impairment of the output 2x2 coupler. The proposed switch has shown the capability of broadcasting input packets, thus offering a great potential for packet routing applications.

REFERENCES