Design and high-speed modulation of a compact and low-voltage silicon microring resonator-loaded Mach–Zehnder modulator (Si MRR-MZM) with a lateral P–N junction are discussed. The driving voltage or the size of a Si MZM is expected to be significantly reduced owing to an enhanced phase shift in an MRR. Modulation characteristics of the MRR-MZM are analyzed on the basis of different device parameters, such as the coupling efficiency $K$ and round-trip length of an MRR. Si MRR-MZMs with different device parameters are fabricated using a complementary metal–oxide–semiconductor (CMOS)-compatible process and their high-speed modulation characteristics are compared. A half-wave voltage of 3.4 V is demonstrated in an MRR-MZM with $K = 0.12$ and a round-trip length of 128 $\mu$m, and the product of the half-wave voltage and the length of a phase shifter $(V_pL)$ was decreased to 0.036 V cm. The 3 dB bandwidth of an MRR-MZM with $K = 0.21$ and a round-trip length of 180 $\mu$m is measured to be approximately 16 GHz, and nonreturn-to-zero (NRZ) modulation up to 32 Gbps is successfully demonstrated for an operation voltage of 4.0 V.

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$= \pi + \phi + \tan^{-1}\left(\frac{r \sin \phi}{\eta a - r \cos \phi}\right)$

$+ \tan^{-1}\left(\frac{\eta a r \sin \phi}{1 - \eta a r \cos \phi}\right), \quad (1)$

$r = \sqrt{1 - K}, \quad \alpha = \exp\left(-\frac{\alpha L}{2}\right), \quad (2)$

$T = \left|\frac{E_2}{E_1}\right|^2 = \frac{\eta^2 (\eta^2 a^2 + r^2 - 2 \eta a r \cos \phi)}{\eta^2 a^2 r^2 + 1 - 2 \eta a r \cos \phi}, \quad (3)$

where $E_1$ and $E_2$ are respectively the optical electric fields at Ports 1 and 2. $\phi$ is the single-pass phase in the MRR, and $r$ and $K$ are respectively the coupling ratio of the optical electric field and the coupling efficiency of the light power at the DC. $\alpha$ and $L$ are the propagation loss coefficient in the MRR and the round-trip length of the MRR, respectively. $\alpha$ and $\eta$ are the transmission coefficient of the electric field for round-trip propagation along the MRR and the coupling loss at the DC, respectively.

Figure 2 shows the effective phase shift $\phi_{eff}$ (mod $2\pi$ rad) and the transmittance $T$ as functions of the single-pass phase shift $\phi$ (mod $2\pi$ rad) for $K = 0.10$, $L = 128 \mu m$, $\alpha = 12.1$ dB/cm, and $\eta = 0$. In the following theoretical discussion, these values of $\alpha$ and $\eta$ are used. In the vicinity of $\phi = 0$, that is, in the on-resonance state, the marked nonlinearity and the single-pass phase shift are strongly enhanced. Here, we define the phase shift enhancement factor $F_{pe}$ as\(^{38,39}\)

$F_{pe} = \frac{\Delta \phi_{eff}}{\Delta \phi}$

$= \frac{3\pi/2 - \pi/2}{\phi|_{\phi_{at}=3\pi/2} - \phi|_{\phi_{at}=\pi/2}}$

$= \frac{\pi}{\phi|_{\phi_{at}=3\pi/2} - \phi|_{\phi_{at}=\pi/2}}. \quad (4)$

I the case of $K = 0.1$ and $L = 128 \mu m$, $F_{pe}$ is approximately 31.5. Using this enhancement of the phase shift, the driving voltage of the MRR-MZM can be reduced to $1/F_{pe}$. The proposed devices are designed to modulate transverse electric (TE) mode lights and to be used in the C band.

### 3. Device design and fabrication

The Q factor and phase shift enhancement factor are the important indices for the characteristics of MRRs. The Q factor of the MRR is decided with the coupling efficiency $K$ at a DC between an MRR and a busline waveguide, and the round-trip length $L$ of the MRR. Figure 3(a) shows the calculated relationship between the Q factor and round-trip length $L$ at various $K$ values. The Q factor increases with decreasing $K$ and increasing $L$, which leads to the larger phase enhancement effect. The modulation speed is limited by the Q factor and the CR time constant of the circuit. Figure 3(b) shows the calculated cut-off frequency $f_0$ decided by the Q factor as a function of $L$ at various $K$ values. To increase modulation speed limited by the Q factor, larger $K$ and smaller $L$ values are required.

The proposed MZM was fabricated on a silicon-on-insulator (SOI) substrate using a CMOS-compatible process. In the proposed MZM, a lateral P–N junction is used in the MRR. Figure 4 shows a schematic cross-sectional view of the rib waveguide. The width and thickness of the rib waveguide are 0.40 and 0.21 $\mu m$, respectively. The thickness of the slabs connected to the P–N junction is 0.06 $\mu m$.

To improve the extinction ratio of the MZM with single-arm driving, a DC with an asymmetric light power splitting.
ratio of $x : 1 - x$ should be used instead of MMI couplers ($x = 0.5$) to reduce the imbalance between the light powers in the two arms. The splitting ratio for the maximum extinction ratio $x_{\text{opt}}$ is given by

$$x_{\text{opt}} = \sqrt{\frac{T_2^2}{T_1^2 + T_2^2}}, \quad (5)$$

where $T_1$ and $T_2$ are the transmittances in the arms with and without the MRR, respectively. In the case of $K = 0.1$, $L = 128 \mu m$, and $\alpha = 12.1$ dB/cm, the optimized $x_{\text{opt}}$ is 0.58.

The MRR-loaded MZMs were fabricated by a CMOS-compatible process. Figure 5 shows an optical microscopy image of the fabricated MRR-MZM. The transmittances in the arms with and without the MRR are $T_1$ and $T_2$, respectively. The optimized $x_{\text{opt}}$ is 0.58.

The phase shifters in the fabricated devices are 105 and 157 μm for the devices with the round-trip lengths of 128 and 180 μm, respectively, because the DCs and their vicinities are non-phase-shifting waveguides.

4. Modulation characteristics

4.1 Static modulation characteristics

Figure 6 shows the measured spectral responses at the output port under various applied reverse voltages for Devices 1-1, 1-2, and 2. The temperature of the modulators were kept at 15 °C using a Peltier element device. In these cases, with the increase in applied reverse voltage, the shift of resonant dips to the longer wavelength side. The slope on the dip is slightly steeper for Device 1-1 than for Devices 1-2 and 2 owing to the larger phase shift enhancement. This steep slope leads to a low driving voltage.

Figure 7 shows the measured extinction ratios of Devices 1-1, 1-2, and 2.

### Table I. Designed device parameters.

<table>
<thead>
<tr>
<th>Device parameter</th>
<th>Designed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round-trip length of MRR $L$ ($\mu m$)</td>
<td>128 180</td>
</tr>
<tr>
<td>Coupling efficiency $K$</td>
<td>0.10 0.15</td>
</tr>
<tr>
<td>Quality factor</td>
<td>10619 10376</td>
</tr>
<tr>
<td>Branching ratio of DC $x$</td>
<td>0.58 0.57</td>
</tr>
<tr>
<td>Phase shift enhancement factor $F_p$</td>
<td>31.5 20.1</td>
</tr>
<tr>
<td>P/N doping concentration ($cm^{-3}$)</td>
<td>4.76 x 10^{17}</td>
</tr>
</tbody>
</table>

Fig. 6. (Color online) Measured spectral responses of the fabricated MRR-MZMs (Devices 1-1, 1-2, and 2) at output port under various applied reverse voltages.

Fig. 7. (Color online) Measured extinction ratios of fabricated MRR-MZMs (Devices 1-1, 1-2, and 2).
The discrepancies between the designed and measured frequencies of Devices 1-2 and 2 were 12 and 16 GHz, respectively. The Q-factors of Devices 1-1, 1-2, and 2 were evaluated to be approximately 9680, 9260, and 8630, which correspond to 122, 111, and 102, respectively. The Q-factors in these devices are larger than the designed ones, as mentioned later, which deteriorated the balance between light powers and phases in both arms. The phase-shift enhancement factors for Devices 1-1, 1-2, and 2 were evaluated to be approximately 9600, 9600, and 8400, which correspond to the coupling efficiencies of 0.12, 0.13, and 0.21, respectively. The discrepancies between the designed and measured coupling efficiencies are probably due to fabrication error.

4.2 Dynamic modulation characteristics

The characteristics of the high-speed modulation of the MRR-MZMs were measured. The temperature of the modulators was kept at 15 °C using a Peltier element device. Unfortunately, since we were unable to measure Device 1-1 owing to the large coupling loss with optical fibers, the modulation characteristics of Devices 1-2 and 2 were measured. Figure 8 shows the measured eye patterns of the optical modulation signals of the fabricated MRR-MZM at bit rates of 20 and 32 Gbps using a bias voltage $V_{\text{bias}}$ of 2.0 V and a voltage swing $V_{pp}$ of 2.0 V without pre-emphasis. The MZM was driven by a 2$^{11}$-1 bit NRZ pseudorandom bit sequence (PRBS) signal. Clear eye openings were observed at 20 and 32 Gbps. The extinction ratios at 32 Gbps were 3.7 and 2.0 dB for Devices 1-2 and 2, respectively. Figure 9 shows the measured eye patterns at bit rates of 32 Gbps and $V_{pp}$ of 2.0 V. Even in these cases, the extinction ratios of 1.9 and 2.4 dB for Devices 1-2 and 2, respectively, were obtained.

Figure 10 shows the frequency characteristics of the transmitted light ($S_{21}$) of the MRR-MZMs. The 3-dB cut-off frequencies of Devices 1-2 and 2 were 12 and 16 GHz, respectively. The modulation speed is mainly dependent on the Q factor of an MRR. Device 2 with the designed $K$ of 0.15 has a higher modulation frequency.

3 dB cut-off frequencies are decided by both the Q-factors of the MRRs and $RC$ time constants. Because the evaluated 3 dB cut-off frequencies of Devices 1-2 and 2 dominated by $RC$ time constants ($f_{\text{RC}}$) are 38 and 35 GHz, respectively, the modulation speeds of the devices are mainly limited by the Q factors of the MRRs. As mentioned before, the Q-factors of Devices 1-2 and 2 evaluated from each measured $F_{pe}$ are approximately 9260 and 8630, respectively. The cut-off frequencies dominated by the Q-factors ($f_{Q}$) are calculated to be 21.0 and 22.4 GHz. With the consideration of $f_{\text{RC}}$ of Devices 1-2 and 2, the total cut-off frequencies are evaluated to be 13.5 and 13.6 GHz, respectively. These values are consistent with the measured 3-dB cut-off frequencies in Fig. 10.

The experimental results show that the modulation speed of 32 GHz of the proposed MRR-MZM is comparable to typical modulation speeds of 10 to 50 Gbps of a normal MZM. On the other hand, the lengths of the phase shifter are successfully decreased to approximately 1/10 to 1/20 of that of a normal Si MZM.

Si MRRs are very sensitive to changes in temperature and a temperature control system for an MRR is required for practical use. Even with this demerit of the Si MRR, we believe that they are promising because of their compactness and excellent functionality. The MRRs with smart mechanisms of automatic temperature control have been proposed so far.$^{41,42}$ This is one of the good options to solve this disadvantage.

5. Conclusions

We discussed single Si MRR-MZM with a lateral P-N...
junction. Modulation characteristics of two types of MRR-MZM with different device parameters, such as the coupling efficiency $K$ and round-trip length of an MRR were investigated. The Si MRR-MZMs were fabricated using a CMOS-compatible process and their high-speed modulation characteristics were compared. A half-wave voltage of 3.4 V was demonstrated in an MRR-MZM with $K = 0.12$ and a round-trip length of 128 $\mu$m, and $V_{3dB}$ was decreased to 0.036 V cm. The 3 dB bandwidth of an MRR-MZM with $K = 0.21$ and a round-trip length of 180 $\mu$m was measured to be approximately 16 GHz, and an NRZ modulation up to 32 Gbps was successfully demonstrated for an operation voltage of 4.0 V.

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