Low-voltage high-speed coupling modulation in silicon racetrack ring resonators

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Abstract: We demonstrate a low-voltage high-speed modulator based on a silicon racetrack resonator with a tunable Mach-Zehnder interferometer coupler. Both static measurement and dynamic modulation experiment are carried out. The 3-dB electro-optic bandwidth is measured to be >30 GHz beyond the limit by the cavity photon lifetime. A 32 Gb/s on-off keying (OOK) modulation is realized under a peak-to-peak drive voltage as low as 0.4 V, and a 28 Gb/s binary phase-shift-keying (BPSK) modulation is realized with a drive voltage of 3 V. The low drive voltages results in low energy consumptions of ~13.3 fJ/bit and ~1.2 pJ/bit for OOK and BPSK modulations, respectively.

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1. Introduction
An electro-optic modulator is one of the basic building blocks in photonic integrated circuits (PICs) for optical communications and interconnects. Broad bandwidth, low drive voltage, low energy consumption and CMOS compatible silicon modulators have been the research highlight in recent years. High-quality silicon modulators based on on-off keying (OOK) have been demonstrated [1–3]. Compared to OOK modulation, binary phase-shift keying (BPSK) modulation has ~3 dB margin of optical signal-to-noise ratio (OSNR) for a given bit-error rate (BER), providing stronger tolerance to fiber nonlinearity in long-haul applications [4]. It is also the basis for high-order modulation formats, such as quadrature phase-shift keying (QPSK). Generally speaking, silicon modulators reported in the literature can be categorized into two different structures. One structure is based on the Mach-Zehnder interferometer (MZI), which has the advantages of large optical bandwidth, excellent temperature stability,
and chirp-free output under the push-pull drive scheme, but the drive voltage is relatively high and the device length is usually in the order of ~mm [5]. Another structure is based on the microcavity, such as microring, microdisk or photonic crystal. This kind of devices has the key merits of compact size, low drive voltage, and low energy consumption, but they are more temperature sensitive, and moreover the modulation bandwidth is inherently limited by the long cavity lifetime [6–8]. Both type of modulators can achieve high speed modulation for OOK and BPSK formats.

Recently, another type of silicon modulators based on coupling modulation of microrings has been proposed and demonstrated [9–11]. Intuitively, this kind of devices is a combination of MZI and microring structures with one output of MZI routed back to form a resonance loop (see Fig. 1). The concept was first put forward by Yariv [12, 13] on control of coupling between the optical resonator and the bus waveguide. In 2005, his group proposed a high-speed and low-power thermo-optic switch on the InGaAsP-InP material platform with this structure [14]. Sacher et al. later theoretically proved that microring modulators with a high extinction ratio (ER), low distortion, and zero chirp at a data rate beyond the resonance linewidth limit can be realized using coupling modulation [9, 15]. Then they experimentally demonstrated this kind of silicon modulators with the OOK modulation speed of 28 Gb/s [10] and the BPSK modulation of 10 Gb/s [11] based on forward biased $pn$ junctions together with a pre-emphasis drive scheme.

In order to further improve the modulation speed, the carrier depletion effect based on reversely biased $pn$ junctions can be employed [16, 17]. However, compared to the forward carrier injection, the modulation efficiency is much lower in the depletion mode. To improve the modulation efficiency, a long device length is required [18]. In this work, we present a silicon modulator based on the coupling modulation. A single-drive push-pull traveling wave electrode (TWE) is integrated in the MZI coupler. The TWE is designed to support high bandwidth modulation [19, 20]. Benefiting from both merits of MZI and microring, a low-voltage high-speed modulator is implemented. A clear OOK eye diagram at 32 Gb/s is observed under a peak-to-peak RF drive voltage as low as 0.4 V. Moreover, BPSK modulation at 28 Gb/s is also realized with a 3 V drive voltage using the same device [16]. The low drive voltages result in low energy consumptions of ~13.3 fJ/bit for OOK modulation and ~1.2 pJ/bit for BPSK modulation.

2. Device design and fabrication

![Fig. 1. Optical microscope image of the fabricated device. The total length of the device including the metal pads is 1.35 mm. The waveguide and the racetrack resonator are emphasized by green lines for guidance. Inset: cross-sectional view of the MZI modulation arms.](image)

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Figure 1 shows the top-view microscope image of the fabricated Mach-Zehnder racetrack resonator. The aluminum lines in the TWE are 10 μm wide and 800 μm long with a thickness of 0.75 μm. The gap size between the signal and the ground metal lines is 18 μm. The characteristic impedance is optimized to approach 50 Ohm. The MZI coupler is composed of two 3-dB 2 × 2 multimode interferometers (MMIs). The two arms of the MZI have a length difference of 6 μm. The bending radius of the racetrack is 20 μm. Light is vertically coupled into and out of the chip through grating couplers with an insertion loss of 5 dB per facet.

The inset of Fig. 1 depicts the cross section of the active arms. The silicon waveguide is 500 nm wide and 220 nm high with a slab thickness of 60 nm. Carrier depletion in the silicon pn junctions is utilized to modulate the optical phase. Doping concentration is a crucial factor that affects the complex impedance of the TWE and the optical loss of the modulator. Taking into account that holes have a higher refractive index modulation efficiency than electrons, we designed the pn junction to have a lateral offset of 100 nm towards the n region side from the ridge waveguide center. Consequently, the width of the p/n region is 350 nm/150 nm. The wider p region also reduces the optical loss due to the smaller absorption coefficient of holes [21]. The heavily doped 20-μm-wide p+ regions are located at the outer sides of the active arms and connected to the signal (S) and ground (G) electrodes of the TWE. The heavily doped 12-μm-wide n+ doping region is located in between the MZI arms and connected to the DC bias line. The highly doped regions are all 800 nm away from the rib edges. The MZI coupler works in a single-drive push-pull mode which reduces the diode capacitance by half, favoring high-speed modulation [22]. The push-pull scheme also ensures chirp-free modulation.

Device fabrication was performed using IME CMOS compatible processes on a silicon-on-insulator (SOI) wafer with a top silicon layer thickness of 220 nm and a buried oxide layer thickness of 2 μm. The device patterns were defined using 248-nm deep ultra-violet (DUV) photolithography and plasma dry etch. The etch depth was ~160 nm with a 60 nm slab remained. Ion implantation was used for doping. The doping concentrations of the lightly doped p and n regions were ~4 × 10^{17} cm^{-3} and ~1 × 10^{18} cm^{-3}, respectively. The doping concentrations of the heavily doped p+ and n+ regions were both ~10^{20} cm^{-3} for good ohmic contact. A 2.3 μm thick silicon dioxide layer was deposited using plasma-enhanced chemical vapor deposition (PECVD) followed by etch of contact holes. Finally, aluminum layer was sputtered and patterned to form metal connections.

3. Experiments and results

Figure 2 shows the experimental setup to characterize the modulator. The RF drive signal was generated by a 32 Gb/s pulse pattern generator (PPG, Agilent N4960A and N4951A) and combined with a DC voltage (V2) using a 65 GHz bias-tee. The drive signal was applied onto the TWE via a 40 GHz ground-signal (GS) microwave probe. The other end of the TWE remains open-circuit. As the TWE is only 800 μm long, the phase match between the microwave and the optical wave is not a big concern for the modulation speed tested for our device. Instead, the reflection of RF signal effectively increases the drive voltage on the electrode, leading to a higher modulation efficiency (see more discussions in the Appendix).

Another DC voltage (V1) was applied onto the bias pad via a DC probe to ensure that the pn junctions were reversely biased. V1 and V2 together can independently set the biases for the two pn junctions, allowing for convenient coupling tuning from under-coupling to over-coupling for each resonance. Therefore,OOK and BPSK can be generated and switched by setting different bias conditions. We used a continuous wave tunable laser (Yenista TUNICS T100S-HP) as the light source. The laser light first went through a polarization controller (PC) to set the transverse electric (TE) polarization. The input light was then coupled into and out of the modulator through on-chip grating couplers.
In the measurement of the device transmission spectrum, the RF signal was turned off and the input laser light was scanned while the output light was collected by an optical component tester (Yenista CT400). We fixed $V_1$ at 1.5 V and changed $V_2$ from 0 V to −8 V, so that one modulation arm was reversely biased at $V_1$ and the other at $V_1 - V_2$. Figure 3(a) depicts a typical spectrum normalized to a straight test waveguide with $V_2 = −2$ V. The resonance free spectral range (FSR) is ~282 pm, and the loaded Q-factor is ~23,000. The on-chip insertion loss of the device is about 3.6 dB. It is evident that resonance notch depth varies with wavelength, which is originated from the coupling variation due to the asymmetric MZI coupler. Critical coupling occurs at the wavelength of 1540.3 nm with the largest ER of ~34 dB. Figure 3(b) shows resonance ER change when $V_2$ varies from −1 V to −2 V. The critically coupled resonance is red-shifted by 1.973 nm. The resonance wavelength for critical coupling is approximately linearly shifted with $V_2$ as shown in Fig. 3(c). From linear fitting, we get the slope of about −1.95 nm/V, which equals to ~7 FSRs. The fast jump of critical coupling indicates that it is crucial to carefully adjust the DC biases in order to get OOK and BPSK modulation waveforms. Figure 3(d) depicts the magnified resonance spectral profiles near 1543.37 nm. The resonance reaches critical coupling when $V_2 = −4$ V. It should be noted that resonance wavelength also shifts with $V_2$, because the phase shift occurs only in one modulation arm when $V_1$ is constant and $V_2$ varies. During RF modulation, however, the MZI coupler works in a push-pull mode with complementary phase shifts in the two arms, giving rise to fixed resonance wavelength. We also note that the resonance notch is broadened at over-coupling ($V_2 > −4$ V) than at under-coupling ($V_2 < −4$ V). Figure 3(e) shows the ER changes as a function of $V_2$. Proper biases are required to get the desired modulation formats: OOK at the quadrature (half transmission) point and BPSK at the critical coupling (null transmission) point.
Fig. 3. (a) Transmission spectrum under $V_1 = 1.5$ V and $V_2 = -2$ V. (b) Comparison of transmission spectrum when $V_2$ is changed from $-2$ V to $-1$ V. (c) Critical-coupling wavelength shifts as a function of $V_2$. The red line is a linear fitting line. (d) Magnified resonance notch profiles with various $V_2$ values. (e) ER of the resonance in (d) changes as a function of $V_2$. Voltage swing ranges for OOK and BPSK modulations are depicted.

We characterized the modulator electro-optic (EO) response using an Agilent 67 GHz vector network analyzer (VNA). The 40 GHz GS probe was first calibrated using a standard calibration procedure. The RF signal from Port-1 of the VNA was applied onto the TWE of the modulator and the modulated optical signal was received by a 100 GHz photodetector and fed back into Port-2 of the VNA. The acquired $|S_{21}|$ was normalized to the value at 10 MHz. The EO responses at two bias conditions (for OOK and BPSK modulations) are shown in Fig. 4. A 3-dB bandwidth of more than 30 GHz was observed. The EO bandwidth exceeds the $\sim$8.4 GHz resonance linewidth, demonstrating the high-speed modulation beyond the limit set by the cavity photon lifetime.

Fig. 4. EO responses at two bias conditions. The 3-dB EO bandwidth exceeds 30 GHz.
We next performed the OOK modulation using the experimental setup shown in Fig. 2. The RF signal was turned on and the output optical signal was amplified by an erbium-doped optical fiber amplifier (EDFA) to compensate for the modulator insertion loss, followed by a 1-nm bandwidth optical filter. Then the optical signal was detected by the 100 GHz photodetector. The converted electrical signal was fed into a 50 GHz bandwidth sampling oscilloscope (Agilent DCA-X 86100D).

In the ideal case, OOK modulation is generated when the resonance is switched between critical coupling (null transmission) and under-coupling (near unit transmission). Under-coupling is chosen rather than over-coupling because it is more sensitive to voltage swing due to the higher loaded Q-factor. Figure 5 shows the OOK eye diagrams for a 32 Gb/s non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) signal with a length of $2^{31} - 1$. The bias voltages were set as $V_1 = 4$ V and $V_2 = 0$ V. The input light wavelength was tuned to around 1553.6 nm (optimized to get the best eye diagram). Even with a small RF peak-to-peak drive voltage of $V_{in} = 0.4$ V, the eye diagram is still open with an ER of ~1.2 dB. The modulation induced loss (MIL), defined as the loss of high level in the modulated waveform with respect to the off-resonance transmission, is 1.8 dB. With $V_{in}$ increased to 1 V and 3 V, clearer eye diagrams are observed with ER improved to 4.5 dB and 8.4 dB, and MIL increased to 2.1 dB and 2.5 dB, respectively. In fact, a higher ER is obtained when the operation wavelength is closer to the resonance wavelength but at the expense of an increased MIL. It is noted that the extinction ratio measured from the eye diagram is smaller than that from the spectral measurement (see Fig. 3). Although the output power can be very low at the critical coupling point, however, the actual received optical power is set by the ASE noise from the EDFA. Besides, the noise floor of the photodetector also limits the minimum detectable optical power. We remark that our device could be used for short-reach optical interconnect applications where a modest modulation extinction ratio is enough.

![Eye diagrams for the 32 Gb/s OOK modulation with three different RF drive voltages of (a) $V_{in} = 0.4$ V, (b) $V_{in} = 1$ V and (c) $V_{in} = 3$ V. The DC bias voltages are $V_1 = 4$ V and $V_2 = 0$ V.](image)

The experimental setup to perform the BPSK modulation is similar to the OOK modulation except that the output optical signal is simultaneously monitored by an oscilloscope and a 23 GHz optical modulation analyzer (Agilent N4392A) as a coherent receiver. The biases were set to achieve critical-coupling with null transmission. The applied RF signal modulates the coupling to swing between under-coupling and over-coupling (see Fig. 3(e)) so that the output power keeps the same but the phase is $\pi$-radian different [11].
input light wavelength was set at 1544.3 nm and DC bias voltages were $V_1 = 1.5 \text{ V}$ and $V_2 = -4 \text{ V}$. The RF drive signal was a 28 Gb/s NRZ PRBS signal with $V_{in} = 3 \text{ V}$. At the received optical power of 1.87 dBm, the demodulated signal has a Q-factor of ~6.3 dB, an EVM of 23.3\% (see Fig. 6), and a bit error rate (BER) of $8 \times 10^{-10}$, estimated from the EVM [23].

![Image](image_url)

**Fig. 6.** 28 Gb/s BPSK modulation result: (a) eye diagram, (b) constellation diagram, and (c) demodulated eye diagram. The RF drive voltage is $V_{in} = 3 \text{ V}$, and the DC biases are $V_1 = 1.5 \text{ V}$ and $V_2 = -4 \text{ V}$.

Energy consumption is a key metric to specify a modulator. A rough estimation can be carried out based on the measured input impedance of the electrode as presented in the Appendix. We choose to directly measure the input RF power to get the accurate power consumption value. In fact, the input power is either absorbed or reflected by the modulator. Although the reflected power is wasted and cannot be used, it is worthwhile to separate these two parts. As an RF circulator is not available in our measurement, we used a broadband power splitter instead to obtain the reflected RF power. We first connected the PRBS generator to a power meter and acquired the input power $P_{in}$. Then we used a three-port RF power splitter (with 50 $\Omega$ input impedance) to divide the input RF signal. The input RF power from any port can be divided equally into the other two ports with power unbalance typically less than 0.1 dB. One output port was connected to the power meter and the other connected to a 50 $\Omega$ terminator. The recorded power is denoted as $P_1$. Hence we got the splitting loss of the power splitter as

$$L_{splitter} (dB) = P_{in}(dBm) - P_1(dBm).$$

The next step was to acquire the reflected power of the device, so we substituted the 50 $\Omega$ terminator with the modulator. The power recorded by the power meter was denoted as $P_2$. The increment of $P_2$ with respect to $P_1$ is due to the reflection from the modulator, and thus, it is expressed as $P_2(mW) = P_1(mW) - P_1(mW)$. Then the power reflected by the modulator is $P_{r,mod}(dBm) = P_2(dBm) + L_{splitter}(dB)$. Consequently, the RF reflectivity of the modulator is

$$\Gamma = \frac{P_{r,mod}(mW)}{P_2(mW)}. $$

It should be noted that different power units (mW and dBm) are used to simplify the equations.

We measured $P_{in}$ under multiple data rates as shown in Fig. 7(a). It can be seen that the measured $P_{in}$ is always lower than the theoretical value calculated by $(V_{in}/2)^2/50\Omega$, and the difference becomes even larger at a higher data rate. This is mainly due to the transition between the high and low levels of the PRBS signal has a certain rise/fall time. By dividing $P_{in}$ by the data rate, we finally obtained the energy consumption per bit of the modulator as shown in Fig. 7(b). It should be noted that the energy consumption incorporates both the absorbed and the reflected RF powers. The 32 Gb/s OOK modulations have energy consumptions of ~13.3 fJ/bit, ~108.4 fJ/bit, and ~1035 fJ/bit for 0.4 V, 1 V, and 3 V drive voltages, respectively. The 28 Gb/s BPSK energy consumption is ~1.2 pJ/bit under 3 V drive voltage. The RF power reflectivity is shown in Fig. 7(c). It can be seen that the RF reflectivity decreases with the increasing data rate, implying the characteristic impedance gets closer to 50 $\Omega$ at a higher data rate. To verify the validity of this measurement method, we also
performed a control experiment in which the modulator was removed (thus ended with an open-circuit), and we got $\Gamma = 1 \pm 0.05$ (indicating full reflection) for the three drive voltages over a data rate from 8 to 32 Gb/s.

Fig. 7. (a) PRBS input power. The dashed lines are the measured results and the solid lines are the calculated results using the drive voltages. (b) Energy consumption of the modulator. (c) RF reflectivity of the modulator.

The above experiments reveals that the actual power consumption of the modulator is in fact lower than the calculation based on the measured impedance. The performance of our modulator in terms of energy efficiency is close to a typical microring modulator with a small radius [24].

4. Discussion

Tables 1 and 2 compare our work with some of the state-of-the-art silicon OOK and BPSK modulators, respectively. It can be seen that typically the MZI modulators feature high speed but large footprint, while the ring/disk modulators feature compact size and low energy consumption. As for the ring modulator with coupling modulation like our work, it turns out to possess a favorable speed, a moderate footprint, a low RF drive voltage, and low energy cost.

| References | Year | Structure         | Speed (Gb/s) | ER (dB) | Length$^a$ (mm) | $V_{in}$ (V) | Energy consumption (fJ/bit) |
|------------|------|-------------------|--------------|---------|-----------------|-------------|--------------------------|
| [25]$^b$  | 2013 | MZI               | 50           | 4.6     | 3               | 1.5         | 450                      |
| [26]      | 2013 | MZI               | 40           | 5       | 2               | 0.36        | 32.4                     |
| [27]      | 2014 | MZI               | 50           | 5.35    | 0.1             | 2.5         | 860                      |
| [5]       | 2014 | MZI               | 40           | 7.1     | 3               | 1.6         | 640                      |
| [24]      | 2011 | Ring              | 25           | 6.45    | NA              | 1           | 7                       |
| [3]$^c$   | 2014 | Ring              | 40           | 6.2     | NA              | 4.8         | 115                      |
| [8]       | 2014 | Disk              | 25           | 6.18    | NA              | 0.5         | 0.9                      |
|           |      | Ring (coupling mod.) | 28           | 10      | 0.2             | 1.5$^d$     | 750$^e$                  |
| This work | 2015 | Ring (coupling mod.) | 32           | 1.2/4.5/8.4 | 0.8 | 0.4/1/3 | 13.3/108.4/1035 |

$^a$Length of active waveguide
$^b$Operated in O-band
$^c$Pre-emphasized drive signal
$^d$Estimated upper-bound

This work...
Table 2. Performance comparison of recent BPSK modulators

| References | Year | Structure | Speed (Gb/s) | Length (mm) | $V_{in}$ (V) | Energy consumption (pJ/bit) |
|-----------|------|-----------|--------------|-------------|-------------|--------------------------|
| [28]      | 2012 | MZI       | 22.3         | 4           | 8           | 28.3p                    |
| [29]      | 2013 | MZI       | 25           | 1           | 6           | 18.95                    |
| [30]      | 2015 | MZI       | 32           | 3           | 6           | 5.63                     |
| [31]      | 2015 | MZI       | 48           | 3.5         | 7.4         | 8.75                     |
| [32]      | 2013 | Ring      | 28           | NA          | ~6          | NA                       |
| [33]      | 2014 | Ring      | 10           | NA          | 3.3         | NA                       |
| [11]      | 2014 | Ring (coupling mod.) | 10 | 0.2 | 1.6d | NA |

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| Structure | Speed (Gb/s) | Length (mm) | $V_{in}$ (V) | Energy consumption (pJ/bit) |
|-----------|--------------|-------------|--------------|--------------------------|
| Ring (coupling mod.) | 28 | 0.8 | 3 | 1.2 |

*a* Length of active waveguide  
*b* Estimated with 50 Ω impedance  
*c* Extracted from the QPSK modulator  
*d* Pre-emphasized drive signal.

Limited by the maximum data rate of our PPG, we can only test the modulation rate up to 32 Gb/s so far. For further improvement, the TWE, $pn$ diode doping concentration, MMI and length of the modulation arm could be further optimized to increase the EO bandwidth and the modulation efficiency, as well as to reduce the optical insertion loss. Other than OOK and BPSK modulation formats, the MZI coupled ring modulator also has the potential to generate pulse amplitude modulation (PAM) signals with segmented phase shifters in each arm of the MZI [34]. With two BPSK modulators connected in parallel with a $\pi/2$ phase difference, QPSK modulation can also be realized.

5. Conclusion

We have demonstrated a MZI coupled racetrack ring modulator to generate high-speed OOK and BPSK modulated signals with low drive voltage and low energy consumption. Spectral measurements showed that the device was very sensitive to bias voltages. High speed modulation experiments show that 32 Gb/s OOK signals can be generated with as low as 0.4 V drive voltage and energy consumption of ~13.3 fJ/bit. Our modulator can also generate BPSK modulation under a relatively low drive voltage of 3 V, and the demodulated signal by the coherent receiver reveals an EVM of 23.3%, a Q-factor of ~6.3 dB and an energy consumption of ~1.2 pJ/bit. The low drive voltage and low power consumption of such a modulator make it suitable for high-speed optical interconnect applications in datacenters and supercomputers.

Appendix

If we look from the input RF port, the impedance of the TWE $Z_{mod}$ is not exactly 50 Ω as the other end of the TWE is unloaded. As a consequence, the incident RF wave (peak-to-peak voltage $V_{in}$) will be partially reflected to become a backward propagating wave (with peak-to-peak voltage $V_{ref}$). The reflection coefficient is $S_{11} = V_{ref} / V_{in}$. The voltage applied on modulator is therefore

$$V_{mod} = V_{in} + V_{ref} = (1 + S_{11})V_{in}$$  (1)

$S_{11}$ is determined by the impedance match between the source impedance at the generator side ($Z_0 = 50$ Ω) and the load impedance of the modulator ($Z_{mod}$) as
The power consumption on the modulator is given by

\[ P_{\text{mod}} = \text{Re} \left( \frac{V_{\text{mod}}}{2} \times \frac{I_{\text{mod}}}{2} \right) = \frac{1}{4} \left| V_{\text{mod}} \right|^2 \text{Re} \left( \frac{1}{Z_{\text{mod}}} \right) \]  

Combining (1)-(3), we get

\[ P_{\text{mod}} = \frac{1}{4} \left| V_{\text{a}} \right|^2 \frac{2Z_{\text{mod}}}{Z_{\text{mod}} + Z_0} \text{Re} \left( \frac{1}{Z_{\text{mod}}} \right) \]  

It indicates that the modulator power consumption is quite dependent on the impedance of the TWE. We employed a 67 GHz microwave network analyzer (Agilent N5247A) to measure \( S_{11} \) and \( Z_{\text{mod}} \) as shown in Figs. 8(a) and 8(b), respectively.

It can be seen that the reflection and the impedance change significantly with RF frequency. In the OOK and BPSK modulations, the input is a digital PRBS signal which contains multiple frequency components. To a first-order estimation, we choose the impedance value at the half data rate. Hence, the energy consumptions estimated from (4) are \( \approx 21 \) fJ/bit and \( \approx 128 \) fJ/bit for the 0.4 V and 1 V OOK modulations at 32 Gb/s, respectively. For the 28 Gb/s BPSK modulation with a 3 V drive voltage, the energy consumption is \( \approx 1.4 \) pJ/bit.

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