High Speed InP Modulator for Beyond 200 Gbaud

Yoshihiro Ogiso, Josuke Ozaki, Kenta Sugiura, Yusuke Saito, and Mitsuteru Ishikawa
NTT Innovative Devices Corporation, 3-1 Morinosato Wakamiya, Atsugi City, Kanagawa, Japan
yoshihiro.ogiso@ntt-devices.com

Abstract: We developed a next-generation InP twin-IQ modulator PIC for beyond 200-Gbaud operations. A 3-dB electro-optic bandwidth of the modulator exceeds 100 GHz while maintaining a half-wave voltage of 1.5 V and total on-chip optical insertion loss of less than 3.5 dB.
OCIS codes: (250.4110) Modulators; (320.7080) Ultrafast optics

1. Introduction

Although spectral efficiency isn't expected to improve, there is still strong demand for ultra-high bandwidth electro-optic components. In particular, the recent growth in artificial intelligence and machine learning (AI/ML) technologies, such as generative AI, has accelerated development of higher-speed and lower-energy optical transmitters. The electro-optic (EO) modulator is a key component for high-speed applications, as well as high-speed electronics such as digital-signal processing (DSP) and amplifier ICs. For realizing the next generation 1.6-Tbps system in which 200-Gbaud-class operation would be required, all of these components must have their bandwidths of around 100 GHz. In addition to needing a high bandwidth, they must also have a low optical insertion loss and low half-wave voltage (V_π) in order to have sufficient optical signal-to-noise ratio (OSNR) characteristics. Here, InP is one of the most promising platforms for practical transceivers, because it not only provides high-modulation efficiency with a small footprint but also has mature epitaxial growth technology for high-precision manufacturing.

We have already developed a first-generation ultra-high bandwidth InP-based modulator photonic IC (PIC) for a 130-Gbaud-class coherent driver modulator (CDM). The CDM has an EO bandwidth of over 80-GHz and an insertion loss of less than 7.0 dB, including applied bias absorption for a 2.0-V V_π [1]. In this paper, we introduce the next generation of InP-based modulator PIC based on an n-i-p-n heterostructure [2,3]. By modifying the RF electrode design and optical waveguide structure, we were able to extend the bandwidth and reduce V_π without increasing the optical loss. The 3-dB EO bandwidth of the twin-IQ modulator exceeded 100 GHz, which means that it can support 200 Gbaud operations and beyond.

2. Modulator PIC

Figure 1(a) shows a schematic diagram and images of a fabricated twin-IQ modulator PIC. The overall layout is almost the same as the one described in our previous report [4]. The symmetrical channel layout provides better IQ phase stability and low-loss microwave feeding into the modulation region. The RF modulation region combines an inverted-trapezoidal ridge waveguide with an n-i-p-n heterostructure and capacitance-loaded traveling-wave electrode (CL-TWE). For the DC phase adjustment, we employ a thermo-optic heater in which the half-wave shift power (P_π) is less than 20 mW. Figure 1(b) shows the extinction characteristics obtained by single-arm driving in the RF modulation region. We also measured optical absorption characteristics and bias voltage characteristics of V_π. Moreover, we estimated the optical absorption dependence of V_π from these results. As shown in Fig. 1(c), the V_π of 1.4 V could be adjustable if up to 1.0 dB of additional loss is tolerated.

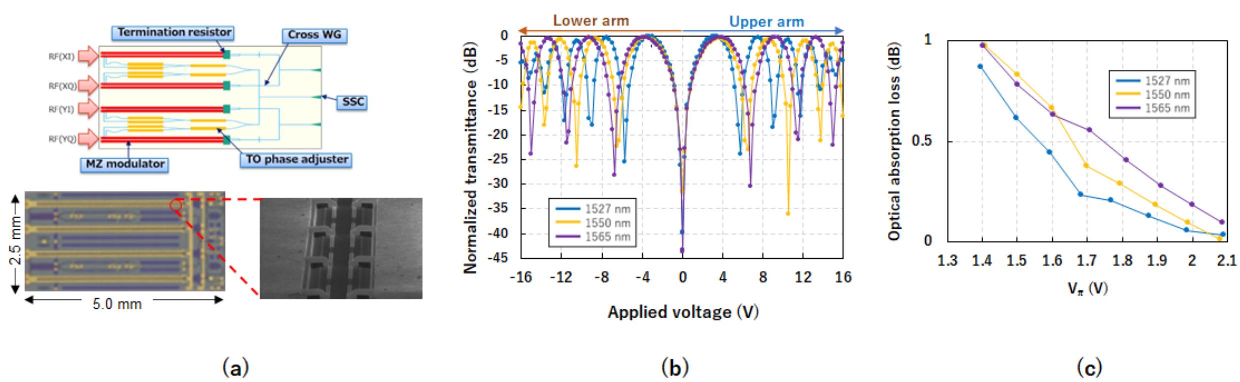

Fig. 1. (a) Modulator PIC outline, (b) extinction characteristics (single-arm drive), and (c) optical absorption loss due to applied bias for required V_π

2. DC characteristics

We measured the optical insertion losses and extinction characteristics under two different V_π conditions determined by the applied bias voltage. We set a low $V\pi$ of 1.5 V, for which the applied voltage was around -10 V in the entire C band. We conducted PIC measurements using 4.5 μmΦ lensed fiber alignment systems. Figure 2(a) shows the optical insertion losses for each and both polarization conditions. The loss of each polarization was less than 11.5 dB, which includes the absorption loss due to the applied bias and fiber coupling losses (2.3 dB/facet [4]). As shown in Fig. 2(b), the extinction ratio was over 25 dB in the entire C band for all child- and parent-Mach-Zehnder interferometer circuits. For reference, we also measured the extinction characteristics under actual push-pull drive conditions (Fig. 2(c)). Next, we investigated the wide-wavelength-range capabilities under the 2.0-V $V\pi$ condition because the optical absorption due to the applied bias was sufficiently low in the entire C+L band. For wide-wavelength-range operations, we fabricated two PICs, one with a multi-mode interferometer (MMI) waveguide, the other with a taper cross waveguide. Figure 3(a) shows the insertion losses of the two different designs. the maximum transmittance of the MMI type was slightly better than that of the taper type in C- or L-band operation. Although degradation due to the wavelength dependence of the MMI coupler can't be ignored in C+L-band operation, we could keep the extinction ratio over 25 dB throughout the C+L band, as shown in Fig. 3(b). On the other hand, the wavelength dependence was improved by the wavelength-insensitive taper cross waveguide.

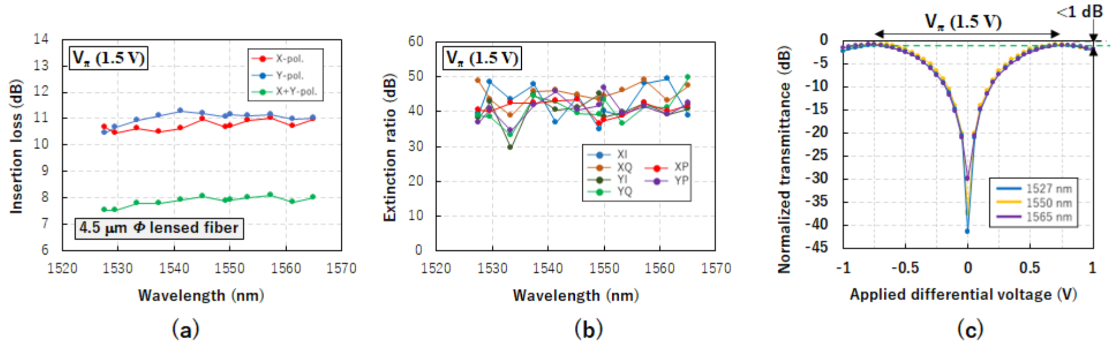

Fig. 2. DC characteristics under 1.5-V V_π condition (a) insertion loss, (b) extinction ratio, and (c) extinction curve (push-pull drive)

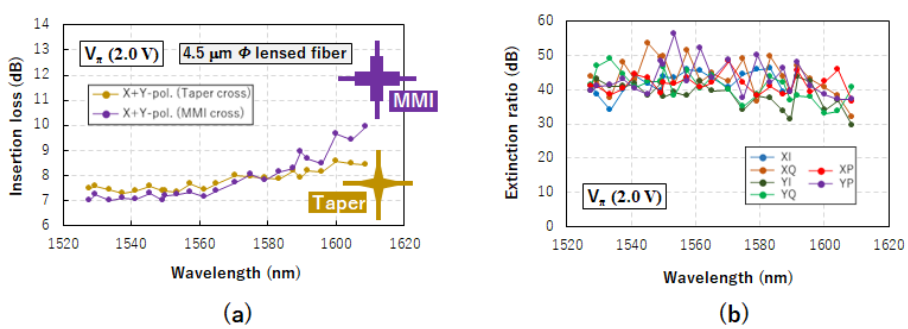

Fig. 3. DC characteristics under 2.0-V V_π condition (a) insertion losses of MMI- and taper-type cross waveguides, and (b) extinction ratio of MMI-type cross waveguide

3. High-frequency characteristics

Figure 4 shows the EO responses of three different modulator PICs which had the same length of CL- traveling-wave electrode (3.6 mm) and characteristic impedances (Z_0) designed to be around 60 Ω. For reference, Fig. 4(a) depicts the EO response of a 130-Gbaud-class commercial PIC. The 3-dB EO bandwidth was around 70 GHz, which was mainly limited by microwave loss and the parasitic capacitance of the TWE. Thus, we modified the electrode design and fabrication process, in which we shortened the period length of the capacitance-loaded TWE from 150 to 120 μm to increase the roll-off frequency determined by Bragg reflection and RC time constant. Figure 4(b) shows the results of the modifications. Although the 3-dB bandwidth reached 90 GHz, it was still not sufficient for 200-Gbaud-class operation. Next, we modified the structure of the optical waveguide because it strongly impacts the capacitance of the RF circuit. Thanks to this modification, we reduced the capacitance, which resulted in a further increase in bandwidth. As shown in Fig. 4(c), the 3-dB and 6-dB EO bandwidths exceeded 100 and 110 GHz, respectively. Owing to the reduction in capacitance, Z_0 of the CL-TWE was increased, which in turn enhanced the

EO response in the low-frequency region. We can flexibly control the response by adjusting the value of the RF termination resistor [5] or/and Z_0 of the CL-TWE. For example, we have room to increase the resister value when a higher Z_0 is required for co-designing with an analog IC. Moreover, we could decrease the Z_0 of the CL-TWE by employing a lower-microwave-loss electrode to increase the bandwidth further.

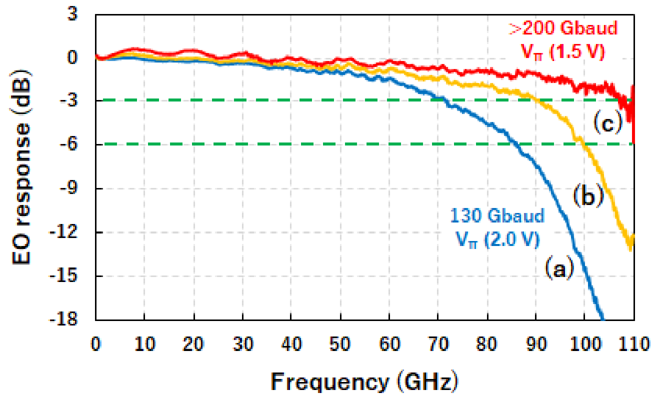

Fig. 4. EO responses of three variant PICs: (a) 130-GBaud-class product (reference), (b) electrode modification, and (c) electrode and optical waveguide modifications

4. Conclusion

We described our recent work on next-generation InP modulator PICs that can operate above 200 Gbaud. Here, we investigated not only the symbol rate but also wavelength scalabilities. The specifications are summarized in Table 1. By modifying both the electrode design and optical waveguide structure, we can extend the EO bandwidth without degrading the optical properties. These PICs will be ready for mass production in the near future. In addition, we expect that higher speed modulation can be achieved by further optimization of the optical waveguide and CL-TWE designs and by integration with a semiconductor optical amplifier (SOA).

Table 1. Modulator PIC spec. summary (Typ. value)

PIC Variants	130 Gbaud	>200 Gbaud (C+L ver.)	>200 Gbaud (Low V_π ver.)	
Wavelength λ	C or L band	C+L band	C or L band	
On-chip insertion loss (dB)	3.5	4.0	3.5	-- Incl. bias absorption for V_π -- X+Y pol. combined -- Excl. optical coupling loss (2.3 dB/facet)
EO bandwidth (dB)	>67 / >80	>100 / >110	←	-- @ 3 dB / 6 dB down
V_π (V)	2.0	←	1.5	-- RF electrode/ half-wave voltage -- DC measurement
V_π L (V·cm)	0.72	←	0.54	-- TWE: 3.6 mm long
P_π (mW)	<20	←	←	-- DC Phase electrode/ half-wave power -- TO heater control
Extinction ratio (dB)	>25	←	←	-- Both parent & child MZI
Impedance Z_0 (Ω)	60	←	←	-- CL-TWE modulation region -- Differential input/ series push-pull drive
Die size (mm^2)	5.0 × 2.5	←	←	

5. References

[1] J. Ozaki et al., "Over-85-GHz-Bandwidth InP-Based Coherent Driver Modulator Capable of 1-Tb/s/λ-Class Operation," J. Lightw. Technol., vol. 41, no. 11, pp. 3290–3296 (2023).
[2] Y. Ogiso et al., "Over 67 GHz Bandwidth and 1.5 V Vπ InP-Based Optical IQ Modulator With n-i-p-n Heterostructure," J. Lightw. Technol., vol. 35, no. 8, pp. 1450–1455 (2017).
[3] Y. Ogiso et al., "80-GHz bandwidth and 1.5-V Vπ InP-based IQ modulator," J. Lightw. Technol., vol. 38, no. 2, pp. 249–255 (2020).
[4] Y. Ogiso et al., "High-Bandwidth InP MZ/IQ Modulator PIC Ready for Practical Use," ECOC2022, paper Mo3F.3 (2022).
[5] X. Liu et al., "Capacitively-Loaded Thin-Film Lithium Niobate Modulator With Ultra-Flat Frequency Response," Photon. Technol. Lett., vol. 34, no. 16, pp. 854–857 (2022).