High-Bandwidth InP MZ/IQ Modulator PIC Ready for Practical Use

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Abstract *We present our recent work on a next-generation of high-bandwidth InP MZ/IQ optical modulator PIC with an n-i-p-n heterostructure which is ready for practical use in 130-GBd-class transmitters. The modulator PIC exhibits superior optical properties with over 67-GHz bandwidth.*

Introduction

Higher speed optical transmitters are becoming key components for overcoming the limitation of per-channel capacity [1, 2]. So far, up to 100-GBd optical transmitters with over 50-GHz bandwidth have been practically implemented for 800G/λ lineside systems. One promising configuration for such a high baud rate application is a coherent driver modulator (CDM), in which an electro-optic (EO) modulator photonic IC (PIC) and driver IC are co-assembled in a package [5, 6]. For the optical IQ modulator element, InP-based modulators have led the field because of their small footprint and superior material properties. On the other hand, high-speed demonstrations using other materials, such as thin-film $LiNbO_3$ (TFLN) with a single-ended drive configuration, have recently been reported [2-5]. Although TFLNs themselves have promising characteristics, they would face issues in co-designs with analog ICs because the single-ended drive configuration requires almost twice the peak-to-peak voltage from individual IC ports as the differential drive scheme given the same V_π. As a result, the high-frequency IC design would be limited by such a restriction on breakdown voltage, a complicated circuit topology, and so on. Furthermore, the increase in optical insertion loss due to the strong optical confinement of TFLN is a remaining challenge for obtaining a sufficient optical signal-to-noise ratio (OSNR).

In this paper, we report a high-bandwidth InP IQ modulator PIC in which a characteristic impedance of RF line is adjusted to be differential 60 Ω. Thanks to the use of an n-i-p-n heterostructure with low optical and electrical loss, we obtained a low insertion loss, high extinction ratio of over 28 dB, and high bandwidth of over 67 GHz while keeping V_π at less than 2.0 V.

Modulator PIC design for 130-GBd-class CDM

Figure 1(a) and (b) show a schematic diagram and microscope image of our twin-IQ modulator PIC, in which four Mach-Zehnder modulators (MZMs) are integrated in parallel. By adopting a new cross-waveguide element (optical crossing loss of less than 0.1 dB/cross for the entire C-band), we minimized the PIC footprint (2.5×5.0 mm^2) and obtained a symmetrical I-Q layout that offers a stable IQ-phase difference under long-term operation. As shown in Fig. 1(c), the PIC consists of an n-i-p-n heterostructure diode for RF modulation [7] and a thermo-optic (TO) heater for DC phase adjustment. Thanks to the thinner p-doped cladding layer, optical absorption due to the p-doping material can be minimized. The optical propagation losses in the RF modulation region and non-RF modulation region are 1.1 and 0.6 dB/cm, respectively. In order to obtain an

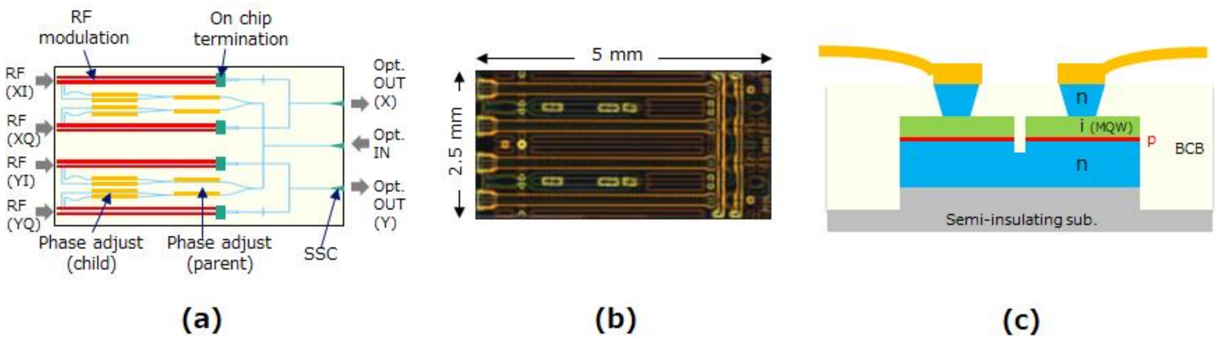

Fig. 1: Modulator PIC design. (a) Cross-section diagram, (b) schematic diagram, and (c) microscope image

efficient modulation depth for 130 GBd, a capacitance-loaded traveling-wave electrode with an on-chip RF termination resister was designed to have a characteristic impedance of differential 60 Ω, a value that was determined by co-designing with the driver IC. For the optical interface, we employed optical spot-size converters (SSC) in which the optical coupling loss between the PIC and lensed fiber (MFD 4.5 μmΦ) was 2.3 dB/facet.

Fundamental PIC characteristics

Figure 2 shows optical insertion losses of the IQ modulator PIC. The fiber-to-fiber insertion losses, which include the lensed-fiber coupling losses of 2.3 dB/facet and a polarization splitting loss of 3 dB, were less than 10.5 dB over the entire C-band. From these measurements, we also estimated that each polarization on-chip loss, which includes SSC mode conversion losses, was less than 6.0 dB, which is equivalent to or less than that of commercial bulk-$LiNbO_3$ DP-IQ modulators. Next, we measured the extinction ratio characteristics for all child- and parent-MZ interferometers. As shown in Fig. 3, the extinction ratio of over 28 dB was obtained over the entire C-band and for all channels, which is high enough for practical use. In the range of over 30 dB, the accuracy of the value was limited by the measurement setup. Figure 4 shows the wavelength dependence of half-wave phase shift power (P_π) at the TO phase adjusters. Although InP-based material has a slight wavelength dependence of TO efficiency, optical absorption due to the power apply can be ignored, which offers long-term high-extinction performance. The measured P_π was around 19 mW which is equivalent to that of a conventional Si-based TO phase adjuster.

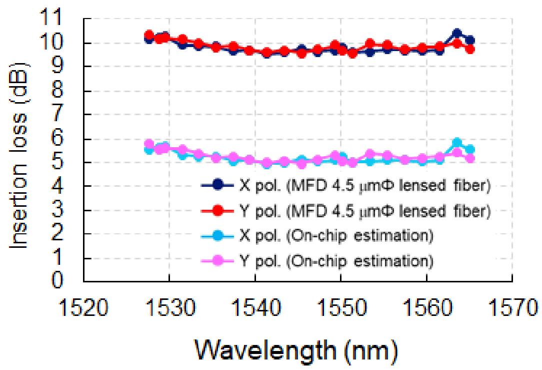

Fig. 2: Optical insertion losses for each polarization

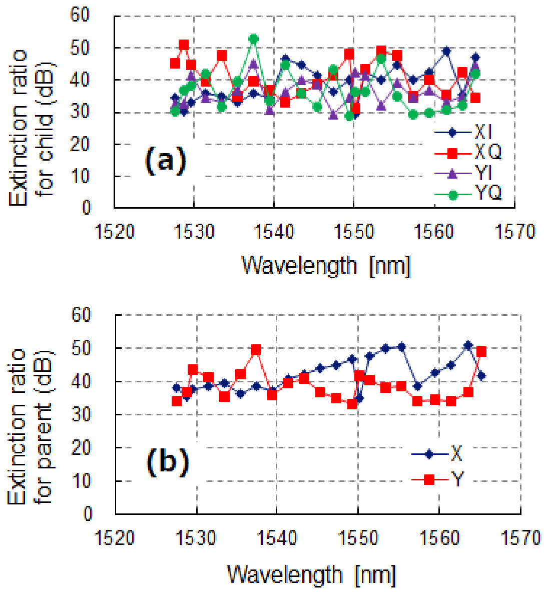

Fig. 3: Half-wave phase shift power (P_π) at TO phase adjusters

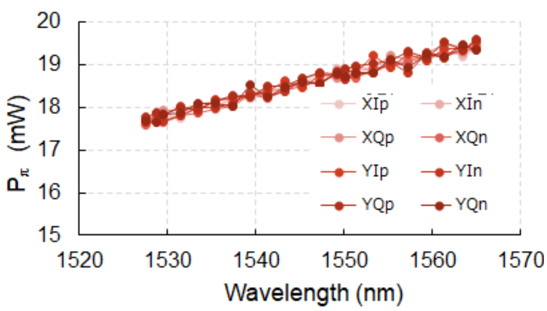

Fig. 4: Wavelength dependence of P_π at TO phase adjusters

High-frequency characteristics

We finally show the small-signal responses of the PIC. A 4-port lightwave component analyser (LCA) was used for the differential signal evaluation. Figure 5(a) and (b) show the EO response and electrical reflection SDD11, respectively, where we defined the input port impedance as differential 60 Ω. In general, there is a trade-off relation between the impedance and bandwidth. In order to increase the output voltage from the driver IC and obtain a deep modulation depth, a design that provides higher impedance for the PIC is preferred. In the experiments, we obtained the 3-dB EO bandwidth of over 67 GHz for the 60 Ω design, while a higher bandwidth of 80 GHz can be obtained by decreasing the impedance to approximately 50 Ω [7]. We also confirmed the clear periodical reflection of less than -14 dB for all channels, which is small enough for practical use.

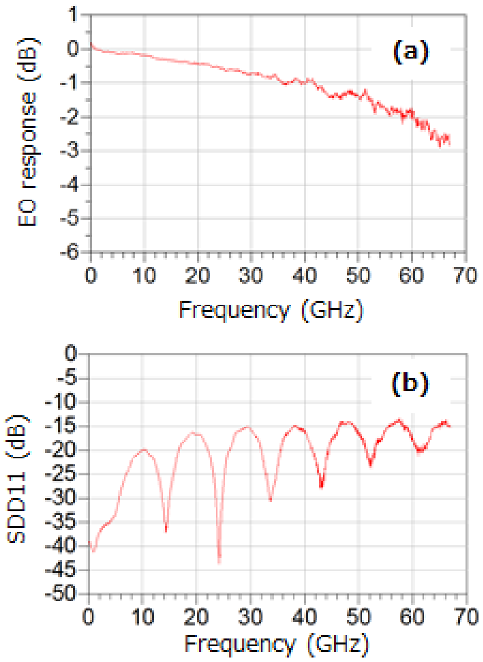

Fig. 5: Measured small-signal S-parameters of (a) EO response and (b) electrical reflection SDD11 without smoothing and averaging

Conclusion

We developed a low-optical-loss and high-bandwidth InP-based MZ/IQ modulator PIC, which is designed for use in a 130-GBd-class transmitter co-assembled with a driver IC. The PIC exhibits a low insertion loss of less than 10.5 dB, high-extinction ratio of over 28 dB, and high-bandwidth of over 67 GHz. This PIC is ready for practical use and is a promising component for the next generation of 130-GBd-class applications. We believe this low loss and high-speed modulator PIC can be applied for not only digital coherent but also IMDD applications.

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