Ultra-Compact DP-IQ Modulator with Hybrid Integration of InP-Based High-Speed Modulator and Si-Based Optical Circuit

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Abstract *We demonstrate a hybrid integration combining InP-based and Si-based PICs with a low-loss butt-coupling of 1.7 dB/facet. Mach-Zehnder modulators with the 3-dB-bandwidth of 85 GHz, a PBS and rotator, VOAs, and MPDs are successfully integrated in the ultra-compact size of 2.7 mm × 6.8 mm.*

Introduction

To meet the demands stemming from increases to global IP traffic, digital coherent optical communication systems have been widely introduced, and higher baud rates and smaller transceivers are now required to further increase capacity and system density. The coherent driver modulator (CDM), which is a key device for digital coherent optical communication, includes several functional optics such as twin in-phase quadrature-phase (IQ) modulators that convert electrical signals into optical phase modulation signals as well as free-space optics that perform polarization multiplexing (Pol-Mux) and optical coupling with optical fiber [1]. High-speed and compact modulators have shown very good potential for achieving high-capacity and high-density communication systems.

In terms of fabrication of such IQ modulators, it becomes more important to utilize both the proper materials and integration techniques. InP-based Mach-Zehnder modulator is widely utilized in practical applications thanks to its compactness, high-bandwidth, and low half-wave voltage ($V\pi$) characteristics [2]. But, although polarization functions can be integrated monolithically in InP-based devices, this comes at the cost of a complicated fabrication process that may lead to unstable characteristics [3]. Thus, free-space optics have been applied for InP-based dual-polarization (DP) IQ modulators, even though this requires a relatively large footprint, as shown in Fig. 1(a). The recently emerged thin-film Lithium niobate (TFLN)-based modulator is also candidate for high-speed IQ modulator that can be monolithically integrated with Pol-Mux [4, 5]. However, comparing InP-based and TFLN-based IQ modulators with high bandwidth and low $V\pi$ (e.g., f_{3dB} > 80 GHz and $V\pi$ < 2 V), InP should be more suitable for miniaturization since it has millimeter order modulator length against the centimeter order modulator length of TFLN. Si-Photonics (SiPh) technology enables one-chip monolithic integration of Pol-Mux and twin IQ modulators in a small size, but the resultant modulator characteristics have not yet reached the level of InP-based ones [6, 7]. A hybrid integration approach can combine practical chips fabricated with appropriate materials for optical functions. For example, the integration featuring an InP chip and silica-PLC chip has been reported [8]. However, lens is also used here to prevent a large coupling loss due to the mode-field mismatch stemming from the large difference in the refractive indices of the materials.

In this study, we demonstrate the hybrid integration of an InP-based compact twin high-speed IQ modulator with a SiPh-based compact Pol-Mux optical circuit by means of butt coupling. Our concept here is that the InP chip focuses on the high-speed modulator and the SiPh chip integrates other optical circuits, (e.g., Pol-Mux) in a compact size, through a simple integration process without lens. This will maximize not only the compactness and functionality but also the yield of the total fabrication. As a result, the size of the DP-IQ modulator can be significantly reduced while retaining the same functionality, as shown in Fig. 1(b). The SiPh chip can also achieve a low-loss coupling with the InP chip since its refractive index is close to that of the InP. We fabricated an InP-based twin IQ modulator chip with a 3-dB bandwidth of 85 GHz and a SiPh-based Pol-Mux chip with a polarization extinction ratio above 18 dB. By using these chips, we were able to demonstrate a compact DP-IQ modulator of 2.7 mm × 6.8 mm and achieve the low-loss coupling of 1.7 dB/facet at 1550 nm.

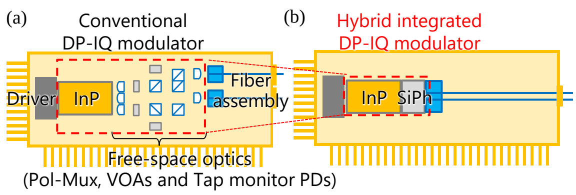

Fig. 1: Schematics of DP-IQ modulator in CDM with (a) free-space optics (conventional) and (b) hybrid integration (proposed).

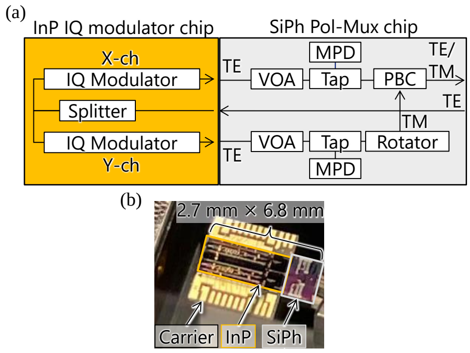

Fig. 2: (a) Block diagram and (b) photograph of fabricated DP-IQ modulator.

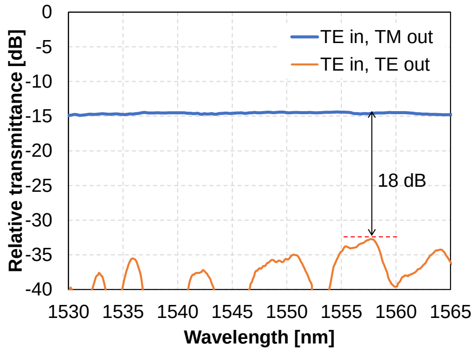

Fig. 3: Relative transmittance via TE-TM rotator and PBC.

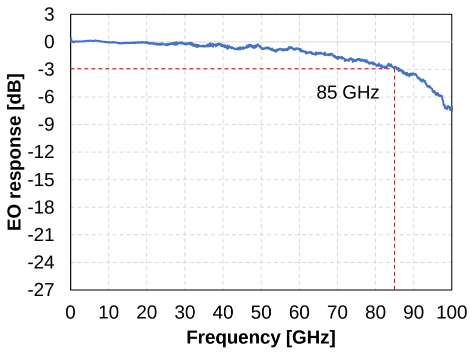

Fig. 4: Small signal EO response.

Design and fabrication

Figure 2(a) shows a block diagram of the DP-IQ modulator we fabricated. The InP chip consists of a splitter and a pair of four Mach-Zehnder modulators that function as the IQ modulator in each channel. To achieve both high-bandwidth and low $V\pi$, the modulator design follows previous design [2]. The SiPh chip includes a polarization beam combiner (PBC), rotator, variable optical attenuators (VOAs), and tap monitor PDs (MPDs). Each compact InP chip (2.5 mm × 5.0 mm) and SiPh chip (2.7 mm × 1.8 mm) is monolithically fabricated in different processes.

Then, we evaluated the characteristics of the fabricated Pol-Mux chip at 1550 nm. On-chip losses of X-ch and Y-ch were 3.0 dB and 3.8 dB, respectively, and the input TE light of Y-ch was converted to TM light through the rotator and coupled with the TE light of X-ch in PBC. Figure 3 shows the relative transmittance via the rotator and PBC. As we can see, the input TE light was effectively converted to TM light, and the high extinction ratio of over 18 dB at wavelengths between 1530 nm and 1565 nm was confirmed. Figure 4 shows the EO response of the modulator chip at 1550 nm. We found that the modulator had the 3-dB bandwidth of 85 GHz and $V\pi$ of less than 2 V, which makes it a candidate for over 150-Gbaud operation. To achieve such a high bandwidth, the modulator includes an InP-based n-i-p-n heterostructure with a differential capacitively loaded traveling-wave electrode (CL-TWE) [1, 2].

We utilized a butt coupling of InP and SiPh waveguides as our hybrid integration approach, as this eliminates the lens required for optical coupling and enables integration with a smaller size and simpler alignment process than free-space optics [9]. First, we optically aligned two optical fibers of the fiber assembly (FA) with two waveguides of the SiPh and fixed them with UV adhesive. When using this SiPh-FA, SiPh and InP waveguides can be aligned and fixed in the same way. The loss difference of between before and after UV adhesive curing is lower than 0.1 dB, which means this butt coupling should be a stable integration process. This simple integration process also reduces the number of assembly terms. As shown in Fig. 2(b), the fabricated DP-IQ modulator has a size of 2.7 mm × 6.8 mm. Thanks to hybrid integration of compact InP and SiPh chips, the fabrication of an ultra-compact DP-IQ modulator is successful.

Experimental Results

We evaluated the optical characteristics of the fabricated DP-IQ modulator and investigated the low-loss optical coupling. The TE light input to the Pol-Mux chip input port and the output optical power was measured at the Pol-Mux chip output port. The bias voltage of each Mach-Zehnder interferometer was adjusted as light through. The insertion loss of 15.4 dB was confirmed at 1550 nm. Next, to see if the optical loss could be reduced, we examined the InP-SiPh coupling loss. A test SiPh chip featuring SSCs with the same design as in Pol-Mux and a new design intended for smaller mode-field adjusting to the InP waveguide was fabricated. Figure 5 shows tolerance curves of InP-SiPh coupling with InP and SiPh test chips. The InP chip has U-shaped waveguide and the SiPh chip has two straight waveguides. The light is input from the SiPh, coupled to the InP, and then coupled back to the SIPh side for light output. Therefore, the tolerance curves with double path of the coupling section become narrower than single path. We confirmed the tolerance curve of the new SSC design is narrower than that of the Pol-Mux, which reflects the intention of introducing the new SSC design to have a smaller mode-field of SiPh. Figure 6 shows the coupling loss with the use of each SSC design in the test SiPh chip. Against the optical coupling with lensed fiber (~3.5 dB/facet), a low-loss of 2.9 dB/facet with the SSC in Pol-Mux and a further low-loss of 1.7 dB/facet with the new SSC design was obtained at 1550 nm. This SSC improvement of –1.2 dB/facet means there is room for a further loss reduction of the DP-IQ modulator insertion loss up to 13.0 dB.

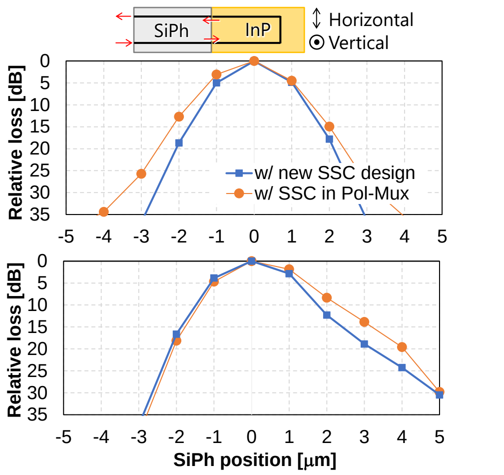

Fig. 5: InP-SiPh tolerance curve (a) horizontal and (b) vertical.

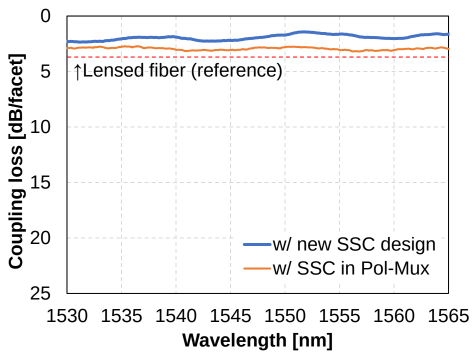

Fig. 6: InP-SiPh coupling loss.

Conclusions

We demonstrated the hybrid integration of InP modulators with SiPh Pol-Mux and successfully fabricated an integrated DP-IQ modulator with the ultra-small size of 2.7 mm × 6.8 mm. A low-loss InP-SiPh optical coupling of 1.7 dB/facet was also achieved. This ultra-high-speed and ultra-compact DP-IQ modulator is a promising candidate for future digital coherent communication systems.

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