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Ultra-high bandwidth and low-drive voltage InP Mach-Zehnder modulators

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Abstract
We report recent advances in high speed electro-optic (EO) modulation utilizing a Mach-Zehnder interferometer (MZ) type modulator for optical fiber communication. By introducing both a new n-i-p-n heterostructure and an optimized traveling-wave electrode, high-frequency electrical losses of the modulator can be drastically reduced. As a result, we extended the bandwidth without degrading other properties such as half-wave voltage (V_π) and optical losses. The 3-dB EO bandwidth of the 1.5-V V_π modulator reaches 80 GHz. We also demonstrated beyond 100-GBd modulations for next-generation terabit signal generation.

1. Introduction
The demand for huge-capacity data transmission is continuously increasing in optical communications. To meet the demand, digital coherent technologies are being intensively developed. In digital coherent systems, IQ modulators that are composed of dual or quad parallel MZ modulators have been generally used because of their low-chirp characteristics as shown in Fig. 1. Thus, higher speed MZ modulators are becoming a key element for realizing next-generation terabit-class high-speed optical transmitters. Regarding an approach for high-speed modulation, a higher baud rate is preferred to higher-level modulations in terms of the transmission distance for a given capacity per lambda [1]. In order to increase the baud rate, both an EO bandwidth and a V_π of the modulator must be further improved, e.g., a bandwidth of over 60-GHz and a V_π of less than 2.0 V would be required for the next beyond-100-GBd-class modulation. InP-based modulators are promising for high baud rate operation because of their superior and stable material properties, and several 100-GBd-class demonstrations have already

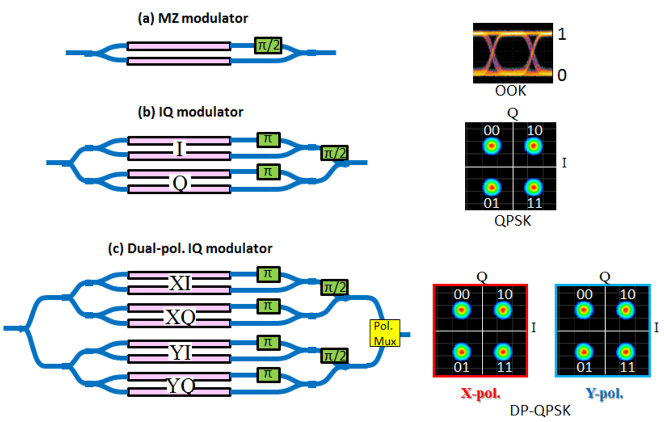

Fig. 1. Schematic images of (a) MZ modulator, (b) IQ modulator, and (c) dual-pol. IQ modulator.

been reported [2]. However, their EO bandwidths are limited to less than 55 GHz by a high series resistance of the p-doped layer, and they are still not sufficient for beyond 100-GBd modulations. Although other material approaches have also been studied by utilizing hybrid and adhesion technologies [3], total performance, including its operation stability, has not been well established for practical implementation.

In this paper, we report an ultra-high speed InP-based modulator for beyond 100-GBd transmitters. By replacing the conventional p-i-n heterostructure with a new n-i-p-n heterostructure, we reduced the series resistance of the semiconductor and extended the bandwidth without degrading other properties such as V_π and optical insertion loss. The IQ modulator exhibits an EO bandwidth of 80 GHz in a 1.5-V V_π design, which is the best modulation performance reported so far. Furthermore, we demonstrated up to 128-GBd IQ modulations by utilizing the modulator with an

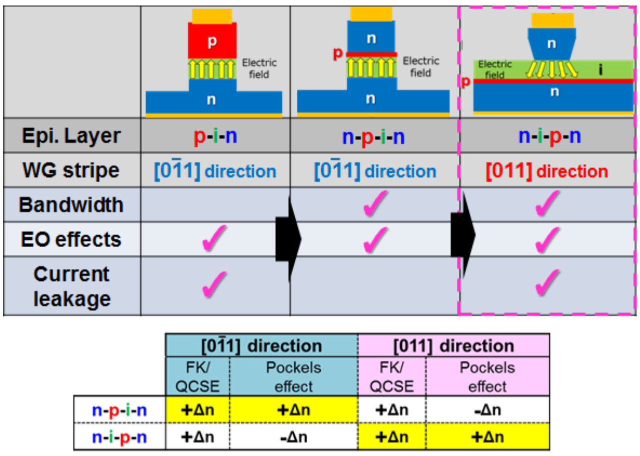

Fig. 2. Progress toward optimized high-speed modulator.

InP-based high-speed driver IC [4].

2. MZ modulator design
First, we describe the progress toward an optimized modulator structure for high-speed modulation. Figure 2 shows a comparison of some modulation structures. The left structure depicts a conventional p-i-n structure. For extending the bandwidth without degrading other properties, we first replace a thick p-doped layer with a thick n-doped layer and thin p-doped layer as shown in the middle structure [9]. The p-doped layer acts as an electron carrier blocker and enables applying efficient voltage across a non-doped core layer. In the structure, however, we have to be cautious about current

leakage because the structure is potentially sensitive to side-wall damage due to dry etch processing. Thus, in order to obtain long-term electrical stability, we rotated the waveguide stripe to the [011] direction and formed an inverted-trapezoidal ridge waveguide for eliminating side-wall leakage current. In addition, we inserted the thin p-doped layer under the non-doped layer for obtaining a synergistic electro-optic effect [5] as shown in the right structure.

Figure 3 shows a schematic illustration and cross-section diagrams of the proposed MZ modulator. The combination of the n-i-p-n heterostructure and a capacitance-loaded traveling-wave electrode (CL-TWE) provides an extremely low electrical loss that extends the bandwidth without degrading other properties [6]. By using the single-MZ modulator, we obtained a clear eye opening of 100-Gb/s NRZ-OOK modulation. In the I/O passive waveguide, we used a deep-ridge shape waveguide.

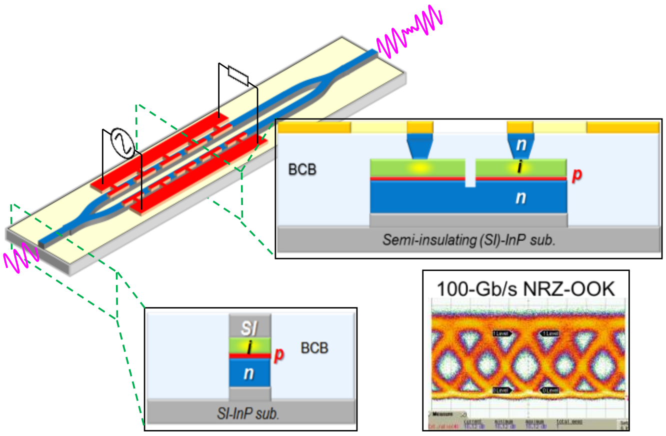

Fig. 3. Progress toward optimized high-speed modulator.

3. Experimental results

Measured DC extinction characteristics at a wavelength of 1550 nm are shown in Fig. 4. We measured on both a single-arm drive and under push-pull drive conditions. Low optical absorption and symmetrical characteristics were obtained. In the push-pull operation, the applied DC bias voltage was adjusted for a V_π of less than 1.5 V. The static extinction ratio (ER) was better than 25 dB for all channels.

Figure 5 shows the EO responses of the IQ modulator. Smooth roll-off characteristics were obtained in the range of over 100 GHz. The 3-dB and 6-dB EO bandwidth reached approximately 80 and 100 GHz, respectively. The results indicate that our modulator has the potential for over 200-GBd operation.

Finally, we obtained back-to-back results of over 100-GBd IQ modulations. In the experiment, we used the IQ modulator co-assembled with a high-speed driver IC. Figure 6 shows the constellation diagrams of 112-GBd 16QAM and 128-GBd QPSK. Clear constellations for both modulations were obtained. Theses bit-error-ratios (BERs) were well below the threshold for soft-decision 20%-overhead forward error collection.

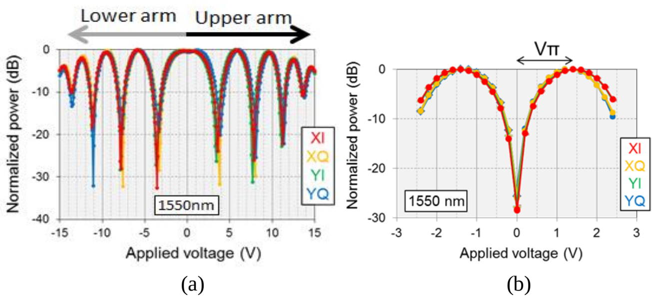

Fig. 4. Static extinction characteristics of the dual-pol. IQ modulator. (a) single-arm drive and (b) push-pull drive conditions

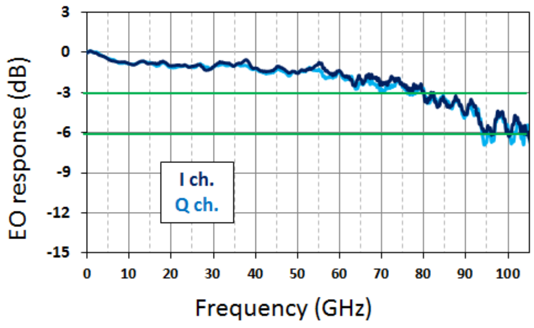

Fig. 5. EO response of IQ modulator.

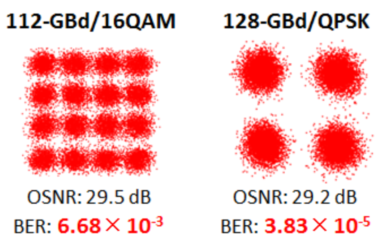

Fig. 6. Constellation diagrams of 112-GBd 16QAM and 128-GBd QPSK signals.

4. Conclusion

We developed promising MZ and IQ modulators for terabit signal generation. The device exhibits a 3-dB EO bandwidth of approximately 80 GHz and 1.5-V V_π. We demonstrated up to 128-GBd IQ modulations. Furthermore, up to 192-GBd IQ modulations were also reported by combining high-speed analog ICs [7].

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