

Miniaturized Optical DP-QPSK Modulator Module with 3.2-W Power Dissipation Using InP-Based Modulator and Driver ICs

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Abstract— We have fabricated a compact and low-power dual-polarization quadrature phase-shift keying (DP-QPSK) modulator module for optical coherent transceivers. This module includes an InP-based electro-optic modulator, four driver ICs, and polarization multiplexing micro-optics. The package size is 16.5 mm × 34.0 mm × 6.0 mm. We demonstrate 128 Gbit/s DP-QPSK operation capability with a very low power dissipation of 3.2 W. This low power dissipation was achieved by using a low-power two-stage limiting driver IC with 3.3-V and 5.2-V power supplies in combination with an InP-based low- V_{π} modulator and 1.4V $_{\pi}$ driving.

Keywords— Coherent communication; integrated optics; III-V semiconductors; advanced modulation format; Mach-Zehnder modulators; driver circuits

I. INTRODUCTION

There is growing interest in optical transmission systems based on digital coherent technology with multi-level modulation formats at data rates of 100 Gbit/s and higher [1], and first generation commercial systems are now being deployed for ultra-long-haul transmission. In the next generation, the application area will be expanded to metropolitan area networks, and smaller-sized, lower-power optical components are in high demand in order to achieve such next generation digital coherent systems.

InP-based electro-optic modulators are very attractive in creating small-sized, low-power modulator modules because of

their smaller die size and low- V_{π} characteristics, compared with conventional LiNbO₃ modulators. Such low- V_{π} characteristics contribute to reducing the power dissipation of driver ICs. InP-based modulators for the dual-polarization quadrature phase-shift keying (DP-QPSK) format have recently been demonstrated [2–4]. These modulators are, however, not packaged with both of the polarization multiplexers and driver ICs.

We have created a DP-QPSK modulator module in which an InP-based modulator, four driver ICs, and polarization multiplexing micro-optics are all assembled in one package with hybrid integration technology [5]. The package dimension is merely 16.5 mm × 34.0 mm × 6.0 mm. A 128 Gbit/s DP-QPSK modulation at a low differential driving voltage of 2.5 V_{pp}, corresponding to 1.4V $_{\pi}$, is demonstrated. Because of the low driving voltage, the total power dissipation for the four driver ICs and thermo-electric cooler (TEC) was suppressed to 3.2 W.

II. MODULE CONFIGURATION

Fig. 1 shows a block diagram and a photograph of a fabricated module, which includes an InP-based DP-QPSK modulator, four differential driver ICs, polarization multiplexing micro-optics, and a TEC. Four Mach-Zehnder (MZ) modulators are monolithically integrated on the InP substrate. The TEC is placed under the modulator and the micro-optics to keep those temperatures constant.

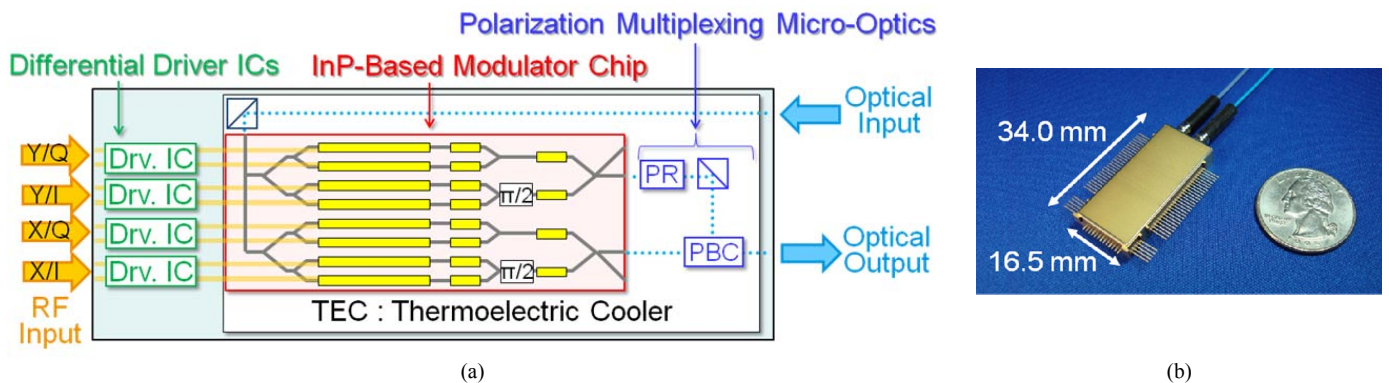


Fig. 1. DP-QPSK optical modulator module, including driver ICs and polarization multiplexing micro-optics: (a) Block diagram and (b) photograph. PR : Polarization Rotator. PBC : Polarization Beam Combiner.

To implement four driver ICs within this small package, we designed these ICs so that they could be operated without any inductors for DC biasing. In addition to the small size of the package itself, this built-in driver IC configuration saves the total footprint compared to a conventional configuration consisting of a separated modulator and driver ICs. For further space saving, we locate the input and output optical fibers on the same side, and RF interfaces on the opposite side.

III. INP-BASED MODULATOR

A. Design and Fabrication

Fig. 2(a) shows a top-view photograph of the modulator chip with a 3-mm modulator section. Fig. 2(b) is a cross-sectional view of the MZ modulator section. We adopted a differential S-G-S type electrode configuration, because it enables us to locate RF line traces within a limited area.

The optical waveguides are deeply etched into the n-InP layer, with a height of 3 μm . The waveguides are buried with a thick benzocyclobutene (BCB) layer in the modulator section [6]. RF feed lines are located on the BCB layer. The differential characteristic impedance of the modulator section and feed lines was designed to be 90 Ω . Thus, the driver IC output impedance was designed to match with 90 Ω .

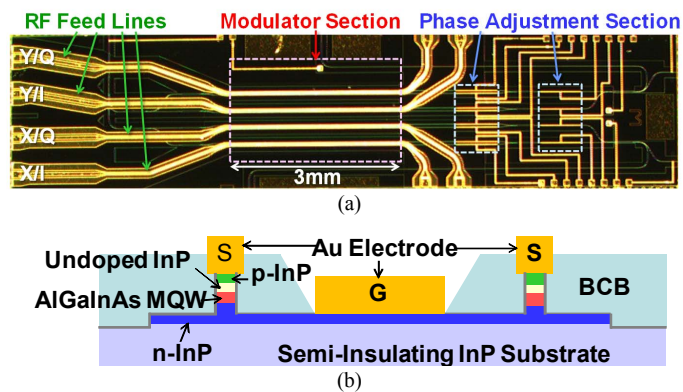


Fig. 2. InP-based modulator: (a) Top-view photograph and (b) cross-sectional view of modulator section.

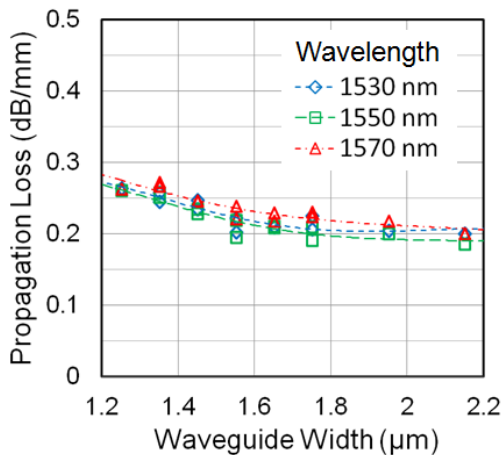


Fig. 3. Propagation loss of passive optical waveguide as a function of waveguide width.

We designed the optical waveguides so that both propagation loss and V_π became low. The undoped core was made of AlGaInAs multiple quantum wells (MQWs), which exhibit higher modulation efficiency (phase shift per loss) compared with GaInAsP MQWs at high bias voltage. The core thickness was 500 nm, and we obtain the maximum optical confinement with this thickness while keeping the single-mode condition. In addition, an undoped InP layer was inserted between the core and p-doped cladding layer for further reduction of the propagation loss.

B. Chip Characteristics

Fig. 3 shows the measured optical propagation loss characteristics of a passive waveguide as a function of the waveguide width [6]. The propagation loss for 1.6- μm width waveguides was as low as 0.23 dB/mm over the C band.

Fig. 4 shows the optical loss increase due to the reverse bias of the MZ modulator section. The loss was well suppressed even with high voltages of up to 12 V at a wavelength of 1570 nm, as expected. Fig. 5 shows a typical DC extinction characteristic for a wavelength of 1570 nm, and we obtained a DC extinction ratio (ER) of more than 25 dB.

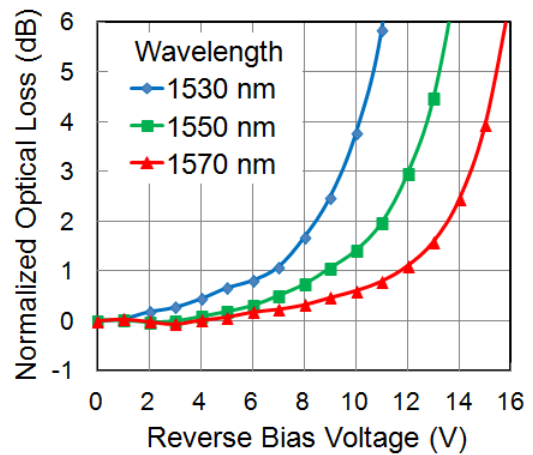


Fig. 4. Dependence of optical loss on bias voltage.

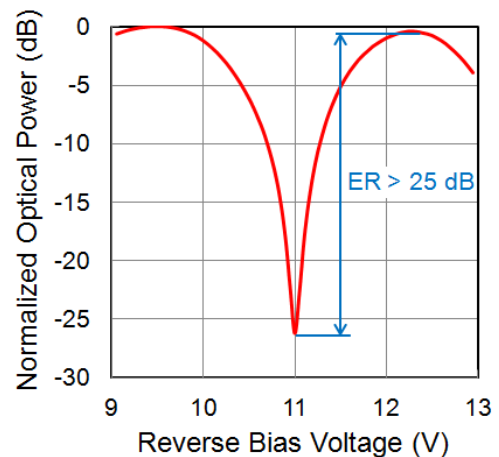


Fig. 5. Typical DC extinction characteristics.

IV. DRIVER ICs

As mentioned above, the driver IC we developed does not require any inductor for DC biasing. In general, such inductorless configuration saves space but consumes much power [7]. Therefore, we adopted a two-stage differential limiting amplifier configuration to the driver IC with 3.3-V and 5.2-V power supplies, and fabricated it with a high performance InP double heterojunction bipolar transistor (DHBT) process with f_T/f_{\max} of 150/200 GHz.

As shown in Fig. 6, high quality output waveforms at 32 Gbit/s, with a fast rise/fall time ($t_r/t_f < 9$ ps) and little noise, were confirmed. The minimum differential input voltage swing is 500 mV_{pp}. The power dissipation of the single IC is only 0.6 W when the differential output voltage swing is 2.5 V_{pp}. The chip size is 1.06 mm × 2.04 mm.

V. MODULE PERFORMANCE

A. High-Speed Performance

On-off-keying (OOK) eye diagrams with 32 Gbit/s non-return-to-zero differential signal inputs were measured to examine the high-speed performance of the fabricated module. The differential output voltage swing of the driver ICs was set at 1.8 V_{pp}, and the DC bias voltage was adjusted so that the dynamic ER became maximized. The additional loss induced by DC biasing was less than 1 dB.

As shown in Fig. 7, we obtained clear eye-opening for all the four MZ modulators. Fig. 8 shows dynamic ERs at the three wavelengths covering the C band. All the ERs are higher than 10 dB. These results indicate V_π is as low as 1.8 V at each bias condition, because a differential driving voltage swing

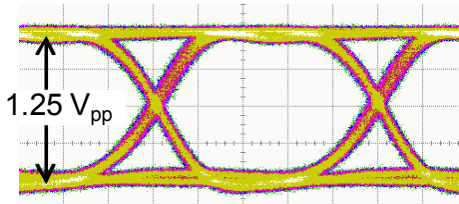


Fig. 6. 32 Gbit/s driver output waveform for single port.

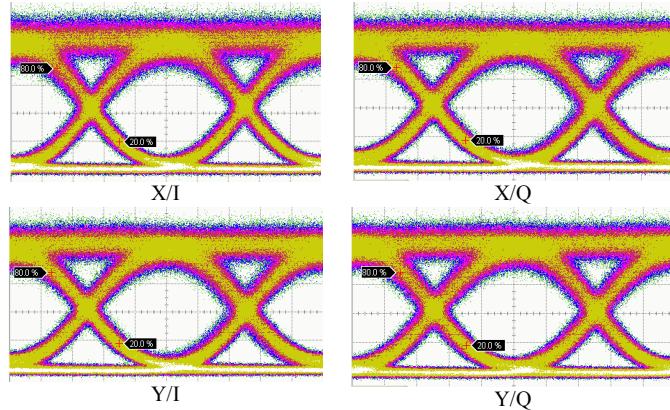


Fig. 7. 32 Gbit/s OOK output optical waveforms of module.

giving the maximum dynamic ER is supposed to be equal to V_π in the OOK modulation condition.

B. DP-QPSK Modulation Performance

Fig. 9 shows QPSK eye diagrams for each polarization of X and Y. The triple lines for the QPSK modulated signal are clearly observed. We tuned the driver ICs so that the differential output voltage was as low as 2.5 V_{pp}. Although this under driving condition (1.4V_π) reduces the peak optical output power by 1 dB compared with the conventional 2V_π driving condition, this saves the IC power dissipation by 25%.

We measured the DP-QPSK constellations at 128 Gbit/s (32 Gbaud) with use of digital coherent detection. The local oscillator power, the optical signal-to-noise ratio, and the input signal power to the receiver were set at 10 dBm, 20 dB, and -10 dBm, respectively. The clear constellations shown in Fig. 10 were obtained with this under driving condition.

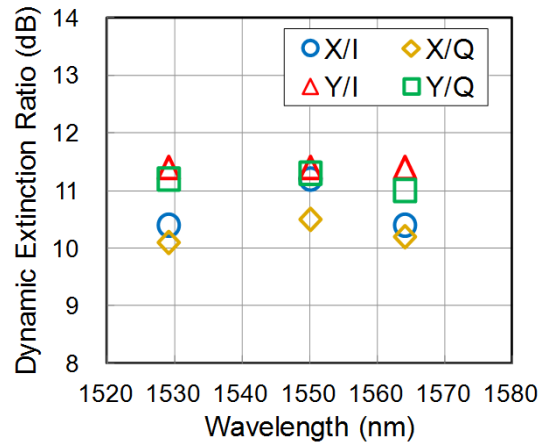


Fig. 8. Dynamic extinction ratios.

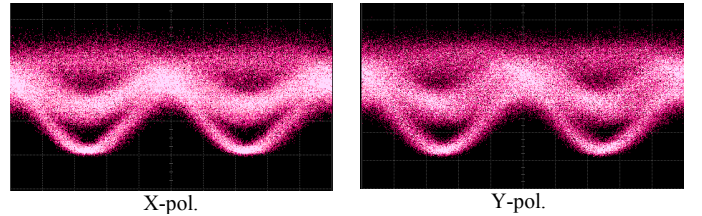


Fig. 9. QPSK output waveform.

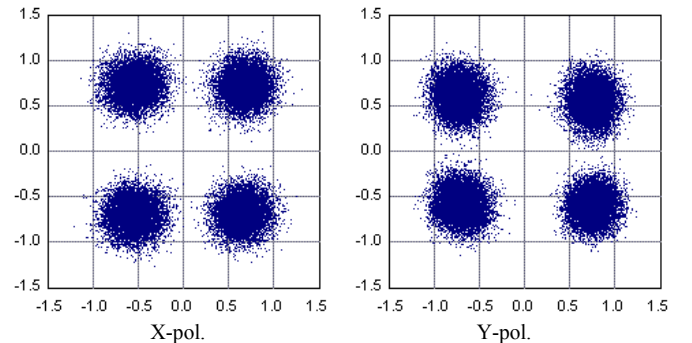


Fig. 10. 128 Gbit/s DP-QPSK constellation.

C. Power Dissipation

We evaluated the power dissipation of the TEC and driver ICs, both of which dominate the power dissipation of the module. In the module, the InP modulator is on the TEC, while the driver ICs are off the TEC. The specified case temperature range is from -5°C to 75°C .

Fig. 11 shows the power dissipation of the TEC for the case temperatures of -5°C and 75°C . At the modulator chip temperature of 39.5°C , the power dissipation was 0.8 W for both case temperatures. Fig. 12 shows the power dissipation of the four driver ICs. It was slightly below 2.4 W and almost constant over the three measured temperatures. Adding 0.8 W for the TEC and 2.4 W for the driver ICs, the total power dissipation becomes 3.2 W.

VI. CONCLUSION

We have presented an optical DP-QPSK modulator module, including an InP-based modulator, four differential driver ICs, and polarization multiplexing micro-optics. In spite of such complexity, the package size is only $16.5\text{ mm} \times 34.0\text{ mm} \times 6.0\text{ mm}$.

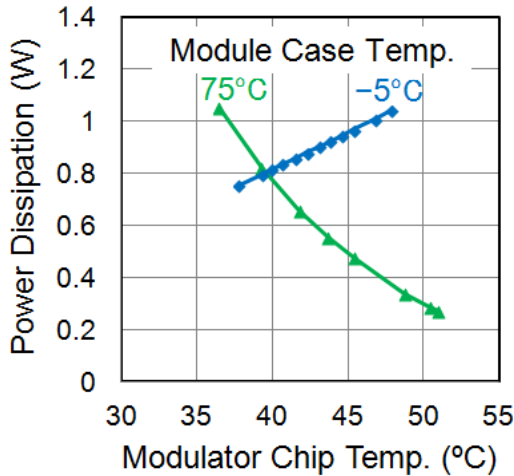


Fig. 11. Power dissipation for TEC.

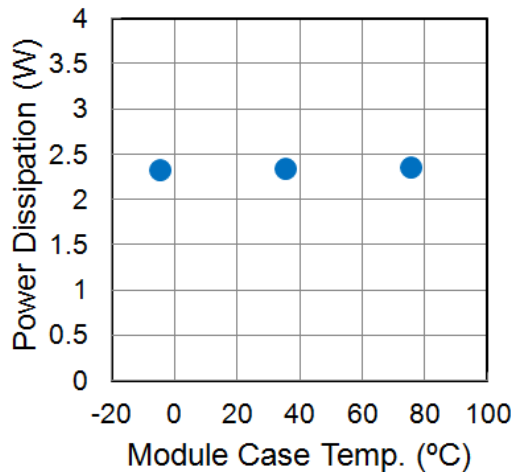


Fig. 12. Power dissipation for four driver ICs.

The power dissipation was as low as 3.2 W: 0.8 W for the TEC and 2.4 W for the four driver ICs. This is because of (i) a low differential modulator driving voltage of 2.5 V_{pp} , achieved by the InP-based low- V_{π} modulator and 1.4 V_{π} driving, and (ii) the two-stage InP-DHBT-based driver ICs with 3.3-V and 5.2-V power supplies.

The small footprint and low power dissipation make our module highly suitable for next generation transceivers for metropolitan area networks.

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