Demonstration of 155 Gbaud PAM4 and PAM6 EML with Narrow High-Mesa EA Modulator for 400 Gbps per Lane Transmission

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Abstract: We experimentally demonstrated 400 Gbps-per-lane EML with narrow high-mesa EA modulator. TDECQ less than 3.3 dB at 310 Gbps (155 Gbaud PAM4) and clear eye diagram at 400 Gbps (155 Gbaud PAM6) were achieved.

OCIS codes: (140.5960) Semiconductor lasers; (250.4110) Modulators

1. Introduction

Recent emerging technologies such as machine learning and artificial intelligence expedite the growth of data traffic in data centers, which require high-speed optical communication. Generally, higher speed optics can realize fast and energy efficient communication scheme. 400 Gbps transceivers using 4-lanes of 100 Gbps are now installed in datacenters, and the next generation of 800 Gbps and 1.6 Tbps transceivers are being discussed [1]. Electro-absorption modulator integrated laser (EML) is eligible for high-speed intensity modulation and direct detection (IM-DD) transmitter for intra-data center network because of wide bandwidth, small footprint, and low power consumption. Some groups demonstrated 200 Gbps per lane PAM4 transmission using EMLs [2-5], which are recognized as a promising solution.

As data traffic is expected to continue to increase, high-speed optics faster than 200 Gbps per lane should be considered in near future. When data rate evolution is considered, 400 Gbps per lane transmitter will be expected because they could contribute to 8-lane 3.2 Tbps transceiver and single lane 400 Gbps transceiver. Some studies regarding 400 Gbps per lane EMLs have already been reported [6, 7]. However, more data is needed to discuss the feasibility of IM-DD 400 Gbps per lane operation.

In this work, we developed high-speed EML for 400 Gbps per lane operation with a narrow high-mesa electro-absorption modulator (EAM) and experimentally demonstrated 310 Gbps (155 Gbaud PAM4) and 400 Gbps (155 Gbuad PAM6) operations. To increase the bandwidth, we optimized a termination resistor value connected to an EAM and wire lengths between an EAM to a sub-mount. In addition to that, we developed a breakthrough EML chip by narrowing the width of a high-mesa EAM, which resulted in an improvement in 3-dB bandwidth by 4 GHz compared with the conventional-width high-mesa EAM without a reduction of an extinction ratio. An improved 3-dB bandwidth of 85 GHz enabled the EML to operate at 155 Gbaud PAM4 and 155 Gbaud PAM6. TDECQ less than 3.3 dB at 310 Gbps (155 Gbaud PAM4) was achieved from back-to-back eye diagram. We also successfully obtained clear eye diagram at 400 Gbps (155 Gbaud PAM6) both at back-to-back and after 500 m transmission. Our result suggests the possibility for optical communication to realize a 400 Gbps per lane IM-DD operation.

2. EML design

A schematic structure of our developed EML is shown in Figure 1. This EML has a unique hybrid waveguide structure, which combines a buried heterostructure distributed feedback laser diode (DFB-LD) for high optical output power and a high-mesa EAM waveguide for a high extinction ratio and a high-speed operation [5, 8]. A spot-size converter (SSC) contributes to a high fiber coupling coefficient. The EML chip was assembled on a wide bandwidth sub-mount designed for 200 Gbps modulation with a conventional junction-up bonding method and bonding wire [9]. To increase the bandwidth, we chose a 40-ohm termination resister instead of 50-ohm which we applied in our previous work [5]. The length of the wires from EAM to the sub-mount was also optimized.

We fabricated two types of EML chips with a wavelength of 1311 nm. One of them has a high-mesa EAM with the same waveguide width as the EAM for 100 Gbaud operation [5], and the other has a high-mesa EAM with a narrower waveguide width to reduce the electrostatic capacity by about 20 %. A short EAM is a well-known option for small electrostatic capacity, but it also decreases an extinction ratio because it is proportional to the length of an EAM. On the other hand, a narrow-waveguide EAM is supposed to show approximately the same extinction ratio as

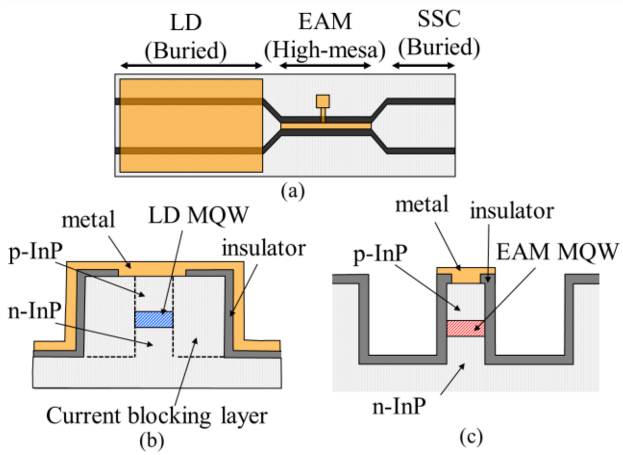

Fig. 1. Schematic structure of hybrid-waveguide EML
(a) Top view of entire chip
(b) Cross-sectional view of buried LD
(c) Cross-sectional view of high-mesa EAM

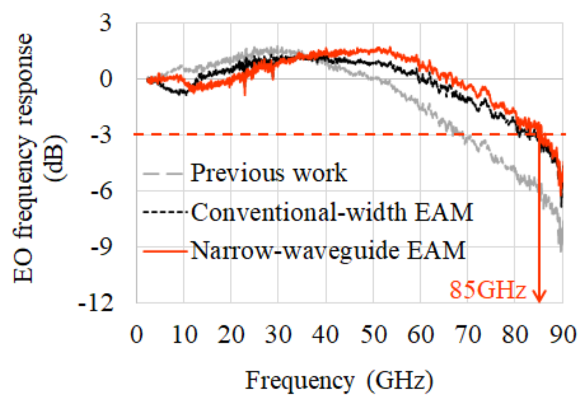

Fig. 2. EO frequency response (S21) of the EML chip on sub-mount, If = 60 mA, EA bias = -1.8 V at 50°C

a conventional-width-waveguide EAM in a high-mesa structure. As the refractive index of the insulator layer that works as a cladding layer in the EAM is lower than that of semiconductor, light strongly confined in the absorption layer of the EAM. Under this condition, the optical confinement factor in the absorption layer of the EAM is kept roughly the same even if the width of the absorption layer is different. This is the reason the extinction ratio does not decrease in a narrow-waveguide EAM. Therefore, we consider a narrow-waveguide high-mesa EAM is the best solution for beyond 200 Gbps per lane operation.

3. Experimental result

Figure 2 shows the electro-optic (EO) frequency response (S21) of the EMLs on sub-mounts. We confirmed that the bandwidth is improved by 18 GHz by optimizing the termination resister and the wire lengths compared with our previous work. We also verified that the EML with the narrow-waveguide EAM obtained an 85 GHz 3-dB bandwidth which is higher by 4GHz than the EML with the conventional-width EAM.

We experimentally evaluated 145 Gbaud, 150 Gbaud and 155 Gbaud PAM4, and 155 Gbaud PAM6 optical eye diagrams. Measurements were conducted by contacting a probe directly to a sub-mount. An electrical signal was generated by an arbitrary waveform generator (AWG, Keysight M8199B). An output electrical signal was constructed with a raised cosine pulse shaping filter, and the peak-to-peak modulation amplitude was about 0.8 Vpp, which was the maximum voltage swing available in the evaluation setup. Optical eye diagrams were captured by a sampling oscilloscope (Keysight, N1030A) applying a 60-GHz 4^{th} order Bessel-Tomson filter, which was the maximum filter bandwidth in the setup, followed by a 5tap T-spaced transmitter and dispersion eye closure quaternary (TDECQ) reference equalizer. The EMLs were measured at 50°C controlled by a thermo-electric cooler (TEC). DC bias voltage which makes a linear optical eye diagram was applied to the EAM part through a bias tee, and a DC operation current of 60 mA was applied to the DFB-LD part.

Figure 3 (a) shows electrical signal, back-to-back (BTB) optical eye diagram, and optical eye diagram after 500 m transmission obtained from the EML with the narrow-waveguide EAM after a TDECQ reference equalizer. Clear eye diagrams were obtained at 155 Gbaud PAM4 (310 Gbps) and 155 Gbuad PAM6 (400 Gbps) both at BTB and after 500 m transmission. Figure 3 (b) compares the measured PAM4 extinction ratio dependences on symbol rate between EMLs with the narrow-waveguide EAM and the conventional-width EAM. This figure clearly shows that the extinction ratios of these EMLs are similar value, which is reasonable because the simulated optical confinement factor of these EAMs was approximately the same. Figure 3 (c) compares the measured PAM4 TDECQ dependence on symbol rate of EMLs with the narrow-waveguide EAM and the conventional-width EAM at BTB configuration. TDECQ was calculated with a target symbol error ratio (SER) at 9.7×10^{-3}, which is for KP4 Forward Error Correction (FEC) with soft decision concatenated FEC proposed in IEEE802.3df [1]. The EML with the narrow-waveguide EAM showed lower TDECQ than the one with the conventional-width EAM. We suppose the small electrostatic capacity of the narrow-waveguide EAM contributes to this improvement of TDECQ even if the 4-GHz improvement of the 3-dB bandwidth does not seem substantial. TDECQ of the EML with the narrow-waveguide EAM were less than 3.3 dB up to 310 Gbps (155 Gbaud PAM4) operation. This result suggests that the wider bandwidth of narrow-waveguide EAM improves the eye diagram quality without decreasing the extinction ratio.

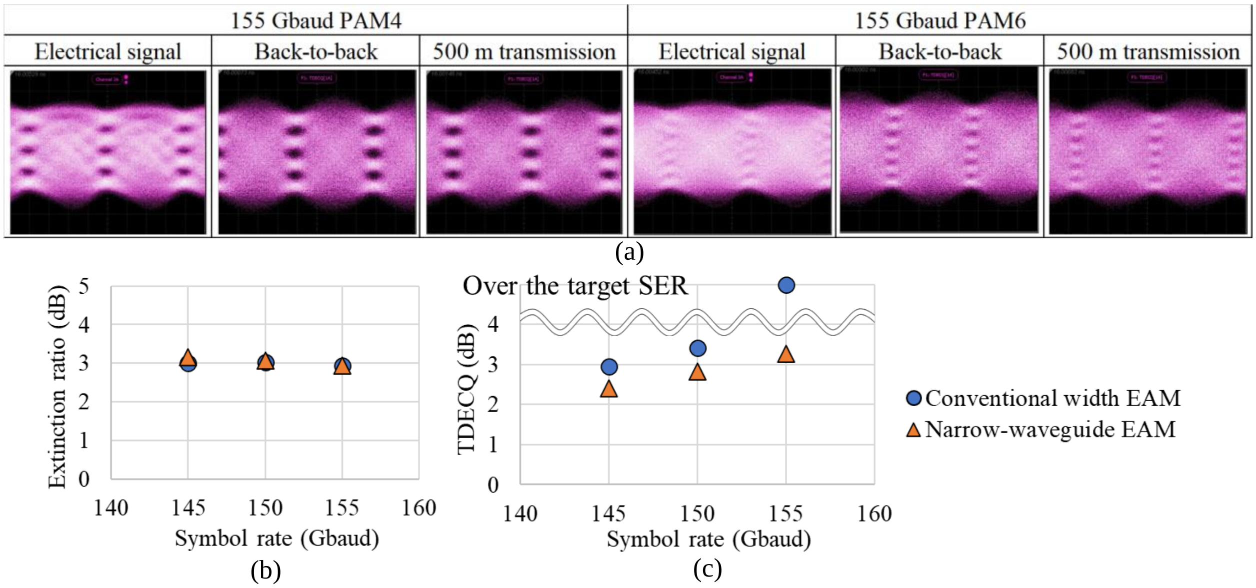

Fig. 3. (a) 155 Gbaud PAM4 (310 Gbps) and 155Gbaud PAM6 (400 Gbps) eye diagrams of the EML with a narrow-waveguide EAM after a TDECQ reference equalizer. (b) Symbol rate dependence of PAM4 extinction ratios compared between EMLs with a conventional-width EAM and a narrow-waveguide EAM. (c) Symbol rate dependence of PAM4 back-to-back TDECQ compared between EMLs with a conventional-width EAM and a narrow-waveguide EAM.

4. Conclusion

We developed a high-speed EML for 400 Gbps per lane operation with a narrow high-mesa EAM and experimentally demonstrated 310 Gbps (155 Gbaud PAM4) and 400 Gbps (155 Gbaud PAM6) operations. To increase the bandwidth, we optimized the termination resister value and the wire length between an EAM and a sub-mount. We also developed a breakthrough EML chip by narrowing the width of high-mesa EAM. TDECQ less than 3.3 dB at 310 Gbps (155 Gbaud PAM4) was achieved from BTB eye diagram. We also successfully obtained clear eye diagrams at 400 Gbps (155 Gbaud PAM6) both at BTB and after 500 m transmission. Our result suggests the possibility for optical communication to realize a 400 Gbps per lane IM-DD operation.

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