40 Gb/s Traveling-Wave Electroabsorption Modulator-Integrated DFB Lasers Fabricated Using Selective Area Growth

Yong-Hwan Kwon, Joong-Seon Choe, Jae-Sik Sim, Sung-Bock Kim, HoGyeong Yun, Kwang-Seong Choi, Byung-Seok Choi, and Eun-Soo Nam

In this paper, we present the fabrication of 40 Gb/s traveling-wave electroabsorption modulator-integrated laser (TW-EML) modules. A selective area growth method is first employed in 40 Gb/s EML fabrication to simultaneously provide active layers for lasers and modulators. The 3 dB bandwidth of a TW-EML module is measured to be 34 GHz, which is wider than that of a lumped EML module. The 40 Gb/s non-return-to-zero eye diagram shows clear openings with an average output power of +0.5 dBm.

Keywords: Electroabsorption modulators, traveling-wave, distributed-feedback lasers, selective area growth.

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I. Introduction

High speed electroabsorption modulator-integrated lasers (EMLs) have attracted much attention as a good solution for 40 Gb/s optical transmission systems because of the beneficial properties of electroabsorption modulators (EAMs), such as small size, high modulation frequencies, and low driving voltage operations [1], [2]. Several integration processes, such as butt-coupling, selective area growth (SAG), and vertical mode coupling, were reported with the aim of process simplicity together with high device performance [1]-[3]. Recently, 40 Gb/s commercial EML modules utilizing a butt-coupling integration method have been introduced in the market [1]. Although this approach allows independent optimization of the laser and modulator active layers, it seems difficult to get a reproducible joint geometry due to critical etching and regrowth steps. Even though there have been no reports on 40 Gb/s SAG-EML applications due to rather strict design margins for realizing lasers and 40 Gb/s EAMs at the same time, the successful adoption of SAG methods would drastically lower the fabrication cost due to simpler and more reproducible processing steps and help the rather expensive 40 Gb/s EMLs penetrate into the market.

In this paper, we present 40 Gb/s traveling-wave EML (TW-EML) modules fabricated using an SAG method, which demonstrate a wide 3 dB bandwidth of over 40 GHz and a high extinction ratio of about 15 dB at a modulator bias voltage of –3 V. The TW-EML module shows a 3 dB bandwidth of 34 GHz, which is wider than that for a lumped EML

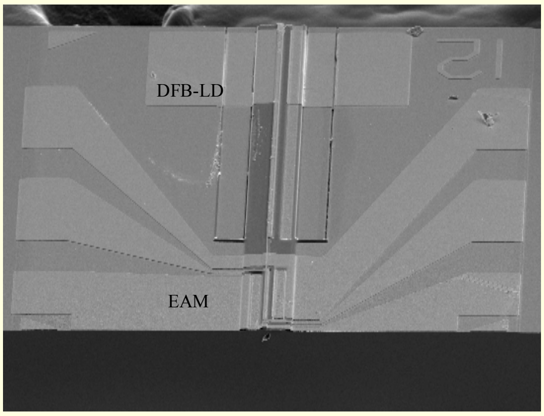

Fig. 1. SEM image of TW-EML.

module, and clear 40 Gb/s non-return-to-zero (NRZ) eye diagrams.

II. Device Structure and Fabrication

An SEM image of the TW-EML is shown in Fig. 1. The DFB laser and EAM are 400 μm and 100 μm long, respectively. Different active regions of these devices, whose operating wavelengths are 1,550 nm and 1,500 nm, respectively, were obtained by an SAG method. The total intrinsic waveguide thickness of the EAM region was determined to be 0.25 μm including seven compressive-strained 55 Å InGaAsP quantum wells (QWs) (λ = 1.6 μm, ε = –0.35%), tensile-strained 80 Å InGaAsP barriers (λ = 1.2 μm, ε = 0.45%), and a separate confinement heterostructure (SCH). The small number of QWs for EAM was chosen to make a uniform E-field across each QW and to improve carrier sweeping out from the QW region [4]. Although the thicker SCH layer is favorable in view of RC-time limitation, a relatively thin SCH layer (about 750 Å each) for the EAMs was used based on experimental optimization conditions of DFB laser operations. The optimized DFB laser active regions were composed of seven compressive-strained 65 Å InGaAsP QWs (λ = 1.67 μm, ε = –0.48%), tensile-strained 95 Å InGaAsP barriers (λ = 1.25 μm, ε = 0.33%), and an SCH layer. The DFB laser and EAM were electrically isolated by an 80 μm long isolation trench, and an isolation resistance of about 20 kΩ was acquired. The single reverse-mesa-ridge structure was adopted to ensure a small series resistance for the DFB laser and low capacitance for the EAM [5]. The widths of the mesa bottom were 2 μm and 1.5 μm for the DFB laser and the EAM, respectively. Polyimide was used to passivate the exposed interface and planarize the surface, which was followed by SiN_x thin film deposition. The total thickness of the polyimide layer was 3.5 μm, and its width was 50 μm; thus,

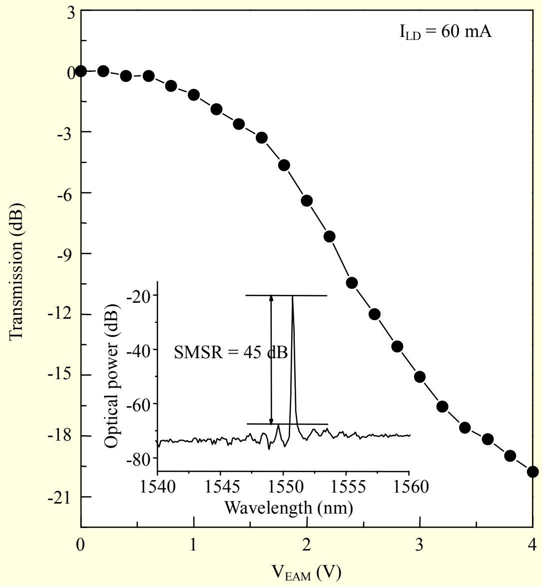

Fig. 2. Static extinction curve of TW-EML chips as a function of modulator bias voltage at a DFB laser current of 60 mA. In the inset, optical spectrum is shown.

it only covered the nonplanar regions around the reverse mesa. P-type and n-type contacts were both made on the top side of the semi-insulating InP substrate. A TW electrode was procured to overcome the RC-time limitation caused by the comparatively thin (0.25 μm) intrinsic waveguide thickness of the EAM. The TW electrode has both signal line and spacing widths of 4 μm on the reverse mesa, which were optimized in the FDTD simulations and confirmed through experiments. For a comparison study, a lumped electrode with a signal line width of 4 μm was also prepared using the same processing steps. Finally, TiO2/SiO2 layers were deposited as an anti-reflection coating after the cleaving process.

III. Device Characteristics

The threshold current of the TW-EML was 18 mA, and the fiber-coupled optical output was 5 dBm at a laser current of 60 mA and a modulator bias voltage of 0 V at 25°C. As shown in the inset of Fig. 2, a high side-mode-suppression ratio of 45 dB was obtained at a 60 mA laser current level [6]. Figure 2 shows a static extinction ratio of over 15 dB at an applied modulator bias voltage of –3 V, which shows a high extinction per volt for this small number of QWs [4].

For high-speed measurement over 40 GHz, we employed an Anritsu 87300C 65 GHz vector network analyzer (VNA) and a calibrated optical receiver. A ground-signal-ground coplanar-type probe from GGB Industries Inc. was used for on-chip measurements [7], [8]. The microwave and E/O modulation frequency responses of the TW-EML chips under 50 Ω

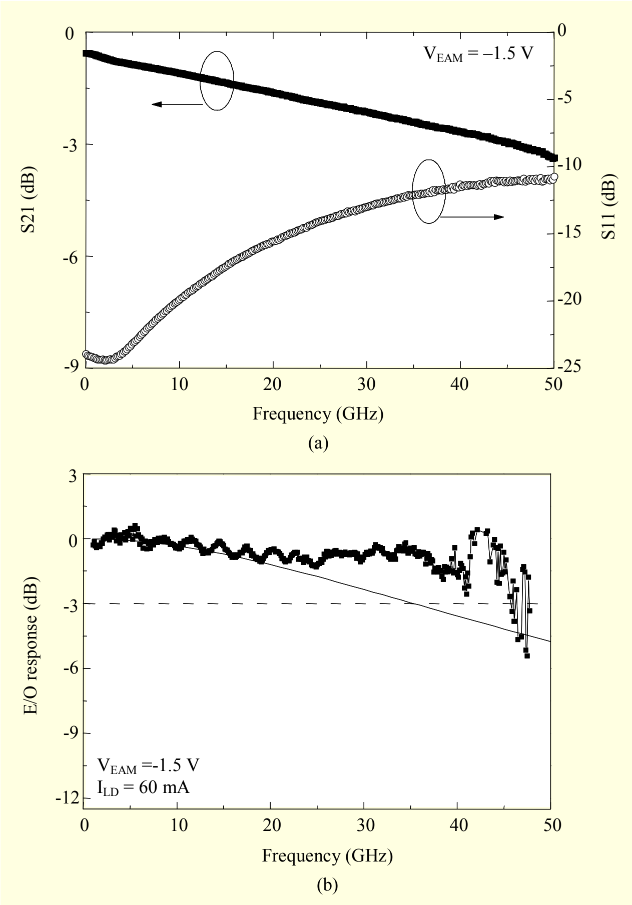

Fig. 3. (a) Transmission and reflection characteristics and (b) E/O modulation characteristics of TW-EML chips. Solid line represents simulated E/O responses derived from lumped EAM equivalent circuit model for comparison.

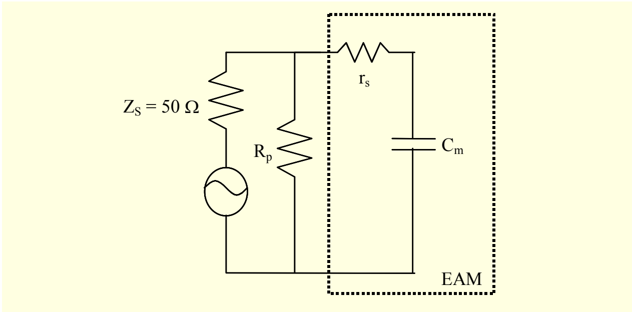

Fig. 4. Equivalent circuit model for lumped EAM.

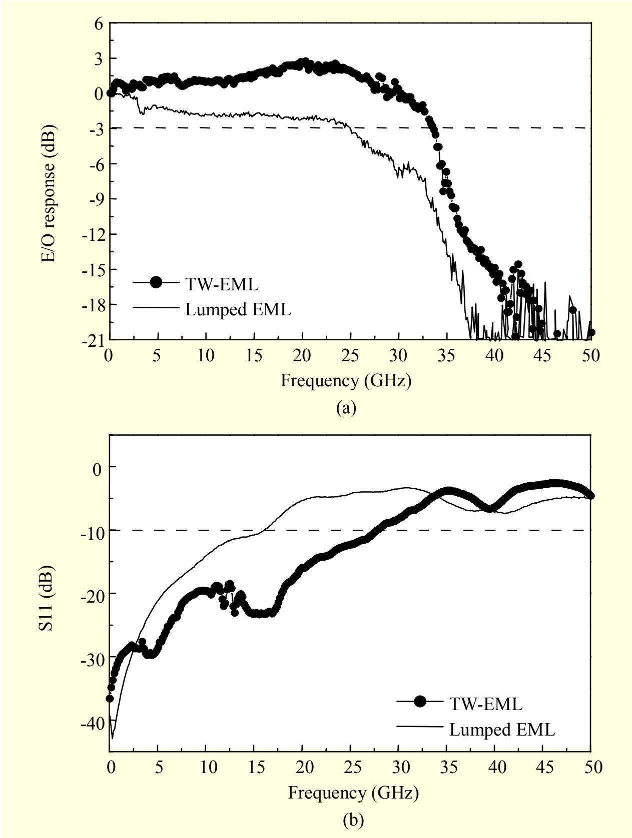

Fig. 5. (a) E/O frequency response and (b) S11 characteristics of TW-EML and lumped EML modules.

termination are shown in Figs. 3(a) and (b), respectively. On-chip E/O and S21 measurements for the lumped EML chips were not accessible in our study; therefore, an E/O response simulation for lumped EML chips was performed as a comparison. The S21 and E/O 3 dB bandwidths for the TW-EML chips were measured to be 45 GHz and about 40 GHz, respectively. That of S11 remained below –10 dB up to 50 GHz. The fluctuations in E/O response data above 40 GHz seen in Fig. 3(b) were attributed to the combined effect of the sharp increase in the noise level of the VNA and the decrease in the optical receiver gain in this high-frequency region. The E/O response for the lumped EML was simulated using an equivalent circuit model for a lumped EAM, as shown in Fig. 4, and was compared with TW-EML data as in Fig. 3(b) [9]. Measured values of 20 Ω and 0.1 pF were used for series resistor r_s and capacitor C_m of the EAM, and a matching resistance of 50 Ω was used as a shunt resistor R_p. This comparison study could indicate the probable increase in the E/O bandwidth of a TW electrode in comparison with a lumped electrode, even though the epistructures and device structures are shared.

We fabricated EML modules consisting of EML chips, a ceramic submount, a two-lens system for optical alignment, a thermoelectric cooler, and a monitor-photodiode [10], [11]. For comparison, modules with EML chips with lumped electrodes were also prepared. Figure 5 shows the E/O response and electrical return loss S11 of the TW-EML and lumped EML modules, respectively. In comparison with the chip characteristics, the microwave characteristics were degraded due to packaging-induced parasitics and transmission line losses on the ceramic submount. S11 was observed to be

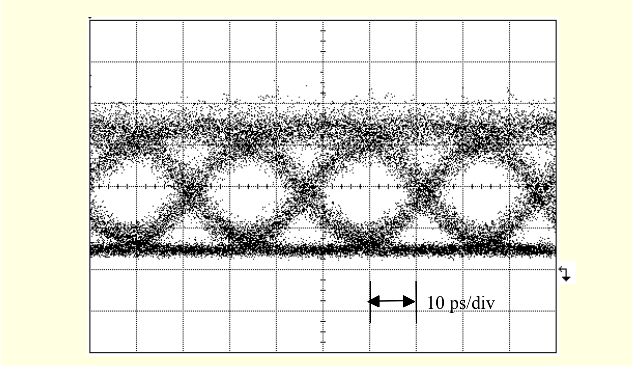

Fig. 6. 40 Gb/s NRZ eye diagram.

less than –10 dB in the frequency range up to 28 GHz and 16 GHz for the TW modules and lumped modules, respectively. The larger electrical return loss with the lumped electrode was attributed to the signal electrode structure which has two open-ended terminations. In addition to the smaller S11, the TW effect mitigating the RC-time-limitation could account for the wider E/O 3 dB bandwidth of 34 GHz for the TW-EML modules, which was wide enough for 40 Gb/s applications. A 40 Gb/s NRZ eye measurement result for the TW-EML module is shown in Fig. 6. The DFB-LD current and EAM bias were set to 60 mA and –1.5 V, respectively, and a modulator driver with 3.0 V output voltage was used. NRZ eye diagrams with clear eye openings and a relatively high output power of +0.5 dBm were obtained. Little overshoot phenomena was observed and could be partially attributed to the insufficient anti-reflection coating. It can be enhanced by improving the coating process and/or the adoption of an InP window layer in the front facet [7].

VI. Conclusion

We developed 40 Gb/s TW-EMLs by a simplified process adopting an SAG method and a single reverse-mesa-ridge structure. The 3 dB bandwidth of the E/O frequency responses of TW-EML chips reached over 40 GHz, and a high extinction ratio of over 15 dB was obtained at an EAM bias of –3 V. The TW-EML module showed superior characteristics of an E/O 3 dB bandwidth of 34 GHz and a low electrical return loss S11 of < –10 dB up to 28 GHz, in comparison with a lumped EML module.

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