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# Integrated Light Sources for 40 Gbit/s and Beyond

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## 1. Introduction

The recent explosive growth of data traffic has accelerated the demand for high-capacity information networks. In order to achieve the very large capacity of TDM/WDM-based transmission networks, the bit-rates per WDM channel should be increased more than 40 Gbit/s, in addition to using the denser WDM technology. A high-frequency optical modulator is the key to achieving a high bit rate per channel with a bandwidth of 40 GHz or higher.

$LiNbO_3$ interferometric modulators are the most reliable external modulators now widely available, and they have been used in recent WDM transmission experiments based on 40-Gbit/s channels [1]. On the other hand, electroabsorption (EA) modulators are also very promising due to their compactness, lower driving voltage [2]-[3], and integrability with lasers, amplifiers and photodetectors [4]-[7]. Conventional EA modulators have a lumped-element (LE) electrode, whose speeds are limited by the total device capacitance. Although LE-EA modulators and LE-EA modulators integrated with DFB lasers up to 50-GHz operation have been achieved so far [8]-[11] by reducing the parasitic capacitances, the traveling-wave (TW) electrodes structure is vital for ultrafast EA modulators in order to overcome the CR limitation and thereby extend the bandwidth without sacrificing modulation efficiency.

This paper describes our activities on high-speed EA modulators with LE and TW electrodes. Starting from the 40-Gbit/s EA-modulator integrated with a DFB (EA-DFB) with a LE electrode, the first-ever TW EA-modulator integrated with a DFB laser (TW-EADFB) with a wide bandwidth of over 50 GHz is described [13].

## 2. 40-Gbit/s LE-EA modulator integrated with a DFB laser (LE-EADFB)

For high-speed operation of the LE-EADFB shown in Fig. 1, a smaller modulator length and smaller electric capacitance are desirable. But reducing the modulator length is followed by a smaller extinction ratio in the attenuation characteristics. This is quite problematic in practical use. A larger number of pairs of modulator's MQWs could possibly overcome this problem.

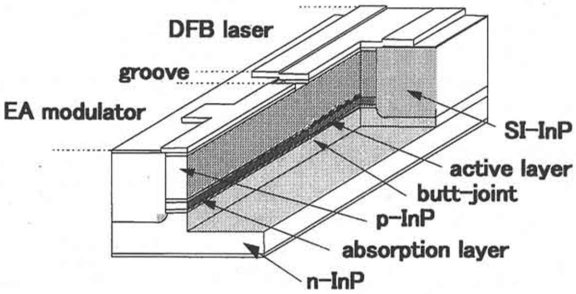


**Figure 1 Schematic of LE-EADFB**

The fiber pigtailed LE-EADFB module has an integrated modulator with a length of 90 μm and a 14-period MQW. The 3-dB bandwidth is over 30 GHz. A clear eye opening at the 40-Gbit/s NRZ modulation is observed. The dynamic extinction ratio estimated from the observed eye diagram is about 10 dB when the applied peak-to peak voltage is 3 V. This is smaller than the static extinction ratio by about 3 dB. The bit error rate performance of the back-to-back transmission is examined and the receiver sensitivity, measured at the bit error rate of $10^{-9}$, is from -27.2 to -25.2 dBm. Error-free back-to-back transmission for each channel is confirmed down to the bit error rate of $10^{-12}$.

## 3. TW-EA modulator integrated with a DFB laser (TW-EADFB)

The widest modulation bandwidths of conventional LE EA-DFBs seem to be around 40-50 GHz. We have demonstrated, for the first time, an EA-DFB that has a TW electrode in the EA-modulator section (TW-EADFB) in order to overcome the CR limitation.

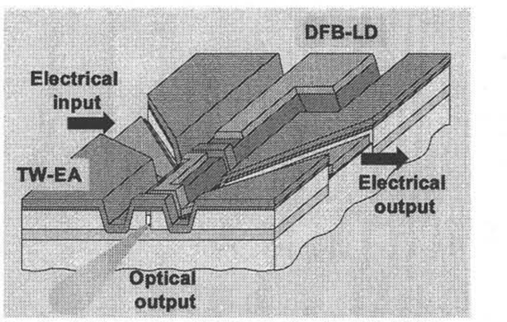


**Fig. 2 Schematic of TW electrode EA-DFB**

A bird's eye view of the TW-EADFB is schematically shown in Fig. 2. The device is fabricated on an Fe-doped semi-insulating InP substrate to form a co-planar feeding electrode. The InGaAsP/InGaAsP MQW absorption layer of the TW-EA modulator and the MQW active layer of the DFB laser are monolithically integrated by a butt-joint technique. After the 2-μm-wide stripes are formed by using $CH_4/H_2$ reactive ion etching, both devices are buried with Fe-doped semi-insulating InP. The co-planar waveguide TW electrode is formed in the modulator section. The lengths of the DFB laser and the EA modulator are 450 and 225 μm, respectively.

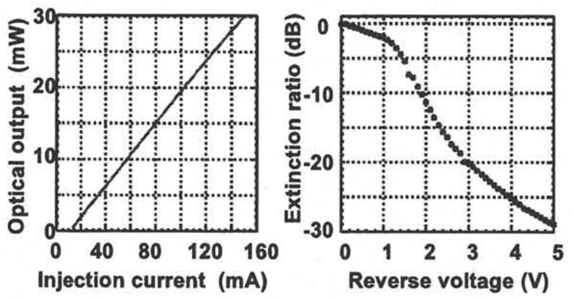


**Fig. 3 Static characteristics of TW-EADFB**

Figure 3 shows the static characteristics of the TW-EADFB. The lasing wavelength of the DFB laser is 1552 nm and the optical output power is about 20 mW at a laser current of 100 mA when the TW-EA circuit is open. The differential resistance of the DFB laser is about 6 Ω. The extinction ratio of the TW-EA modulator is about 22 dB at the bias of −3 V. These static characteristics are almost the same as those of a conventinal EA-DFB on an n-InP substrate with a LE electrode in the EA-modulator section.

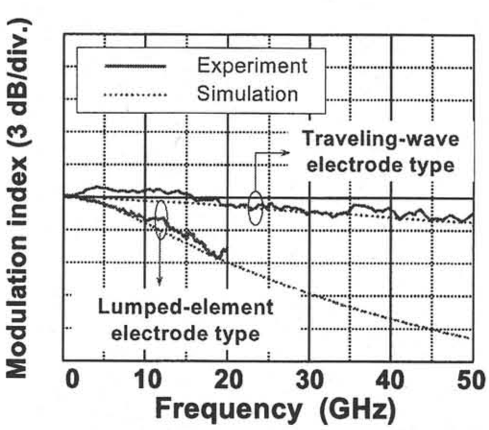


**Fig. 4 Small-signal frequency response**

Figure 4 shows the measured small signal frequency response of the modulated light from the TW-EADFB. As shown in this figure, the electrical 3-dB-down bandwidth exceeds 50 GHz. The bandwidth is expected to reach about 70 GHz from our numerical simulation as also shown in Fig. 4. As a reference, the response of the EA-DFB with a LE electrode, which has the same EA modulator length, is also plotted. Compared with the conventional LE-EADFB, the frequency response of the TW-EADFB falls much more gradually. As depicted in Fig. 2, the microwave signal propagates parallel to the light wave in the optical waveguide. We fed the microwave signal from the opposite electrode side in order to verify the interaction between the two waves. The electrical signal propagates opposite to the direction of the light from the DFB laser, decreasing the bandwidth to about 40 GHz. This is a proof that the electrode works, at least in major aspects, in a TW manner. By optimising the design and fabrication process, this modulator has the potential to achieve a bandwidth exceeding 100 GHz.

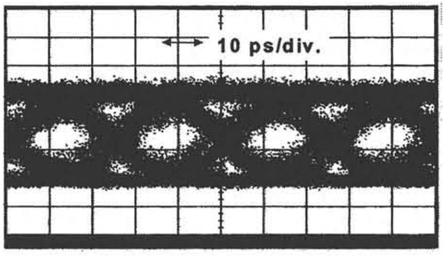


**Fig. 5 40-Gbit/s eye diagram**

Figure 5 shows the eye-diagram of the 40 Gbit/s modulated light from the TW-EADFB. The injection current of the DFB laser is set to 110 mA, and the modulating-voltage to the TW-EA modulator is 1.5 V. The eye opening is successfully observed.

**4. Summary**

40-Gbit/s EA-modulators integrated with a DFB laser (EA-DFB) with a LE electrode and a TW electrode are presented. By optimizing the structure of the LE-EADFB, 40-Gbit/s modulation is achieved. Owing to the freedom from the CR-induced limitation, the developed TW-EA modulator achieved a 3-dB optical modulation bandwidth of over 50 GHz without sacrificing the extinction performance. The first-ever TW-EA modulator monolithically integrated with DFB lasers (TW-EADFB) has been developed. A 40-Gbit/s eye-diagram is successfully observed

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