High Saturation Power 1.3-μm MQW Electroabsorption Waveguide Modulators on GaAs Substrates

K. K. Loi, L. Shen, H. H. Wieder, and W. S. C. Chang

***Abstract*— An analog InGaAs/InAlAs multiple-quantum-well electroabsorption waveguide modulator operating at 1.32-μm wavelength has been designed, fabricated, and characterized for the first time on a GaAs substrate. A typical 3-μm-wide 115-μm-long device exhibits a high optical saturation power in excess of 17 mW and a 3-dB electrical bandwidth of 20 GHz. An equivalent half-wave voltage V_π of 2.8 V has also been achieved.**

***Index Terms*—Electroabsorption modulators, microwave photonic links, semiconductor quantum wells.**

I. Introduction

RECENTLY, high-performance GaAs-based MESFET, HBT, and PHEMT drive circuitry for III–V modulators have been demonstrated [1]–[3]. Electroabsorption modulators grown on GaAs substrates cannot only take advantage of the well-developed GaAs processing technology, but also offer the potential for monolithic integration with these electronic driver circuits. Vertical-cavity 1.3-μm electroabsorption modulators on GaAs substrates based on the quantum confined Stark effect have been demonstrated by growing the multiple quantum wells (MQW) on top of a compositionally linearly graded or multistep-graded buffer [4]–[7]. The relaxed buffer alleviates the strain and confines the misfit dislocations. We have developed the *first* high-speed 1.3-μm GaAs-based electroabsorption *waveguide* modulator. In this letter we describe the high-frequency performance of the waveguide modulator for microwave photonic link applications.

II. Device Structure and Fabrication

The p-i(MQW)-n waveguide modulator structure is grown on an n^+ GaAs substrate using a solid-source molecular beam epitaxy (MBE) system. The nominally undoped region consists of ten periods of 9.5-nm-thick $In_{0.38}Ga_{0.62}As$ quantum wells and 10-nm-thick $In_{0.36}Al_{0.64}As$ barriers. The active MQW region is embedded between 0.5-μm-thick p-doped and n-doped $In_{0.36}Ga_{0.32}Al_{0.32}As$ passive waveguide layers, followed by a 0.5-μm-thick p^+ InAlAs cap layer. The waveguide stacks are built atop a 0.7-μm-thick three-stage compositionally step-graded n-doped InAlAs buffer [7]. Ridge waveguides were fabricated using CCl_2F_2 reactive ion beam etching. The ridge height is 1.3 μm and the waveguide width is 3 μm. The wafer was cleaved into bars with waveguide lengths between 90 and 240 μm. Measurements were made on these as-cleaved devices *without* any antireflection coating on the waveguide end facets.

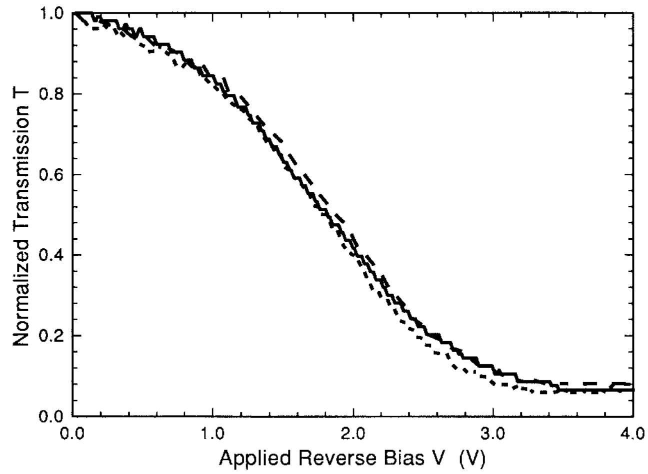

Fig. 1. Low-frequency transmission-voltage characteristic of a 115-μm-long modulator at 4 mW (dotted), 8 mW (dash), and 17 mW (solid) input optical power.

III. Modulator Performance

TE-polarized light was pigtailed into and out of the modulator using lensed single-mode fibers. The fiber-to-fiber optical insertion loss of a typical 130-μm-long device is 12.5 dB. The cutback analysis reveals that the large insertion loss is mainly attributed to the 10.4-dB coupling loss due to Fresnel reflection and mode mismatch. The waveguide propagation loss is found to be 17 dB/mm. Reduction of the insertion loss can be achieved by depositing antireflection coatings on the end facets as well as changing the refractive index or thickness of the passive InGaAlAs waveguide layers to increase the dimension of the waveguide mode. Further improvement in the propagation loss can be obtained by optimizing the processing techniques.

The electrical-to-optical transfer characteristics were measured at 1 kHz with different incident optical power. The transmission curve illustrated in Fig. 1 is independent of the available laser source power, indicating that the optical saturation threshold of the modulator exceeds 17 mW. The best electrooptic slope efficiency dT/dV is determined from the

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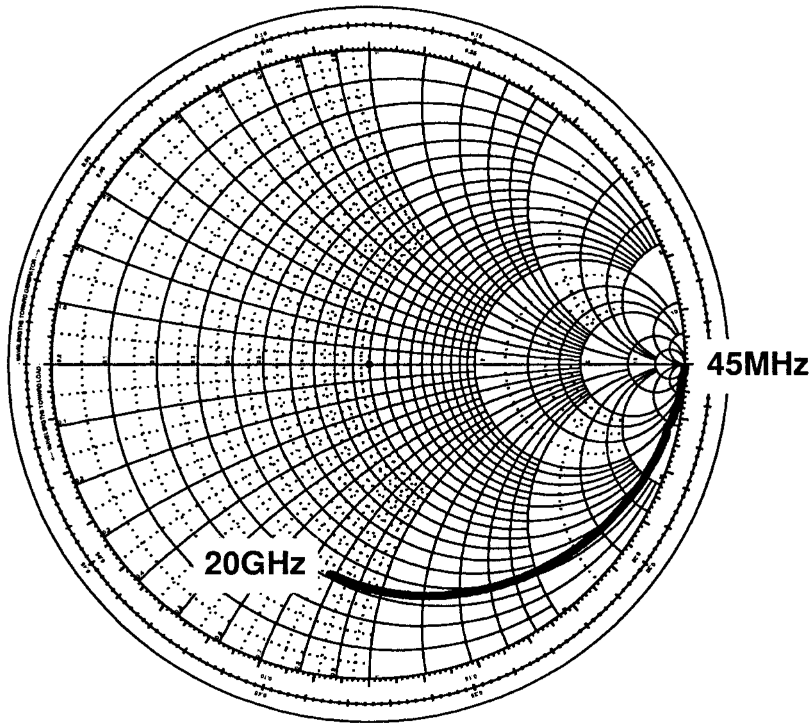

Fig. 2. Input reflection coefficient S_{11} of a 3-μm-wide 115-μm-long modulator.

experimental transfer curve. A 115- and a 165-μm-long device exhibit a dT/dV of 0.49 and 0.55 V^{-1}, respectively. The 0.55-V^{-1} slope efficiency is equivalent to a Mach–Zehnder (MZ) interferometric modulator with a V_π of 2.8 V. In comparison, the commercially available lithium niobate ($LiNbO_3$) MZ modulator has a typical V_π of 5 V with 3-GHz bandwidth.

The input reflection coefficient S_{11} from 45 MHz to 20 GHz is shown in Fig. 2. The measured S_{11} is independent of the applied dc bias, which implies that the intrinsic region of the modulator is fully depleted even at zero external bias. The electrical length of the modulator is much shorter than the microwave subcarrier wavelength. Therefore, the input impedance follows an equivalent simple lumped *RC* circuit with a series resistance of 17 Ω and a capacitance of 0.19 pF. The 0.19-pF depletion capacitance agrees well with the waveguide dimensions. The series resistance can be reduced by improved processing and optimizing the doping profiles of the contact layers.

Fig. 3 displays the small-signal frequency response of a 115-μm-long modulator with an external 50-Ω load termination. The modulation response is independent of both the applied dc bias and input optical power up to 17 mW, confirming that the modulator saturation intensity exceeds 17 mW at microwave frequency at least to 20 GHz. The theoretical frequency response of a series lumped *RC* circuit is also shown in Fig. 3. The simple *RC* model correlates reasonably well with the experimental data. The electrical bandwidth of the modulator is dictated by the depletion capacitance and series resistance. The measured 3-dB bandwidth for a 115- and 165-μm-long modulator is 20 and 13 GHz, respectively. By scaling down the modulator length from 165 to 115 μm, the bandwidth increases 54% while the measured slope efficiency

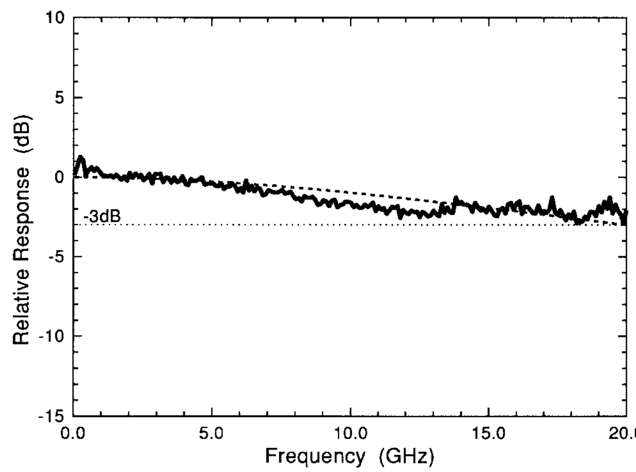

Fig. 3. Modulation response of a 115-μm-long modulator with a 50-Ω termination (solid: measured; dash: theoretical response of a series *RC* circuit with $R = 17$ Ω and $C = 0.19$ pF).

dT/dV decreases only 12%. The tradeoff between radio frequency (RF) efficiency and frequency bandwidth distinctly favors electroabsorption waveguide modulators over $LiNbO_3$ modulators. In contrast to the electroabsorption modulators, the electrooptic efficiency of $LiNbO_3$ modulators decreases linearly with the device length, i.e., inversely proportional to bandwidth.

A 165-μm-long waveguide modulator *without* 50-Ω termination is inserted into an amplifierless RF fiber-optic link comprising a calibrated 1.32-μm cw Nd:YLF laser and a 25-GHz photodetector. The responsivity of the photodetector is 0.53 A/W. The modulator is biased at −1.85 V and the RF input power is 0 dBm. The RF link gain η_{RF}, defined as the

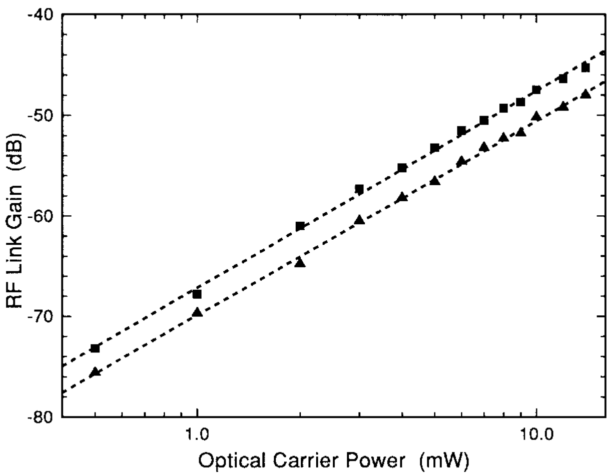

Fig. 4. RF link gain as a function of input optical carrier power at 1 GHz (square) and 5 GHz (triangle). Dash lines are the best linear fit with a slope of 2 dB/dB.

ratio of output RF power from the photodetector to input RF power to the MQW modulator, is measured as a function of input optical power. Fig. 4 clearly shows that the η_{RF} increases linearly with a slope of 2 dB/dB with the optical carrier power. The linear increase in η_{RF} substantiates that the optical saturation intensity of the MQW modulator is in excess of 17 mW. With 17-mW optical carrier power, a RF link gain of -42 dB has been achieved at 1-GHz subcarrier frequency. The η_{RF} will improve with an increased laser source power. A higher RF link gain can also be obtained using optical and/or electrical amplification at the expense of increased noise level.

IV. Conclusion

We have demonstrated the first high-speed operation of a 1.32-μm InGaAs/InAlAs MQW electroabsorption waveguide modulator grown on a GaAs substrate. The modulator structure is built on a step-graded InAlAs strain-relief buffer. The modulator exhibits a slope efficiency as high as 0.55 V^{-1} and an input optical saturation intensity in excess of 17 mW. The 3-dB electrical bandwidth is *RC* limited and a 20-GHz bandwidth has been obtained for a 3-μm-wide 115-μm-long modulator.

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