35-GHz Bandwidth, 5-V-cm Drive Voltage, Bulk GaAs Substrate Removed Electrooptic Modulators

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***Abstract*—Bulk GaAs–AlGaAs true push–pull electrooptic modulators with 5-V-cm V_π and 35-GHz bandwidth were demonstrated using substrate removal techniques. The traveling wave electrodes showed almost no dispersion, making it ideal for broadband applications.**

***Index Terms*—Electrooptic modulator, optical modulator, semiconductor modulator, traveling wave electrode.**

I. Introduction

OPTICAL modulators are enabling components for a wide range of applications such as fiber-optic transmission, radio-over-fiber, and instrumentation. All these applications require low-cost, low drive voltage external modulators with very wide bandwidth. This work reports a technology based on compound semiconductors and substrate removal processing to deliver these requirements. Although compound semiconductors have relatively small electrooptic coefficients, they have high index of refraction and very small dielectric constant dispersion up to optical frequencies. Furthermore, high-quality epitaxial growth and advanced processing techniques enable flexibility in designing and fabricating novel designs. Low dielectric constant dispersion requires microwave velocity slowing for velocity matching. This can be achieved using capacitively loaded slow wave electrodes. The substrate removal technique allows placing metal electrodes on both sides of an epitaxial layer which provides the required capacitive loading without increasing microwave loss. This also enables the fabrication of an ideal push–pull modulator and keeps the drive voltage low. We have demonstrated such bulk GaAs–AlGaAs modulators with a drive voltage of 3.7 V-cm [1]. In this letter, we report optimized modulator designs with a drive voltage as low as 5 V-cm and bandwidths as high as 40 GHz.

II. Device Description and Design

Fig. 1 shows the cross-sectional schematic of the optical waveguide used in this work. The design of the waveguide is identical to that reported in [1]. The 2-μm-wide ribs are etched 0.65 μm into the top clad of a 0.75-μm $Al_{0.9}Ga_{0.1}As/0.44$ μm $GaAs/0.75$ μm $Al_{0.9}Ga_{0.1}As$ undoped epilayer. The 2-μm waveguide width was chosen for ease of fabrication. The etch

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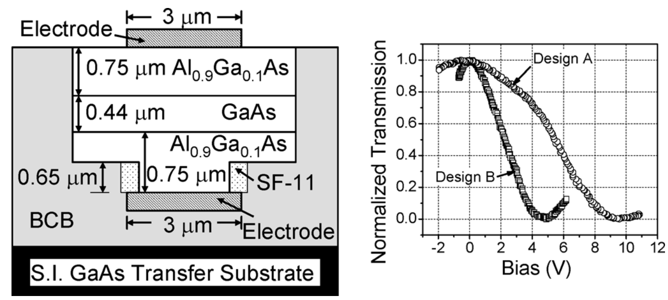

Fig. 1. Cross-sectional schematic of the optical waveguide and measured optical transfer functions of both types of modulators.

depth is the maximum allowable for single-mode operation. Epilayer is removed from the substrate it is grown on and is glued onto a transfer substrate using the polymer benzocyclobutane. The remaining undoped epilayer self depletes and behaves as a dielectric electrooptic material with slight optical loss. Removing the growth substrate increases the mode confinement and allows the placement of metal electrodes on both sides of the epilayer making the electrode gap the same as the epilayer thickness, which can be made very small and uniform. This arrangement creates a very high vertical modulating field overlapping very well with the optical mode. Furthermore, high dielectric constant epilayer is removed where not needed and replaced with low dielectric constant polymer. The overlap of the optical mode and the electrodes is negligible and electrodes do not increase the optical loss. The worst case on chip propagation loss was 2.9 dB/cm and excess loss due to the electrodes was less than 0.2 dB/cm [1].

Realizing the high-speed version of this modulator requires a traveling wave design due to the length of the electrode. In such designs, the modulator electrode is designed as a microwave transmission line. Maximizing the bandwidth requires matching the microwave phase velocity of the electrode to the optical group velocity of the optical waveguide [2], [3]. Furthermore, microwave loss of the electrode should be as low as possible since for a velocity-matched electrode, the electrical 3-dB bandwidth is at the frequency where the electrode loss becomes 6.34 dB. In compound semiconductors dielectric constant change due to dispersion between microwave and optical frequencies is very slight. As a result microwave signal on the electrode sees a combination of air and semiconductor and travels faster than the optical signal which is almost entirely in the optical waveguide. Therefore, velocity matching requires reducing the microwave velocity. This can be realized by increasing the capacitance per unit length of the microwave transmission line electrode. Such an approach is used in

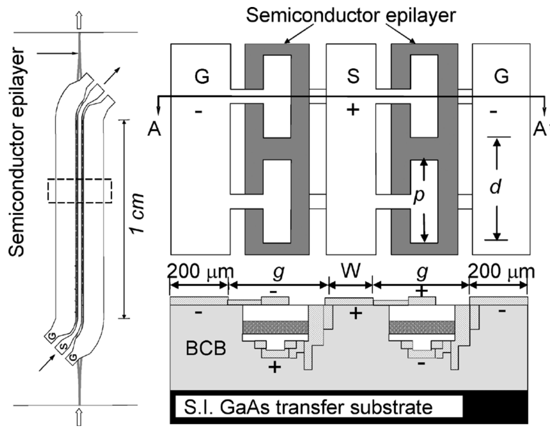

Fig. 2. Top down and cross-sectional schematics of high-speed Mach–Zehnder modulator. Polarity of the applied voltage is also shown.

this work and schematic of the resulting capacitively loaded traveling wave electrode modulator is shown in Fig. 2. This electrode consists of a regular ground-signal-ground (GSG) coplanar waveguide (CPW) loaded periodically with small capacitances. The loading capacitances are formed between the electrodes on the top and the bottom of the optical waveguide. The top and the bottom electrodes are connected to ground and signal lines of the CPW using short stems. These electrodes are called T-rails due to their shape. The connection is done such that modulating electric field direction reverses between the arms of the modulator resulting in true push–pull operation. If the period of loading d is such that the Bragg frequency of the loaded line is much larger than the highest frequency of interest, the loading is mainly capacitive and inductance per unit length remains unchanged [3]. The microwave phase velocity and characteristic impedance of the capacitively loaded line are given as [3]

$$v_{\rm ph} = \frac{1}{\sqrt{L_0(C_0 + 2\Delta C)}} \quad \text{and} \quad Z = \sqrt{\frac{L_0}{C_0 + 2\Delta C}} \tag{1}$$

where L_0 and C_0 are the inductance and capacitance of the unloaded CPW and ΔC is the additional capacitance per arm due to loading. ΔC is a fraction of the capacitance between the electrodes sandwiching the optical waveguide C_T such that $\Delta C = FC_T = (p/d)C_T$. $F = p/d$ is the fill factor of the electrodes, i.e., the fraction of the interferometer arm that is electrooptically active. As seen in Fig. 2, the appropriate fill factor is achieved by segmenting the electrode on the waveguides. This segmentation also helps to keep the microwave loss low since no axial currents can flow along the segmented T-rails. Axial currents only flow along the conductors of the CPW where the electric field and current density is low. The operating voltage of a velocity matched modulator can be expressed as

$$V_\pi = \frac{\lambda_0}{2l}\frac{t}{n_e^3 r_{41}\Gamma}\frac{1}{F} = \frac{V_{\pi 0}}{F} \tag{2}$$

where l is the electrode length, Γ is the overlap of the vertical microwave electric field with the optical mode, n_e is the effective index, and r_{41} is the electrooptic coefficient of the material and t is the thickness of the epilayer. As mentioned earlier we obtained $V_{\pi 0}$ values as low as 3.7 V-cm using this design [1].

For the waveguide shown in Fig. 1, Γ improves very little for rail widths larger than 3 μm. So electrode width is chosen as 3 μm. The group velocity of the optical waveguide used is 8.43 cm/ns at 1.55 μm. Therefore, using (1), a velocity-matched 50-Ω electrode requires $L_0 = 5.9$ nH/cm and $C_0 + 2\Delta C = 2.4$ pF/cm. Hence, the unloaded line dimensions should be chosen such that $L_0 = 5.9$ nH/cm, C_0 and the propagation loss are as low as possible. Another constraint is the arm separation of the interferometer. If this is large, input and output Y-branches tend to be long making the modulator long. This typically limits the width of the CPW signal line to less than 50 μm. The ground conductor widths of the CPW were chosen as 200 μm since line properties do not change for larger widths. The loss coefficient of the unloaded CPW saturates if the g and W product is larger than a few thousand micrometers squared [4]. Using these constraints, W and g were chosen as 40 and 80 μm, respectively, resulting in $L_0 = 5.9$ nH/cm and $C_0 = 0.73$ pF/cm. The required segmentation F, and the resultant V_π were 0.47 and 8.4 V-cm, respectively. This design is called Design A.

Another possible design is to have only a velocity-matched electrode. If the electrode is terminated by its characteristic impedance, there will not be a standing wave on the electrode and bandwidth will be maximized. Based on (1), velocity matching is possible with larger ΔC values if L_0 is reduced. This comes at the expense of reduced electrode impedance. Again, while keeping the ground signal width at 200 μm, a range of signal line widths and gaps were explored and W and g were chosen as 50 and 20 μm, respectively, resulting in $L_0 = 3.62$ nH/cm and $C_0 = 1.05$ pF/cm. For the velocity-matched configuration, the segmentation F and drive voltage was 0.85 and 4.6 V-cm, respectively. The characteristic impedance was 30 Ω. This design is called Design B. The actual fabrication of the device was very similar to the one reported in [1]. The only difference was the electrode mask shape and dimensions.

III. Results and Discussion

Modulators were characterized at 1.5 μm using endfire coupling under TE polarization. Output was observed on an IR camera and measured using a photodetector. The optical transfer functions of the two different Mach–Zehnder modulators are shown in Fig. 1. The measured drive voltage for Designs A and B were 9.5 and 5 V-cm, respectively. This is larger than the design values of 8.4 and 4.6 V-cm. This discrepancy is attributed to fabrication errors. In this case, electrodes on the top and bottom of the waveguide are fabricated separately. It is difficult to align the top and bottom electrodes with respect to one another and to the optical waveguide over centimeter-long lengths with contact lithography. Calculations show that alignment accuracy better than 0.25 μm is required. Even a 0.5-μm misalignment between the top and the bottom electrodes reduces the vertical component of the electric field. Furthermore, the electrical field does not overlap with optical mode as efficiently. Both of these effects increase the drive voltage.

The s-parameters of the electrodes along with extracted electrode parameters using the technique in [5] are shown up to 40 GHz in Fig. 3. In both cases, s-parameters show periodic

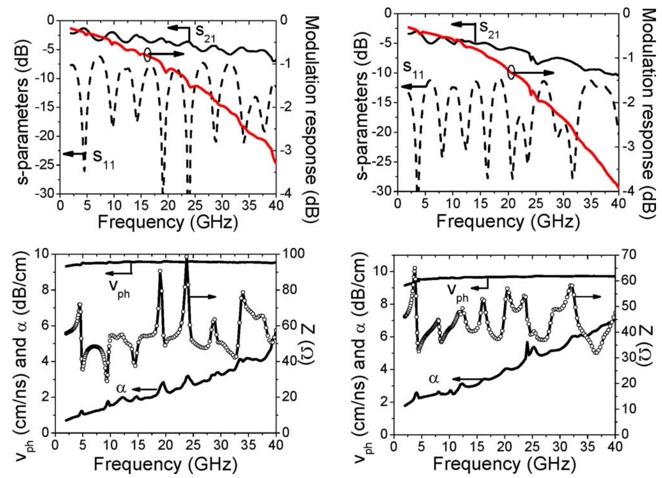

Fig. 3. S-parameters, optical modulation response, microwave phase velocity $v_{\rm ph}$, characteristic impedance Z, and microwave loss coefficient α, as a function of frequency for Design A (left) and Design B (right).

oscillations due to interference arising form the reflections at both ends of the electrode. TRL calibration was used for microwave measurements. The on chip CPW used for calibrating Design A and B had impedance of 97 and 60 Ω, respectively. The impedance difference between the electrodes and calibration lines resulted in resonances seen in s_{11}. When s_{11} becomes very small due to destructive interference, the electrodes appear to be impedance matched to these values. The phase velocity mainly depends on the period of the oscillations and is very smooth and does not show any dispersion. For both designs, the phase velocity is 9.5 cm/ns. Since the optical group velocity is 8.43 cm/ns, this results in a 10% velocity mismatch. Designs A and B had about 57 and 46 Ω impedance. The microwave loss coefficient of Designs A and B at 40 GHz were 6 and 7 dB/cm, respectively. Simulated optical modulation response of the devices based on the electrode data are also shown in Fig. 3. Bandwidth of Devices A and B are 40 and 35 GHz, respectively. Bandwidth is limited by velocity mismatch. The higher than expected velocity and impedance values are due to the misalignment of the top and bottom electrodes as explained before. Reduced field strength reduces the loading capacitance increasing the velocity and the impedance. Loss difference is due to different unloaded CPW dimensions and impedance levels of two different designs. The loss coefficient of the electrode can be approximated as

$$\alpha \approx \frac{R}{2Z} = \frac{R}{2\sqrt{\frac{L_0}{C_0+2\Delta C}}} = \frac{R}{2Z_0}\sqrt{1+\frac{2\Delta C}{C_0}} = \alpha_0\sqrt{1+\frac{2\Delta C}{C_0}}. \tag{3}$$

In the loaded line design electrode resistance per unit length changes very little between loaded and unloaded lines. Design B had higher α_0 due to unloaded CPW dimensions and higher $2\Delta C/C_0$ ratio due to increased loading. As a result, it has higher attenuation.

IV. Conclusion

Bulk GaAs traveling wave electrooptic modulators with bandwidths as high as 40 GHz and drive voltages as low as 5 V-cm were reported. These modulators use substrate removal which allows placement of metal electrodes on both sides of the epilayer. This makes it possible to apply very high electric fields overlapping very well with the optical mode. Furthermore, required velocity matching can be achieved using a capacitively loaded slow wave electrode. Using such electrodes, different designs are possible by adjusting the fill factor of the loading with only slight changes of the electrode microwave loss. This ability makes this a very flexible technology. Two velocity-matched designs, one with a 50-Ω and the other with 30-Ω impedance, were reported. Results were slightly different due to a slight misalignment of the top and the bottom electrodes resulting in the reduction of the overlap, vertical component of the electric field, and the loading capacitance. For both devices, microwave phase velocity was flat over the entire measurement frequency with a value around 9.5 cm/ns. Increasing the electrooptic coefficient by utilizing epilayers with quantum wells similar to [6] should enable very wide bandwidth intensity modulators with a drive voltage less than 1 V.

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