GaAs/AlGaAs Traveling Wave Electro-optic Modulators

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ABSTRACT

A GaAs/AlGaAs traveling wave Mach-Zehnder electro-optic modulator with novel slow wave electrodes was fabricated on undoped epitaxial layers. Using appropriate electrode engineering velocity matching with matched impedance and low microwave loss was achieved. Device had a measured electrical bandwidth greater than 40 GHz at 1.55 μm. The measured bandwidth at 1.3 μm was 37 GHz. The mechanism limiting the bandwidth was identified as phase velocity matching rather than group velocity matching.

Keywords: traveling wave modulator, optical modulator, Mach-Zehnder modulator, GaAs modulator

1. INTRODUCTION

External optical modulators with very wide electrical bandwidths are essential components for optical control of microwaves and millimeter waves as well as high speed optical communication systems. A very desirable approach to obtain very wide electrical bandwidths is the so-called traveling wave design [1, 2, 3, 4, 5, 6]. In such a design electrode is designed as a transmission line. Therefore, electrode capacitance is distributed and does not limit the modulator speed. Modulating electrical signal on the electrode travel in the same direction as the modulated optical signal. If they travel with the same velocity the phase change induced by the electrical signal is integrated along the length of the electrode. Since the electrode capacitance is not the bandwidth limit one can make the electrode very long, typically thousands of wavelengths. This allows even a very small phase change over a wavelength to accumulate to an appreciable value. Therefore, drive voltage requirements can be significantly relaxed without sacrificing electrical bandwidth. This paper describes such a modulator with novel slow wave coplanar electrodes. The next section describes the design issues that need to be addressed in order to obtain very wide electrical bandwidths. After that device structure is described. Next experimental results on the electrode geometry is presented. This is followed by the experimental results on the modulator. Next section describes a very interesting experimental observation on the choice of velocity to be matched. Finally conclusions of this work is given.

2. DESIGN ISSUES FOR TRAVELING WAVE MODULATORS

Based on earlier description it is clear that in a traveling wave modulator modulation will be most efficient if the optical signal experiences the same phase change along the length of the electrode. This requires matching of the velocities of the electrical and optical signals. This, of course, is a well known fact and is stated in a wealth of literature over the last 50 years [1, 2, 3, 4, 5, 6]. However, the velocity that needs to be matched presents a choice. It can either be the group or the phase velocity. In the bulk of the existing literature this velocity is identified as the phase velocity. There are mathematical derivations showing the importance of phase velocity matching and the resulting expressions can be used to calculate the bandwidth of a traveling wave modulator for a given phase velocity mismatch. The physical argument supporting these derivations is the requirement of the optical and electrical phase fronts to travel at the same velocity. Therefore, the velocity to be matched is the velocity of a phase front, which is the phase velocity. However, there are a few very early publications that identify the relevant velocity to match as the group velocity [7]. We will clarify this point in this paper based on experimental results. In the case of velocity matching electrical bandwidth is limited by the loss of the microwave electrode. The small signal modulation response of a traveling wave modulator with a characteristic impedance matched to both the driver and the load impedance is given as

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$$M(f) = e^{-(\frac{\alpha L}{2})}\left[\frac{\sinh^2(\frac{\alpha L}{2}) + \sin^2(\frac{\xi L}{2})}{(\frac{\alpha L}{2})^2 + (\frac{\xi L}{2})^2}\right]^{\frac{1}{2}}, \text{ where } \xi = (n_\mu - n_o)\frac{2\pi f}{c}. \quad (1)$$

α and L are the loss coefficient and the length of the electrode respectively. f is the electrical frequency and c is the speed of light in vacuum. n_μ and n_o are the microwave and optical indices and are related to the microwave and optical velocities through well known expressions. Based on Equation 1 if there is no velocity mismatch 3 dB bandwidth will be at the frequency where the total electrode loss becomes 6.34 dB. Therefore, a low loss velocity and impedance matched electrode is essential for the realization of a very wide bandwidth traveling wave modulator. In III-V compound semiconductors velocity matching requires a slowing down of the microwave signal. The refractive index variation between microwave and optical frequencies in III-V compound semiconductors is rather small. The optical signal is entirely confined in the semiconductor, which has a refractive index of about 3.4. On the other hand microwave and the millimeter wave signal fringes into the air and experiences an effective index between that of the air and semiconductor. For example for a coplanar line of zero conductor thickness the effective dielectric constant is exactly the arithmetic mean of the dielectric constants of the air and the semiconductor. Therefore, the effective dielectric constant is around 7 which corresponds to a microwave index of about 2.65. Therefore there is about 38% of index mismatch between the optical and microwave signals. This requires about 23% velocity reduction. This can be achieved by capacitavely loading a uniform transmission line. One can use the capacitance of a p-i-n or a Schottky-i-n junction for this type of loading [6]. Using doped layers present some difficulties for very high frequency operation. Capacitance associated with such layers is usually high, which may result in excessive slowing and low characteristic impedance. If one reduces the loading by segmenting the p-i-n junction electric field strength along the length of the device is reduced, which in turn reduces the modulation efficiency. Furthermore, doped semiconductors have high but finite conductivity that is much lower than the conductivity of metals such as Gold. That finite conductivity results in excessive conductor losses that in turn can severely limit the bandwidth of the device. For these reasons we decided to use unintentionally doped epitaxial layers to keep optical and microwave losses very low. The required velocity slowing can be achieved using a properly designed electrode as described in the next section.

3. DEVICE STRUCTURE

The schematic of the device structure is shown in Figure 1. Optical structure is a guided wave Mach-Zehnder interferometer. A specially designed slow wave electrode structure runs parallel with the interferometer. A [100] oriented GaAs/AlGaAs heterostructure grown by MBE on semi insulating GaAs provides vertical optical

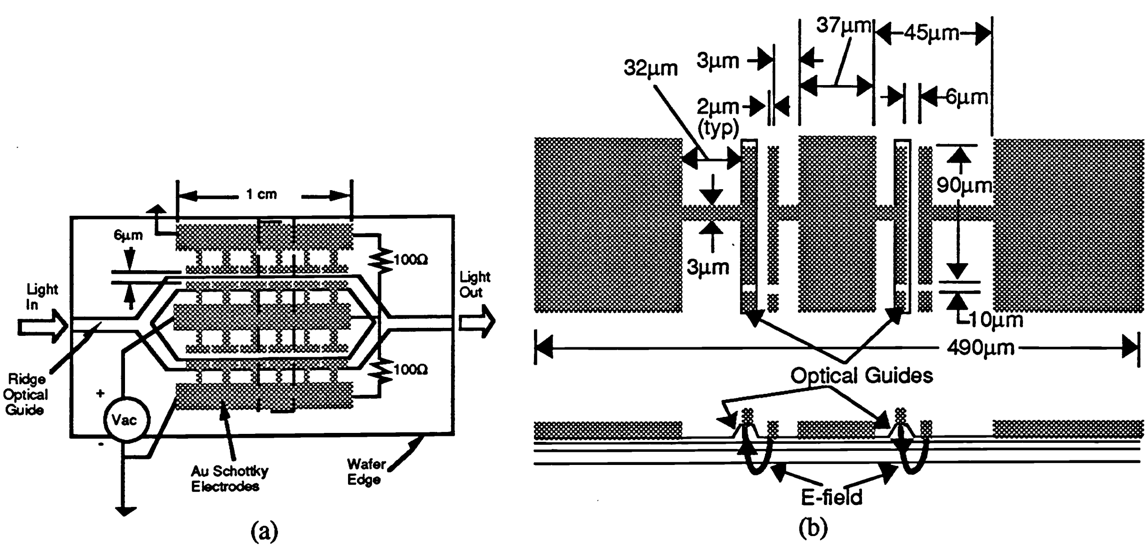


Figure 1. (a) Schematic top view of the modulator, (b) Top view schematic of the modulator section delineated by the dashed line in (a) together with a cross sectional schematic.

waveguiding. The bottom cladding layer is 1.8 μm thick $Al_{0.25}GaAs$. The core of the guide is 0.635 μm thick GaAs. The upper cladding is 0.7 μm thick $Al_{0.25}GaAs$. The lateral waveguiding is obtained by etching 0.52 μm ridges down into the top 0.7 μm thick $Al_{0.25}GaAs$ layer. The base of the trapezoidal ridges is 3 μm. Unintentionally doped epitaxial layers self deplete due to Fermi level pinning at the surface and the depletion originating at the semi insulating substrate interface. The optical guide is single mode both at 1.3 μm and 1.55 μm hence the device is expected to operate in the wavelength range from 1.3 to 1.55 μm. Since velocity matching is very important and this velocity is identified as the phase velocity in the bulk of the literature we calculated the phase velocity of the resulting optical guide using a finite difference solver. We can do this very accurately since the dimensions of the waveguide and the refractive indices of undoped bulk layers are known to a very good accuracy. The results of the calculations together with the refractive indices of the undoped epitaxial layers are given in Table 1. Calculated effective indices, n_{oph}, determine the phase velocity and are about 1% lower than that of the GaAs core. We chose the optical phase velocity at 1.3 μm as the target microwave phase velocity. Optical phase velocity varies about 1% between 1.3 μm and 1.55 μm. Therefore, achieving phase velocity matching

Table 1: Summary of the various indices. n_μ and n_{og} are calculated from the measured data. n_{oph} is calculated using a finite difference solver.

λ(μm)	n_{GaAs}	$nAl_{0.25}GaAs$	n_μ	n_{oph}	n_{og}	n_{og}/n_μ
1.3	3.41	3.28	3.38	3.38	3.73	1.10
1.55	3.37	3.25	3.38	3.34	3.55	1.05

at 1.3 μm virtually guarantees phase velocity matching at 1.55 μm. Therefore the target value for the microwave velocity and index were chosen as 8.88 cm/nsec and 3.38. Since the entire epitaxial structure is undoped, the electrode is designed as a slow wave transmission line to lower the microwave velocity to this target value. As seen in Figure 1 it is a modified coplanar line, in which T-rails stem from either side of the center conductor and from the inner side of the both ground planes [8]. These T-rails form tiny capacitors, which periodically load the line and increase its capacitance per unit length. That slows the microwave signal propagating on the electrode. For this structure, axial transmission line currents cannot flow along these T-rails. Only displacement current flows in these tiny capacitors. Therefore, current crowding and the microwave loss is determined by the distance between the center conductor and the ground plane of the unloaded line. One can make that gap large to keep microwave loss low [8]. On the other hand the gap between the T-rails determine the field applied to the optical guides for a given voltage. In this design this gap can be reduced significantly with a very small increase in the microwave loss [8]. As a result the electrode gap has been decoupled from the electrode loss. The microwave electrodes are fabricated by evaporating 200Å/200Å/1μm of Ti/Pt/Au. This forms a Schottky contact with the epitaxial layers. A voltage applied between the electrodes biases two back to back Schottky diodes. This makes it possible to apply mainly [100] directed electric fields of opposite polarity on the optical guides as shown in Figure 1(b). This generates phase shifts of opposite sign on both arms through the linear electro-optic effect, creating a net differential phase shift between the arms of the interferometer. Hence push pull modulation results.

4. EXPERIMENTAL RESULTS ON ELECTRODE GEOMETRY

The electrode geometry is shown in more detail in Figure 2. As described earlier it is a modified coplanar transmission line in which T-rails stem from either side of the center conductor and from the inner side of both ground planes. In order to find the right design parameters we fabricated over one hundred electrodes of different dimensions by lifting off 1μm thick Au on semi-insulating GaAs. We measured their phase velocity, v_{ph}, characteristic impedance Z_0 and loss coefficient α up to 40 GHz using microwave probes and an HP 8510B automatic network analyzer. The study consisted of incrementally varying the dimensions labeled in Figure 2. We found out that as W, g, s and d increase v_{ph} increases. Increasing G decreases v_{ph} while r has no effect on v_{ph}. Z_0 decreases with increasing W and r, and increases with increasing G and g. s and d do not greatly affect Z_0. α decreases with increasing W, G, g and d, and increases with increasing r and L. s effects α minimally. Based on the experimental results we found an optimum geometry. Figure 3 shows the measured characteristics of the actual modulator electrode used in the experiments described later. Measurement is limited up to 40 GHz due to equipment limitations. In this case g is 6μm. The other parameters are W = 37 μm, G = 45 μm, L = 90 μm, d = 100 μm, s = 3 μm, and r = 2 μm. The measured phase velocity shows virtually no dispersion and is within 1% of the target value calculated earlier. The characteristic impedance is 46 Ω which is very close to the target value of 50 Ω. The microwave loss is also very

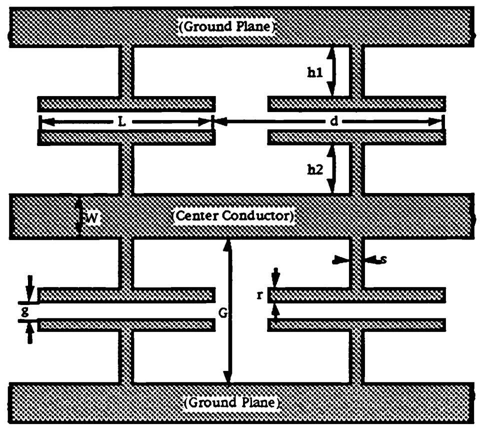


Figure 2. Schematic of the T-rail electrode geometry.

low. It increases with frequency and reaches to a value of about 3 dB/cm at 40 GHz. This value is considerably less than the 6.34 dB loss limit that determines the 3 dB electrical bandwidth when velocity and impedance matching is obtained. Therefore, a very high electrical bandwidth approaching 100 GHz is expected from this device.

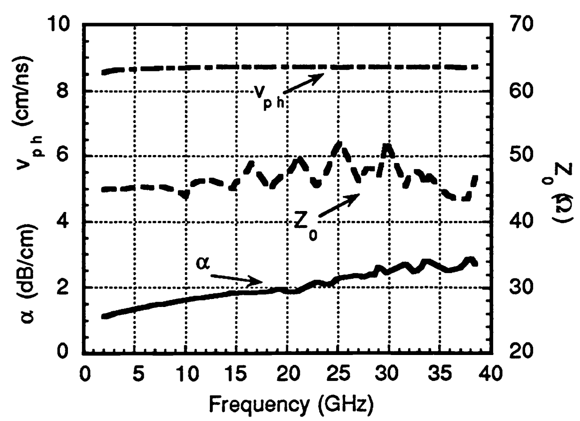


Figure 3. Measured microwave characteristics of the modulator electrode.

Another advantage of this design is the symmetry of the high field region and the large segmentation factor. The 6 μm gap extends over 90% of the electrode length. The increase in α of the unperturbed coplanar line due to the presence of the T-rails is measured to be less than 1 dB over the entire frequency range.

It is possible to reduce the gap further. Figure 4 shows the measured microwave loss at 35 GHz as a function of g with r as a parameter. As shown, r = 2 μm and g = 3μm results in an α of 4.3 dB/cm at 35 GHz. Such small g and r values make this geometry suitable for both directional coupler and Mach-Zehnder type electro-optic modulators. However, for small gaps the capacitive loading was excessive, resulting in v_{ph} and Z_0 which were smaller than desired. For the above g = 3μm and r = 2μm example, the measured v_{ph} and Z_0 were 8.0 cm/nsec and 43Ω respectively. This results in a 10% phase velocity mismatch with respect to the target value of 8.88 cm/nsec and a 7.5% (-22.5 dB) reflection coefficient with respect to a 50Ω line. This excessive loading may be overcome by adjusting other dimensions. For example by choosing W = 40 μm, G = 23 μm, s = 3 μm and d = 100 μm it was possible to get a v_{ph} of 8.6 cm/nsec with Z_0 of 37 Ω and α of 3 dB/cm at 40 GHz, while keeping g at 3

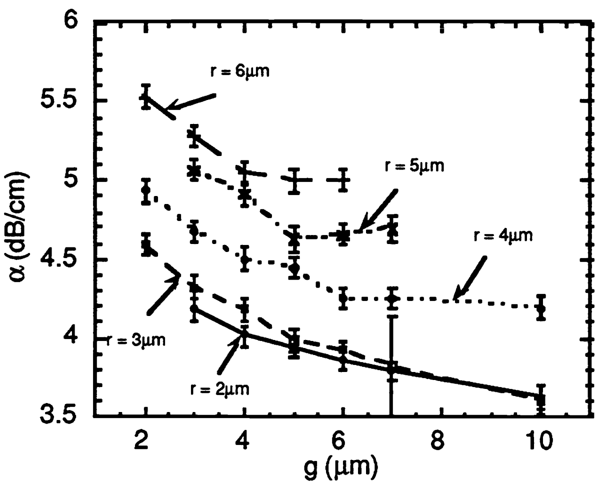


Figure 4. Measured microwave loss at 35 GHz as a function of T-rail gap, g, for different T-rail widths, r, for W = 21 μm, G = 30 μm, L = 45 μm, d = 50 μm, and s = 5 μm.

μm. Obviously a smooth coplanar line with a gap this small would experience excessive current crowding losses and a low electrical bandwidth.

5. EXPERIMENTAL RESULTS ON THE MODULATOR

After fabricating devices electrical and optical characterization was performed. Electrical tests indicated that we

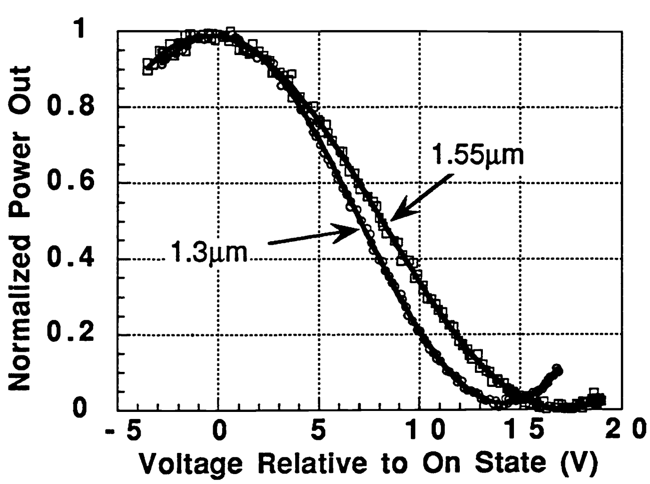
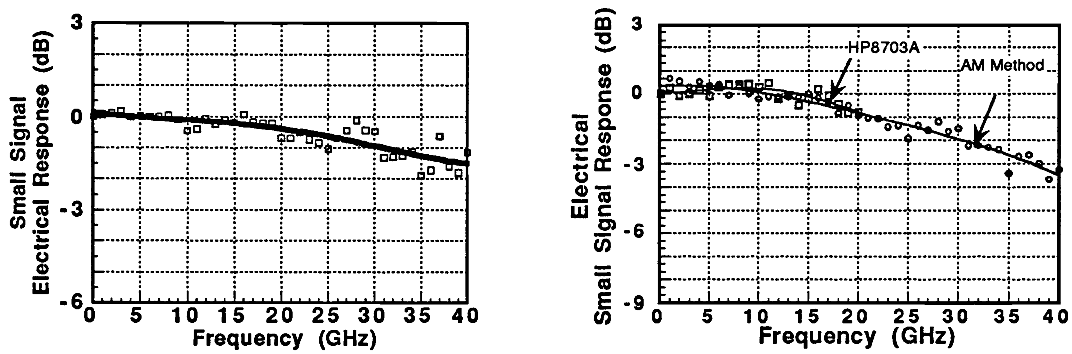


Figure 5. 1 MHz transfer functions of the modulator at 1.3μm and 1.55μm.

indeed had two back to back Schottky diodes. Measured leakage currents between two electrodes was less than 20 μA for up to 20 V bias. In the experiments current injected into the device over the entire electrode length of 1 cm was never larger than 100 μA. For the low frequency optical measurements the output of a DFB laser was coupled in and out of the waveguide using lensed fibers. The electrical signal was applied using commercially available microwave coplanar probes. Figure 5 shows the 1 MHz transfer functions of the device at 1.3μm and 1.55μm. The transfer functions follow the expected cosine squared voltage dependence very closely. The switching voltages are 14V at 1.3μm and 16.8V at 1.55μm. As predicted, the switching voltage varies inversely with wavelength. Calculated overlap values between the vertical electric field component and the optical mode are in the 40 to 50 % range, which agree with the theoretical calculations on similar geometries [2]. The extinction ratio is 20.1 dB at 1.3μm and 22.6 dB at 1.55μm. We also measured the small signal electrical bandwidth of the device both at 1.3 μm and 1.55μm. The measurement technique is outlined in [9]. It utilizes the nonlinear optical response of the device. The microwave signal applied to the device is AM modulated at a low frequency, typically 10 kHz. At the optical output of the modulator harmonics of this AM modulated waveform are generated due to the nonlinearity of the optical response. In particular a harmonic appears at the AM modulation frequency of 10 kHz. Small signal modulation response of the modulator is obtained by monitoring the amplitude of this signal using a low frequency photodetector as a function of the microwave frequency. The measured small signal modulation response of the device at 1.3 and 1.55 μm are shown in Figure 6. The maximum measurement frequency is 40 GHz due to equipment limitations. This figure also shows



(a) (b)

Figure 6. Measured small signal response of the modulator (a) at 1.55 μm and (b) at 1.3 μm. The fitted curve is a fourth order polynomial.

an independent measurement at 1.3 μm up to 20 GHz using a commercially available instrument. The two independent measurements agree within a fraction of a dB verifying the accuracy of the measurement based on AM modulation. The lines are 4 th order polynomial curve fits to the data points. The bandwidth at 1.55 μm is in excess of 40 GHz. It is basically flat up to 20 GHz and starts to roll off gradually and becomes about 1.5 to 2 dB down at 40 GHz. Extrapolating the curve fit we estimate the bandwidth between 50 to 60 GHz. Although this is a rather high bandwidth it is still less than the bandwidth expected based on the electrode data. At 1.3 μm the 3 dB bandwidth is about 37 GHz. This is considerably less than what is expected. Furthermore, the variation between 1.55 μm and 1.3 μm is much more than expected since the phase velocity variation between these two wavelengths is about 1% as explained earlier. Since we are measuring the same device at two different wavelengths the electrode characteristics are exactly the same. Then the only explanation for the bandwidth change is a change in the velocity mismatch. This prompted us to measure the velocity mismatch as described in the next section.

6. WHICH VELOCITY TO MATCH?

The velocity mismatch between the optical and microwave signals can be measured by counter propagating the optical and microwave signals. Since they travel in opposite directions they are badly velocity mismatched and one expects a null in the modulation response at a frequency that can be calculated using Equation 1. Measuring this null frequency and knowing the microwave index we can calculate the optical index. The null frequency based on the measured microwave index was expected to be very close to 4.5 GHz. The measured small signal modulation response of the modulator when electrical and optical signals counter propagated is shown in Figure 7. The measured null frequency is less than expected and is different for both wavelengths. It is hard to determine this frequency by locating the position of the null since at that frequency measured signal becomes so small that accuracy is lost due to poor signal to noise ratio. But it is possible to determine this frequency accurately by curve fitting the measured data to the expression given in Equation 1. Results obtained this way are shown in Table 1 together with other relevant indices. The result is very surprising, because optical index n_{og} measured this way turned out to be larger than the index of the GaAs which is the core of the waveguide. Clearly this cannot be the index determining the phase velocity. It can only be the group index. This makes a lot of physical sense because once the optical signal starts to interact with the electrical signal it is no longer a single frequency waveform. It is clearly phase modulated and this phase modulated waveform travels with the group velocity. This velocity should

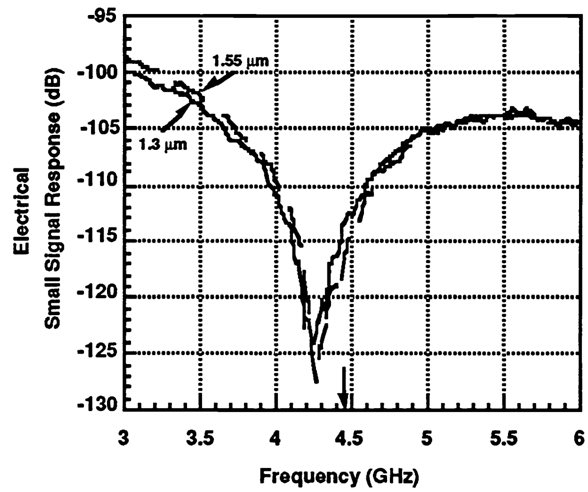


Figure 7. Measured small signal modulation response of the modulator when electrical and optical signals counter propagate. Arrow indicates the expected position of the null frequency if optical and microwave phase velocities were matched.

be the same as the group velocity of the electrical waveform so that they keep interacting and the phase modulation accumulates. Therefore group velocities should match. Since we are dealing with a quasi-TEM transmission line on the electrode, there is no dispersion and phase and group velocities are the same. This is also obvious from the measured data. However, for the optical guide phase and group velocities are different as seen in Table 1. Actually the change in the group velocity going from 1.3 to 1.5 µm is twice as the corresponding phase velocity change. Also the group velocity values are lower than the phase velocity values for which the electrode velocity was matched. When these two results are combined we see that there is about 10% group velocity mismatch at 1.3 µm which explains the measured bandwidth. The mismatch at 1.5 µm is about 5% and the measured bandwidth is consistent with that result. In our case even though we operate far away from the band edge our electrode is long. As a result we are very susceptible to slight fractional changes in the velocity mismatch. Actually this experimental observation is consistent with the claims made on one of the early publications on this topic [7]. This point is also very important and should also be observed for other types of shorter modulators. Although their lengths are shorter they may be very susceptible to index mismatches since they usually operate closer to the band edge where material index dispersion is much more significant. Therefore providing the right kind of velocity match is very important to get the widest possible bandwidth in traveling wave modulators.

7. CONCLUSIONS

A traveling wave GaAs/AlGaAs electro-optic modulator with electrical bandwidth larger than 40 GHz is reported. Device uses unintentionally doped epitaxial layers to keep optical and microwave losses low. A novel slow wave coplanar electrode design makes it possible to get velocity matching, very low microwave loss, a virtually impedance matched electrode and a small electrode gap, hence efficient modulation. It is also experimentally identified that to achieve the maximum bandwidth optical and microwave group velocities should be matched.

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