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Modeling and preliminary testing of a monolithic coplanar waveguide (CPW) phase shifter using both optical and Schottky-contact control techniques has been performed. Simulation work on a periodically illuminated structure has been completed, showing that some improvement in performance may be possible, although with a reduction in frequency bandwith. CPW transmission lines have been fabricated on semi-insulating GaAs, on heavily doped epi GaAs, and on an AlGaAs/GaAs heterostructure, and initial electrical characterization has been performed. Optically controlled phase shift has been obtained with the heterostructure device, and Schottky-bias controlled behavior has been seen with the epi sample.

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Microwave Laboratory Report No. 87-P-10

Monolithic Phase Shifter Study

D. P. Neikirk and T. Itoh
University of Texas at Austin
Department of Electrical and Computer Engineering
Austin, TX 78712

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I. Summary

Modeling and preliminary testing of a monolithic coplanar waveguide (CPW) phase shifter using both optical and Schottky-contact control techniques has been performed. Simulation work on a periodically illuminated structure has been completed, showing that some improvement in performance may be possible, although with a reduction in frequency bandwidth. CPW transmission lines have been fabricated on semi-insulating GaAs, on heavily doped epi GaAs, and on an AlGaAs/GaAs heterostructure, and initial electrical characterization has been performed. Optically controlled phase shift has been obtained with the heterostructure device, and Schottky-bias controlled behavior has been seen with the epi sample.

II. Objectives and Status of Research

As discussed in our original proposal "Monolithic Phase Shifter Study," the objective of this work is to model, construct, and test prototype planar waveguide structures that could be used in monolithic millimeter-wave phase shifters. During the last year of our research project we have undertaken the following major tasks necessary to achieve the objectives of the proposal

i) A simple model which clarifies the modes of operation of a slow wave phase shifter has been developed. This model shows the fundamental differences between Schottky contact and optical control techniques;

ii) Theoretical analysis of wave propagation in a CPW with periodic optically-induced lossy patches has been performed. Such a device is predicted to provide better performance than the uniformly illuminated phase shifter;

iii) Picosecond time-domain measurements of the dispersion properties of the optically controlled heterostructure CPW have been initiated in collaboration with Dr. M. Downer's group in the UT-Austin Physics Department;

iv) A prototype CPW phase shifter has been fabricated on both semi-insulating and heterostructure substrates, and preliminary rf testing has been performed. Optically induced phase shift has been obtained between 1 and 18GHz, although packaging parasitics must be reduced to make more accurate measurements.

2

The following discussion presents a summary of work performed during this period, and indicates some of the issues which will be addressed in the third year of the research project.

III. Introduction and Background

In 1965 Hyltin [1] suggested that microstrip transmission lines could be fabricated on the same substrate as microwave devices to serve as interconnects, thus eliminating the need for hybrid circuits that give rise to parasitic inductances and capacitances. Subsequent theoretical studies by Guckel [2] and Ho [3] showed that when these lines are fabricated on multi-layered semiconductor substrates (such as silicon dioxide (SiO_2) on silicon (Si) or aluminium gallium arsenide ($Al_xGa_{1-x}As$) on gallium arsenide (GaAs)), the lines could support three different characteristic modes of propagation. This analysis showed that the occurrence of the modes at a particular frequency is a function of the resistivity and the thickness of the layers of the substrate, as well as the dimensions of the transmission line. These modes are generally referred to as the skin-effect mode, the slow-wave (SW) mode, and the lossy dielectric mode.

In 1971 Hasegawa [6,7] experimentally verified the existence of these modes on a SiO_2-Si system over a wide range of substrate resistivity, dielectric thickness and microstrip width. Hasegawa attributed the occurrence of these modes to a Maxwell-Wagner effect that modifies the effective dielectric constant of the system. Hughes and White [4,5] subsequently identified the physical origin of these modes by considering the dielectric relaxation time (which is essentially the Maxwell-Wagner effect) and the fact that the propagating wave can be approximated by a quasi-transverse electromagnetic (TEM) wave.
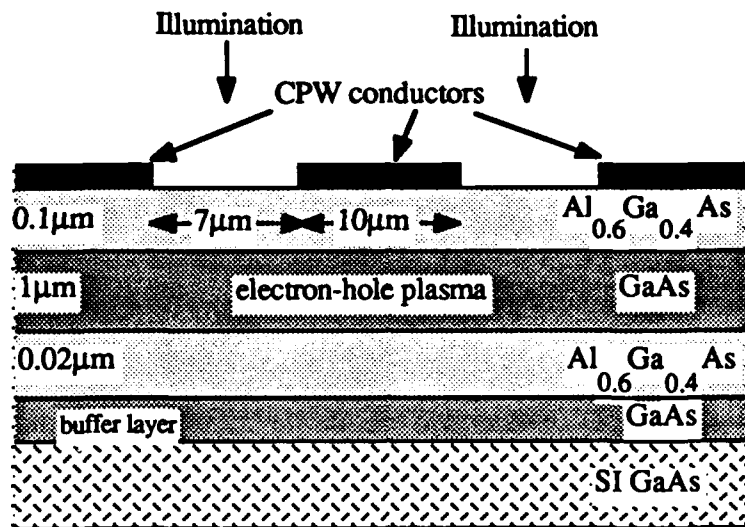
The field configuration in a coplanar waveguide (CPW) transmission line is more complex than that in a microstrip. Accurate analysis of CPWs on lossy, layered substrates

has been performed using "full wave" analysis which can take into account the complicated electric field distribution. These analyses use techniques such as spectral domain analysis (SDA), the mode matching technique, and the finite-element method (FEM). Of the three techniques, the first two techniques (SDA (Shih and Itoh [9,10]) and mode matching (Fukuoka and Itoh [8,10])) have been performed for CPW on an MIS and Schottky-contacted structure. In the analysis of the Schottky-contacted structure, a uniform depletion layer is assumed across the structure. The only full wave analysis that takes into account the actual geometry of the depletion layer is the FEM technique. The analysis for the Schottky-contacted CPW that takes into account the actual geometry of the depletion layer has been performed by Tzuang and Itoh [11] using this technique.
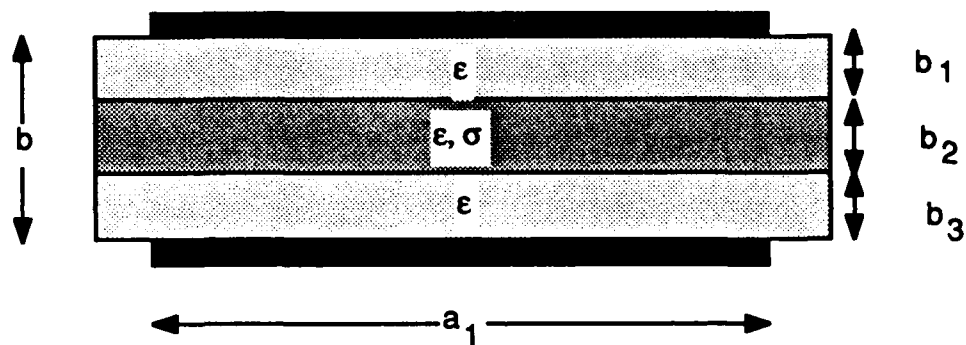
One problem with the numerically intensive analyses discussed above is the extraction of physical insight into the modes of device operation. Using a quasi-TEM approximation, however, it is possible to construct a simple model of dielectric-supported transmission lines which can include the effect of a lossy layer in the substrate. Although this model will not yield exact results, it does allow the development of physical insight, which can guide the choice of structure which should be analyzed with the more accurate full wave techniques. The next section discusses such a simple physical model.

## IV. Parallel Plate Model of Slow Wave Transmission Lines

Figure 1 illustrates the model used here. The transmission line (whether microstrip or coplanar waveguide (CPW)) is treated as a parallel plate waveguide with a layered dielectric between the plates of the guide. So long as the dielectric constants and conductivities of each layer are not too different, this guide will support a quasi-TEM mode of propagation. Conventional transmission line analysis can then be applied, and the line is characterized by its equivalent series impedance per unit length Z_l and shunt admittance per unit length Y_l.

Illumination   Illumination

CPW conductors

0.1μm ←7μm→←10μm→ Al$_{0.6}$Ga$_{0.4}$As

1μm   electron-hole plasma   GaAs

0.02μm   Al$_{0.6}$Ga$_{0.4}$As

buffer layer   GaAs

SI GaAs

(a) Optically controlled coplanar waveguide
phase shifter structure.

ε b$_1$

ε, σ b$_2$

b

ε b$_3$

a$_1$

(b) Simple plane parallel plate waveguide model
which exhibits slow wave behavior.

$$C_1 = \frac{a_1 \varepsilon}{b_1}$$

$$R_2 = \frac{b_2}{a_1 \sigma}$$

$$C_2 = \frac{a_1 \varepsilon}{b_2}$$

$$C_3 = \frac{a_1 \varepsilon}{b_3}$$
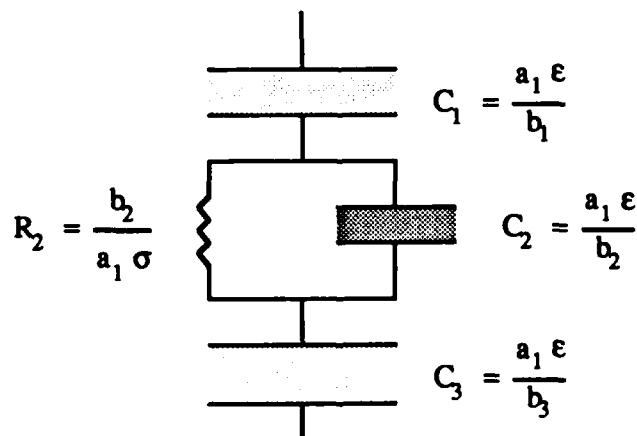
(c) Equivalent circuit for shunt admittance Y in
transmission line model of the waveguide shown
in (b).

Figure 1

5

The complex characteristic impedance of the line is

$$Z_o = \sqrt{\frac{Z_1}{Y_1}} \qquad (1)$$

and the complex propagation constant is

$$\gamma = \sqrt{Z_1 Y_1} \qquad (2)$$

The slow wave structure shown in Fig. 1 contains three layers of dielectric. The top and bottom layers are lossless with relative permittivity ε_r, while the center layer is lossy with conductivity σ. In terms of the response of the structure to an applied voltage, if the frequency of the applied voltage is much less than the dielectric relaxation frequency f_s in layer 2, given by

$$f_s = \frac{\sigma}{2\pi \varepsilon_r \varepsilon_o} \qquad (3)$$

then the charges of layer 2 can respond to the applied voltage so rapidly that it essentially forms a short between the two cladding dielectric layers. In this case $Y_1 = j\omega C$, where the capacitance/unit length C of the structure is

$$C = \varepsilon\, a_1\, \frac{1}{b_1 + b_3} = \varepsilon\, a_1\, \frac{1}{b - b_2} \qquad (4)$$

When the frequency is such that $f \gg f_s$ the charges in layer 2 can no longer follow the applied field, and the capacitance is that of a parallel plate capacitor filled with a uniform dielectric material of permittivity $\varepsilon = \varepsilon_r \varepsilon_o$. The capacitance/unit length C is thus reduced, and is now

$$C = \varepsilon\, a_1\, \frac{1}{b} \qquad (5)$$

If L is the inductance per unit length for the structure, then $Z_1 = j\omega L$, and for a TEM mode the propagation velocity is given by

6

$$v = \frac{\omega}{\text{Im}(\gamma)} = \frac{1}{\sqrt{LC}} \qquad (6)$$

So long as the frequency is low enough that the skin depth in the lossy layer is much greater than the thickness of this layer, the inductance/unit length is

$$L = \mu \frac{b}{a_1} \qquad (7)$$

Thus, for low frequencies, i.e. $f \ll f_s$, the phase velocity is

$$v = \frac{1}{\sqrt{\mu \varepsilon_r \varepsilon_o}} \sqrt{\frac{b - b_2}{b}} = \frac{c}{\sqrt{\varepsilon_r}} \sqrt{1 - \delta} \qquad (8)$$

where $\delta = b_2/b$ is the fractional amount of the guide filled with lossy material, and c is the speed of light in a vacuum. For high frequencies, i.e. $f \gg f_s$, the phase velocity increases, and is

$$v = \frac{1}{\sqrt{\mu \varepsilon}} = \frac{c}{\sqrt{\varepsilon_r}} \qquad (9)$$

We can now clearly see the origin of the slow wave phenomenon: at low frequencies the effective capacitance of the structure is increased relative to that at high frequencies, thus leading to a slower propagation velocity. The effective index of refraction of the guide n' (also referred to as the slow wave factor) is given by

$$n' = \frac{c}{v} = \sqrt{\frac{LC}{\mu \varepsilon_o}} \qquad (10)$$

Thus, the low frequency value is increased over the high frequency value by a factor of $1/\sqrt{1 - \delta}$, as shown by eqns. 8 and 9.

There are two limits that govern the occurrence of the slow wave (SW) mode in the frequency domain. The first limit, as discussed above, is the dielectric relaxation frequency f_s. The second limit is determined by the penetration of the magnetic field into the lossy layer. This limit is reached if the skin depth in the lossy layer becomes less than the thickness b_2, since under these circumstances the magnetic field does not penetrate the entire volume of the substrate, and we cannot assume that the inductance of the line is given by eq. 7. This frequency limit is given by

$$f_\delta = \frac{1}{\pi \mu \sigma b_2^2} \tag{11}$$

Thus, for a given conductivity and lossy layer thickness, the propagating mode will be slow only if the operating frequency f_{op} is chosen such that it is below both f_s and f_δ.

These two limits on SW behavior produce characteristics of the type shown in Figs. 2 and 3. Given a fixed frequency f_{op}, as the conductivity of the second layer is decreased (i.e. the resistivity is increased), the characteristic propagating mode changes from a skin depth mode to a SW mode, due to the change in effective inductance of the structure. As the conductivity is further reduced, the SW mode eventually changes to a lossy dielectric mode. On the other hand, for fixed conductivity, if the frequency increases, the SW mode eventually changes to either a lossy dielectric mode or skin effect mode, depending on whether $f_s < f_\delta$ or $f_\delta < f_s$, respectively.

This graph also illustrates that there are two fundamentally different ways to gain control over the propagation velocity in this transmission line. For instance, if the thickness of the lossy layer could be controlled, eq. 8 clearly shows how the propagation velocity would vary, assuming $f_{op} \ll f_s$. One way to achieve this control is through the use of Schottky contacted metal lines to a doped semiconductor. Here, a change in the thickness of the depletion layer causes a change in the limiting frequency between the SW mode and the lossy dielectric mode, as shown in Fig. 2. There is another possible way to
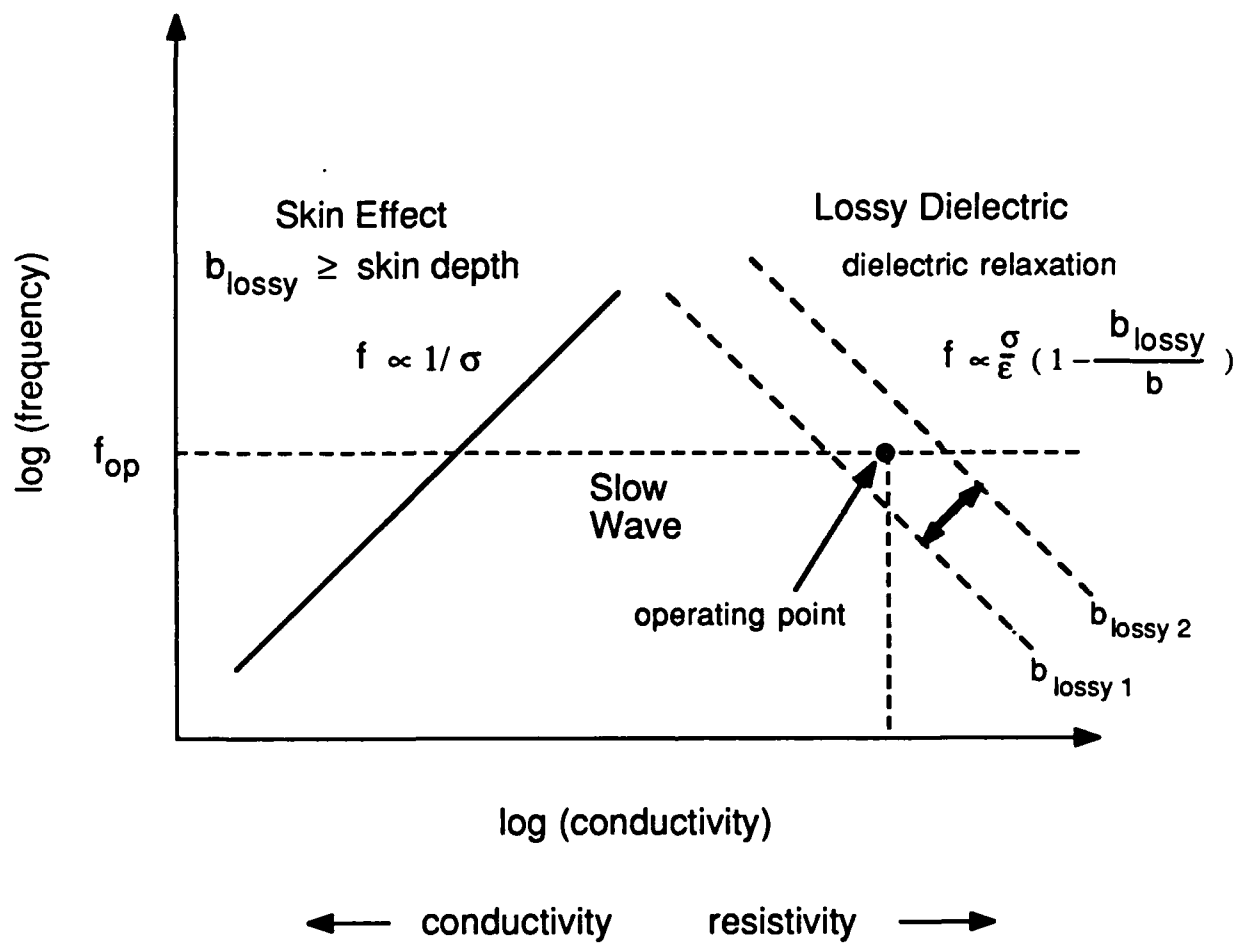
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Figure 2

control the propagation velocity, as illustrated by Fig. 3. Here the resistivity of the lossy layer is varied directly; this change in the resistivity moves the operating point of the device between the lossy dielectric region and the slow wave region. The easiest way to externally control the resistivity of the lossy layer is via an optically-induced electron-hole plasma in the semiconductor. This is the basis for the optically controlled phase shifter under study.

The simple model discussed above can be used to estimate the behavior of these devices. Figure 4 illustrates the effect of varying the percentage δ of the dielectric substrate which is lossy. Since all the frequency dependent behavior scales with the dielectric relaxation frequency, the frequency is given in units of $f_s = \sigma/2\pi\varepsilon$. The units of n' and n" are scaled to $\sqrt{\varepsilon_r}$. The slow wave factor n' clearly exhibits a strong dependence on the amount of lossy material, with a maximum normalized slow wave factor of $1/\sqrt{1-\delta}$ (e.g. 10 for 99% lossy dielectric). Examination of Fig. 4 shows that the frequency at which the slow wave factor begins to drop is given by

$$f_{SW} = \frac{\sigma}{2\pi\,\varepsilon_r\,\varepsilon_o}\,(1-\delta) = f_s\,(1-\delta) \qquad (12)$$

As the frequency is increased beyond f_s (which equals one in normalized units), the propagating mode is no longer slow, but has changed to a lossy dielectric mode.

Figure 4 also clearly illustrates the difference between the two control methods, i.e. Schottky and optical. With Schottky control the variable δ is directly controlled, so the effect is to shift from one curve to another in Fig. 4, while remaining at a fixed normalized operating frequency (since σ is fixed). Thus, for Schottky control it is desirable to operate at "low" frequency, i.e. $f \ll f_{SW}$, in the flat part of the dispersion curve. Figure 5 illustrates how such a device might behave, assuming the material system is GaAs doped to 10^{17} cm^{-3}. In this case $f_s \approx 10^{14}$ Hz, while f_{SW} varies from 10^{12} Hz for $\delta = 99\%$ to 7×10^{13} Hz for $\delta = 30\%$. Thus, this device could in principle be used beyond 100 GHz, and provide slow wave factors of up to about 35.
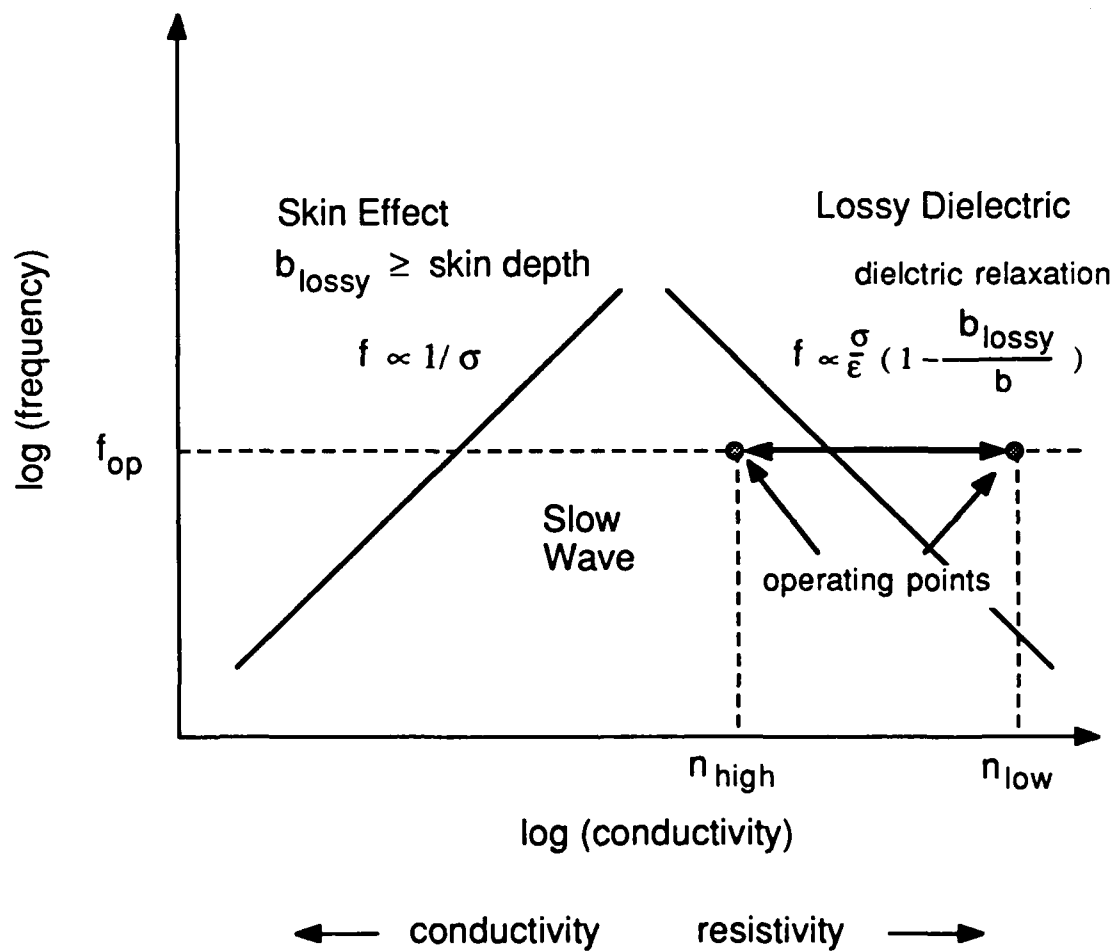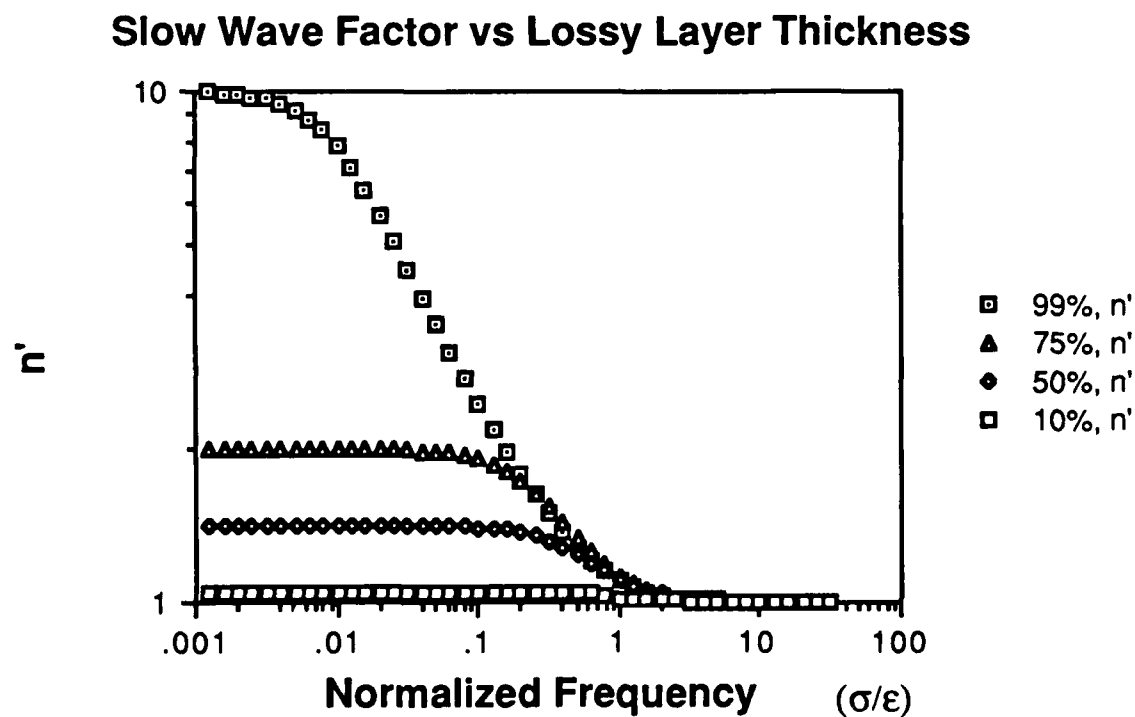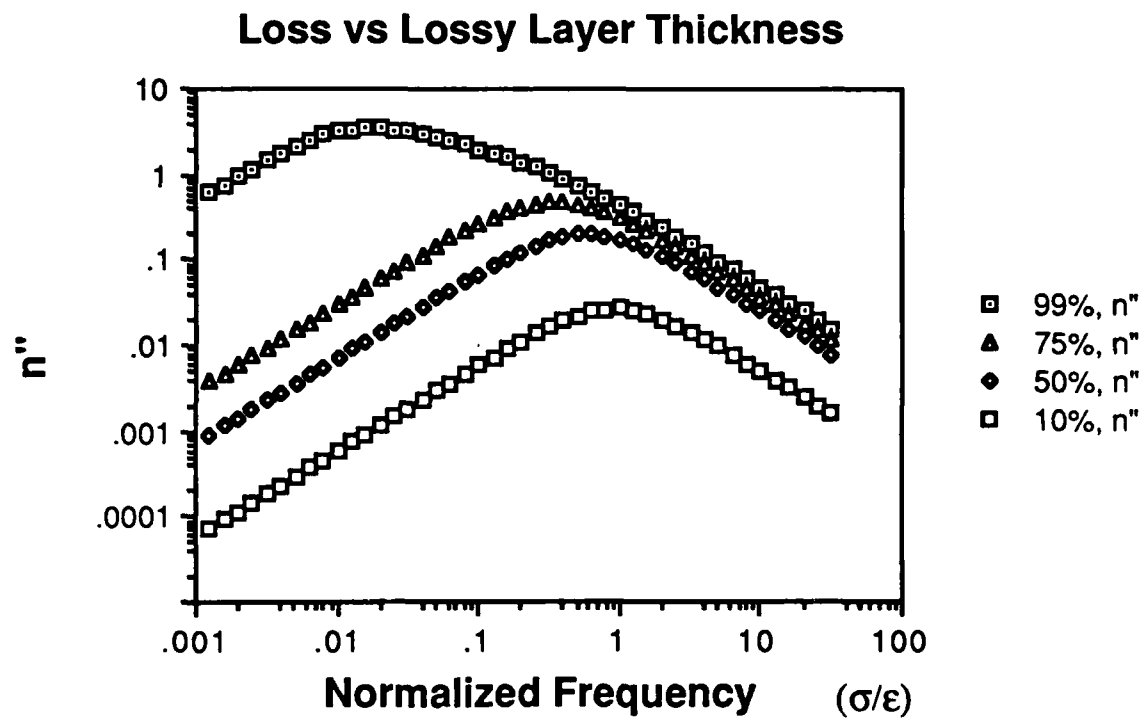
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Figure 3

11

Loss vs Lossy Layer Thickness

Slow Wave Factor vs Lossy Layer Thickness

Figure 4

12

Loss vs Lossy Layer Thickness

Legend:
- □ n", 99% lossy
- ◆ n", 95% lossy
- ▫ n", 80% lossy
- ◈ n", 30% lossy

Slow Wave Factor vs Lossy Layer Thickness

Legend:
- ▣ n', 99% lossy
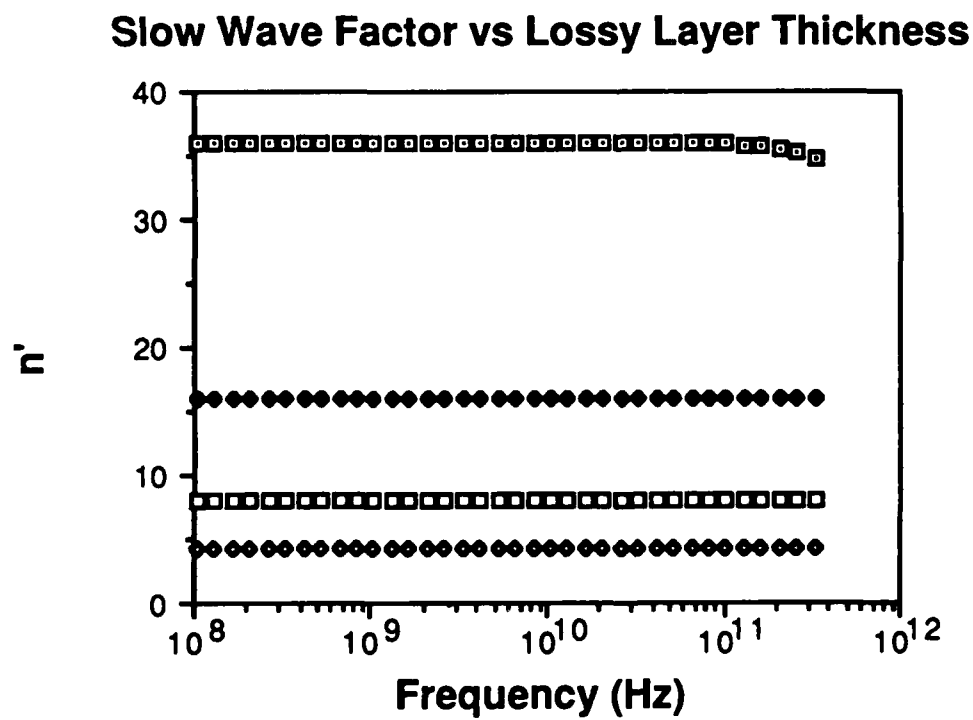- ◆ n', 95% lossy
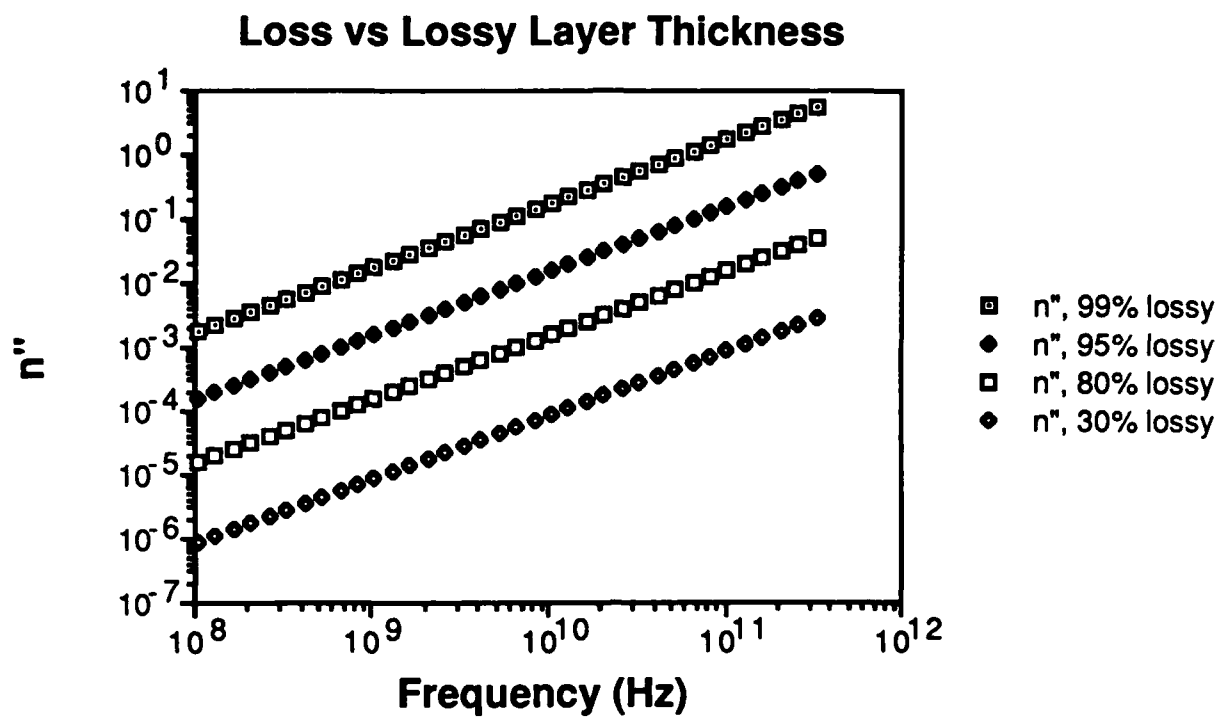- □ n', 80% lossy
- ◈ n', 30% lossy

Figure 5

13

In contrast to the Schottky control technique, optical control varies the conductivity of the lossy layer rather than its thickness. In such a case, in Fig. 4 the device would always operate on curve of fixed δ; slow wave control would be obtained through a variation in the normalized frequency of operation, f_{op}/f_s, via a variation in σ. Here it is necessary to operate in a region of strong dispersion to achieve large phase shifts, as illustrated in Fig. 6. The requirements on operating frequency now become

$$f_{SW}(\sigma_{low}) < f_{op} < f_S \quad (\sigma_{high}) \tag{13}$$

where σ_{low} is the conductivity for low levels, and σ_{high} for high levels, of illumination intensity. Note it is essential to use values of δ which place f_{SW} below the frequency of operation. Since f_s for GaAs is very high (even at the lowest doping level of 10^{15}cm^{-3} f_s is about 1000 GHz) δ must be large (i.e. the fraction of the substrate which is lossy must be large) to reduce f_{SW} below the operating frequency. The example shown in Fig. 6 required $\delta = 99\%$ in order to reduce f_{SW} to 10 GHz, thus allowing large changes in slow wave factor near 100 GHz.

In addition to predicting the variation of propagation velocity, this model can also be used to estimate changes in the characteristic impedance of the transmission line. Equation 1 leads to

$$Z_o(f, \delta) = \frac{Z_o}{n'(f, \delta)} \tag{14}$$

where Z_0 is the characteristic impedance of the structure at high frequencies, and $n'(f,\delta)$ is found from eq. 10. Thus, the impedance of the guide should be inversely proportional to the slow wave factor. This relationship should be useful in interpreting experimental results, since the effective impedance of the guide is relatively easy to determine from time domain reflectometry measurements. This will be discussed further in the Fabrication and Testing section of this report.

14

Loss vs Carrier Concentration
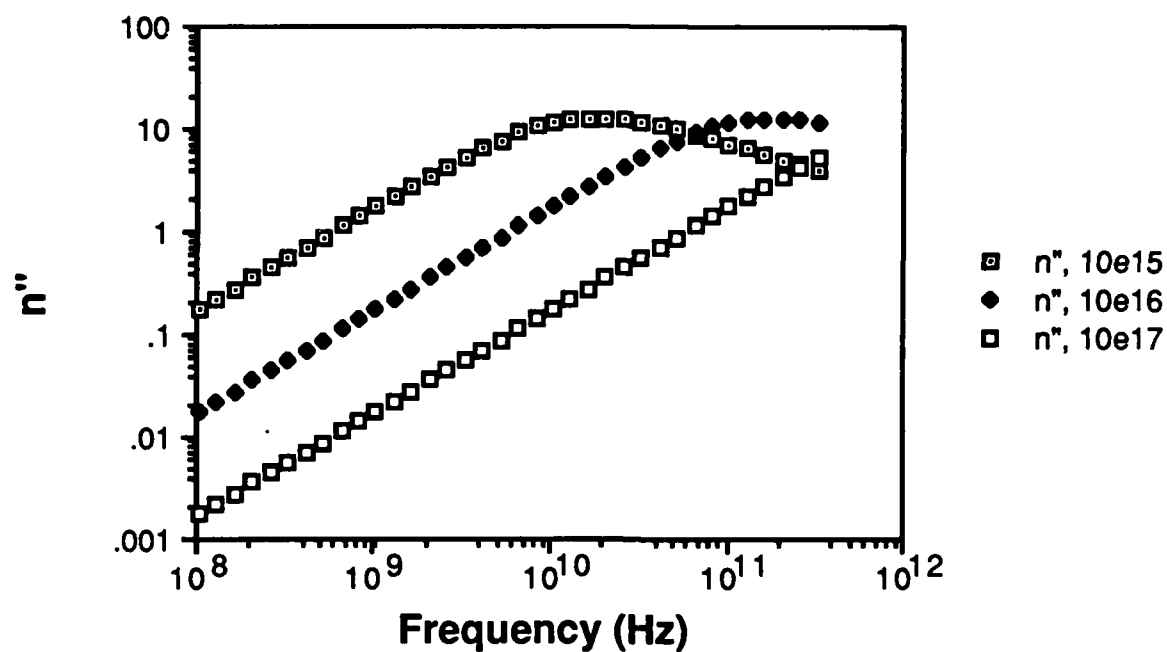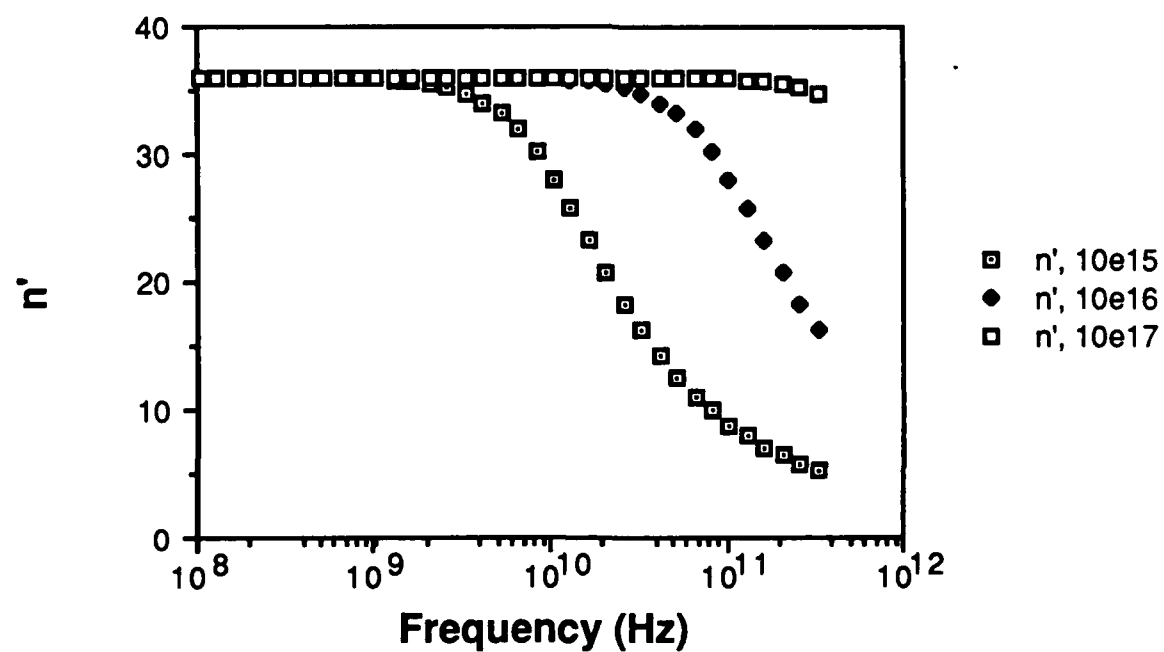

Slow Wave Factor vs Carrier Concentration

Figure 6

15

V. Simulation of the Periodically Illuminated CPW Phase Shifter

In the hope of reducing loss, a structure illuminated periodically along the wave propagation direction has now been analyzed [12]. Here, the structure is made of a successive chain of alternating lossy and lossless coplanar waveguides. The primary objective is to find a structure which has a reduced insertion loss and yet retains good phase shifting properties. To analyze this structure we first use the spectral domain technique to find the propagation constants and characteristic impedances of individual sections of lossless and lossy CPW transmission lines. The periodic structure is then modeled as a series of these transmission lines, and the cascaded transmission line matrix calculated based on the spectral domain results. We have found that if the length of the period is much smaller than the wavelength, the only effect obtained is a reduced slow wave factor accompanied by a reduced attenuation loss. These reductions are in proportion to the duty factor (i.e. the ratio of lossless to lossy line). If a fixed phase shifting capability is required, these reductions exactly cancel one another, since a reduction in slow wave factor requires a longer line, which increases the final insertion loss.

When the period of the lossy/lossless sections becomes comparable to a guide wavelength, resonant effects can occur. For instance, in a cascaded lossless line where only the characteristic impedances are varied, Bragg reflection occurs if the length of the period is approximately one half of the wavelength. Near this point, strong dispersion can cause large phase shifts. This phenomenon does not occur in exactly the same way in our structures because the lines are lossy, although the calculations do indicate pass-band like characteristics.

At present we are continuing to study the properties of these structures to try to find an optimum set of parameters for a given design frequency. The initial calculations are for a structure with fixed total length and internal period, which makes it difficult to extract phase shifter design information. Future work will determine the optimum line length for a

16

desired phase shift, and allow comparisons of insertion loss on a per unit phase shift basis. One advantage of the optical control technique is that we can easily vary the period, duty cycle, and carrier densities in the CPW lines to experimentally investigate this device.
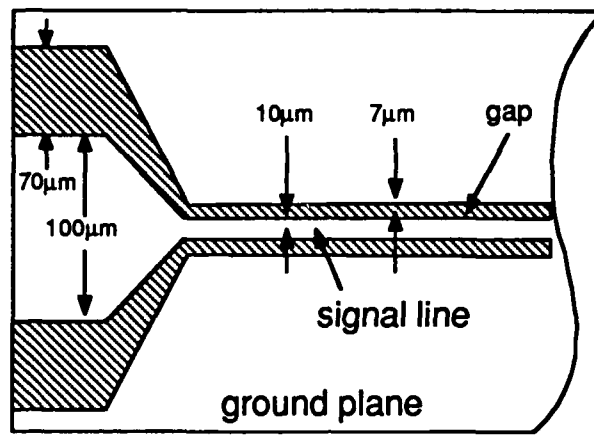
VI. Time Domain Studies of the Optically Controlled CPW

The dispersive behavior of slow wave propagation in lossy transmission lines is an essential feature of the optically controlled CPW phase shifter. It is this physical phenomenon that actually gives rise to a controllable phase shift. In order to study the dynamics of this process we have begun a study of very high speed pulse propagation on our device structure. This work is being pursued in collaboration with Dr. Mike Downer of the UT-Austin Physics Department, who is an active researcher in the area of sub-picosecond lasers and high speed transport. Our research group is now fabricating a device which will be used by Downer to study pulse dispersion using an opto-electronic sampling technique. These techniques are extremely promising for very high bandwidth measurements, and we hope to use them to obtain data for our device for pulse widths of approximately 10psec. This work is in the set-up and basic calibration stage at this time.
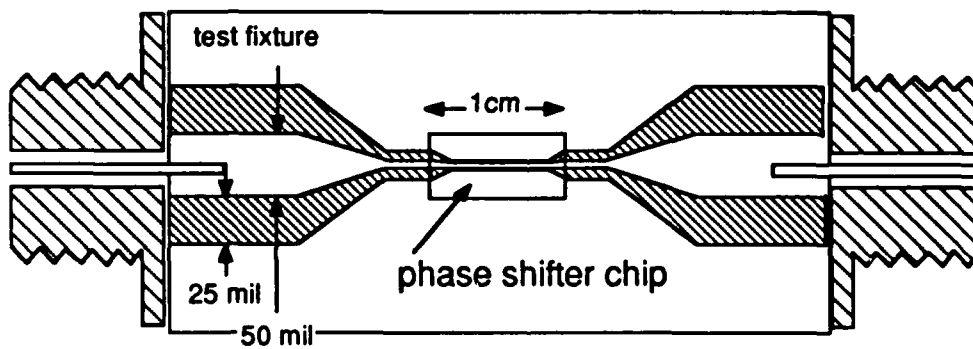
VII. Fabrication and Testing of Prototype CPW Phase Shifters

Device Fabrication

The fabrication of several CPW devices has recently been completed. The device cross section for a heterostructure substrate is shown in Fig. 1, and the microwave package used to mount the device is shown in Fig. 7. At present, a lift-off technique is being used, with gold conductors approximately 200nm thick. The guide dimensions are chosen to give a nominal 50Ω impedance when the guide is not illuminated, based on a quasi-static calculation. The growth sequence for the heterostructure sample is: on a semi-insulating GaAs substrate a GaAs buffer layer is grown first, followed by $0.02\mu m$ of $Al_{0.6}Ga_{0.4}As$, $1\mu m$ of GaAs, and finally $0.1\mu m$ of $Al_{0.6}Ga_{0.4}As$. All layers are unintentionally doped

17

(a) bond pad detail

10μm   7μm   gap

70μm

100μm

signal line

ground plane

test fixture

1cm

25 mil

50 mil

phase shifter chip

(b) chip-to-SMA adapter jig; pc board
is RT Duroid 8050, 20 mil thick, dielectric
constant 10.25, conductor backed.

Figure 7

18

(p-type, approximately 10^{15}cm^{-3}). Identical CPWs have been fabricated directly on semi-insulating GaAs to serve as a reference standard. To test the Schottky control technique, CPWs have also been fabricated on doped epitaxial layers grown on a semi-insulating substrate. Several different doping levels will be examined; at present only fabrication on a heavily doped (10^{17}cm^{-3}) sample has been completed.

A constant impedance flare is added to each end of the guide to allow wire bonding to a microwave copper-clad pc board. This board is patterned with another constant impedance CPW flare to allow transitions to SMA connectors. Packaging parasitics (primarily impedance mismatc) were severe in our preliminary experiments, due to errors in the quasi-static design theory used for the pc board. Emperically designed boards are now in use, which provide a very nearly 50 Ω characteristic impedance in the package; Fig. 7 shows the dimensions for a conductor-backed CPW which provides 50 Ω impedance.

Device Testing

As a reference standard we have fabricated a CPW with the dimension shown in Fig. 1 directly on a semi-insulating GaAs substrate. Ideally, this transmission line should have a 50 Ω characteristic impedance, and should not exhibit any slow wave behavior. To measure the actual characteristics of the line we have used an HP 8510B Network Analyzer to obtain the S-parameters for the device in the frequency range 0.5-18 GHz. The results can be most easily interpreted by first Fourier transforming the frequency domain data into the time domain, thus obtaining the equivalent time domain step response of the device. Figure 8 shows such a step response for the semi-insulating substrate CPW. Marker 1 in the figure corresponds to the measurement reference plane, and serves as the zero point for matched characteristic impedance. Steps up correspond to an increase in impedance, while steps down correspond to a decrease. Unfortunately, the apparent impedance of the CPW on the SI GaAs (located between marker 3 and marker 4 in Fig. 8) is considerably higher than the expected 50 Ω, closer to 200 Ω. At the present time the origin of this large

impedance error is not understood; however, we believe this is most likely do to limitations in the quasi-static design theory used to chose the guide dimensions. Further experimentation is currently being performed, including fabrication of the same CPW on a glass substrate to eliminate the possibility of any semiconductor related effects.

To test the Schottky control techniques we have also fabricated a CPW on a heavily doped GaAs epi layer. The equivalent time domain step response of this device is shown in Fig. 9. The characteristic impedance of the device has now dropped dramatically, to approximately 12 Ω at zero bias. As noted earlier, the simple parallel plate model would predict a large slow wave factor to accompany this drop in impedance, caused by the much higher effective capacitance in this device. For this device both the ground planes and the center conductor are actually Schottky contacted. When a positive bias is applied to the center conductor (the rf signal line) relative to the side conductors (the rf ground planes), the center Schottky contact is forward biased while the side contacts are reversed biased; by convention this case will be referred to as a forward bias condition. Thus, for this bias condition, the induced depletion layers are primarily under the rf ground planes. For a 5 V forward bias the impedance has fallen to 7.8 Ω. Since the effective geometric filling factor by lossy material (δ in the simple parallel plate model) would be expected to be larger in the forward bias case than in zero bias, this result is at least qualitatively correct. In contrast, when the center conductor is reverse biased (negative bias with respect to the side contacts) the depletion layer formed is under the rf signal line, and therefore δ should decrease; we now find that the impedance has increased to about 11 Ω. Again, this is in qualitative agreement with the expected results. The most serious problem illustrated by this device is the dramatic drop in characteristic impedance compared to the CPW on a SI substrate. The dimensions of the guide will have to be redesigned to more closely approach 50 Ω to allow measurements of actual phase shift through the line. We are also investigating the influence of background doping level; at lower levels of doping the characteristic impedance should rise, allowing better impedance matching.
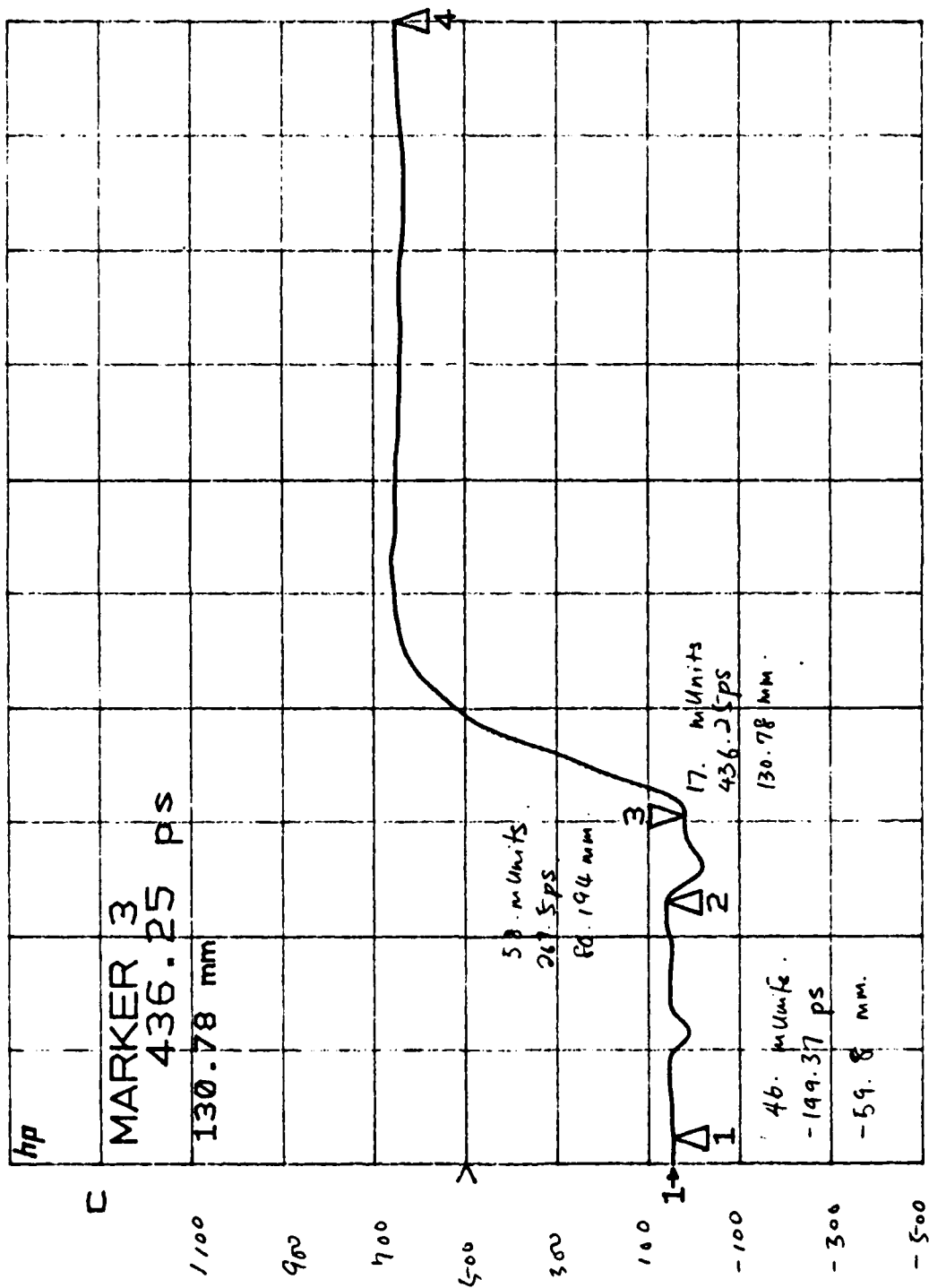
20

Figure 8
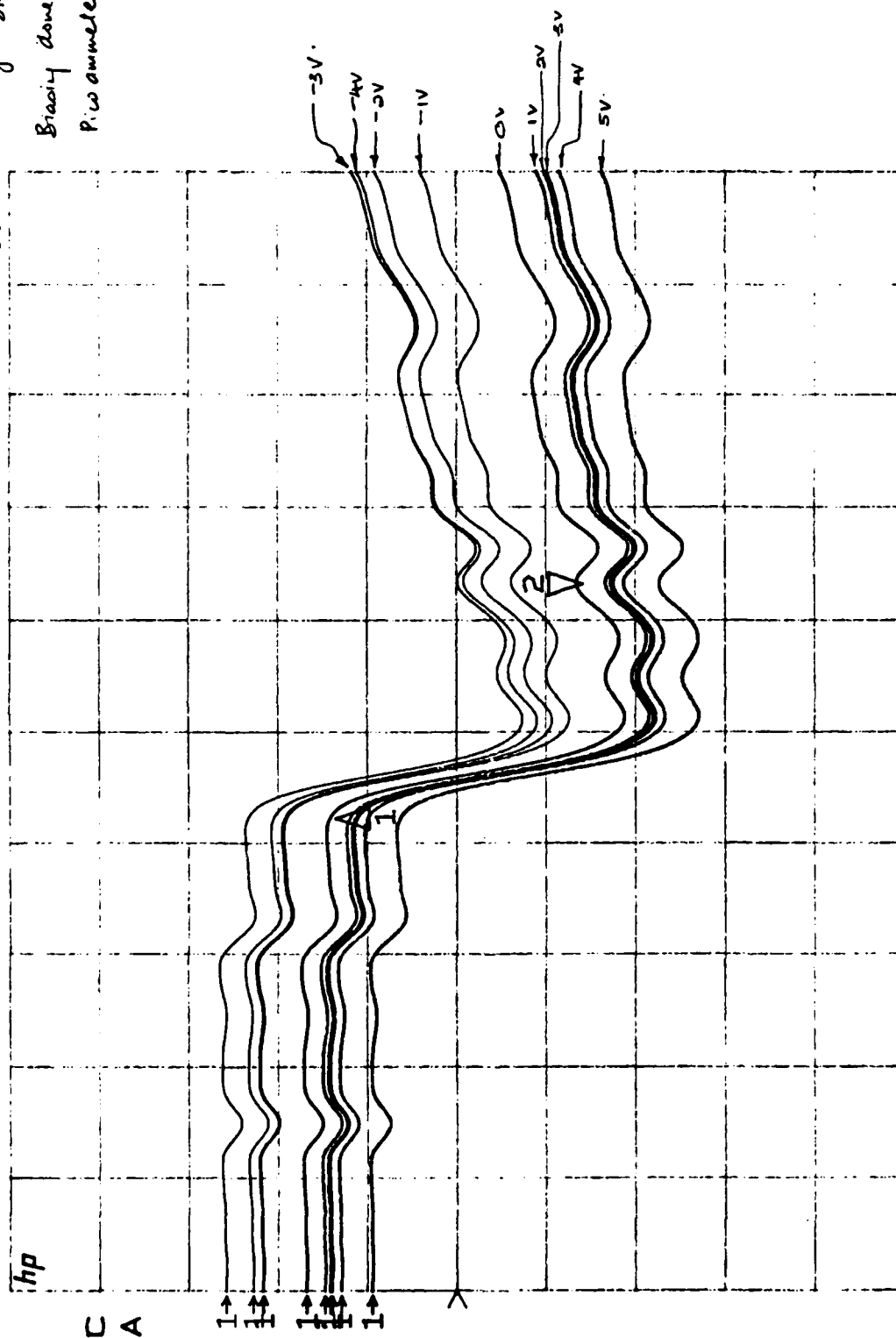
21

S11
REF -200.0 mUnits

Re
200.0 mUnits/

hp

C
A

START -250.0 ps
STOP 1.5 ns

Figure 9

22

The optically controlled CPW device requires the use of a heterostructure substrate, as shown in Fig. 1. The illuminating source used in the preliminary work was a microscope illuminator fitted with a red filter. The filter cut-off was 550 nm, producing an illumination source peaked at about 700nm. For the aluminum concentration (60%) used in the top layer of the substrate the AlGaAs is indirect, and is transparent for wavelengths longer than 620nm. For photon energies above the GaAs band gap (1.42eV, or 870nm) electron-hole pair generation in the GaAs layer will take place. The phase shifter and its package was connected to the HP 8510B, and the phase of S_{21} was measured in the dark and at three different intensity levels: 25mW/cm^2, 50mW/cm^2, and 70mW/cm^2 (integrated power between 550nm and 850nm). As in the Schottky contacted device, impedance mismatch between the device and the test package caused significant reflections; reliable phase measurements were only possible in the range 0.9GHz to 1.3GHz. The relative changes in the phase as a function of the change in illumination intensity were then used to calculate the change in effective refractive index of CPW guide, Δn_{eff}, given by:

$$\Delta n_{eff}(I) = n_{eff}(I_i) - n_{eff}(I_0) = -\frac{\lambda_0}{2\pi l}(\theta(I_0,f) - \theta(I_i,f)) \qquad (15)$$

where I_0 = dark, l = the physical length of the CPW, λ_0 = the free space wavelength at the operating frequency, and $\theta(I_0,f)$ is the measured phase at the frequency f. Figure 10 shows the change in n_{eff} from 0.9GHz to 1.3GHz. At these low illumination intensities the change in phase shift is approximately proportional to the illumination intensity. The preliminary measurements of the relative phase shift demonstrate such phase shift can be obtained even at relatively low levels of intensity. The extremely small active area of the device (about 2.4x10^{-3} cm^2 here) should allow much higher levels of intensity to be used, yielding larger phase shifts, even at very low total powers.
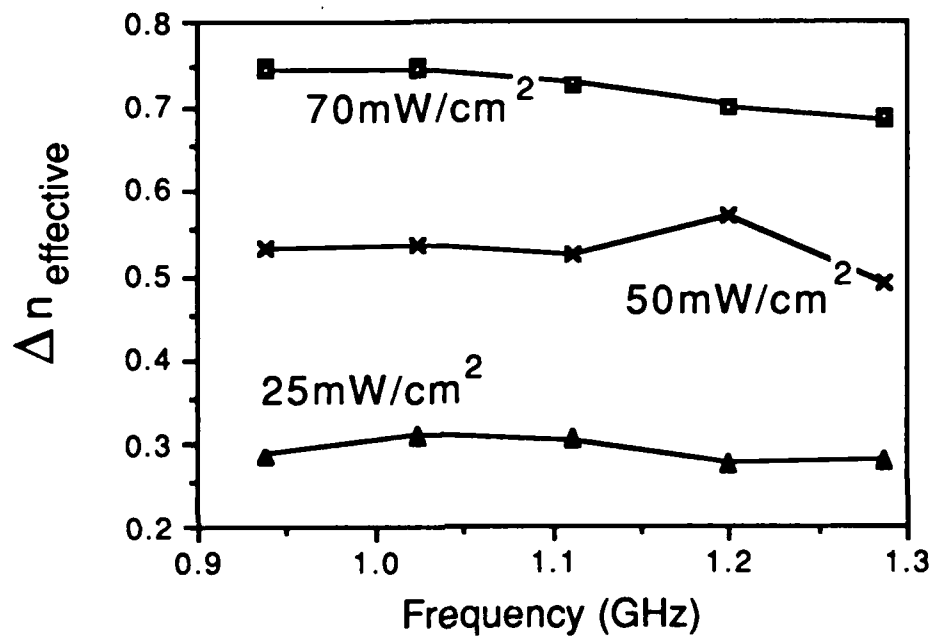
23

Figure 10: Measured change in CPW effective index of refraction (slow wave factor) as a function of optical illumination intensity.

Figure 10

24

VIII. Future Research Efforts

We are at present fabricating another series of CPW devices on a variety of different substrates. The source of the large discrepancies between measured and calculated impedances must be determined; examination of the various substrates should provide physical insight into this problem. Optically induced phase shift has been demonstrated, but insertion loss has been dominated by the large impedance mismatches. Once sufficient information has been obtained relating impedance and substrate, a new CPW design will be determined which will allow better matching. Periodic illumination will also be investigated experimentally to determine its possible use in the phase shifter.

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Conference and Technical Journal Publications

1. "Optically Controlled Coplanar Waveguide Millimeter Wave Phase Shifter," Tenth International Conference on Infrared and Millimeter Waves, p.303, Lake Buena Vista, FL, Dec. 9-13, 1985, (P. Cheung, D. Fun, D. Miller, C.-K.C. Tzuang, D.P. Neikirk, and T. Itoh)

2. "Finite element analysis of slow-wave Schottky printed line," 1986 IEEE MTT-S Microwave Symposium Digest, June 2-4, 1986, Baltimore, MD, (C-K Tzuang, Q. Zhang and T. Itoh).

3. "Finite Element Analysis of Slow Wave Coplanar Waveguide with Localized Depletion Regions," 16th European Microwave Conference, pp. 471-476, Sept. 8-12, 1986, Dublin, Ireland, (C.-K. C. Tzuang and T. Itoh).

4. "Finite Element Analysis of Slow Wave Schottky Contact Printed Lines," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-34, No. 12, December 1986 (C.-K. Tzuang and T. Itoh).

5. "Analysis of an Optically Controlled CPW Phase Shifter Containing Laterally Non-uniform Lossy Layers, Eleventh International Conference on Infrared and Millimeter Waves, Pisa, Italy, Dec., 1986, (C.,-K. Tzuang, P. Cheung, D. P. Neikirk, and T. Itoh).

6. "Picosecond Response of an Optically Controlled Millimeter Wave Phase Shifter," Second Topical Meeting on Picosecond Electronics and Optoelectronics, Jan., 1987, (C.-K. Tzuang, D. Miller, T.-H. Wang, D. P. Neikirk, T. Itoh, P. Williams, and M. Downer).

7. "High Speed Pulse Transmission Along a Slow-wave CPW for Monolithic Microwave Integrated Circuits," IEEE Trans, Microwave Theory and Techniques, Vol. MTT-35, August 1987 (C.-K. Tzuang and T. Itoh).

8. "Coplanar Waveguide Phase Shifter Controlled by a Spatially Periodic Optical Illumination," Int. J. Infrared and Millimeter Waves Vol. 8, Sept. 1987, (Y.D. Lin, D.P. Neikirk, and T. Itoh).

9. "Periodically Illuminated CPW Phase Shifter," to be presented at the 12th International Conference on Infrared and Millimeter Waves, Dec. 14-18, 1987, (Y.-D. Lin, D.P. Neikirk, and T. Itoh).

10. "Measurements of an Optically Controlled Coplanar Waveguide Phase-Shifter," to be presented at the 12th International Conference on Infrared and Millimeter Waves, Dec. 14-18, 1987, (P. Cheung, D.P. Neikirk, and T. Itoh).

11. "Optically Controlled Coplanar Waveguide Devices," Int. J. Infrared and Millimeter Waves, to be submitted, March, 1988, (P. Cheung, T. Itoh, D. Neikirk)

Technical Interactions and Oral Presentations at Seminars and Conferences

D.P. Neikirk, "Optically Controlled Coplanar Waveguide Millimeter Wave Phase Shifter," Tenth International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, Dec. 9-13, 1985.

D. P. Neikirk, "Exotic Heterojunction Devices for Microwave Circuits," NSF Workshop on Future Research Opportunities in Electromagnetics, Arlington, TX, January 29-31, 1986.

D.P. Neikirk, "Optical Control of a Monolithic Millimeter Phase Shifter," ARO Workshop on Fundamental Issues in Millimeter and Submillimeter Waves, Los Angeles, Ca., Sept. 15-16, 1986.

T. Itoh, presentation at ARO Workshop on Fundamental Issues in Millimeter and Submillimeter Waves, Los Angeles, Ca., Sept. 15-16, 1986.

T. Itoh, presentation at DoD Symposium on Millimeter Wave/Microwave Measurements and Standards, Redstone Arsenal, Huntsville, Alabama, November 6-7, 1986.

D. P. Neikirk, "Picosecond Responses of an Optically Controlled Millimeter Wave Phase Shifter," Topical Meeting on Picosecond Electronics and Optoelectronics, Lake Tahoe, NV, (January 14-16, 1987).

P. Cheung, "Experimental Performance of an Optically Controlled Coplanar Waveguide Phase Shifter," 12th International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, (Dec. 14-18, 1987).

D. P. Neikirk, "Periodically Illuminated CPW Phase Shifter," 12th International Conference on Infrared and Millimeter Waves, Lake Buena Vista, FL, (Dec. 14-18, 1987).

Technical Reports

1. "Finite Element Analysis of Slow-Wave Schottky Contact Printed Lines," Microwave Laboratory Report No. 87-P-2, AFOSR Grant 86-0036, Feb. 16, 1987, (C-K Tzuang, D. P. Neikirk, and T. Itoh).

Participating Professionals and Advanced Degrees Awarded

Dean P. Neikirk, Assistant Professor, UT Austin
T. Itoh, Professor, UT Austin

C-K Tzuang, UT Austin, PhD awarded: December, 1986, "Slow-wave propagation on monolithic microwave integrated circuits with layered and non-layered structures."

Yu-De Lin, UT Austin, M.S. awarded: May 1987, "Metal-Insulator-Semiconductor and Optically Controlled Slow-Wave Structures."

P. Cheung, UT Austin, MS awarded: December, 1987, "A preliminary study of an optically controlled coplanar waveguide phase-shifter."

28

<u>Consultative and Advisory Functions</u>

T. Itoh has been on the Committee on Army Basic Research for National Research Council.

T. Itoh participated in the U.S. Army Electronics Research Strategy Workshop held at Quail Roost, NC on May 3-6, 1987 as an invited speaker and a panel member to identify millimeter-wave and electromagnetic research areas important to the Army.

On July 13-15, 1987, T. Itoh participated in a DARPA Workshop on Electromagnetic Simulations, Packaging and Measurements of High-Speed Devices organized by the Materials Research Council. Prof. Itoh presented an invited talk on, "2D and 3D Electromagnetic Models at Frequencies above 5 GHz."

Professors Itoh, Neikirk and Streetman were visited by Dr. D. Arndt from NASA Johnson Space Center on November 13, 1987 to discuss microwave and millimeter-wave integrated circuit research.

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