Optically Controlled Coplanar Waveguide Phase Shifters

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(Invited Paper)

Abstract —This paper reviews the progress and ongoing development of optically controlled phase shifters, primarily those based on the use of coplanar waveguide (CPW) printed on semiconductor substrates. We first qualitatively describe slow-wave phenomena in such guides, their possible use to produce variable phase shifts, and several different approaches using these phenomena to implement phase shifters. Two main techniques, one based on the use of Schottky-contacted CPW electrodes and the other on optically generated carriers, are discussed, together with the experimental performance of prototype devices using these control mechanisms. Finally, we discuss a newer technique, based on the combined use of Schottky contacts and optical illumination. Preliminary results on such a device indicate that this technique is a promising alternative to a purely Schottky contact or purely optical control while preserving advantages of both techniques.

I. Introduction

THE SUGGESTION was made in 1965 by Hyltin [1] 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 showed that when these lines are fabricated on multilayered semiconductor substrates (such as silicon dioxide (SiO_2) on silicon (Si) or aluminum gallium arsenide ($Al_xGa_{1-x}As$) on gallium arsenide (GaAs)), the lines could support three different characteristic modes of propagation [2], [3]. These studies showed that the occurrence of the different 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. One of the more interesting applications of these phenomena is their use in distributed phase shifters, realized by controlling slow-wave propagation on layered semiconductor substrates.

In 1971 Hasegawa *et al.* [4] experimentally verified the existence of these modes for a microstrip on an SiO_2–Si substrate over a wide range of substrate resistivities, dielectric thickness, and microstrip widths. The occurrence of the various modes was attributed to a Maxwell–Wagner effect that modifies the effective dielectric constant of the system. Hughes and White [5], [6] 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 wave.

More recently, there has been increasing interest in the use of coplanar waveguide (CPW) transmission lines in microwave and millimeter-wave integrated circuits. The field configuration in a coplanar waveguide transmission line can be considerably more complex than that in a microstrip; however, one would expect qualitatively similar slow-wave propagation on both microstrip and CPW lines. Accurate analysis of CPW's on lossy, layered substrates has been performed using full-wave techniques which takes into account the electric field distributions in the substrate [7]–[13]. These models clearly predict the occurrence of slow-wave effects, and suggest a number of designs of possible use in phase shifter applications. Experimental verification of the existence of slow-wave propagation with coplanar waveguide structures has also been obtained by several investigators [14], [15].

One difficulty with the numerically intensive analyses discussed above is the extraction of simple physical insight into device operation. Using a quasi-TEM approximation, however, it is possible to construct a simple model of dielectric-supported transmission lines which illustrates the main effects caused by a lossy layer in the substrate [15]–[18]. 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 this approach, which indicates how slow-wave propagation can be controlled to allow construction of a variable phase shifter.

II. Theory of Operation

Fig. 1 illustrates a simple model useful for understanding slow-wave phenomena. The transmission line (whether microstrip or coplanar waveguide) is treated as a parallel-plate waveguide with a layered dielectric between the plates of the guide. The most common substrate configura-

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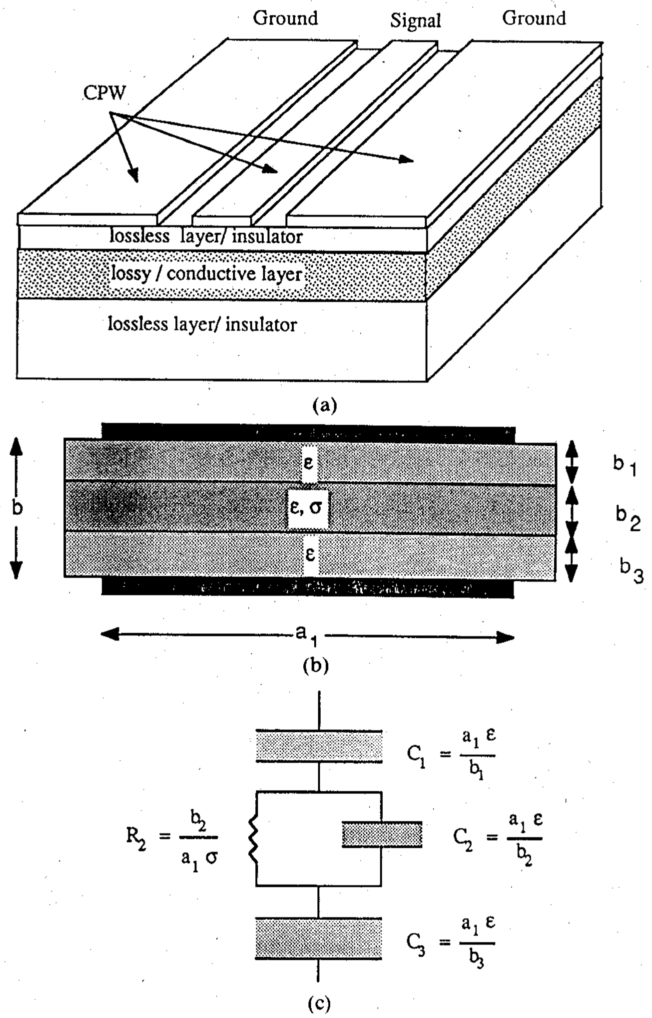

Fig. 1. (a) Typical CPW transmission line on a layered semiconductor substrate. (b) Parallel-plate model of the device shown in (a). (c) Simple equivalent circuit of the shunt admittance for the transmission line.

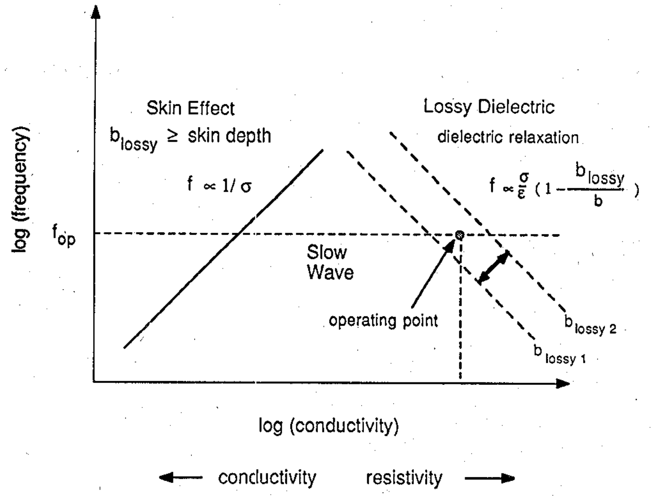

Fig. 2. Diagram illustrating the various propagation modes that can be supported by a transmission line on a substrate containing a lossy layer with thickness b_{lossy}. For a fixed operating frequency f_{op}, if the thickness of the layer is changed from $b_{\text{lossy 1}}$ to $b_{\text{lossy 2}}$, the mode of operation can be changed from slow-wave to lossy dielectric; this corresponds to the mechanism used in a Schottky-contact controlled phase shifter.

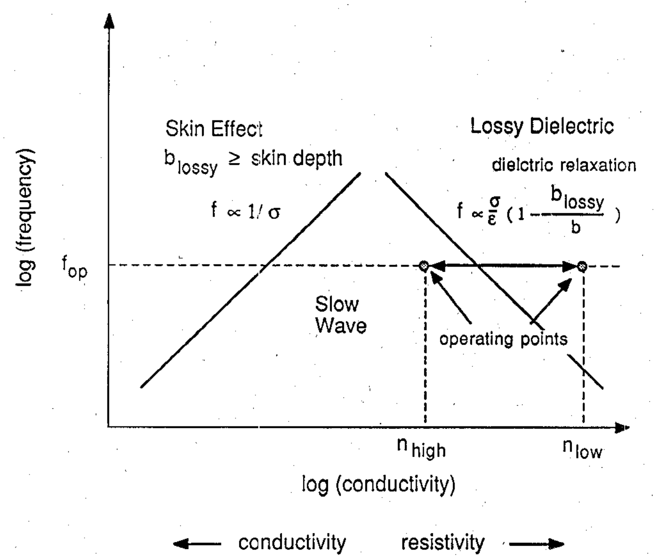

Fig. 3. Diagram illustrating the behavior of an optically controlled slow-wave phase shifter. Here the lossy layer thickness b_{lossy} is fixed, while the conductivity of the lossy layer depends on the optically generated carrier density n. For high-intensity illumination, n, and hence the conductivity, are large, placing the operating point in the slow-wave region; for low intensity the conductivity is reduced, moving the operating point into the lossy dielectric region.

tion consists of three layers, the topmost and bottommost lossless, and the middle lossy. 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 characterized by its equivalent series impedance per unit length Z_l and shunt admittance per unit length Y_l.

There are two limits that govern the occurrence of slow-wave propagation in such structures. One limit is determined by the penetration of the magnetic field into the lossy layer. This is reached if the skin depth in the lossy layer becomes comparable to the layer's thickness (b_2 in Fig. 1(b)). In such a case the model shown in Fig. 1 is no longer valid; under these circumstances the lossy layer is better approximated as a lossy ground plane, rather than as a dielectric. The frequency associated with this limit is given by

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

where σ is the conductivity of the lossy layer. Thus, for a given conductivity and lossy layer thickness, the propagating mode can be slow only if the operating frequency is chosen such that it is below f_δ. This frequency, which is characterized by a $1/\sigma$ dependence, marks the separation between the slow-wave and skin-effect modes of propagation (see Figs. 2 and 3).

The other characteristic frequency for these transmission lines is determined by the dielectric relaxation frequency of the lossy layer. If the frequency of the applied voltage is much less than the dielectric relaxation frequency f_{dr} in layer 2, given by

$$f_{dr} = \frac{\sigma}{2\pi\epsilon_r\epsilon_0} \tag{2}$$

then the free charge in layer 2 can respond to the applied voltage. This effectively forms a short between the two cladding dielectric layers. Hence the capacitance per unit length C of the structure is

$$C = \epsilon a_1 \frac{1}{b_1 + b_3} = \epsilon a_1 \frac{1}{b - b_2} \tag{3}$$

where b_1 and b_3 are the thicknesses of the top and bottom layers, respectively, and b is the total effective thickness of the structure. When the frequency is such that $f \gg f_{dr}$, the free charge 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 $\epsilon = \epsilon_r\epsilon_0$. The capacitance per unit length C is thus reduced, and is now

$$C = \epsilon a_1 \frac{1}{b}. \tag{4}$$

If the frequency is low enough that the skin depth in the lossy layer is much greater than the thickness of this layer (i.e., $f \ll f_\delta$), the inductance per unit length is approximately the quasi-static value of the entire structure with plate separation b. Thus, for low frequencies, i.e., $f \ll f_{dr} < f_\delta$, the phase velocity is

$$v = \frac{1}{\sqrt{\mu\epsilon_r\epsilon_0}}\sqrt{\frac{b - b_2}{b}} = \frac{c}{\sqrt{\epsilon_r}}\sqrt{1-\Delta} \tag{5}$$

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

$$v = \frac{1}{\sqrt{\mu\epsilon}} = \frac{c}{\sqrt{\epsilon_r}}. \tag{6}$$

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_{eff} (also referred to as the slow-wave factor), is given by

$$n_{\text{eff}} = \frac{c}{v}. \tag{7}$$

Thus, the low-frequency value of the slow-wave factor is increased over the high-frequency value by a factor of $(1-\Delta)^{-1/2}$, as shown by (5) and (6).

The two limits on slow-wave behavior (i.e., the dielectric relaxation frequency f_{dr} and the skin depth frequency f_δ) produce characteristics of the type shown in Fig. 2. Given a fixed frequency f, as the conductivity of the lossy 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. 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 $f_{dr} < f_\delta$ or $f_\delta < f_{dr}$, respectively.

Figs 2 and 3 illustrate two fundamentally different ways to gain control over the propagation velocity in these transmission lines. For instance, if the thickness of the lossy layer could be controlled, (5) clearly shows how the propagation velocity would vary, assuming $f \ll f_{dr}$. One way to achieve this control is through the use of Schottky-contacted metal lines on a doped semiconductor. Here, application of a reverse dc bias produces a depletion layer; changes in bias then cause corresponding changes in the depletion layer thickness, changing the limiting frequency between the SW mode and the lossy dielectric mode, as shown in Fig. 2.

There is another possible way to control the propagation velocity, as illustrated by Fig. 3. Here the resistivity of the lossy layer is varied directly; the change in 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 basic operating principle for the optically controlled phase shifter [19].

The simple model discussed above can also be used to estimate the behavior of various slow-wave devices. For instance, the slow-wave factor n_{eff} clearly exhibits a strong dependence on the amount of lossy material Δ; if the structure were 99% lossy (i.e., $\Delta = 0.99$) a maximum slow-wave factor of $10\sqrt{\epsilon_r}$ could be achieved. In addition, the frequency at which the slow-wave factor begins to drop is given by

$$f_{\text{sw}} = \frac{\sigma}{2\pi\epsilon_r\epsilon_0}(1-\Delta) = f_{dr}(1-\Delta). \tag{8}$$

As the frequency is increased beyond f_{dr}, the propagating mode is no longer slow, but has changed to a lossy dielectric mode.

The dispersion curves shown in Fig. 4 also clearly illustrate the differences between the Schottky control and optical control methods. With Schottky control the variable Δ is directly affected, so a shift from one low-frequency slow-wave factor to another is produced (Fig. 4(a)), with no change in the basic shape of the dispersion curve (since σ, and hence f_{dr}, are fixed). Thus, for Schottky control it is desirable to operate at "low" frequency (i.e., $f \ll f_{\text{SW}}$). For a device using GaAs doped n-type at $10^{17}\,\text{cm}^{-3}$, for instance, $f_{dr} \approx 10^{13}$ Hz, while f_{SW} varies from about 10^{11} Hz for $\Delta = 99\%$ to 7×10^{12} Hz for $\Delta = 30\%$. Such a device could in principle be used near 100 GHz and provide slow-wave factors up to about 35. The main frequency limitation for such a device would likely be the transition from a slow-wave mode to a skin-effect mode, rather than to the lossy dielectric mode.

In contrast to the Schottky control technique, optical control varies the conductivity of the lossy layer rather

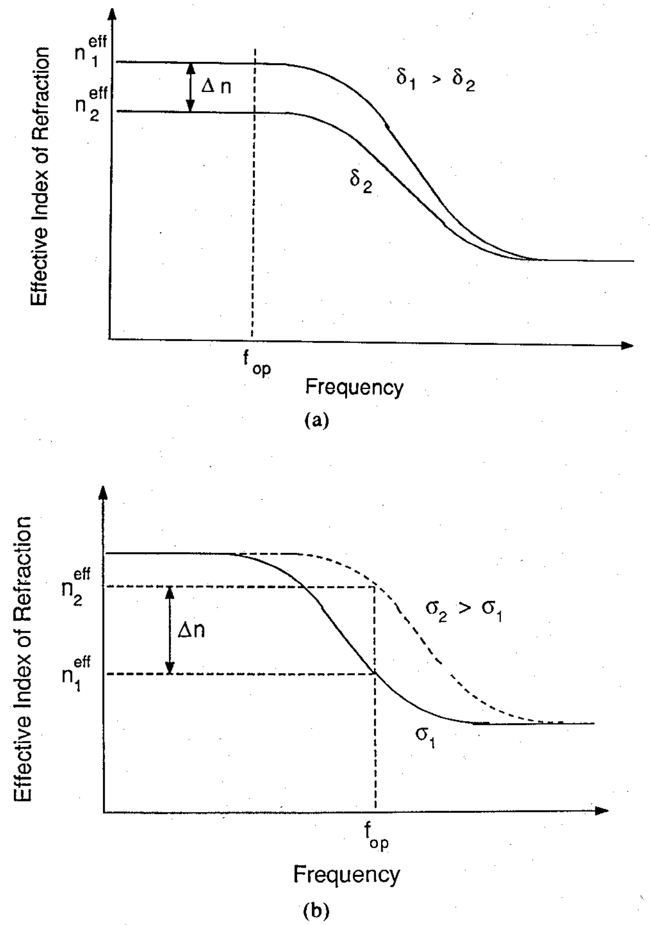

Fig. 4. (a) Dispersion curves for a Schottky-contact controlled phase shifter; application of a reverse bias changes the fraction of the substrate which is lossy, Δ, inducing a change in the effective index for the guide. (b) Dispersion curves for an optically controlled phase shifter; illumination of the guide changes the conductivity, σ, of the lossy layer, inducing a change in the effective index for the guide.

than its thickness. Fig. 4(b) illustrates the behavior of a device with fixed Δ, where slow-wave control is obtained through a variation in the dielectric relaxation frequency f_{dr} via a variation in σ. Here it is necessary to operate in a region of strong dispersion to achieve large phase shifts, i.e.,

$$f_{\mathrm{SW}}(\sigma_{\mathrm{low}}) < f < f_{\mathrm{SW}}(\sigma_{\mathrm{high}}) \tag{9}$$

where σ_{low} and σ_{high} are the conductivities for low and high levels of illumination intensity, respectively. Note it is essential to use values of Δ which place f_{SW} (eq. (8)) near the frequency of operation. Since f_{dr} for GaAs is fairly high (at n-type doping levels of $10^{15}\,\mathrm{cm}^{-3}$, f_{dr} is about 140 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. One concern is that this may result in relatively large amounts of insertion loss for the device.

III. Schottky-Contacted Slow-Wave Phase Shifters

As discussed above, a variable phase shifter may be implemented electronically using Schottky-contacted microstrip or CPW conductors [20]–[25]. A reverse bias is

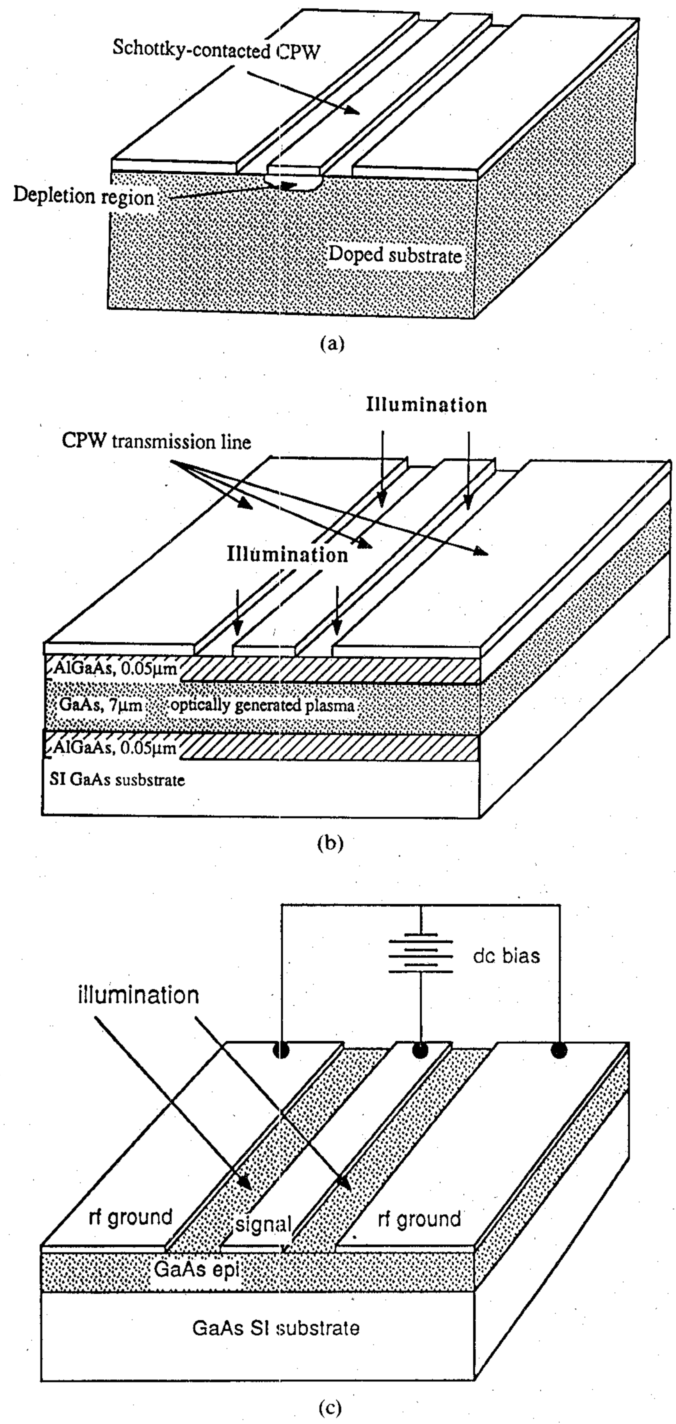

Fig. 5. Cross sections of various phase shifters. (a) Schottky-contacted CPW phase shifter showing the depletion layer under the center conductor of the guide. (b) Heterostructure used for an optically controlled CPW phase shifter. (c) Combined Schottky-contact/optically controlled phase shifter. For all the devices the central CPW conductor is 10 μm wide, and the gap between the central conductor and ground planes is 7 μm.

used to vary the depletion layer thickness (Fig. 5(a)), and hence the phase delay experienced, as the wave propagates through a fixed length of line. For a CPW, if only the central conductor is reverse biased, the depletion layer will be localized under this conductor. Ideally the depletion layer forming the first insulating layer should extend uniformly across from ground plane to ground plane. However, since a significant fraction of the field lines pass directly beneath the central conductor, the depletion region under the central conductor can still be used to control the slow-wave factor.

A number of Schottky-contacted phase shifters have been demonstrated to date. All of these devices have been rather short, ranging from 1.6 mm [20]–[23] to 2.4 mm [24]. Such short lengths are possible because these devices make use of heavily doped layers (on the order of 10^{18} cm^{-3}), which produce large swings in the slow-wave factor (for example, at 18 GHz, about 150°/mm from [22] and 120°/mm from [24]). The short length is useful, since it is then possible to save space on the semiconductor substrate. However, because Schottky contacts on highly doped substrates are difficult to fabricate, somewhat more complex processing steps are required. Often this is done by using a thin, lightly doped layer on top of the highly doped substrate. Most devices fabricated with these highly doped layers have also exhibited extremely high insertion loss per unit length (typically 5–10 dB/mm [22], [24]), although because of the very large phase shifts per unit length, acceptable performance can still be achieved.

IV. Optically Controlled Phase Shifters

The technique of using optical illumination to obtain phase shift was first demonstrated using high-resistivity semiconductor dielectric waveguides by Lee *et al.* [26], [27]. In their work, an optical source with wavelength shorter than the band gap of the semiconductor generates a plasma layer near the surface of a dielectric waveguide, causing a change in the propagation constant for the guide, which in turn produces a phase shift. Assuming a uniform electron–hole plasma is formed by the optical irradiation, extremely large phase shifts have been predicted [27] for very high plasma densities. A very intense source of illumination is used to produce the large carrier concentrations. Typically, a powerful pulsed laser has been used. An additional feature of this kind of phase shifter is its potentially high speed. By using Cr-doped GaAs with very short carrier lifetimes in conjunction with picosecond optical pulses, Li *et al.* [28] demonstrated modulation of a 94 GHz signal with switching times on the order of 100 ps.

A similar approach for controlling the propagation constant in a CPW could also be used. The conductivity of the lossy layer, which depends on the density of the electron–hole pairs generated, is controlled by varying the intensity of the optical illumination. As in the dielectric waveguides, depending on the carrier lifetimes in the semiconductor, the speed of such a device could be very high. However, as discussed in Section II, for this technique to be effective the conductivity of a large fraction of the substrate must be controlled, and therefore accessible to the effects of the optical illumination. In this regard, a CPW transmission line is much better suited for optical control than a microstrip line. This is because virtually all field lines extend across the gaps between ground plane and central conductor, which is also where the electron–hole pairs are generated. For a microstrip, the central conductor casts a shadow in the region where most field lines are concentrated. In addition, for a CPW the optically generated carriers may diffuse into the region shadowed by the central conductor, so long as the width of the central conductor does not exceed the diffusion length in the semiconductor. To satisfy this condition in a microstrip line would require the use of extremely thin substrates.

Another issue which should be considered for both optically controlled dielectric waveguides and CPW's is the impact of spatially nonuniform carrier generation. For both devices a combination of surface recombination and diffusion will produce nonuniform carrier distributions. In an analysis by Butler *et al.* [29] it was shown that phase shift is not dramatically affected in a dielectric waveguide, although there may be a considerable increase in attenuation. For a CPW, analysis using finite element methods shows that a uniform carrier density needs to be maintained a distance under the ground planes equal to the gap width for the propagation characteristics to be unaffected [30]. A quasi-static analysis including the effects of carrier diffusion has also been developed [31]. This model yields insertion loss estimates for CPW's with optically induced electron–hole plasmas.

The optically controlled CPW device shown in Fig. 5(b) makes use of a heterojunction substrate which is chosen to allow optical carrier generation to take place in a buried layer instead of at the surface. For the material system AlGaAs/GaAs/AlGaAs, a light source with energy below the band gap for the AlGaAs layer but well above that of the GaAs layer can be selected. When the substrate is illuminated by this source, electron–hole pairs are generated only in the GaAs layer. The band gap discontinuity between the AlGaAs/GaAs layer presents a barrier to the diffusion of the electron–hole plasma out of the GaAs layer, thus confining the optically generated carriers. The AlGaAs layer also serves to passivate the GaAs, producing a reduced surface recombination velocity ($\approx$ 400–500 cm/s for a AlGaAs/GaAs interface compared to 10^6–10^7 cm/s for a GaAs/air interface); this allows more efficient generation of carriers by the optical illumination [32]. A layered-substrate approach has also been discussed for use in dielectric waveguide phase shifters. The analysis by Scott *et al.* [33] showed lower attenuation for this approach while maintaining similar phase shifts.

A major constraint on the operation of the devices discussed above is the requirement that the optically generated carriers significantly affect the conductivity of the layer. This requires raising the optically generated carrier concentration to near or above that of the background doping. By definition, high level injection is needed to achieve this condition; most of the dielectric waveguide devices which have been demonstrated use high-power pulsed lasers to provide sufficient carrier generation. For a CPW device fabricated on a AlGaAs/GaAs substrate, continuous wave (CW) illumination intensities in the

W/cm^2 range would be required to produce significant phase shift [19].

V. Experimental Results for Optically Controlled CPW Phase Shifter

To test the optically controlled CPW phase shifter, we have fabricated and tested several prototype devices on heterojunction substrates. The devices were fabricated using a lift-off technique based on a chlorobenzene soak process. A metal scheme of chrome/silver/gold with a total thickness of ~ 1.2 μm was used for the metal conductors. Measurements on the devices were made with an HP8510B automatic network analyzer in conjunction with wafer probes made by Design Technique. The epitaxial layer thicknesses and the device dimension are given in Fig. 5(b). The dimensions for the CPW were calculated using quasi-static methods to yield a 50 Ω characteristic impedance. For the AlGaAs mole fraction used (40% Al) all the conduction band valleys (Γ, L, and X) of the AlGaAs layer are at about the same energy level above the conduction band (Γ valley) of the GaAs layer. In principle, by illuminating at a wavelength close to the band gap of the GaAs layer, all the optically generated carriers should be well confined to the GaAs by the potential barrier due to the AlGaAs/GaAs band gap discontinuities. The illuminating source used was a 1.0 W CW (total output power) GaAs laser diode array (SDL 2462P1, manufactured by Spectra Diode). The wavelength of the diode was 798 nm.

The results of the measurements are shown in Fig. 6(a) and (b). Fig. 6(a) shows the phase shift of the device under the maximum level of optical illumination obtained with the laser diode. The optical intensity was approximately 3.5 W/cm^2. Fig. 6(b) shows the accompanying insertion loss of the device. The insertion loss for the unilluminated case is relatively low, and only slightly greater than that for a semi-insulating substrate. This is due to both the thin, low conductive AlGaAs layer, and the very light doping in the GaAs layer ($<10^{15}$ cm^{-3}, p-type). Note that the phase shift obtained is relatively small; this is not surprising, since for the illumination intensities used the optically generated carrier density is probably still less than the background doping concentration. In order to obtain larger phase shifts, sources with significantly higher optical intensity than that obtained with the laser diode must be used. This is a major limitation on this optical control technique, since it would generally require large power supplies for the high-intensity illuminator.

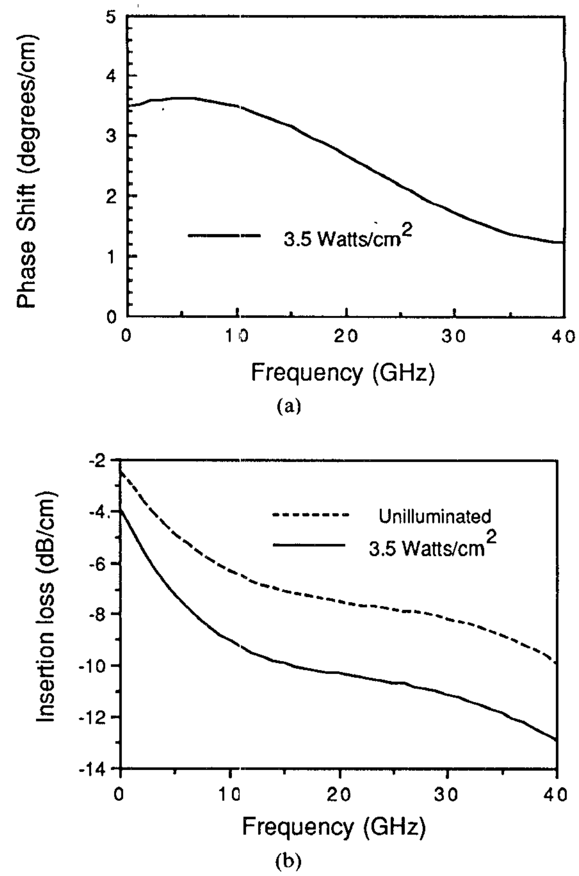

Fig. 6. (a) Phase shift per unit length for the purely optically controlled device illuminated at about 3.5 W/cm^2. (b) Insertion loss per unit length for this device, with and without illumination.

VI. Schottky-Contacted/Optically Controlled Phase Shifters

The preceding discussions clearly indicate that purely optically controlled phase shifters require the use of very high intensity optical sources. It would be desirable to reduce the illumination intensities required. One device which is very sensitive to low levels of illumination is a reverse-biased junction. For instance, the capacitance of such a junction can be changed quite easily, since carrier generation takes place within the depletion region, where background carrier concentration is extremely small. Herczfeld *et al.* first used this approach to build a hybrid phase shifter using discrete p-i-n diodes mounted across a CPW transmission line [34]. They used a fiber-optic cable to illuminate the dc-biased p-i-n diodes, producing a phase shift of 10°. To further improve the performance of the phase shifter, lateral p-i-n diodes have also been monolithically integrated into a CPW structure [35], [36]. Initial results for a reflection-type phase shifter gave total phase shifts of 110°–120° for frequencies between 1 and 3.5 GHz, and 150°–170° between 4 and 8 GHz.

The p-i-n diodes used above present a "lumped" circuit loading of the CPW. A logical extension of this approach is the use of a dc-biased "distributed" Schottky diode to construct the entire CPW transmission line, in conjunction with optical illumination to control the propagation constant of the line (Fig. 5(c)) [37]. With this device, we can control the thickness of the depletion layer, as in the Schottky-contact controlled method, but rather than varying the dc bias, we vary the optical illumination intensity. This should provide much greater optical sensitivity than the purely optically controlled approach, which required high-level illumination to achieve appreciable phase shifts.

To perform initial tests on a Schottky-contact/optically controlled CPW phase shifter, we have used an MBE-grown

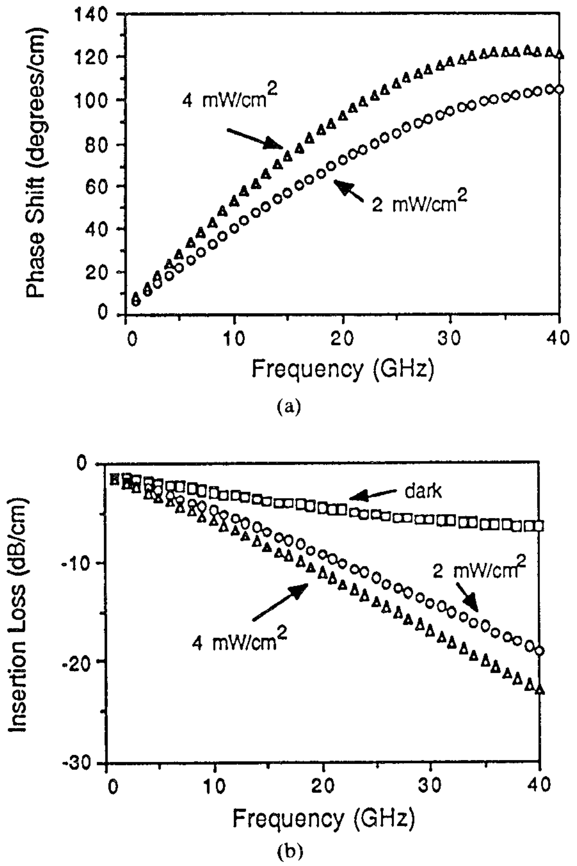

Fig. 7. (a) Phase shift per unit length for the Schottky-contacted/optically controlled device illuminated at about 2 and 4 mW/cm². (b) Insertion loss per unit length for this device, with and without illumination. The central conductor of the CPW was reversed biased at 35 V

epitaxial GaAs layer on an SI GaAs substrate. The epitaxial layer used was 7 μm thick, with a p-type doping concentration in the low 10^{15} cm^{-3}. CPW devices were then fabricated on the substrate. The central conductor was held at a reverse bias of 35 V dc, and the device was then illuminated with a filtered incandescent microscope illuminator. The filter cut off all wavelengths shorter than 750 nm, with spectral irradiance at longer wavelengths typical of a blackbody source. The phase shift and insertion loss of the device were then measured in the dark and under illumination. We used the two illuminating intensities of 2 and 4 mW/cm², integrated over the full bandwidth of the filtered source. Since light can be absorbed only through the gaps between the center conductor and the ground planes of the CPW, the device has an absorbing area of approximately 1.4×10^{-3} cm². Thus, the maximum absorbed optical power for the two intensities is about 3 and 6 μW, respectively. This represents an upper bound on the actual absorbed power, since any power at wavelengths longer than 867 nm is not absorbed by the GaAs.

The measured phase shift and insertion loss for this device as a function of illumination intensity are given in Fig. 7(a) and (b). Note that this device exhibits extraordinary sensitivity to illumination. At 20 GHz, with

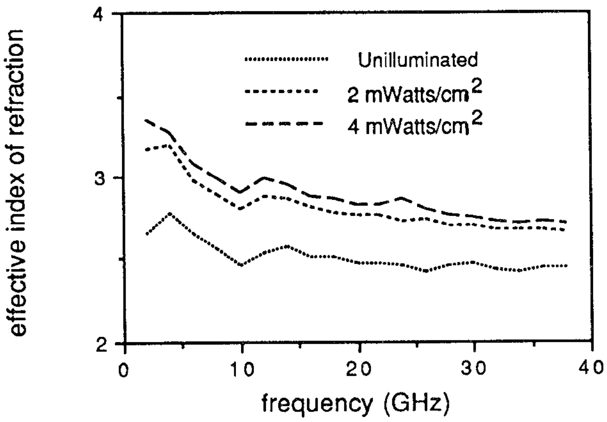

Fig. 8. Slow-wave factor (or effective index of refraction) for the Schottky-contacted/optically controlled device in the dark and illuminated

4 mW/cm² unilluminated (less than 6 μW absorbed power), the device showed a phase shift of 90°/cm (referenced to the illuminated case) with 12 dB/cm of insertion loss. The largest phase shift measured here was about 120°/cm at 40 GHz for a 4 mW/cm² illuminating intensity. Even at these very low intensities, evidence of optical saturation is seen, since doubling of the intensity produces significantly less than a doubling of the phase shift.

The slow-wave factor (or the effective index of refraction n_{eff}) was calculated from the measured data using

$$\text{SWF} = \frac{\lambda_0}{\lambda_g} = n_{\text{eff}} = \frac{\theta c}{2\pi l f} \tag{10}$$

where θ is the measured phase, l is the physical length of the device, c is the speed of light, and f is the frequency. Fig. 8 shows n_{eff} for the Schottky-contacted/optically controlled device. The slow-wave factor of the device under bias but unilluminated is about 2.5. This is quite close to the quasi-static value of 2.67. It is also quite constant throughout the range of frequency measured, showing that the device is essentially dispersionless. As the illumination is increased, n_{eff} increases to about 2.7, and begins to saturate as the optical intensity is increased further. The slow-wave factor, however, remains essentially dispersionless under optical illumination, as expected for a device in which control is via a change in the effective lossy layer thickness (Section II and Fig. 4(a)).

A useful measure of the performance of any phase shifter is the amount of insertion loss the device produces per degree of phase shift achieved. For all the devices based on slow-wave effects, this insertion loss also tends to vary as the phase is changed. Fig. 9 shows the insertion loss of the Schottky-contact/optically controlled device per 180° of phase shift for 4 mW/cm² illumination. The insertion loss with no illumination is also shown in Fig. 9; in operation, the loss would vary between this value and the 4 mW/cm² curve. As seen from the graph the device has a broad range of optimum performance, where 180° of phase shift results in about 20 dB of insertion loss. This

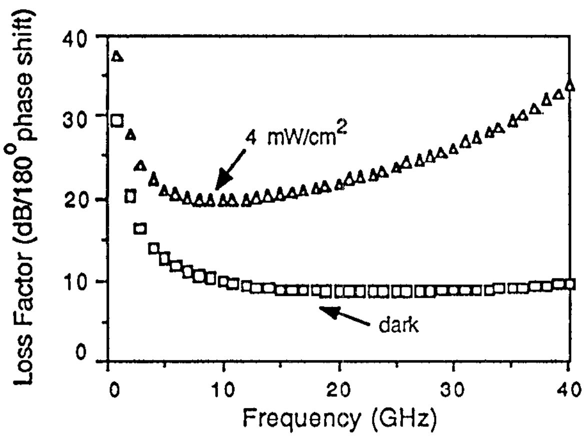

Fig. 9. Insertion loss of a device which would produce 180° of phase shift if illuminated at 4 mW/cm². The lower curve is the loss experienced with the light off; upper curve is the loss with light on.

is quite comparable to the losses reported for purely Schottky-controlled CPW phase shifters [22], [24].

Another important characteristic of a phase shifter is the speed of the device. For distributed CPW devices the control mechanism should play an important role in determining the speed. For a Schottky-controlled device, the high-frequency behavior of the bias circuit is probably the practical limitation. In a purely optically controlled device, the speed is dependent on the minority carrier lifetime. Here the trade-off is between fast response (requiring short lifetimes) and efficient generation (which requires long lifetimes). Fast devices would require very intense light sources, while sensitive devices would probably be very slow. The Schottky-contact/optical control approach, however, has the advantage that it is not limited by the bias circuit or directly affected by minority carrier lifetimes. It may be possible to use this approach to achieve both very sensitive control and very high speed phase modulation.

VII. Periodic Structures for Enhanced Performance

In addition to the use of a single section of uniform transmission line, it should be possible to use a series of cascaded transmission line sections of appropriate design to increase the phase shift sensitivity over a narrow frequency band. For instance, a series of $\lambda_g/4$ stubs can form a Bragg reflector where the phase shift generated is very sensitive to the characteristics of each section of transmission line. This approach has been proposed to help reduce the significant insertion loss for Schottky-contacted CPW phase shifters [38], [39]. A key trade-off for these devices is between bandwidth and sensitivity; very sensitive structures also have a tendency to have very narrow bandwidths. The periodicity of the structure can be imposed using a periodic variation in the doping of the substrate [38]–[41] or, more conveniently, through the use of periodic illumination [42], [43]. A combination of Schottky contacts and optical control could also be applied to these structures to enhance their photosensitivity.

VIII. Conclusion

Coplanar waveguide transmission lines on semiconductor substrates, while structurally suited for optical control of the slow-wave factor, will require very high optical illumination intensities to produce useful phase shifts. Thus, this technique is probably not practical for MMIC applications. However, by combining a reverse-biased, Schottky-contacted CPW with controlled optical illumination, large phase shifts at very low intensities have been achieved. The advantages of optical control are thereby preserved, while requiring optical input powers well within the reach of light emitting diodes or low-power diode lasers. A prototype device has produced insertion loss performance comparable to the best results reported to date on Schottky-contact controlled CPW phase shifters.

Since the prototype device has not yet been optimized in terms of dc bias, epitaxial layer thickness, doping concentration, or wavelength of the illuminating source, an optimized Schottky-contacted/optically controlled CPW may be able to achieve significantly better performance. The use of periodic structures may also allow larger phase shifts over narrower bandwidths at very low loss. Even so, the extremely high sensitivity of the current device (at least 20°/cm/μW at 40 GHz) may allow the development of a number of new applications of slow-wave effects in coplanar waveguides.

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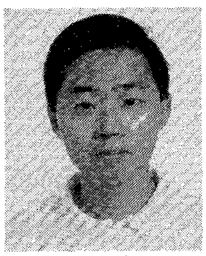

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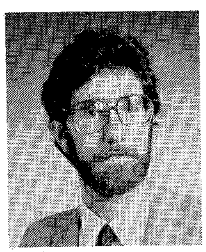

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