DIODE STRUCTURES FOR A MILLIMETER WAVE PHASE SHIFTER

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Abstract

PIN diode design rationale and performance characteristics for a phase shifter compatible with dielectric waveguide is presented. This phase shifting technique exhibits good performance capability and is particularly applicable to a dielectric radiating element at millimeter wave frequencies.

Introduction and Background

In the 30GHz to 300GHz region, optical techniques have been suggested for millimeter wave circuits[1]. The building block of the integrated optics approach is the rectangular dielectric waveguide as the transmission medium. This approach is attractive at millimeter wavelengths because of low loss characteristics and the ease of fabrication. Furthermore, the dielectric guide can be end tapered to function as a conventional polyrod radiating element[2]. It has been demonstrated that active elements (IMPATT and GUNN diodes) can be resonated in dielectric waveguide cavities. Comparable performance to metal waveguide cavities was obtained.

Jacobs and Chrepta[3] reported on an electronic phase shifting technique compatible with dielectric waveguides. This approach utilizes conductivity modulation to alter the boundary conditions of the guide. This effect is achieved by using the distributive characteristics of a PIN diode appended to the guide similar to that shown in Figure 1. Two amps of current were required to achieve a 40° phase shift.

The purpose of this paper is to report on PIN diode structures that have been optimized to obtain similar phase shifts at significantly lower current levels of 20mamps. The importance of this effort is the practical realization of a phase shifter that can be used with active sources in dielectric guides. An attractive application of this technology is the construction of an integrated module for a phased array at millimeter wavelengths.

Principle of Operation

Confined propagation in a dielectric waveguide occurs because of total internal reflection[4,5,6]. An exponential decaying evanescent field will exist external to the guide. Confinement improves by either decreasing the wavelength, increasing the guide dimensions, or increasing the dielectric constant of the guide. Low loss silicon (ϵ_r =11.7) and alumina (ϵ_r =9.8) were used for the guides reported here.

The phase shift action of the diode in Figure 1 can be explained by considering the limit of large conductivity in the diode's intrinsic region. For this condition, the diode effectively appears as a metal ground plane. The solution to this boundary value problem, as pointed out by Jacobs, is equivalent to recalculating the propagation constants of a guide with double the height of the original[6,7]. As an example, for a guide of width a= .314cm and height b= .157cm, Figures 20 and 21 of reference 5 can be used to calculate 187° of phase shift for the principle mode over a 1cm piece of metal using a silicon guide.

For the large conductivity condition, conduction current is much greater than the displacement current in the diode's intrinsic region. A quantitative measure of this ratio is given by $\sigma/\omega\epsilon$. A critical conductivity value, $\sigma_c = \omega\epsilon$ can be used to define a cross over point of conductivity required to yield a phase shift condition characteristic of a metal boundary. This measure is qualitative, but provides an insight to the phase shifter that is consistent with experimental results.

PIN Diode Design

When a PIN diode is operated under forward bias in a state of high carrier concentration, the average conductivity of the intrinsic region is given by[8]

$$\sigma = \frac{1830\,\tau}{WA} \cdot I$$

where
τ = excess carrier lifetime
W = intrinsic region width
A = cross sectional area of the device
I = current through the device.

In order to minimize the required current for a given conductivity, the coefficient of I should be maximized. This requires a diode design with a minimum depletion region, large τ, and small cross sectional area.

A narrow depletion region structure that spans the waveguide dimensions can be achieved by series stacking devices as shown in Figure 2. This sandwich type structure not only results in a low current device, but also a lower total voltage drop even though the devices are in series[9].

Several geometrical shapes using this type structure were used to measure phase shift performance. For the basic design shown in Figure 2, forward voltage drops of 2.0 volts at 10ma and excess carrier lifetimes of 30μsec were measured. Shown in Figure 3 is a plot of conductivity versus current for this device. Also shown is the critical value of conductivity calculated at 70GHz. It is seen that these curves intersect at an applied current level of 20ma. Current levels greater than this will drive the intrinsic region of the diode to high conductivity levels yielding a phase shift characteristic of a metal boundary.

Measurement Technique

Phase and loss measurements were made at 70GHz with the bridge arrangement shown in Figure 4. The signal from the klystron source is split between two paths. One path provides the reference phase, while the other includes the phase shifter. The probe of the slotted waveguide section is moved along the guide until a null is encountered in the standing wave produced by the two bridge arms. Next the phase shifter bias current is increased and the resulting null tracked. Phase shift is calculated for a Δ z null shift by $\Delta\phi = \frac{4\pi}{\lambda_g}\Delta z$ where λ_g is the slotted guide wavelength. The attenuator in the phase shifter path is adjusted to keep the tapped power levels in the linear region of the detector. The attenuator in the reference path is adjusted to obtain deep nulls in the standing wave pattern for zero applied bias current. To preserve reference phase integrity, this attenuator remains fixed over a run. Reference power is monitored to account for any drifting effects of the source. Reflected and transmitted power levels are monitored for each bias current condition.

A 5 inch section of dielectric waveguide, tapered at both ends for a smooth transition, was inserted between the exposed ends of the metal guide. The exposed length was about 3.5 inches with the PIN diode located midway on the dielectric guide. Experiments were performed with several dielectric guide sizes and silver putty was used to plug the unfilled space at the metal to dielectric guide transition. This prevents RF leakage and assures power coupling only through the dielectric guide.

Experimental Results

Typical measured phase shift and dynamic loss characteristics at 70GHz are shown in Figure 5. These results are for the diode of Figure 2 and silicon waveguide measuring .2cm x .1cm. The diode width of .15cm does not completely span the .2cm width of the guide for this particular example. This result illustrates that full width coverage of the guide is not a requirement. However, minimum diode width to achieve useful performance has not yet been determined.

Two important performance characteristics are immediately apparent from this figure. The first is that there is a rapid increase in phase shift for small current values followed by a thresholding effect where further increases in current or conductivity yield no appreciable change in phase shift. The breakpoint between these two regions occurs at approximately 20mamps. This result is consistent with the critical conductivity model as seen from Figure 3 which predicts a breakpoint at 20mamps. The second observation is the behavior of the dynamic loss characteristic. At low current levels, the loss is extremely high but rapidly tails off at higher current levels as would be expected when the metallic condition is approached. It is interesting that this phase shift/loss characteristic resembles that obtained for PIN diodes positioned in metal waveguide to conductivity modulate one wall of the guide[10].

The type of phase shift action characterized in Figure 5 is ideally suited for a digital implementation. By forward biasing the diode at a current level past the breakpoint, maximum phase shift is achieved where the dynamic loss is low. For the example shown here, approximately 45^{o} of shift is obtainable at a loss penalty of 1db for current levels of the order of 50mamps. Since the applied voltage is approximately 2v, this corresponds to a .1 watt drive power requirement.

In addition to the dynamic loss characteristic, two additional loss mechanisms occured during these experiments. The first of these is launching loss relating the efficiency of coupling power from metal to dielectric guide. The launching technique used here is admittedly crude. The combined transmit loss for launching and recoupling was measured to be 2.2db in the absence of the diode phase shifter. A more refined approach is to use flared sectoral horns attached to the metal waveguides with the aperture field chosen as nearly like the desired mode to be propagated in the dielectric guide. Launching efficiencies of 98% have been achieved[4]. However, the purpose of this investigation was not directed toward maximizing the launching efficiency.

A second and more fundamental type of loss is the static loss associated with the phase shifting diode. When the diode is placed on the guide in a zero bias condition, a discontinuity in the boundary condition results. This discontinuity gives rise to a reflected wave in the guide and a coupling of energy into radiation modes. Marcuse[11] has analysed this problem for the case of the slab guide. For block shaped or short tapered diodes, the height of the diode determines the radiation loss. By gradually tapering the diode ends, radiation losses can be reduced. Marcuse[12] has suggested that an advantage can be gained for short geometries by exponential tapering. This approach has not yet been attempted. The diode in Figure 2 has a 2:1 taper. Measured static loss for this geometry was 3.5db. Lower static losses have been measured for other diode geometries, but leads were not attached to measure phase shift and dynamic loss as of this writing.

Finally, in contrast to reference 3, the diode structures discussed here require low drive power. The heat generated is small so that loss due to heating of the waveguide is negligible, not affecting the loss tangent of the guide.

Summary

PIN diode design rationale and performance data have been presented for a phase shifter at 70GHz. The phase shifting technique is compatible with dielectric waveguides which can be end tapered for use in a phased array. Recommended future activity is the extension of this technique to higher frequencies and the development of analytical models in order to more fully understand and predict performance bounds, particularly reflections caused at boundary discontinuities.

The importance of this work lies in the fact that a practical phase shifter at millimeter wavelengths can be constructed. Low driving current and power can be achieved. Ferrite devices do not appear practical past 50GHz, and driving power at the higher frequencies may be excessive. PIN diode phase shifters offer an attractive alternative.

References

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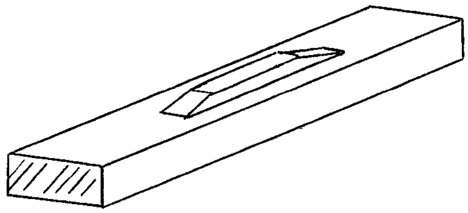

Fig.1 PIN diode phase shifter geometry

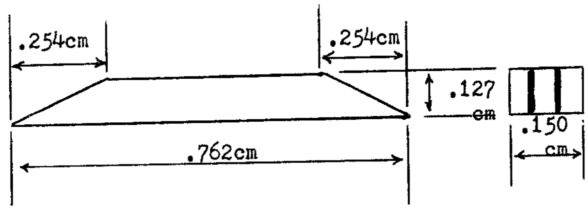

Fig.2 Sample PIN diode size characteristics

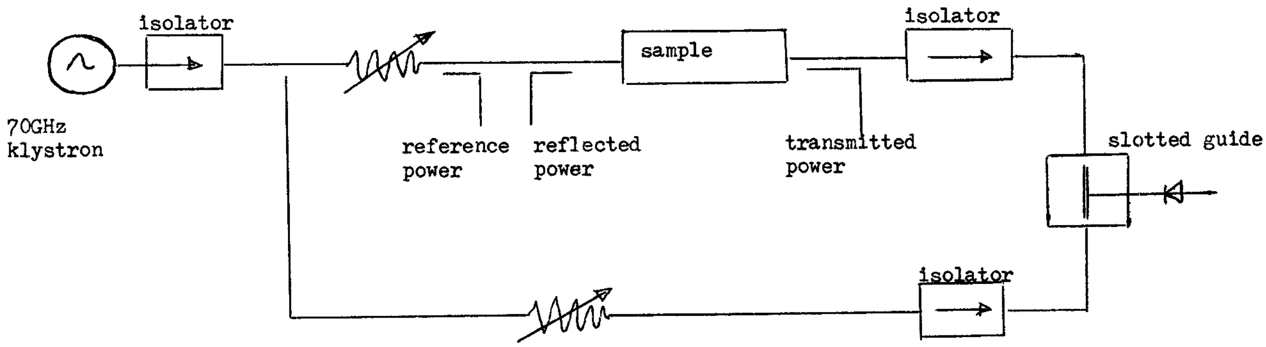

Fig.4 Meausrement test setup for phase shift and loss determination

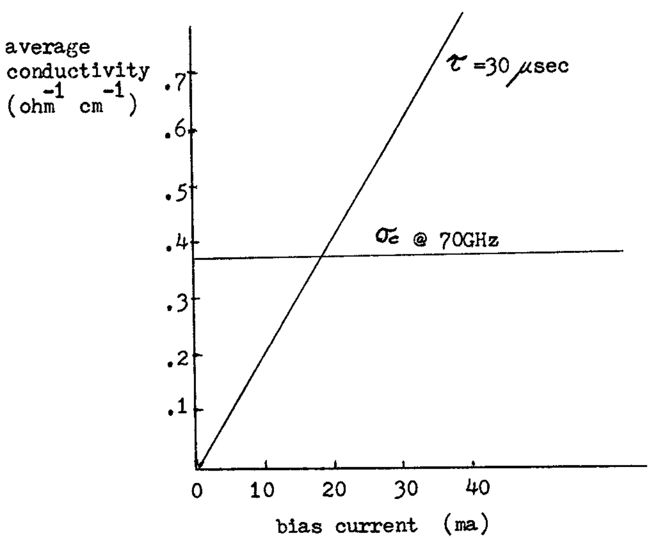

Fig.3 Conductivity of PIN diode as a function of forward current

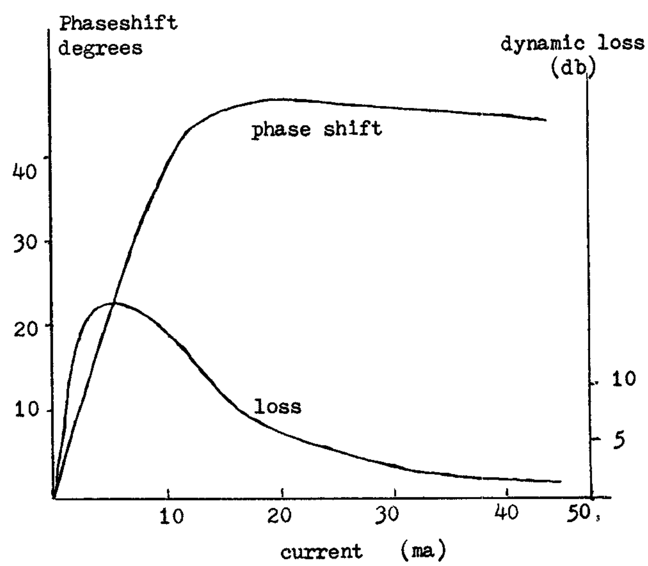

Fig.5 Measured phase shift and dynamic insertion loss at 70GHZ