A DISTRIBUTED PIN DIODE PHASER FOR MILLIMETER WAVELENGTHS*

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ABSTRACT

A technique particularly applicable at millimeter wavelengths is described for electronically varying the phase shift per unit length in rectangular waveguide using a distributed PIN diode. Design, construction, and experimental evaluation at 140 GHz are described.

Introduction

Electronic systems for communications, reconnaissance and surveillance, and monitoring are beginning to appear in the millimeter wave band. The advantages of using the higher frequencies vary depending on the applications, while the disadvantages are almost wholly due to the lack of appropriate components. Many of the phenomena used in the successful development of microwave devices cease to exist or become impossible to implement at the higher millimeter wave frequencies, thereby requiring new approaches to device implementation. One such device is the phase shifter needed for electronically scanned phased array antenna applications. Some work has been reported on the use of ferrites at frequencies in the 35-100 GHz region.[1,2,3] In general, these devices exhibit increased insertion loss at the higher frequencies. An important exception is the dual mode phaser, whose predicted performance at 95 GHz appears promising.

This paper describes a novel approach to the problem using a distributed PIN diode phaser. The device produces useful phase shift/insertion loss characteristics over the full millimeter wave band. In addition, these phasers may be fabricated in groups to form the composite phasing section of an array antenna.

Operating Principles

The operation of the distributed PIN diode phase shifter is fairly simple. The diode is placed at or near the narrow wall of a section of rectangular waveguide, as shown in Fig. 1. Conductivity modulation of the I-region of the PIN diode produces the various phase states. Under zero or reverse bias, the intrinsic region is in its high-resistivity, insulating state. Under this condition the diode dielectrically loads the waveguide, causing it to have an effective width greater than its normal width. Applying a forward bias results in the injection of a plasma of electrons and holes into the I region, lowering its resistivity. In this state, the width of the waveguide will appear to be reduced by the effective thickness of semiconductor slab. This controls the guide wavelength for the dominant mode, and hence controls the phase of the transmitted millimeter wave.

The normal modes of propagation for a guide loaded with a semiconductor slab are not, in general, solely transverse electric or transverse magnetic modes, but a combination of a TE and a TM mode. The boundary conditions at the semiconductor-air interface of Fig. 1 are satisfied if the electric field normal to this interface is set equal to zero. This leads to a mode in which the electric field lies in the longitudinal interface plane. This mode is referred to as a longitudinal-section electric (LSE) mode and is a natural mode for the phase shifter geometry.

A theoretical analysis neglects the thin P+ and N+ regions and assumes that the conductivity modulation of the I region is uniform. The boundary conditions at the semiconductor-air interface lead to a complex transcendental equation for the propagation constant. Numerical solutions of this equation have been obtained by use of a root-search algorithm.

Typical computer-generated data are shown in Fig. 2. The phase shift per centimeter and insertion loss per centimeter are plotted for silicon slabs of various thickness at 140 GHz in RG-138/U waveguide as a function of slab conductivity. Useful phase shift at reasonable insertion loss is seen to be realized at the low and high conductivity states.

For slab thicknesses greater than one-quarter wavelength (which occurs at $t/a \approx 8.36\%$ for silicon slabs at 140 GHz) the dominant mode fields become concentrated in the semiconductor portion of the waveguide and they decay exponentially in the unloaded section. The resulting phase shift and insertion loss are not as well behaved as the data shown in Fig. 2; generally there is less phase shift/insertion loss for the thicker diodes.

Diode Fabrication

The distributed PIN diode samples used in this investigation were formed by means of conventional diffusion techniques. The "intrinsic" material from which sample diodes were made was N-type silicon having various resistivities in the range 50 to 2000 ohm-cm. The material was obtained from commercial sources (Monsanto and Wacker) in the form of wafers whose thickness would constitute the height of the diodes from contact to contact. The heavily doped N and P layers were formed by phosphorus and boron diffusions respectively to depths in the 2 to 15 micron range. Metal contacts were formed by sputtering a conductor onto the faces of the wafer and then masking and etching patterns to delineate individual diodes. Dicing was done by means of a laser scriber or multiple wire saw. Figure 3 shows diodes before and after separation. Measurements were made of spreading resistance, I-V characteristics, and excess carrier lifetime. While the measurements confirmed that PIN diodes had been formed as desired and that conductivity modulation was occurring, the carrier lifetime data indicated that the lifetimes obtained were too short for conductivity modulation to occur throughout the entire length of the I region. It is estimated that an order of magnitude increase in the lifetime to, say, 30 microseconds would result in complete conductivity modulation.

Experimental Data

The initial experimental effort concerned the measurement of the effects of bulk silicon slabs located on the side wall of rectangular waveguide at 140 GHz. A group of 10 silicon slabs was made up, each slab having dimensions 6.2 mils wide, 40 mils high, and 1 cm long. The slabs were doped to various conductivities covering the range 1 $(\text{ohm-m})^{-1}$ to 10^4 $(\text{ohm-m})^{-1}$. The slabs were placed, one at a time, along the sidewall of a section of RG-138/U waveguide and their relative phase shift and insertion loss were measured. The phase measurements were made with a slotted line in a bridge circuit, while the attenuation measurements were done by substitution using a calibrated variable attenuator. The results, plotted in Fig. 4, were in close agreement with the computed performance except for the tails of the loss curve, which are attributed to reflections from the slab faces (no matching was done).

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Having established the potential feasibility of this distributed semiconductor phase shifter by means of the measurements on slabs, several PIN diodes were made to approximate the semiconductor slabs. Because of carrier lifetime limitations, the height of the diodes had to be limited to about 10 mils. Although a reduced height waveguide mount was used, the PIN diode did not fill the entire height of the waveguide. Attenuation and phase shift for a PIN diode are plotted versus dc bias current in Fig. 5. These curves show good qualitative agreement with the calculations but cannot be directly compared because of incomplete conductivity modulation and the differences in geometry.

Application in Phased Array Antennas

The "storage time" of the PIN diodes is of the same order of magnitude as the excess carrier lifetime. Since, in striving for efficient conductivity modulation, one seeks to maximize the lifetime in the distributed PIN diodes, "very high speed" applications such as phase modulators for wideband communication channels are automatically eliminated. In addition, the high attenuation exhibited by the distributed PIN diodes at intermediate phase shift settings generally precludes their use as analog phase shifters. We are left with a phase shifter having moderately fast switching speed (a few microseconds) and an inclination toward binary operation. Such a device has an important application as the heart of electronically steerable antennas.

Digital beam steering control in a phased array requires that any combination of several "bits" of phase shift be selectable for each antenna element. A typical requirement is that each element have a 4-bit phase shifter. That is, each phase shifter must be capable of producing any combination of 180°, 90°, 45°, 22.5° or 0° of relative phase shift. For the distributed PIN diode phase shifter the 4 bits will be obtained by placing four PIN diodes end to end. Each diode will be of appropriate length for one of the phase shift bits and each will have a separate bias control.

When considering a "package" for the distributed PIN phase shifter, it is desirable to avoid reduced height waveguide. The concentrated fields in the reduced height guide invariably result in increased attenuation relative to full height guide. Yet the PIN diode cannot be made to more than about 1/4 the waveguide height. A solution to this problem can be found in the technique of "diode stacking," whereby a number of diodes are physically bonded together in series. This technique is used in the manufacture of high voltage rectifiers.

Figure 6 is a line drawing of a unique array antenna[4,5] particularly suited for millimeter wave applications and quite compatible with the distributed PIN phase shifter. The antenna radiates a linearly polarized pencil beam which may be electronically scanned in one plane. The principal feature is a completely confined space feed in the form of a lens-corrected dual mode sectoral horn. The use of optical techniques is important, since the losses in a transmission line feed would be substantial at 140 GHz.

Conclusions

The distributed PIN diode phase shifter has been shown useful for array applications at millimeter wavelengths. At 140 GHz, the possibility of a moderate resolution (beam widths less than 1° are easily obtainable) array antenna appears promising. An imaging or tracking system based on such an antenna will be readily portable for airborne as well as ground applications, will offer better range in poor visibility conditions than a visible/IR system, and will offer improved resolution over a microwave system of comparable size and weight. Aside from its simplicity, the unit is economical to fabricate and utilizes current available semiconductor and microwave/millimeter wave technologies.

Acknowledgements

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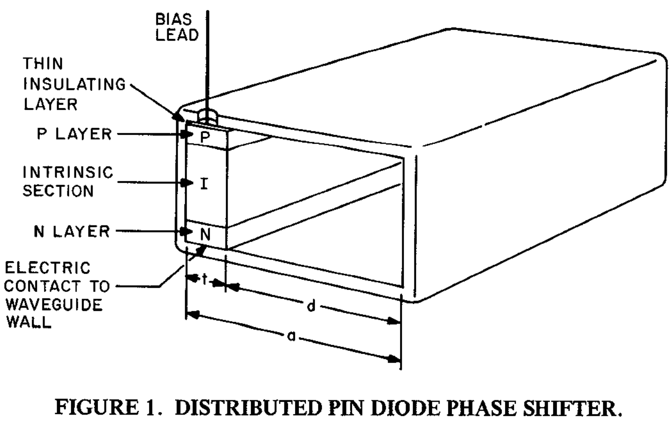


FIGURE 1. DISTRIBUTED PIN DIODE PHASE SHIFTER.

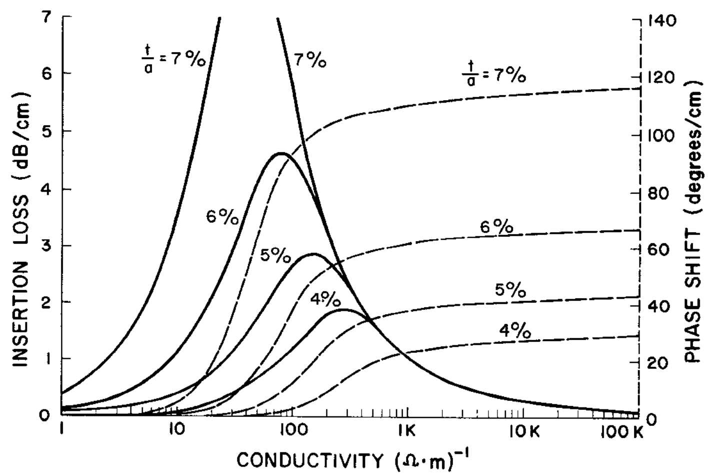
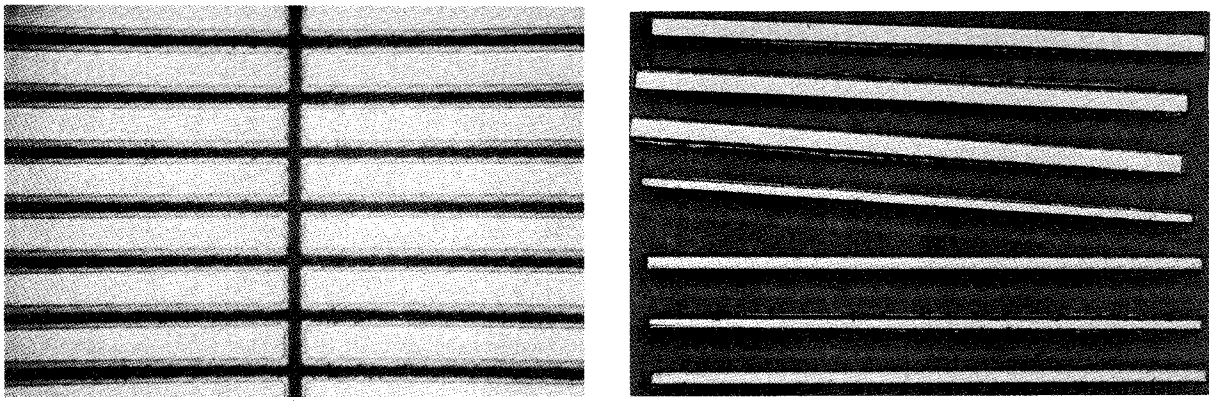


FIGURE 2. PHASE SHIFT AND INSERTION LOSS FOR SEMICONDUCTOR SLAB LOADED WAVEGUIDE AT 140 GHz.



a. Wafer face after laser scribing

b. Finished PIN diodes viewed from top (contact) side; three widths are shown

FIGURE 3. PIN DIODE DICING

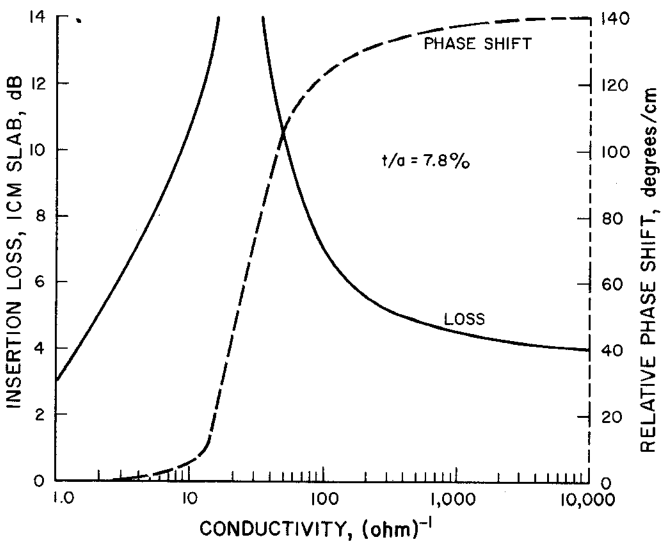


FIGURE 4. MEASURED PHASE SHIFT AND INSERTION LOSS FOR SILICON SLABS IN RG 138/U WAVEGUIDE AT 140 GHz.

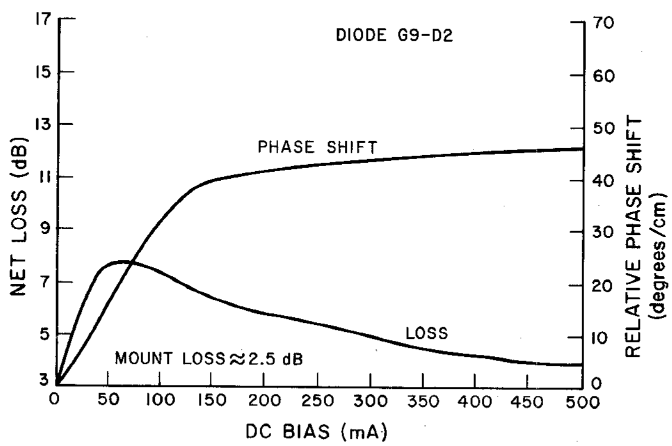


FIGURE 5. MEASURED PHASE SHIFT AND INSERTION LOSS FOR A DISTRIBUTED PIN DIODE AT 140 GHz.

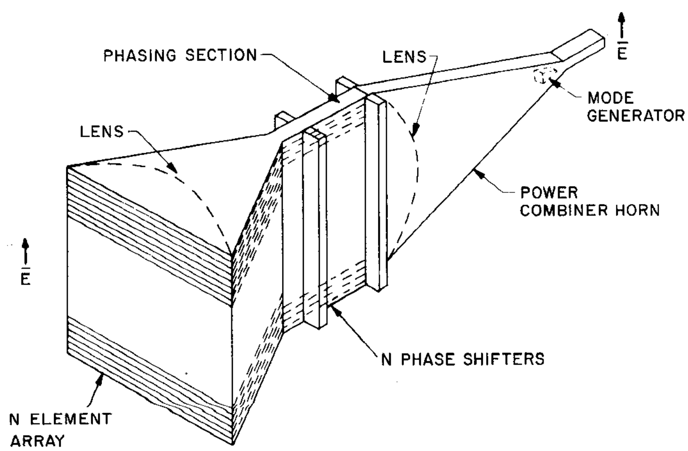


FIGURE 6. LINE DRAWING OF ARRAY ANTENNA.