SEMICONDUCTOR DIELECTRIC WAVEGUIDES FOR MILLIMETER WAVE FUNCTIONAL CIRCUITS

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Abstract

High resistivity silicon has been used as a medium for low loss propagation of millimeter waves. In addition, associated components and devices can be constructed directly in semiconductor dielectric waveguides. The concept is analogous to that employed in integrated optics, except that here the medium is a semiconductor and the active elements are obtained with semiconductor devices.

Introduction

At the present time, most microwave integrated circuits (IC) are based on a microstrip concept. This works well at lower microwave frequencies and is possible up to Ku-band. However, at higher frequencies in the millimeter wave length region and into the submillimeter regions, the losses are prohibitively greater. A new concept, using high resistivity silicon, recently obtainable as a quasi-optical dielectric waveguide, offers promise of lower losses for propagation. An additional factor here is that, since the "optical pipes" are made of silicon, components and devices can be built into the line. In this report measurements of transmission and wavelength in silicon waveguides have been carried out at Ku-band, in order to verify theories proposed by Marcatili[1] and Goell.[2] With respect to propagation, substantial agreement occurs in theory and experiment. Preliminary work has been started on phase shifters, amplitude modulators, oscillators, and detectors.

Text

In the measurement of propagation by means of field probes, it was found that most of energy was concentrated in the guide material; losses were low, and propagation constants could be determined by measurements of wavelength. For slightly oversized silicon waveguides and with wave launched from the TE_{10} mode in a metal waveguide to form the E_{11}^{y} mode of propagation in the silicon guide, agreement with the theory (Fig. 1) was almost perfect. As the cross-sectional area was reduced to half wavelength dimensions or less, a greater disparity appeared; the experimental propagation constant in the z direction approaching a considerable decrease over that predicted by simple approximations. However, even here the theories proposed give good qualitative insight into the behavior of the wave motion.

The next part of this work was to develop active devices in the semiconductor line such as electronic phase shifters, amplitude modulators, generators, and detectors. The first such device developed has been the electronic phase shifter. This particular device is important, since it provides a means of changing the effective wavelength of the electromagnetic radiation in the guide and, hence, can provide tuning, phase shifting, matching, etc. The mechanism can be described by a simple experiment. Suppose we have a bridge providing the capability of measuring amplitude (attenuation) and phase. In one arm of the bridge we replace the metal waveguide with a section of silicon dielectric waveguide with proper transition pieces for low loss. The bridge is then balanced to a null, indicating a small loss in the semiconductor and a reference for phase, Next, if a small metal plate is placed on the top surface of the semiconductor, a phase shift can be measured with no loss. This was interpreted as due to the presence of the metal layer causing an increase in k_z, the propagation constant in the longitudinal direction of the dielectric guide, resulting in a smaller wavelength along the axial direction. This has been verified by a measurement of wavelength with a carriage mounted probe (Figs. 2 and 3). Next, if the metal sheet is replaced with a silicon layer in which are imbedded P-type and N-type junctions, the silicon sheet of PIN diodes can be rendered conductive or non-conductive by forward or reverse bias, resulting in an electronic means of changing the phase of the radiation in the medium. Two forms of such phase shifters are shown in Figs. 4 and 5, illustrating the process of flooding carriers along the z axis and across the x axis, respectively, by forward bias of the PIN sections. Tests of this type have shown that in slightly oversized dielectric guide, the theoretical phase shift is 32°/cm, the metal plate experiment gave about 32°/cm and the semiconductor PIN structure has been demonstrated at about 20°/cm. With smaller cross-section silicon guides, about 160°/cm should be obtainable with neglible insertion loss and changes in amplitude during the phase shifting process.

In still another arrangement, amplitude modulation has been demonstrated at 70 GHz. With the P- and N-regions placed on the upper and lower side of the silicon guide and with a forward bias driving injected carriers into the body of the semiconductor, an attenuation $>$ 50 dB was observed (Fig. 6). This family of devices could be used as a switch or amplitude modulator for a millimeter wave line. In other experiments, IMPATT diodes inserted in the semiconductor line are being tried as generators and point contact or Schottky barrier diodes are being tried as detectors.

Conclusion

It is our feeling that an entire integrated system can be constructed in this manner for a receiver and/or transmitter. In using this technology, low cost and high quality components will become available for general use in millimeter wave electronics.

References

1. E. A. J. Marcatili, "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics," BSTJ, Vol. 41, No. 7, pp. 2071-2012, September 1969.

2. J. E. Goell, "A Circular-Harmonic Computer Analysis of Rectangular Dielectric Waveguides," BSTJ, Vol. 48, No. 7, pp. 2133-2160, September 1969.

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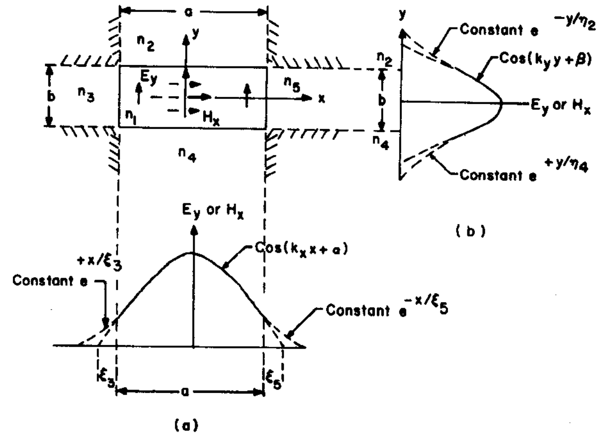

FIG. 1. CROSS-SECTION OF DIELECTRIC WAVEGUIDE AND FIELD DISTRIBUTION OF THE FUNDAMENTAL E^y_{11} MODE.

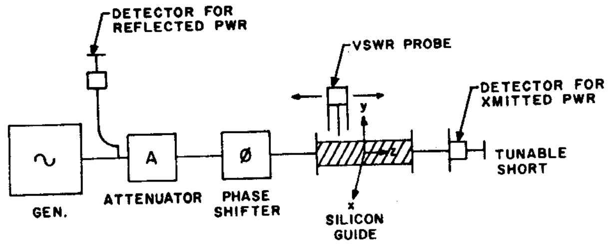

FIG. 2. EXPERIMENT FOR MEASUREMENT OF λ_z.

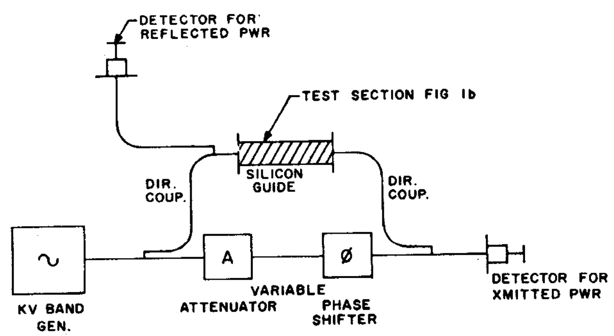

FIG. 3. EXPERIMENT FOR MEASUREMENT OF ATTENUATION AND PHASE.

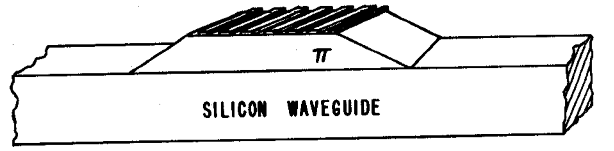

FIG. 4. ARRANGEMENT FOR ELECTRONIC PHASE SHIFTER. THE STRIPES ON TOP INDICATE ALTERNATING P- AND N-LAYERS WHICH WHEN FORWARD BIASED PROVIDE PIN DIODE FLOODING. THE PHYSICAL SEPARATION OF THE TWO SILICON PIECES IS TO PREVENT EXCESS CARRIERS FROM FLOODING THE BASIC WAVEGUIDE STRUCTURE.

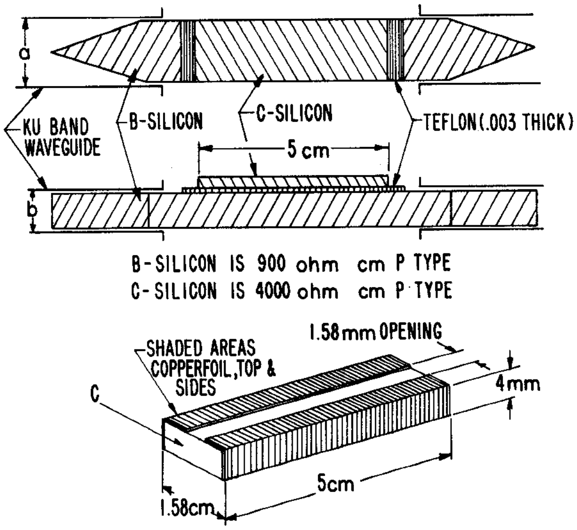

FIG. 5. ARRANGEMENT FOR ELECTRONIC PHASE SHIFTER. FLOODING BY FREE CARRIERS IS CARRIED OUT BY BIASING THE PIN DIODE WITH A FIELD DIRECTED ACROSS THE UPPER SURFACE OF THE UPPER APPENDAGE.

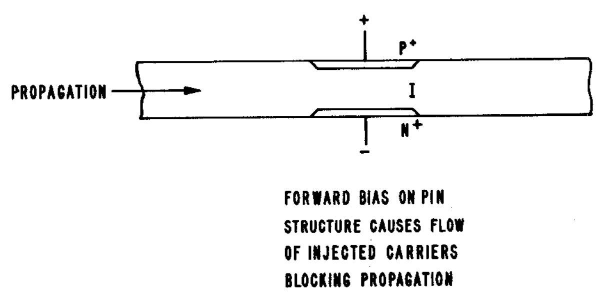

FIG. 6. CONSTRUCTION OF AN ELECTRONIC ATTENUATOR. FORWARD BIAS ON PIN STRUCTURE IN THE GUIDE CAUSES A FLOW OF INJECTED CARRIERS WITH DIRECTION BLOCKING THE ELECTROMAGNETIC PROPAGATION.