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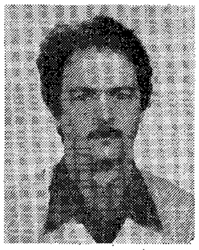

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Millimeter-Wave Passive Components and Six-Port Network Analyzer in Dielectric Waveguide

JEFFREY A. PAUL, MEMBER, IEEE, AND PERCY C. H. YEN

***Abstract*—A cost effective scheme of fabricating millimeter-wave passive components in dielectric waveguide has been conceived and a computer program has been written for analyzing their frequency responses. By inlaying Teflon guides in the properly designed contours cut in a low dielectric constant foam material, passive components such as quadrature hybrids, in-phase power dividers, and six-port network analyzers have been developed. Design and performance data are presented.**

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I. Introduction

IN THE PAST, various active and passive millimeter-wave devices based upon the concept of dielectric waveguide have been reported [1]–[4]. In this paper, a cost

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effective scheme for fabricating dielectric waveguide components and integrated circuits with reasonable mechanical tolerance requirements is reported. The performances of these components at 94 GHz demonstrate the feasibility of this method for millimeter-wave component fabrication.

II. Dielectric Waveguide

The basic dielectric waveguide structure considered in this paper consists of Teflon waveguides sandwiched between two sheets of low dielectric constant foam material [5], such as Eccofoam PS with dielectric constant 1.02, 0.5 in thick. The Teflon guides are inlaid in the foam after the contours are milled. Transitions from metal to dielectric waveguide are made using a horn with a nominal gain of 25 dB and an aperture of linear dimensions extending over five free-space wavelengths. The Teflon guide has a linearly tapered tip and is inserted into the waveguide section of the horn [6].

Measurements show that such a transition introduces an insertion loss at 94 GHz of less than 0.25 dB and a VSWR better than 1.20:1. Aspect ratio of the dielectric guide is chosen to have the same cross section as the standard W-band guide (WR-10) and is accurately formed by pulling a Teflon strip through a metal die. Insertion loss of the guide measured over a length of 10 in is less than 0.1 dB per inch at 94 GHz. Matched terminations are formed by launching the Teflon guide into a lossy dielectric material [5] such as Eccosorb AN-72. A VSWR of 15.1:1 or better is achievable with such a termination.

III. Directional Couplers and Power Dividers

Coupling between two guides [7] is introduced by placing them in close proximity to each other and coupling them via either the sidewall or the broadwall. The length and width of the gap determine the coupling coefficient. Utilizing available formulas for calculating the coupling coefficients [7], a computer program has been generated for analysis purposes.

As an example, consider an E_{11}^x mode broadwall coupler with its cross-sectional view as given in Fig. 1. It is made of two identical guides of a straight section length l, a guide cross section $(a\times b)$ and a relative dielectric constant n_0^2, immersed in a uniform medium of a relative dielectric constant n_1^2. The power ratio of output over input in decibels can be expressed as [8]

$$\text{Output of Coupled Arm} = -20\log_{10}\sin\left(\frac{\pi}{2}\times\frac{l}{L}\right) \quad (1)$$

and

$$\text{Output of Direct Arm} = -20\log_{10}\cos\left(\frac{\pi}{2}\times\frac{l}{L}\right) \quad (2)$$

where L is the minimal length for complete transfer of power from one to the other arm and can be written as

$$L=\frac{\pi}{k_{zs}-k_{za}} \quad (3a)$$

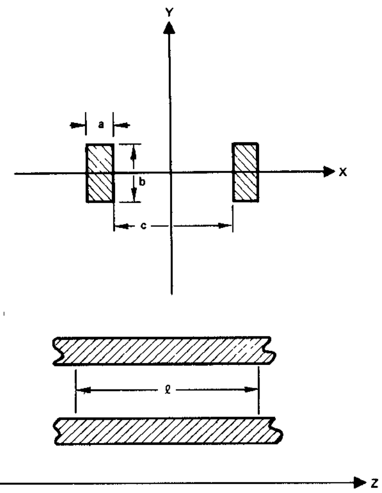

Fig. 1. Uniform coupling section of dielectric guide coupler.

or

$$L=\frac{\pi^2 a k_{z0}}{4Ak_{x0}^2}\left[1-\left(\frac{k_{x0}A}{\pi}\right)^2\right]^{-1/2} \cdot\left\{\exp\left[\left(\frac{\pi C}{A}\right)\left(1-\left(\frac{k_{x0}A}{\pi}\right)^2\right)\right]^{1/2}\right\} \quad (3b)$$

where K_{zs}, K_{za} are the propagation constants of the symmetric and antisymmetric modes, respectively,

C = gap between two guides

a = guide width

$k_{z0}=\left(k_0^2-k_{x0}^2-k_y^2\right)^{1/2}$, propagation constant along the z axis for a single guide

$$k_{x0}a=\pi-2\tan^{-1}\left(\frac{n_1^2}{n_0^2}k_{x0}\xi\right)$$

$$k_y b=\pi-2\tan^{-1}(k_y\eta)$$

$$\xi=\frac{1}{\left[\left(\frac{\pi}{A}\right)^2-k_{x0}^2\right]^{1/2}}$$

$$\eta=\frac{1}{\left[\left(\frac{\pi}{A}\right)^2-k_y^2\right]^{1/2}}$$

$$A=\frac{\lambda_0}{2\left[n_0^2-n_1^2\right]^{1/2}}$$

$$k_0=2\pi n_0/\lambda_0$$

λ_0 = free-space wavelength.

Coupled power versus gap length with gap width as a parameter is plotted in Fig. 2, in which the periodic variation of the coupling effect as given in (1) and (2) is clearly demonstrated. Also shown in Fig. 2 are the half decibel bandwidths centered about the 3-dB points, which are encircled and expressed in gigahertz. To a first-order ap-

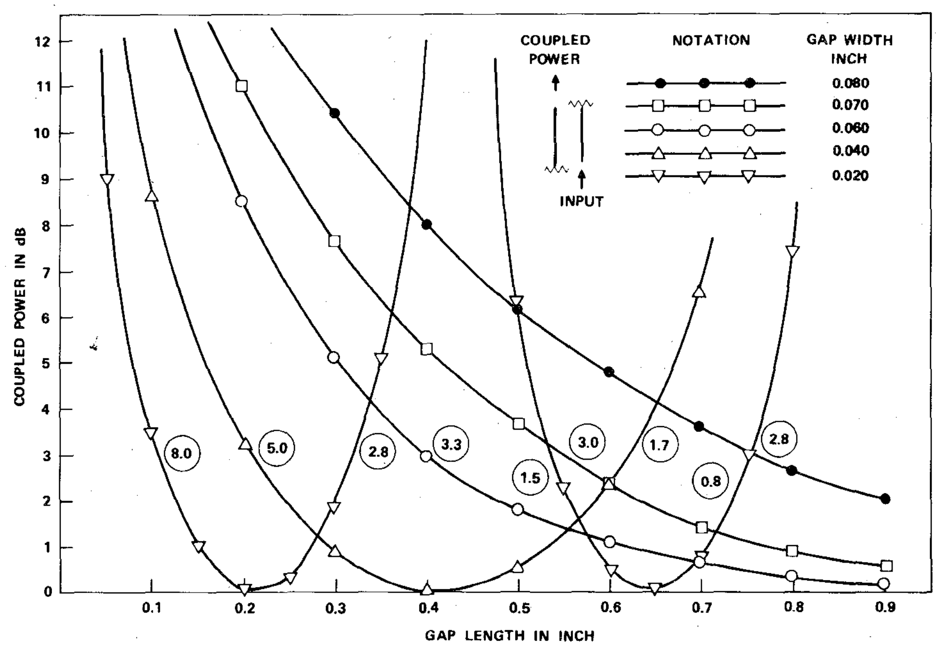

Fig. 2. Broadwall coupling at 94 GHz.

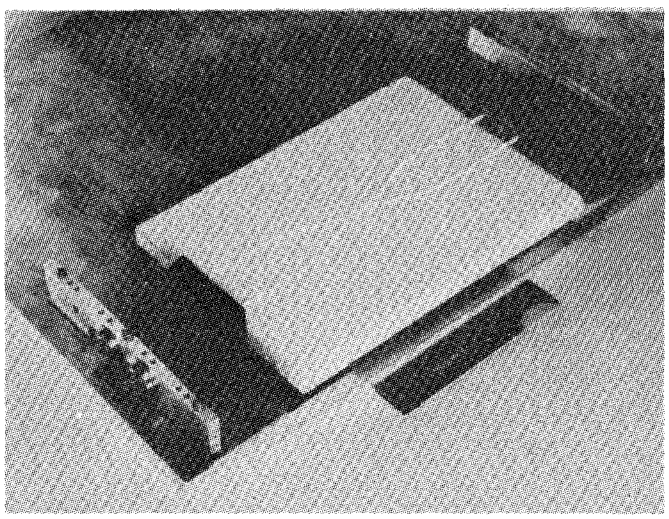

Fig. 3. 90° hybrid.

proximation, the coupling is proporational to the product of length and frequency. Therefore, as the coupling length increases, the bandwidth decreases. Because of radiation losses, the bending radius of the guide should be held to no less than two inches and as a result, the coupling effect of the connecting arms must be taken into consideration [8]. Such an effect has been included in the program by introducing an equivalent coupling length, l_{eq}, into (1) and (2). The equivalent coupling length can be approximated as

$$l_{eq} = l + \frac{2L}{\pi} \int_{z_0}^{z_1} \left[k_{zs}(z) - k_{za}(z) \right] dz \tag{4}$$

where the limits of the integration, taken along the axial direction of the coupler, are points on the connecting arms to extend the coupling to a place where it can be neglected.

For a gap width of 0.040 in or less, calculations indicate that the equivalent coupling length is so long that the 3-dB broadwall hybrid cannot be designed around the first 3-dB crossing point. Because of this lengthening effect, the bandwidth of sidewall coupling is generally greater than that of the broadwall coupling. However, from the mechanical construction viewpoint, bending the Teflon for the broadwall coupler is much easier than for the sidewall version, especially for guides of larger dimensions.

A broadwall coupled hybrid formed by two guides is shown in Fig. 3, and an in-phase power divider formed by one input and two output guides is shown in Fig. 4. The well balanced outputs for these couplers are shown in Figs. 5 and 6. Outputs of the 90° hybrid are 4 dB below the input with one dB loss attributed to insertion loss. VSWR is typically 1.2:1 and directivity is better than 30 dB. A difference of 0.002 in in gap width, a tolerance limit which can be maintained with this fabrication method, changes the coupling by 0.5 dB or shifts the center frequency by 1

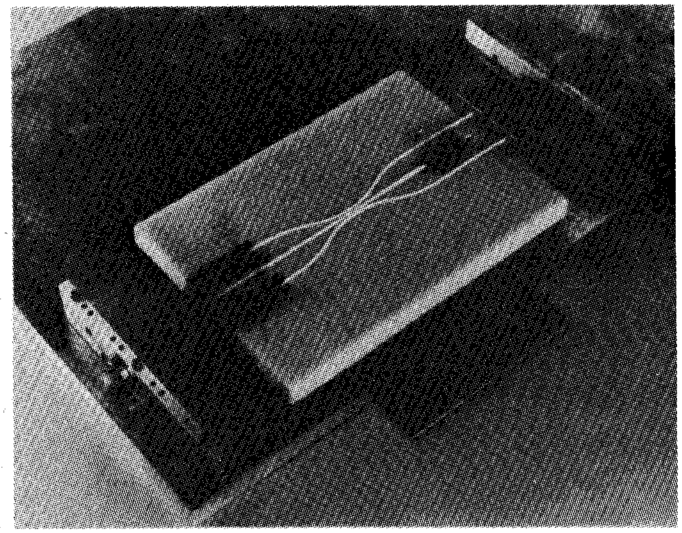

Fig. 4. Power divider.

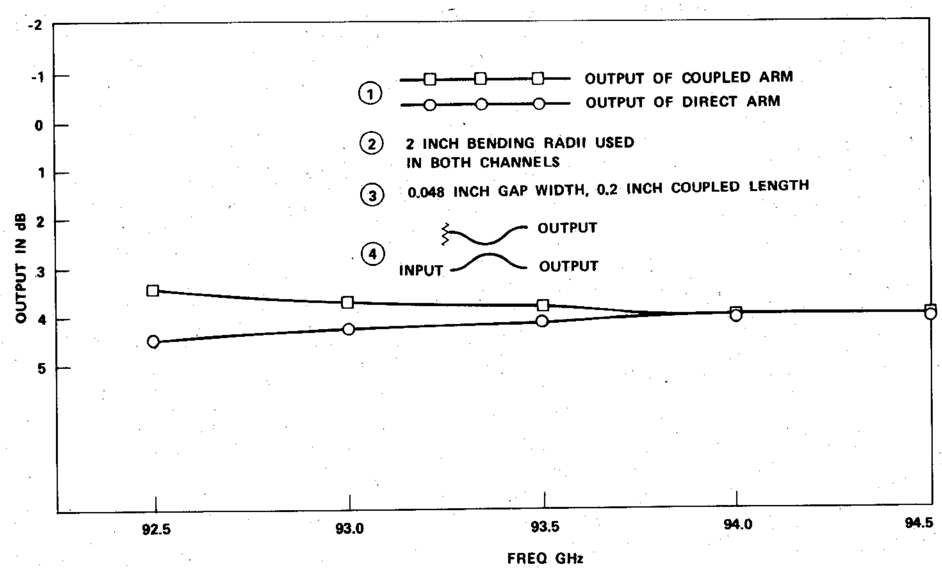

Fig. 5. Performance of broadwall coupled hybrid.

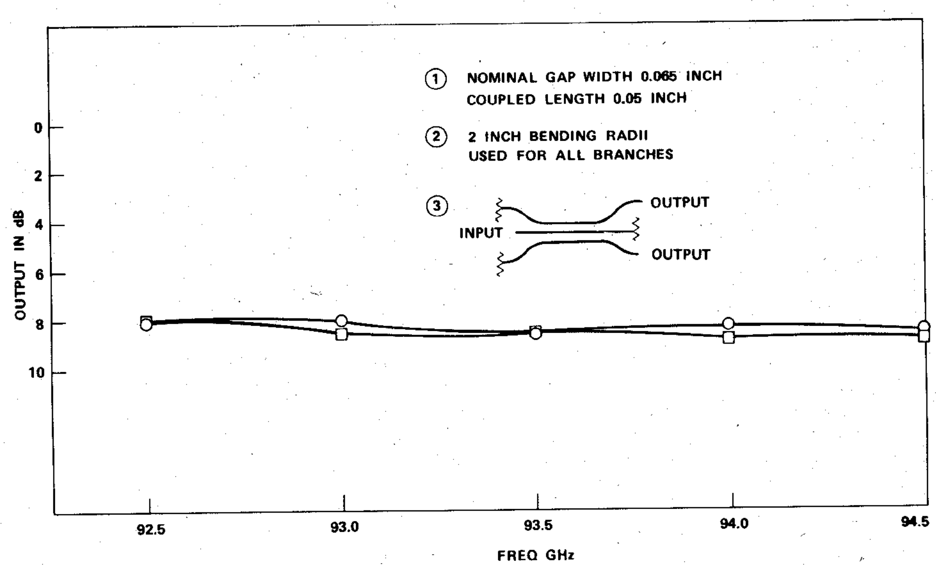

Fig. 6. Performance of broadwall coupled divider.

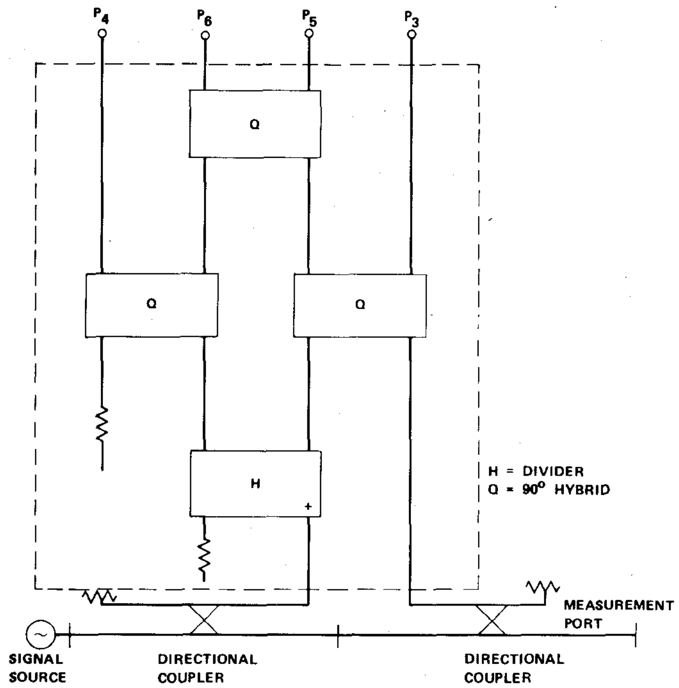

Fig. 7. Six-port network topology.

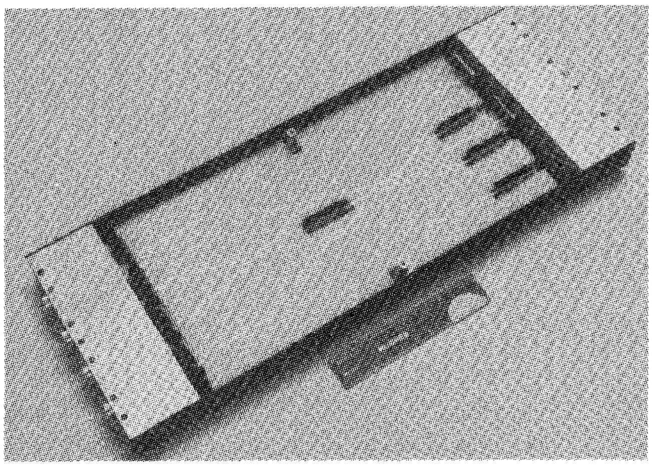

Fig. 8. Six-port network (dielectric waveguide portion).

GHz. By wrapping a thin Teflon tape around the guide, minor effects on coupling can be induced which can be used for fine tuning.

Outputs of the power divider are 7 to 8 dB below the input and the VSWR is typically 1.2:1. The reduced output power is due to loose coupling as the balance of the input power is absorbed by the load located at the end of the input guide. Loose coupling offers an advantage in that the power division is less sensitive to the gap width variations.

IV. Six-Port Network

As an application toward integrated circuits, a six-port network analyzer [9] at 94 GHz has been made. The analyzer is a useful tool for measuring insertion loss and reflection coefficient. Once the system calibration is completed, the unknown can be derived by taking power readings at four measuring ports. The circuit shown in Fig. 7 [9], [10] is one of many possible candidates for implementing this measurement scheme. It was realized by direct integration of three hybrids and one divider.

The analyzer interior is shown in Fig. 8. Each dielectric guide component can be tested separately by inlaying the related waveguides into the channels. Results show that the imbalance between outputs of individual devices can be kept within 1 dB from frequencies to 93 to 94.5 GHz. With all Teflon guides inlaid and input power delivered at the divider, the four outputs are tracked within 1 dB typically. A metal enclosure is used for protection and no degradation is detected due to the presence of the metal planes.

V. Conclusion

Based upon the existing theory, a computer program has been developed to predict the performance of the 90° hybrid and power divider in dielectric waveguide. Results at 94 GHz are in close agreement with the measured data.

In addition, a fabrication scheme to realize millimeter-wave dielectric waveguide components is also described. This method offers a valid approach toward low cost millimeter-wave component and integrated circuit developments.

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Millimeter-Wave Dielectric Image Line Detector-Circuit Employing Etched Slot Structure

KLAUS SOLBACH

Abstract—**In an earlier paper [1] slots in the ground plane are investigated as new circuit elements in dielectric image lines. In this paper slots in dielectric image lines employing metallized dielectric substrates as the ground plane are investigated. It is shown that this configuration can be used to realize truly integrated dielectric image line semiconductor circuits. As an example the design and performance of a detector circuit for 26 to 40 GHz is presented.**

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I. INTRODUCTION

IN AN EARLIER paper slots in the ground plane of the dielectric image line were proposed as mode launchers and circuit elements [1]. It is shown that the slot discon-