by design, it follows from (32)–(34) that

$$x \cong \frac{k}{1+k} \tag{35}$$

for all practical slot widths and thicknesses.

From physical considerations, it is known that $0 \leqslant k < 1$ and, hence from (35), the range of x is $0 \leqslant x < 0.5$. In order to satisfy this constraint, it is necessary to select the solution with the negative sign before the square root in (28). Therefore

$$x = \left(1-\sqrt{1-t^2}\right)/t \tag{36}$$

and from (35) it follows that

$$k = \frac{1-\sqrt{1-t^2}}{t-\left(1-\sqrt{1-t^2}\right)} \tag{37}$$

which is the desired relationship between t and k.

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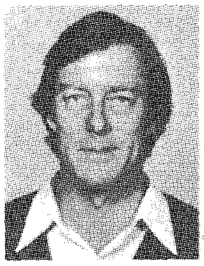

J. H. Cloete (M'77) was born in Clocolan, South Africa, in June, 1945. He received the B.Sc., B. Eng., and Ph.D. (Eng.) degrees in electrical engineering from the University of Stellenbosch, Stellenbosch, South Africa, in 1968 and 1982, and the M.S. degree in electrical engineering from the University of California at Berkeley, in 1972.

In 1970, he joined the Council for Scientific and Industrial Research in Pretoria. From August 1972 to March 1973, he worked at Scientific Atlanta, Atlanta, GA, and from March 1977 to February 1978 at the University of Stellenbosch. In July 1981, he joined the Department of Electronic Engineering at the University of Pretoria as an Associate Professor and Consultant to the Laboratory for Advanced Engineering.

Experimental Study of the *W*-Band Dielectric-Guide *Y*-Branch Interferometer

ALEXANDER AXELROD, STUDENT MEMBER, IEEE, AND MOSHE KISLIUK, SENIOR MEMBER, IEEE

***Abstract*—Applicability of a *W*-band dielectric-guide *Y*-branch (DGY) interferometer as a modulator and switching element for the millimeter-wave planar dielectric-guide integrated circuits is established. The switching element includes a phase shifter formed by a metal wall proximate to a dielectric guide.**

The influence of the branches asymmetry on the on/off switching ratio was measured and found to comply with theory. On/off switching ratios of about 25 dB were obtained over a 98–104-GHz frequency range.

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The authors are with the Department of Electron Devices and Electromagnetic Radiation, School of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel.

I. Introduction

Although the dielectric-guide *Y*-branch (DGY) interferometer is extensively applied in the optical integrated circuits for power splitting, light intensity modulation, and switching [1], to our knowledge no experimental data on this subject has been published with respect to the millimeter-wave range. This study seeks to establish the applicability of the *Y*-branch element in the *W*-band integrated circuits. Low radiation losses under even excitation, near-3-dB power division, and low VSWR values were observed in the *Y*-junction.

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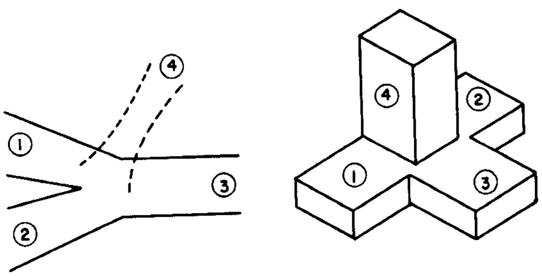

Fig. 1. The Y-junction analogy to the "magic-T".

In Section II, application of a DGY interferometer as a low-loss near-3-dB coupler is discussed. The modulation and switching properties of the DGY interferometer are studied in Section III, which contains test data on a phase shifter using a metal plate proximate to a broad wall of the guide.

These phase shifters may be designed using a distributed p-i-n diode structure attached to a sidewall of a millimeter-wave dielectric guide [2], [3]. Another attractive phase-shifting mechanism based on an induced plasma state in semiconductor guide [4], [5] may serve for ultrafast switching. We believe that DGY interferometers using similar phase shifters may be successfully applied as millimeter-wave modulators and switches.

II. Y-Junction

A detailed discussion of the near-3-dB Y-junction coupler is given [6]. Relevant results are borrowed here in the original notations.

A remarkable property of the absolutely symmetric lossless dielectric guide Y-junction is the identity of its S-matrix with that of "magic-T" in microwave circuits. A Y-junction may be considered as a four-port device in which the fourth port takes all power radiated out of the guided-wave system (see Fig. 1). Assuming no reflected waves, near-3-db power division means coupling of $1/2(1+\delta)$ of port 3 input power into port 1 and $1/2(1-\delta)$ of port 3 input power into port 2. The four-port scattering matrix correlates the output (E') and input (E) electric fields

$$\begin{bmatrix} E_1' \\ E_2' \\ E_3' \\ E_4' \end{bmatrix} = \begin{bmatrix} 0 & 0 & \sqrt{\frac{1+\delta}{2}} & \sqrt{\frac{1-\delta}{2}} \\ 0 & 0 & \sqrt{\frac{1-\delta}{2}} & -\sqrt{\frac{1+\delta}{2}} \\ \sqrt{\frac{1+\delta}{2}} & \sqrt{\frac{1-\delta}{2}} & 0 & 0 \\ \sqrt{\frac{1-\delta}{2}} & -\sqrt{\frac{1+\delta}{2}} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix}. \quad (1)$$

A DGY junction was tested over a range of 98–104 GHz (Fig. 2). All three ports of the Y-junction are single-mode 2×1-mm teflon ($\epsilon_r = 2.057$) guides. The broad wall of branch 3 tapers to 4 mm, and splits symmetrically into branches 1 and 2.

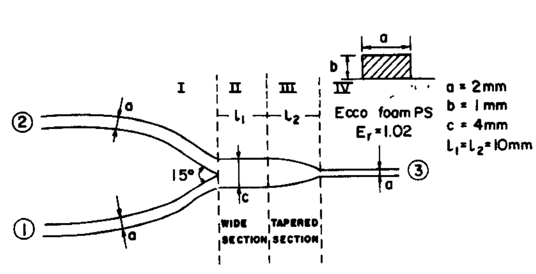

Fig. 2. The geometry of the Y-junction.

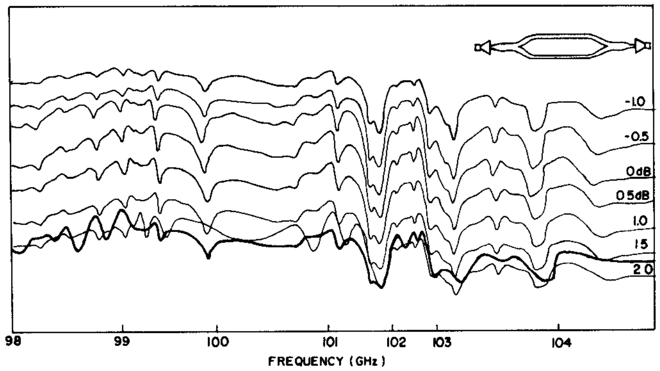

Fig. 3. Insertion loss (dB) of the Y-branch interferometer referenced against the insertion loss of a straight guide section.

The test program included measurements of insertion losses in the transitional sections of a Y-junction under even excitation ($E_1 = E_2$; $E_3 = E_4 = 0$). For this purpose, two Y-junctions were connected back-to-back, forming an interferometer. Fig. 3 represents the total insertion losses in an interferometer, as referred to the loss in a straight section of the teflon rectangular guide of identical length, cross section, and excitation. The measured insertion loss of the interferometer was less than 2 dB, or 1 dB per Y-junction.

The test setup and power division data are given in Fig. 4. The P_1/P_2 exhibits deviation less than 0.5 dB from the ideal 0-dB power division over most of the frequency range, which is generally tolerable for Y-junction applications.

The VSWR's in ports 1 and 2 were measured using a sliding electric-field probe [7]. VSWR's less than 1.05 were registered for both even and odd ($E_1 = -E_2$; $E_3 = E_4 = 0$) excitations.

The obtained data supports our assumptions adopted in deriving the scattering matrix (1).

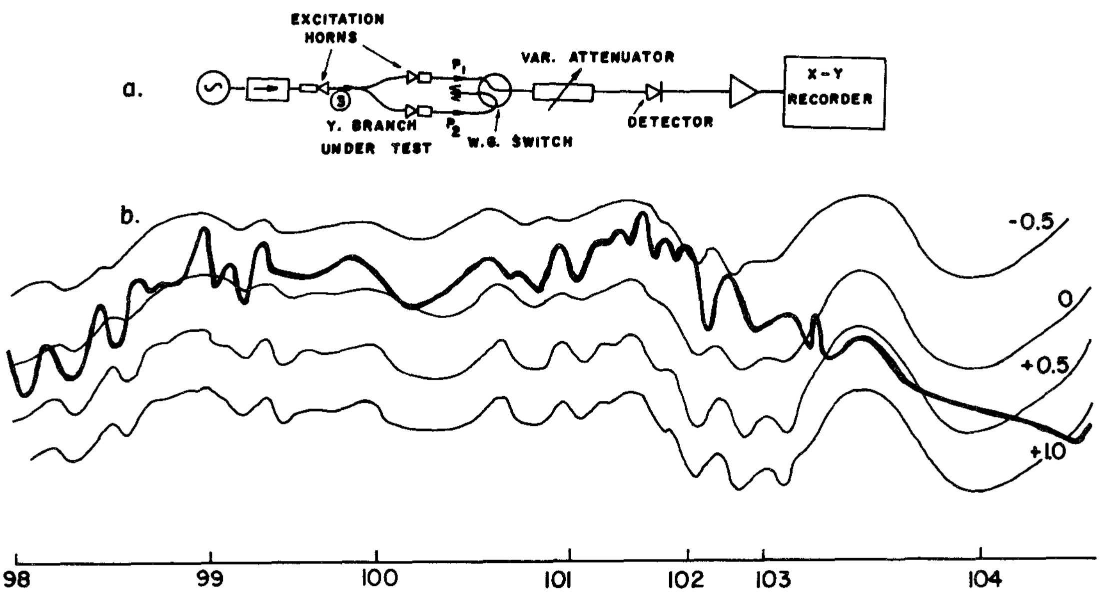

Fig. 4. The measurement of the power division in a Y-junction. (a) Test setup. (b) Measured power ratio $10\log(P_1/P_2)$.

III. Y-BRANCH INTERFEROMETER

The modulator and switch applications of the dielectric-guide Y-branch interferometer take advantage of the dependence of output power in the third arm (P_3') on a phase shift φ between phasors E_1 and E_2. The phase shift φ causes mixed even and odd excitation in the wide section of the Y-branch (see Fig. 2). Only the even mode of the wide section passes through tapered Section III, where it gradually transforms to an E_{11}^y mode of a single-mode guide 3, while the odd mode totally radiates out. Low measured VSWR's indicate that most of insertion losses in odd excitation modes are due to radiation rather than reflection.

Let us now obtain the on/off power ratio $R = P'_{3_{max}}/P'_{3_{min}}$ that is important for the switch applications. In order to obtain port 3 output power (P_3'), substitute $E_1 = \sqrt{P_1}$; $E_2 = \sqrt{P_2}\,e^{i\varphi}$; $E_3 = E_4 = 0$ into (1)

$$P_3' = E_3' \cdot E_3' = 1/2\Big[P_1(1+\delta) + P_2(1-\delta) + 2\sqrt{P_1 P_2 (1-\delta^2)}\cos\varphi\Big]. \quad (2)$$

Substitute $\varphi = 0$ into (2) in the case of $P'_{3_{max}}$ and $\varphi = 180°$ at $P'_{3_{min}}$, resulting in

$$R = \frac{\left[1+\sqrt{(1-\delta^2)(1-\Delta^2)} + \delta\cdot\Delta\right]^2}{(\Delta+\delta)^2}. \quad (3)$$

Here δ characterizes the actual asymmetry of the Y-junction and Δ gives the rate of input powers asymmetry: $P_1 = P_0(1+\Delta)$ and $P_2 = P_0(1-\Delta)$.

A Y-junction modulation capability is measured as shown in Fig. 5. Attenuator 1 in the first arm adjusts amplitude ratio P_1/P_2, while the variable phase shifter in the second arm sets the phase difference φ between input fields E_1 and E_2. The total interferometer insertion loss from point A to point B was measured for each φ. Attenuator 2 was readjusted to keep the output voltage of the detector 1 on a constant reference level.

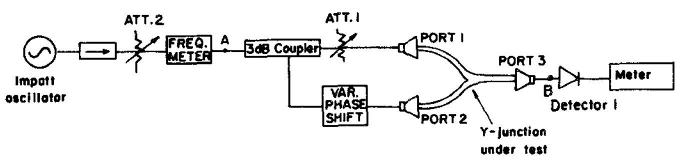

Fig. 5. Interferometer setup for the Y-branch modulator tests.

Further experiments contributed to better understanding of modulation and switching properties of the Y-branch. After adjusting attenuator 1 for equal powers in both branches, the output power P_3' was measured as a function of φ (Fig. 6, $\Delta = 0$). The R value was measured as 200 or 23 dB. For $\Delta = 0$, an absolute value of parameter $|\delta| = 0.1305$ was calculated from (3). The real value of δ will be negative ($\delta = -0.1305$), since tuning attenuator 1 down enhances the R value. In other words, 43 percent of the power incident at port 3 will be coupled to port 1 and the rest, 57 percent, to port 2.

According to (3), one may obtain theoretically unlimited R values, by making $\Delta = -\delta$. $\Delta = 0.1305$ was achieved when attenuator 1's reading was reduced by 1.15 dB. Corresponding test results (curve $\Delta = 0.1305$ in Fig. 6) show the enhancement of R to 36 dB, at least. The measurement of the actual R value was obscured by noise.

A phase shifter incorporating metal wall proximity to a dielectric guide was recently applied for electronically steerable dielectric antennas [8]. A trapezoidal metal plate used for phase shifting in the test setup (Fig. 7) provided gradual transition in the direction of propagation and reduction of reflections.

Attenuator 1 was set for $\Delta = -\delta = 0.1305$. Then the metal plate was brought in a distance d to the broad wall

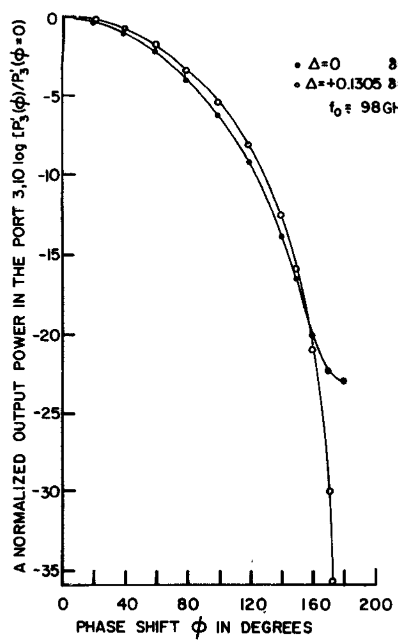

Fig. 6. The measured dependance of the arm 3 output power on the phase shift between two input arms.

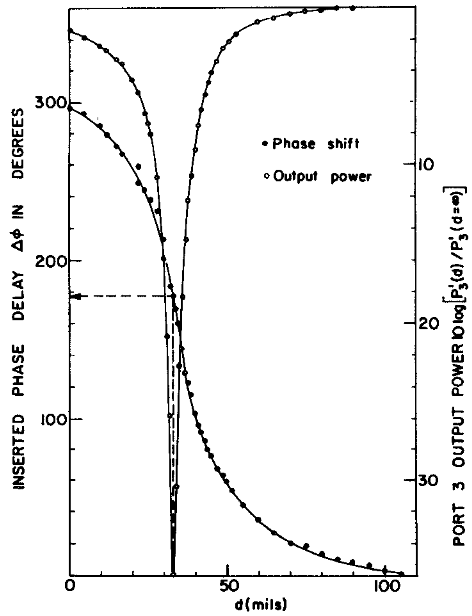

Fig. 8. Measured phase delay in the first branch due to metal plate proximity and the port-3 output power as a function of d.

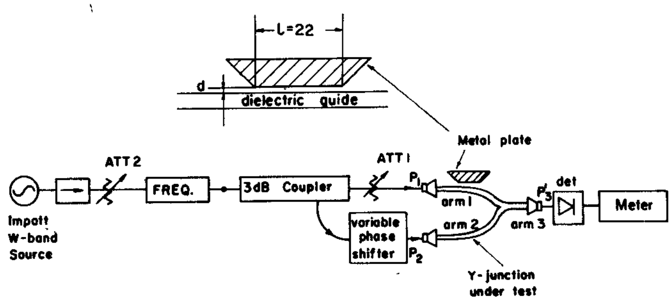

Fig. 7. A setup for the metal plate phase-shifting element tests.

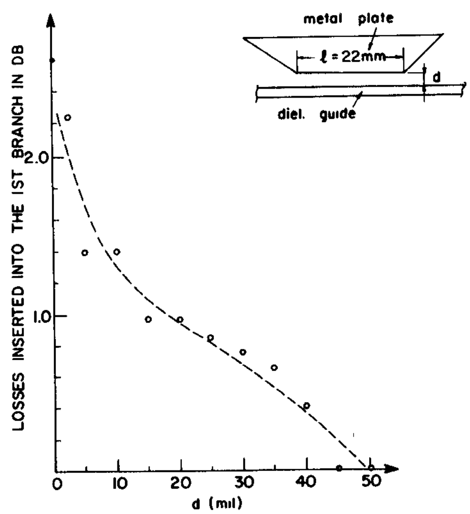

Fig. 9. Losses inserted in the first branch due to the metal plate proximity.

of the interferometer arm 1. This caused a phase delay in the arm 1, due to the increased propagation constant β. Fig. 8 presents the measured phase shift inserted into arm 1, and the port 3 output power as a function of gap width d. The maximum phase delay of 297° is observed at $d = 0$ and may be compared with the computed value

$$\Delta\varphi = l \cdot [\beta(d=0) - \beta(d=\infty)]$$

where $\beta(d=\infty)$ and $\beta(d=0)$ are propagation constants in isolated dielectric and image guides, respectively. The effective dielectric constant (EDC) method determining propagation constants gives

$$\Delta\varphi = 22\ (\text{mm}) \cdot [2.4929 - 2.1963]\ \text{rad/mm} = 375°$$

which is substantially higher than the measured value. This discrepancy may be attributed either to the air gap still existing between the plate and a guide at $d = 0$, or to the uncertainty of the ϵ_r value. As anticipated, the minimum of P_3' corresponds to a 180° phase delay.

The observed peak-to-valley ratio was $R = 36.0$ dB. The degradation of the R value as compared to the case where $\Delta = -\delta = 0.1305$ (Fig. 6) was caused by losses inserted into branch 1 due to the metal plate proximity. These measured losses are shown in Fig. 9 as the function of d. The 180° phase shifter inserts 0.7-dB losses in branch 1, which must be taken into account in power balance between branches in order to obtain optimal R values.

Finally, tests were performed on a completely dielectric Y-branch interferometer (see insert in Fig. 10) using the same trapezoidal metal plate ($l = 22$ mm) as a phase shifter in one of the interferometer arms. The 180° phase shift was obtained at $d = 32$ mils, which coincides with the results in Fig. 8. The observed R value was 36.5 dB. The phase shift of 360° obtained at $d = 0$ is in good agreement with the EDC calculated $\Delta\varphi = 375°$.

Fig. 10 illustrates some difficulties in fabrication of the mechanical switch. The gap width d required for device operation in the off-state dictates tolerances as high as a few mils. In contrast, electronically controled phase shifters

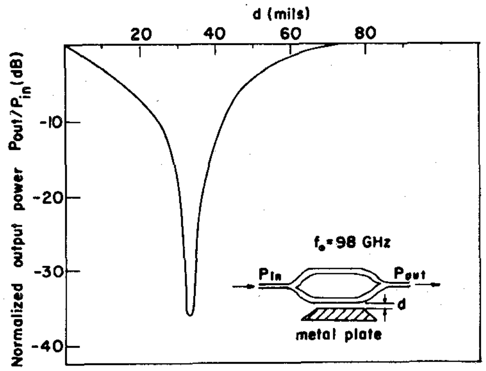

Fig. 10. Measured dependence of the Y-branch interferometer output power on the gap width d between the metal plate and the interferometer arm.

using either distributed p-i-n diodes or a plasma state in a semiconductor makes the whole construction rugged.

Let $\beta_1(f)$ and $\beta_2(f)$ be propagation constants of the dominant modes in an isolated dielectric guide and one with the proximate metallic plate, respectively. Then with d and l adjusted for a $180°$ phase delay at central frequency of f_0, the phase delay due to the metallic wall in the vicinity Δf of f_0, will be

$$\Delta\varphi(f_0+\Delta f) = [\beta_2(f_0+\Delta f) - \beta_1(f_0+\Delta f)]\cdot l$$

$$\doteq 180° + \left[\frac{\partial\beta_2}{\partial f} - \frac{\partial\beta_1}{\partial f}\right]_{f=f_0} \cdot l \cdot \Delta f.$$

Making slopes of dispersion curves $\beta_1(f)$ and $\beta_2(f)$ close to each other, one can achieve a high value of R over a wide frequency range.

For illustration, let us consider the phase shifter for the teflon 2×1-mm guide providing $\Delta\varphi = 180°$ at $f_0 = 98$ GHz under the $d = 0$ condition. The computed length l for the $180°$ phase shift is 10.6 mm. Assuming $\Delta = \delta = 0$, one can readily determine the minimum permissible switch on/off power ratio R_{min} from (2)

$$R_{min} = \frac{1}{1+\cos(180° + \Delta\varphi_{max})}$$

where $\Delta\varphi_{max}$ is a maximum deviation of the phase delay from the $180°$ value. For $R_{min} = 25$ dB, $\Delta\varphi_{max}$ is $6°30'$. On dispersion curves for the isolated guide (on-state) and image guide (off-state), such a $\Delta\varphi$ value corresponds to the points ± 2.7 GHz apart from f_0. The Y-branch interferometer (insert in Fig. 10), when adjusted for the minimum output power at $f_0 = 98$ GHz ($d = 32$ mils), exhibited R values better than 25 dB over the whole 98–104-GHz frequency range.

Obviously, the bandwidth may be expanded by widening the d gap required for the $180°$ delay.

IV. Conclusion

The experiments conducted in the course of this study allowed us to draw the following conclusions.

1) The DGY interferometer may be applied as a switching and modulating element for low-cost millimeter-wave integrated circuits.

2) A maximum-to-minimum switching ratio is theoretically unlimited for a given frequency. Even with the rough teflon interferometers, values as high as 36 dB at a single frequency and about 25 dB over a 98–104-GHz range were observed.

3) A DGY interferometer in combination with electronical phase shifters promises to be very useful electronically steerable modulators and switches.

4) The Y-junction may be applied for power splitting in millimeter-wave balanced mixers and antenna feeders.

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Alexander Axelrod (S'83) was born in Moscow, USSR, on June 18, 1947. He received the Engineer Diploma in electrical engineering from the Power Engineering Institute, Moscow, USSR, in 1971. He is currently working towards the Ph.D degree in the field of the millimeter-wave dielectric guide components at the Engineering Department of Tel-Aviv University, Israel.

From 1973 to 1975, he was employed at the Research Laboratory of the Moscow Communication Institute. During 1978–1981, he worked at Tadiran Electronics, Israel.

Moshe Kisliuk (M'76) received the Engineer Diploma from the Polytechnic Institute, Odessa, USSR, in 1950, and the Ph.D. degree from the Institute of Electrical Communications, Leningrad, USSR, in 1960, both in electrical engineering.

During 1950–1957, he worked as a Senior Engineer at a naval development office. In 1960, he was appointed Senior Lecturer, and in 1962, Associate Professor in the Department of Theoretical Electrical Engineering of the Institute of Electrical Communications, Leningrad, USSR, a position that he held until 1973. In 1975, he emigrated to Israel and joined the Tel-Aviv University, Ramat-Aviv, Israel, where he is currently an Associate Professor of Electrical Engineering. Since 1950, he has worked in different areas of electromagnetics, including static fields, waveguide components, coupled cavities and circuits, waveguide and cavity excitation, electric- and magnetic-field integral equations, and millimeter-wave components.