be obtained. Over the feedback configuration, the main advantages are the design simplicity and flexibility of output circuitry choice. Noise performance was observed to be comparable to the other two above-mentioned configurations.

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Coupling Between Microstrip Line and Image Guide Through Small Apertures in the Common Ground Plane

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***Abstract*—A design theory is described for coupling between microstrip line and image guide through small coupling holes in a common ground plane. A five-slot Chebyshev coupler is designed based on coupling through a rectangular slot. The theoretical results are compared with experimental results.**

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I. INTRODUCTION

During the past several years, much work has been done on the image guide for millimeter-wave circuit applications. Since the image guide is an open structure, any discontinuity created in it causes radiation loss. To minimize radiation in coupling structures, Solbach [1] proposed to locate coupling slots in the ground plane. In the present work, we study the coupling between an image guide and a microstrip line through slots in the common ground plane. This arrangement may be used for sampling the signal in the image guide, or for diverting a part of the power in the image guide into a solid-state device mounted in a microstrip circuit.

We have designed a 15-dB five-slot Chebyshev array coupler based on an approximate theory. The latter is essentially an application of the small-hole analysis found in a standard textbook [2]. This method has also been applied recently to the problem of coupling between two image guides through holes in a common ground plane [3]. Although we neglected radiation completely in the analysis, the measured properties of the directional coupler fabricated in accordance with the present theory have been found to agree well with theoretical predictions.

II. FIELDS IN WAVEGUIDE STRUCTURES

The coupling structure, shown in Fig. 1, consists of an image guide and a microstrip line on opposite sides of a ground plane. The coupling element is either a circular hole or a rectangular slot in the ground plane. The coordinate system is shown in Fig. 1(a) where the z direction is defined as the direction of propagation. Before studying the coupling problem, we obtain simplified expressions of the fields in both the image guide and the microstrip line. Specifically, the expressions developed by Marcatili [4] are used for the image guide, and those for the equivalent parallel-plate waveguide model are used for the microstrip line. Introduction of such "closed-form" expressions considerably simplifies the calculation of the coupling coefficients.

Under Marcatili's model, the transverse fields of the E_{11}^y mode are readily given. Here we present only those in the dielectric region ($|x| < a$, $-b < y < 0$ in Fig. 1(b))

$$\bar{E}_{yd}^{\pm} = \hat{y} E_0 \cos(k_x x) \cos(k_y y) \exp(\mp j k_{zd} z) \tag{1a}$$

$$\bar{H}_{xd}^{\pm} = \mp \hat{x} E_0 \frac{1}{\eta} \cos(k_x x) \cos(k_y y) \exp(\mp j k_{zd} z) \tag{1b}$$

$$\eta = \sqrt{\frac{\mu_0}{\epsilon_0}} \frac{k_0}{k_{zd}}$$

where superscripts "+" and "−" represent the propagation along the positive and negative z directions, respectively. $\hat{x}$ and $\hat{y}$ are the unit vectors in the x and y directions. k_x, k_y, and k_{zd} are the propagation constants in the x, y, and z directions, respectively. k_0 is the propagation constant in the free-space. ϵ_0 and μ_0 are the permittivity and permeability in free-space.

The equivalent waveguide model of the microstrip line is shown in Fig. 2. The effective width W' and the effective dielectric constant ϵ_{reff} are such that the TEM mode in the equivalent structure has the same characteristic impedance and phase velocity as the microstrip line. We make use of the expressions derived

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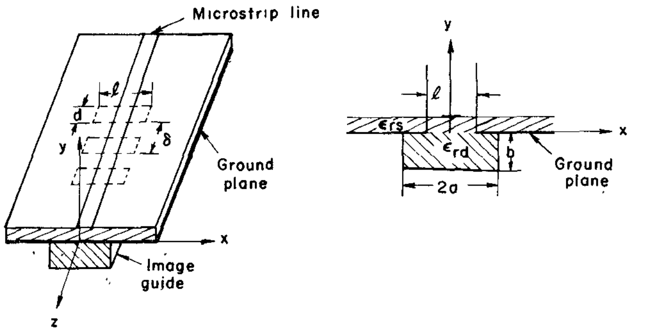
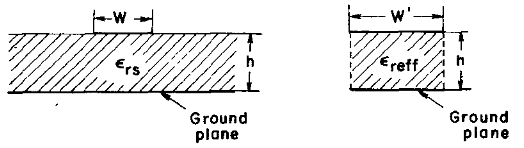


Fig. 1. (a) Slot coupling between a microstrip line and an image guide. (b) Cross-section of coupler between a microstrip line and an image guide.



(a) (b)

Fig. 2. (a) Cross-section of microstrip line. (b) Equivalent waveguide model for microstrip line.

by Schneider [5]

$$W' = \frac{h}{Z_0}\frac{120\pi}{\sqrt{\epsilon_{reff}}} \tag{2}$$

$$\epsilon_{reff} = \frac{\epsilon_{rs}+1}{2} + \left(\frac{\epsilon_{rs}-1}{2}\right)\left(1+10\frac{h}{W}\right)^{-1/2} \tag{3}$$

where ϵ_{rs} and h are the relative dielectric constant and the thickness of the substrate, and W is the width of the microstrip line, respectively. Z_0 is its characteristic impedance.

The TEM field components in the microstrip model can be expressed as follows [6]:

$$\overline{E}_{ys}^{\pm} = \hat{y}H_0\left(\frac{\lambda_{gs}}{\lambda}\right)\eta_0 \exp(\mp jk_{zs}z) \tag{4a}$$

$$\overline{H}_{xs}^{\pm} = \mp \hat{x}H_0 \exp(\mp jk_{zs}z) \tag{4b}$$

$$\lambda_{gs} = \frac{\lambda_0}{\sqrt{\epsilon_{reff}}} \qquad \eta_0 = 377\Omega$$

where λ_0 and λ_{gs} are the wavelength in the air and microstrip line, respectively. k_{zs} is the propagation constant in the z direction.

III. Coupling by a Single Rectangular Slot

Calculation of the coupling coefficient through a small slot essentially parallels the one used by a number of workers [2], [3], [7], [8]. Hence, we only present the outline of the method. Consider the case in which the dominant microstrip mode is incident from $z = -\infty$. The microstrip line is terminated by its characteristic impedance beyond the coupling slots. This field creates equivalent electric and magnetic dipole moments of the slot. They are given by [7]

$$\overline{P} = \frac{\epsilon_{rs}\epsilon_{rd}\epsilon_0}{\epsilon_{rs}+\epsilon_{rd}}[\tau]\cdot\overline{E}_{ys}^{+} \tag{5a}$$

$$\overline{M} = [\rho]\cdot\overline{H}_{xs}^{+} \tag{5b}$$

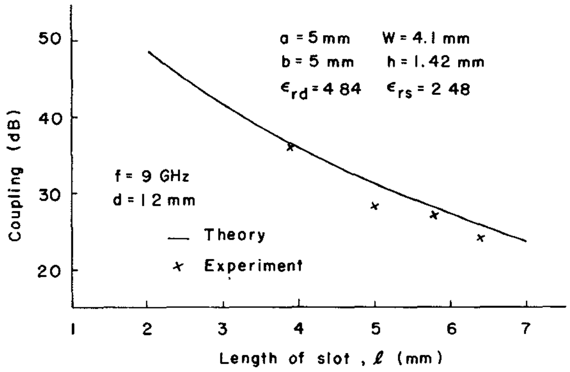


Fig. 3. Coupling between microstrip and image guide through a single rectangular slot in a common ground plane.

where the dyadics $[\tau]$ and $[\rho]$ for a small transverse slot are

$$[\tau] = \frac{\pi d^2 l}{12}\hat{y}\hat{y} \tag{6a}$$

$$[\rho] = (0.233dl^2 + 0.044l^3)\hat{x}\hat{x} + \frac{\pi d^2 l}{16}\hat{z}\hat{z}. \tag{6b}$$

These dipoles are considered to be the equivalent radiating sources which excite the image guide. The amplitude of the excited E_{11}^y image mode propagating in the positive z direction consists of portion A_1 due to the electric dipole, and portion B_1 due to the magnetic dipole. According to the reciprocity theorem [2], they are

$$A_1 = \frac{-j\omega}{P_n}\overline{E}_{yd}^{-}\cdot\overline{P} \tag{7a}$$

$$B_1 = \frac{j\omega\mu}{P_n}\overline{H}_{xd}^{-}\cdot\overline{M} \tag{7b}$$

where

$$P_n = 2\int\int \overline{E}_{yd}^{+}\times\overline{H}_{xd}^{+}\cdot\hat{z}\,ds.$$

The coupling coefficient may be defined as

$$C = -20\log|A_1 + B_1|. \tag{8}$$

Fig. 3 shows the computed and measured coupling coefficient as a function of the transverse size of a rectangular slot. The microstrip line is selected to have the characteristic impedance of 50 Ω. The effect of the ground plane thickness was not taken into account because the copper cladding of the microstrip substrate was less than 30 μm thick. The effect of the large size of the slot was considered by using a correction factor given in [3]. Agreement between the theoretical and the experimental results is good.

IV. Multi-Slot Directional Coupler

Good directivity and tight coupling over a wide band may be realized in a multi-slot coupler. Consider $N+1$ slots at equal intervals δ. The coupling and directivity are [2]

$$C = -20\log\left|\sum_{n=0}^{N} C_n\right| \tag{9a}$$

$$D = -C - 20\log|T_b| - 20\log F \tag{9b}$$

where C_n is the forward coupling coefficient of the nth slot. T_b is the collection of frequency-dependent parts of the backward

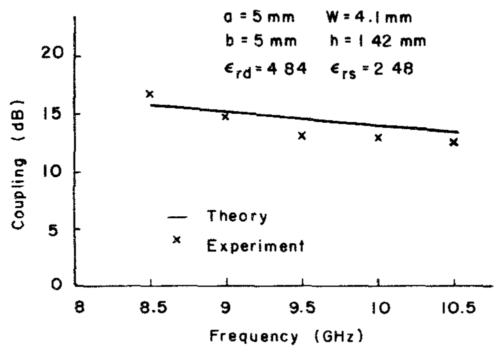


Fig. 4. Coupling characteristic versus frequency of a five-slot coupler.

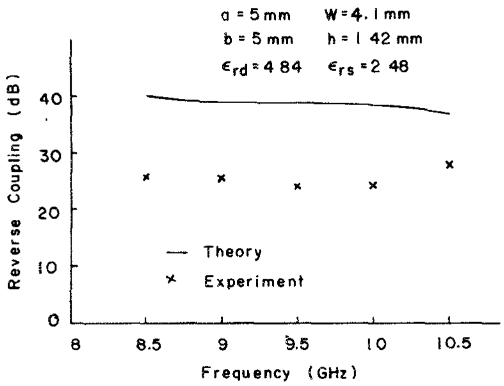


Fig. 5. Reverse coupling characteristics versus frequency of a five-slot coupler.

coupling coefficients of all of the slots. The array factor F is

$$F=\left|\sum_{n=0}^{M} 2d_n \cos(N-2n)\beta\delta\right|. \quad (10)$$

$M=(N-1)/2$ for N odd and $N/2$ for N even, where d_n is the frequency-independent part of the backward coupling coefficient of the nth slot, and β is the propagation constant.

Note that this theory assumes that the coupling at each slot is so small that the propagation constant and the wave amplitude are essentially unaffected. Also note that to apply this theory to the present arrangement we need to choose the propagation constant of the image guide equal to that of the microstrip line at the design frequency.

For the Chebyshev response, we choose

$$F=K|T_N(\sec\theta_m \cos\beta\delta)| \quad (11)$$

where $\sec\theta_m$ is the value of $\sec\beta\delta$ at the upper and lower edge of the passband, and K is chosen to give a desired value of coupling at the center frequency.

We have chosen δ such that $\beta\delta=\pi/2$ at 9 GHz and designed a 15-dB five-slot Chebyshev coupler. The interslot distance δ is 5.75 mm. The slot lengths are 3.9, 5.8, 6.9, 5.8, and 3.9 mm. The slot width d is 1.2 mm.

The frequency characteristics of the forward coupling is shown in Fig. 4. Agreement between computed and measured results is seen to be good. For the reverse coupling shown in Fig. 5, however, agreement is not as good as that of the forward coupling. The reason is conjectured to be the following. A matched load of 50 Ω is terminating the microstrip line by way of a microstrip-to-coaxial transition. Characteristics of the latter are less than desirable. Some reflection is generated which affects the reverse coupling much more than the forward coupling. Also, the manufacturing error, especially the distance δ, seems to affect the reverse coupling more strongly.

Radiation from the structure depends on several structural and material constants. Since the radiation from a single slot depends on the dielectric constant and the thickness of the dielectric rod [9], we selected the thickness to minimize radiation. It should also be noticed that since the spacing δ between the slots is chosen as $\lambda_g/4$, this quasi-periodic array is operating well below the frequency at which leakage radiation starts.

We measured the radiation from the structure by moving a waveguide horn around the image guide. The radiation was found to be less than -43 dB.

V. Conclusion

A design theory for directional hole coupling between an image guide and a microstrip line has been presented. It is based on a simplified theory and neglects radiation and attenuation effects. A five-slot coupler has been designed and constructed, and measured performance agreed well with the theory.

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