Excitation of Waveguide by Stripline- and Microstrip-Line-Fed Slots

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Abstract —This paper presents investigations on coupling between stripline/microstrip line and a rectangular waveguide coupled through a slot in the ground plane which is fixed in the cross-sectional plane of the waveguide. A closed-form expression for the impedance loading on stripline/microstrip line is evaluated from knowledge of the complex power flowing down the rectangular waveguide supporting the dominant mode and discontinuity in the modal voltage in stripline/microstrip line. The reactance cancellation is obtained by terminating the stripline/microstrip line exciting the slot in a short-circuited stub. The structure under this condition forms a transition between stripline/microstrip line and a waveguide. The design curves on slot length versus frequency are presented for different values of dielectric constants. The variation of coupling as a function of frequency and also the location of the slot is evaluated. Numerical results for slot coupling useful for the design of waveguide simulators are also presented.

I. INTRODUCTION

SOME INVESTIGATIONS on aperture coupling between stripline/microstrip line and waveguide through an aperture in the common wall have been reported [1]–[4]. Design of a multi-aperture directional coupler has also been carried out by Kumar and Das [5]. It is found that the coupling between the stripline and the waveguide attained in this process is limited to low values. In order to obtain higher coupling, the length of the coupling region becomes very large. The method of exciting a multimode guide through a stripline-fed slot in the transverse section of waveguide has recently been discussed in the literature [6]. The electric-field distribution required for the analysis has been obtained from conformal transformation in the case of a symmetric stripline and from the equivalent parallel-plate configuration in the case of a microstrip line. When an equivalent parallel-plate configuration is used in the case of microstrip line, the maximum dimension of the aperture is restricted. Evaluation of the electric-field distribution by the method of conformal transformation is quite involved in the cases of asymmetric stripline, symmetric and asymmetric striplines with partial dielectric filling, and microstrip line.

In the present work, excitation of a waveguide by stripline- and microstrip-line-fed slots in the transverse cross section of the waveguide is investigated. The field distribution required for the analysis of both stripline-fed and microstrip-fed slots is determined from one common general formulation. The impedance seen by the line exciting the waveguide is determined from the complex power flowing down the waveguide and the discontinuity in modal voltage in the stripline or microstrip line. The analysis is then extended to the case of a waveguide supporting TE_{10}, TE_{20}, TE_{30} modes for slot locations corresponding to eigen excitations of the form $(1/2, 1, 1/2)$, $(\sqrt{3}/2, 0, -\sqrt{3}/2)$ and $(1, -1, 1)$, when used in the construction of waveguide simulators [7]. Numerical results on the normalized resistance and the reactance are presented. Further, the effect of a reactive stub in the feedline terminating the slot is investigated. The results on coupling between the stripline/microstrip line and waveguide have also been evaluated. Finally, the design curves on slot length L for which the normalized resistance becomes unity are presented as a function of frequency for various values of dielectric constants.

II. GENERAL ANALYSIS

The method of exciting a rectangular waveguide by a slot, the center of which is located at (x_0, y_0) on the ground plane of a stripline, is shown in Fig. 1(a). The length of the slot is parallel to the x-axis. The analysis is carried out for the general case of a stripline having its center strip arbitrarily located parallel to the ground planes and embedded at the interface between the two different dielectric media.

The electric field in the cross section of the stripline/microstrip line can be expressed as [9]

$$\bar{E} = \bar{e}V \tag{1}$$

where $\bar{e}$ is the modal vector and V is the modal voltage satisfying the orthonormality condition

$$\int e^2 \, ds = 1$$

where ds represents the area of an infinitesimally small element in the cross section of the waveguide.

In Fig. 1(a), the coupling of the slot is transverse to the axis of the stripline. Using the formulas by Marcuvitz and Schwinger [13], it can be shown easily that such a slot produces discontinuity in the modal voltage, and the equivalent network of the slot appears as a series element in the transmission-line representation of Fig. 1(c). From a knowledge of this discontinuity in modal voltage ΔV, the

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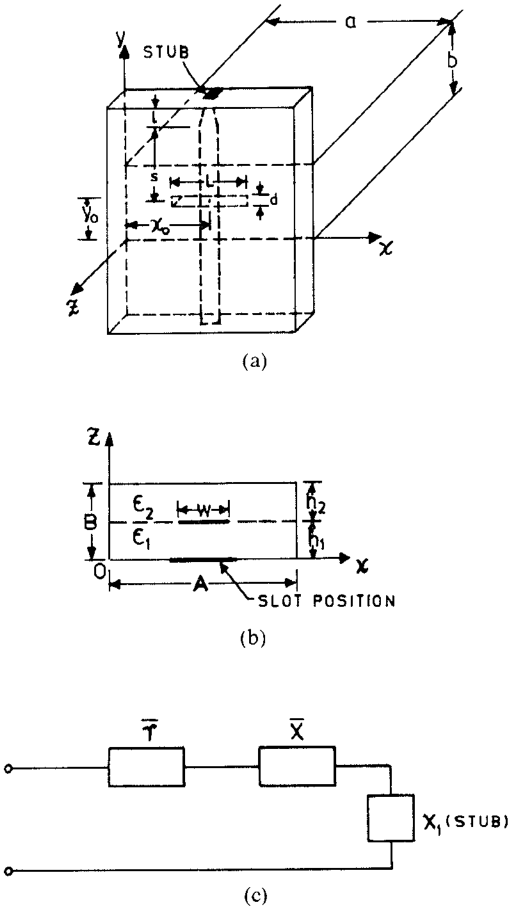

Fig. 1. Configuration of the excitation of a waveguide by a slot in the ground plane of the stripline. (b) Configuration of the stripline used for the determination of modal vector function. (c) Equivalent circuit of the stub-terminated feed arrangement.

normalized admittance loading on the stripline resulting from the power coupled to the waveguide is obtained from the relation

$$\bar{Y}=\frac{P}{Y_0(\Delta V)^2} \tag{2}$$

where Y_0 is the characteristic admittance of the stripline, ΔV is the discontinuity in modal voltage in the stripline, and P is the complex power flowing down the waveguide.

The electric-field distribution in the aperture plane of a slot exciting the guide is assumed to be of the form

$$E_y = E_0 \sin K\left(\frac{L}{2}-|x-x_0|\right) \tag{3}$$

where E_0 is the maximum value of the electric field in the aperture plane of the slot, L is the length of the slot, $K=(2\pi/\lambda_0)\sqrt{\epsilon_r'}$, and the expression for ϵ_r' is given by [8]

$$\epsilon_r'=\frac{2\epsilon_r}{1+\epsilon_r}$$

where ϵ_r' is the effective dielectric constant and ϵ_r is the relative dielectric constant of the medium filling the region between the ground planes of the stripline.

The electric field in the coupling aperture given by (3) excites the TE to x mode in the waveguide, which can be expressed as the superposition of TE and TM modes [9].

The modal amplitudes of the TE_{mn}-mode fields excited in the rectangular waveguide of Fig. 1(a) can be obtained from the formula [9]

$$E_{mn}=\frac{2\mathscr{E}_n}{ab}\iint_{\text{slot}} E_y \sin\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)dx\,dy \tag{4}$$

where

$$\mathscr{E}_n = 1 \quad \text{for } n=0$$
$$= 2 \quad \text{for } n>0.$$

The complex power in the waveguide is given by [9]

$$P=\iint_{z=0}\bar{u}_z\cdot\bar{E}\times\bar{H}^*\,ds \tag{5}$$

where $\bar{u}_z$ is the unit vector along the axis of the waveguide. Substituting (3) in (4) and using (5), an expression for the complex power in the waveguide is obtained as

$$P=\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}(Y_0)^*_{mn}\frac{8\mathscr{E}_n}{ab}V_0^2K^2\left[\frac{\sin\frac{n\pi d}{2b}}{\frac{n\pi d}{2b}}\right]^2 \cdot\cos^2\frac{n\pi y_0}{b}\cdot\sin^2\frac{m\pi x_0}{a} \cdot\left[\frac{\cos\frac{KL}{2}-\cos\frac{m\pi L}{2a}}{\left(\frac{m\pi}{a}\right)^2-K^2}\right]^2 \tag{6}$$

with

$$(Y_0)^*_{mn}=j\frac{\omega^2\mu\epsilon-\left(\frac{m\pi}{a}\right)^2}{\omega\mu\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2-\omega^2\mu\epsilon}}$$

where d is the width of the slot, V_0 is the maximum voltage across the slot, $E_0 d$, a and b are the broad and narrow dimensions of the waveguide, and μ and ϵ are, respectively, the permeability and permittivity of the medium inside the waveguide. Since the waveguide is airfilled, the values of μ and ϵ are assumed to be the same as those of free space. The expression for the modal vector function required for the evaluation of discontinuity in the modal voltage in the structure of Fig. 1(b) having the slot in its ground plane is derived from the potential function. Assuming that the charge distribution in the center strip is of the form

$$\rho(x)=\frac{\rho_0}{\sqrt{1-\left[\frac{2}{W}\left(x-\frac{A}{2}\right)\right]^2}},$$
$$\left(\frac{A}{2}-\frac{W}{2}\right)\leqslant x\leqslant\left(\frac{A}{2}+\frac{W}{2}\right)=0, \quad \text{otherwise.}$$

Following the method suggested by Yamashita and Atsuki [10], the expression for the potential function $\Phi(x,z)$ for the TEM-mode field is obtained as

$$\Phi(x,z) = \sum_{n=1,3,5}^{\infty} \frac{W\pi\rho_0}{n\pi\epsilon_0\Delta_n}\cdot J_0\left(\frac{n\pi W}{2A}\right)\sin\left(\frac{n\pi}{2}\right) \cdot \sinh\left(\frac{n\pi h_2}{A}\right)\sin\left(\frac{n\pi x}{A}\right)\sinh\left(\frac{n\pi z}{A}\right), \quad 0 \leqslant z \leqslant h_1$$

$$= \sum_{n=1,3,5}^{\infty} \frac{W\pi\rho_0}{n\pi\epsilon_0\Delta_n} J_0\left(\frac{n\pi W}{2A}\right)\sin\left(\frac{n\pi}{2}\right) \cdot \sinh\left(\frac{n\pi h_1}{A}\right)\cdot\sin\left(\frac{n\pi x}{A}\right)\cdot\sinh\left[\frac{n\pi}{A}(B-z)\right], \quad h_1 \leqslant z \leqslant B$$

where J_0 indicates the Bessel function of zeroth order, and

$$\Delta_n = \epsilon_1 \cosh\left(\frac{n\pi h_1}{A}\right)\sinh\left(\frac{n\pi h_2}{A}\right) + \epsilon_2\cosh\left(\frac{n\pi h_2}{A}\right)\cdot\sin\left(\frac{n\pi h_1}{A}\right).$$

Following the method suggested by Harrington, the modal vector function $\bar{e}$ appearing in (1) can be found for the TEM mode from the relation

$$\bar{e} = -\nabla_t \Phi$$

where ∇_t is the derivative operator in the cross section perpendicular to the axis of the line, Φ in the potential function for the TEM mode.

The expression for the normalized modal vector function $\bar{e}$ for the electric field is obtained as

$$\bar{e} = -\sum_{n=1,3,5}^{\infty} \frac{\sqrt{2\pi}}{AR\Delta_n} J_0\left(\frac{n\pi W}{2A}\right) \cdot \sin\left(\frac{n\pi}{2}\right)\sinh\left(\frac{n\pi h_2}{A}\right) \cdot\left[\cos\left(\frac{n\pi x}{A}\right)\sinh\left(\frac{n\pi z}{A}\right)\bar{u}_x + \sin\left(\frac{n\pi x}{A}\right)\cosh\left(\frac{n\pi z}{A}\right)\bar{u}_z\right], \quad 0 \leqslant z \leqslant h_1 \qquad (7a)$$

$$= -\sum_{n=1,3,5}^{\infty} \frac{\sqrt{2\pi}}{AR\Delta n} J_0\left(\frac{n\pi W}{2A}\right) \cdot \sin\left(\frac{n\pi}{2}\right)\sinh\left(\frac{n\pi h_1}{A}\right) \cdot\left[\cos\frac{n\pi x}{A}\sinh\left(\frac{n\pi}{A}(B-z)\right)\bar{u}_x - \sin\left(\frac{n\pi x}{A}\right)\cdot\cosh\left(\frac{n\pi}{A}(B-z)\right)\bar{u}_z\right], \quad h_1 \leqslant z \leqslant B \qquad (7b)$$

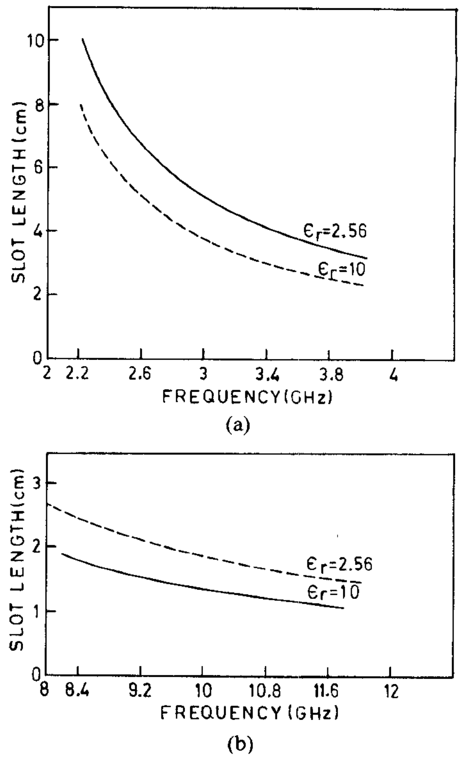

Fig. 2. The variation of resonant slot length as a function of frequency with the dielectric constant of the substrate as a parameter.

where

$$R^2 = \sum_{n=1,3,5}^{\infty} \frac{1}{n} \frac{J_0^2\left(\frac{n\pi W}{2A}\right)\left[\coth\left(\frac{n\pi h_1}{A}\right)+\coth\left(\frac{n\pi h_2}{A}\right)\right]}{\left[\epsilon_1\coth\frac{n\pi h_1}{A}+\epsilon_2\coth\frac{n\pi h_2}{A}\right]^2}.$$

After obtaining the relation for the normalized modal vector function $\bar{e}$, the discontinuity in modal voltage in the stripline due to the slot cut on its ground plane can be determined from [8]

$$\Delta V = \iint_{\text{slot}} \bar{n}\times\bar{E}^s\cdot\bar{h}\cos\beta y\, ds \qquad (8)$$

where β is the phase constant in the y direction, $\bar{E}^s$ is the electric-field distribution in the aperture plane of the slot, and $\bar{h}$ is the normalized transverse modal vector function for the magnetic field of the dominant TEM mode in the stripline, which is related to the normalized modal vector function $\bar{e}$ for the electric field by the relation [9]

$$\bar{h} = \bar{u}_y \times \bar{e}. \qquad (9)$$

Using (7a), (8), and (9), and taking the effect of asymmetry into account, an expression for the discontinuity in the modal voltage for a slot in the lower ground plane of the stripline ($z=0$) is found to be of the form

$$\Delta V = V_0 \sum_{n=1,3,5}^{\infty} \frac{\sqrt{2\pi}}{AR\Delta_n} J_0\left(\frac{n\pi W}{2A}\right) \cdot\sinh\left(\frac{n\pi h_2}{A}\right) K\left[\frac{\cos\frac{KL}{2}-\cos\frac{n\pi L}{2A}}{\left(\frac{n\pi}{A}\right)^2-K^2}\right]. \qquad (10)$$

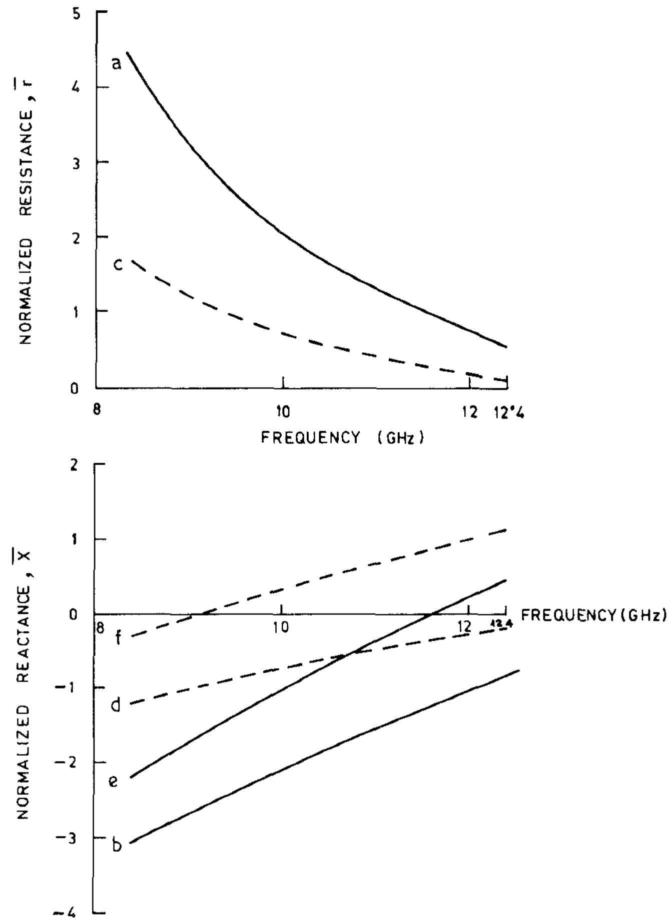

Fig. 3. Variation of normalized resistance and reactance loading on the stripline/microstrip line with frequency (X-band).

Curve	Description
a, b	Impedance seen by a microstrip line without a stub in the feedline.
c, d	Impedance seen by a stripline without a stub in the feedline.
e	Reactance seen by a microstrip line, with a stub in the feedline.
f	Reactance seen by a stripline with a stub in the feedline.

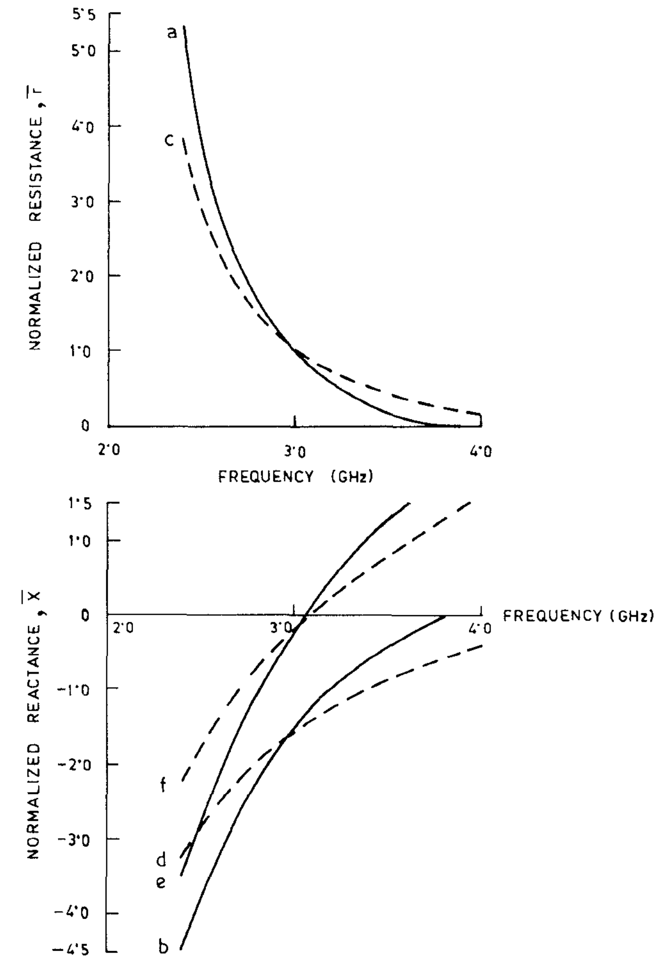

Fig. 4. Variation of normalized resistance and reactance loading on the stripline/microstrip line with frequency (S-band).

Curve	Description
a, b	Impedance seen by a microstrip line without a stub in the feedline.
c, d	Impedance seen by a stripline without a stub in the feedline.
e	Reactance seen by a microstrip line, with a stub in the feedline.
f	Reactance seen by a stripline with a stub in the feedline.

III. Evaluation of Normalized Slot Admittance

The normalized admittance presented to the stripline by the slot located at a position (x_0, y_0) in the cross section of the waveguide and radiating into the guide is given by

$$\bar{Y} = \bar{g} + j\bar{b} = \frac{1}{\bar{z}} = \frac{1}{\bar{r} + j\bar{X}} = \frac{P_r + jP_i}{Y_0(\Delta V)^2}. \tag{11}$$

P_r is evaluated for $n = 0$ and $m = 1$ and P_i is calculated for the other values of m and n in a single-mode guide. For the multimode guide supporting TE_{10}, TE_{20}, and TE_{30} modes, P_r is evaluated for $n = 0$ and $m = 1$, 2, 3, and P_i is calculated for the other values of m and n.

Using (6), (10), and (11), the slot length L, which offers a resistive part of the impedance equal to 50 Ω ($\bar{r} = 1$), has been calculated for different frequency bands (S and X) for the structure having a slot in the ground plane of a stripline exciting the rectangular waveguide when the dielectric constant ϵ_r filling the stripline is 2.56 and 10. The design curves on this slot length L versus frequency are presented in Fig. 2.

After selecting the slot length, corresponding to a particular frequency f_d, the variation of both $\bar{r}$ and $\bar{X}$ as a function of frequency for $Y_0 = 0.02$ mhos is obtained using (6), (10), and (11) for the following cases.

Case 1. Impedance loading due to the slot in the ground plane of symmetric stripline at X-band with $A/B = 10$, $\epsilon_1 = \epsilon_2 = 2.56$, $f_d = 9.375$ GHz, $a = 2.286$ cm, $b = 1.016$ cm, $x_0 = 1.143$ cm, $y_0 = 0.508$ cm, $d = 0.1$ cm, and $L = 2.0516$ cm. The results for this case are presented in Fig. 3.

Case 2. Impedance loading on the microstrip line exciting a single-mode guide through a slot in the ground plane at X-band with $A = 10$ cm, $\epsilon_1 = 2.56$, $\epsilon_2 = 1$, $h_2 = \infty$, $d = 0.1$ cm, $f_d = 11.5$ GHz, $a = 2.286$ cm, $b = 1.016$ cm, $x_0 = 1.143$ cm, $y_0 = 0.508$ cm, and $L = 2.0908$ cm. The results on $\bar{r}$ and $\bar{x}$ for this case are also presented in Fig. 3.

Case 3. Impedance loading due to the slot in the ground plane of symmetrics stripline at S-band with $A/B = 25$,

$\epsilon_1 = \epsilon_2 = 2.56$, $f_d = 3$ GHz, $d = 0.1$ cm, $a = 7.214$ cm, $b = 3.404$ cm, $x_0 = 3.607$ cm, $y_0 = 1.702$ cm, and $L = 5.14065$ cm. The results on normalized impedance are given in Fig. 4.

Case 4. Impedance loading on the microstrip line exciting a single-mode guide through a slot in the ground plane at S-band with $A = 10$ cm, $\epsilon_1 = 2.56$, $\epsilon_2 = 1$, $h_2 = \infty$, $d = 0.1$ cm, $f_d = 3$ GHz, $a = 7.214$ cm, $b = 3.404$ cm, $x_0 = 3.607$ cm, $y_0 = 1.702$ cm, and $L = 6.8184$ cm. The plots on impedance of slot for this case are in Fig. 4.

IV. The Effect of a Reactive Stub in the Feedline Terminating the Slot on the Impedance Seen by the Feedline

It is found from the results presented in Figs. 3 and 4 that the imaginary parts of the impedance seen by the stripline and microstrip line do not become zero in the frequency range of interest. It is possible to cancel the reactive parts of these impedances by terminating the stripline and microstrip line feeding the slot in a stub. The length of the stub becomes shorter if an exponentially tapered line is used as a stub. The expression for the reactance X_1 due to the stub is given by [12]

$$X_1 = \omega L_1 = \frac{K_{01}}{\dfrac{1}{\beta l} - 0.5\left(\dfrac{\delta}{\beta}\right)}, \qquad -2 \leqslant \delta/\beta \leqslant +2$$

where K_{01} is the impedance level of the line at $y = y_0$, l is the length of the line, β is the propagation constant, and δ is the rate of the taper. δ/β is positive when the impedance level changes from a lower value to a higher value from the input end to the short-circuited end of the stub. In the other case, δ/β is negative. The modified reactances in presence of the stub are shown in Fig. 3 as curves (f) and (e) for $l = 3$ mm, and $\delta/\beta = 0.1$ for an X-band waveguide. The modified reactances in presence of the stub are shown in Fig. 4 as curves (f) and (e) for $l = 10$ mm and $\delta/\beta = 0.5$ for an S-band waveguide.

V. Estimation of Coupling in the Presence of a Stub Termination

The reflection coefficient at the slot location because of the impedance seen by the slot into the waveguide when the slot is terminated by the reactive stub is given by

$$\tau = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{12}$$

where Z_L is the effective impedance offered by the slot in the presence of a stub and Z_0 is the characteristic impedance of the feedline.

Assuming the losses are negligible, the coupling in decibels between the feedline and waveguide is calculated from

$$\bar{c} = 10 \log_{10}(1 - |\tau|^2). \tag{13}$$

Using (12) and (13) and the data of curves (c) and (f) of Fig. 3, the variation of coupling between a symmetric stripline and an X-band waveguide, as a function of

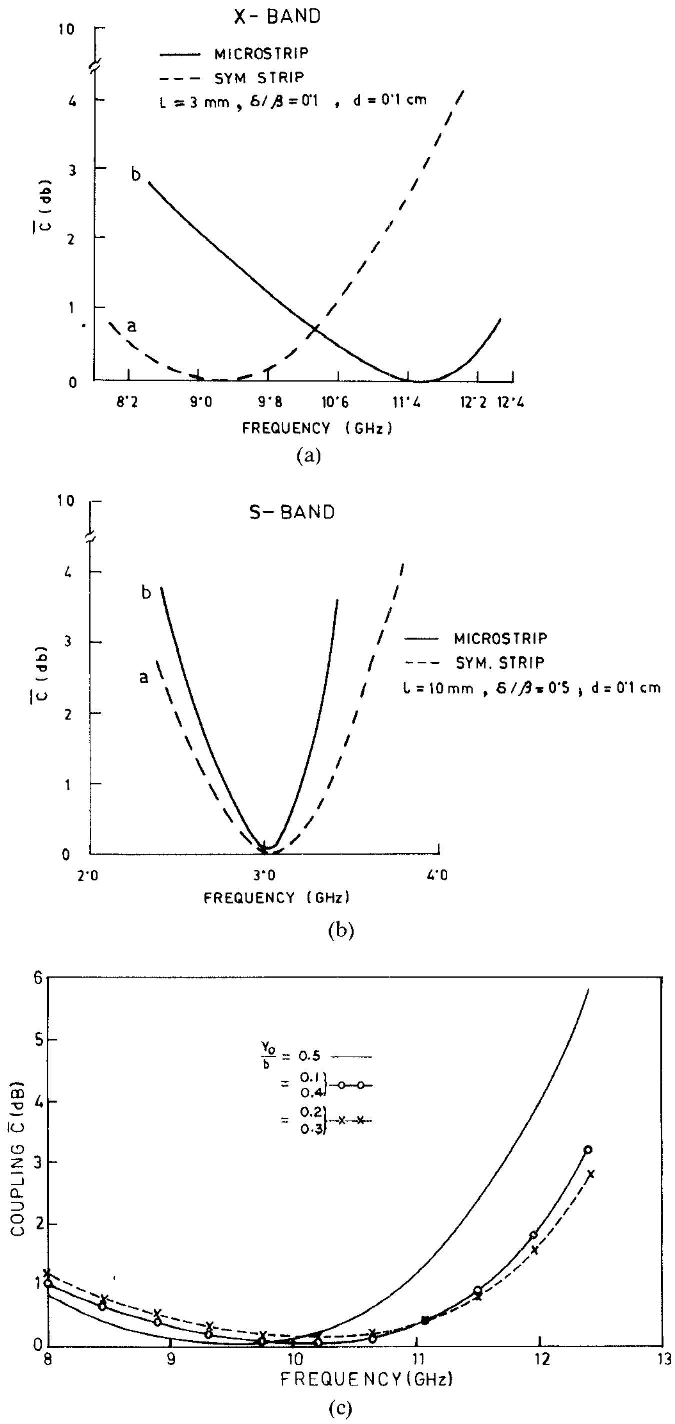

Fig. 5. (a) Variation of coupling in decibels as a function of frequency (X-band).

curve	Description
a	Stripline-fed waveguide slot with a stub in the feedline.
b	Microstrip-fed waveguide slot with a stub in the feedline.

(b) Variation of coupling in decibels as a function of frequency (S-band).

Curve	Description
a	Stripline-fed waveguide slot with a stub in the feedline.
b	Microstrip-fed waveguide slot with a stub in the feedline.

(c) Variation of coupling as a function of frequency for different values of slot offset positions.

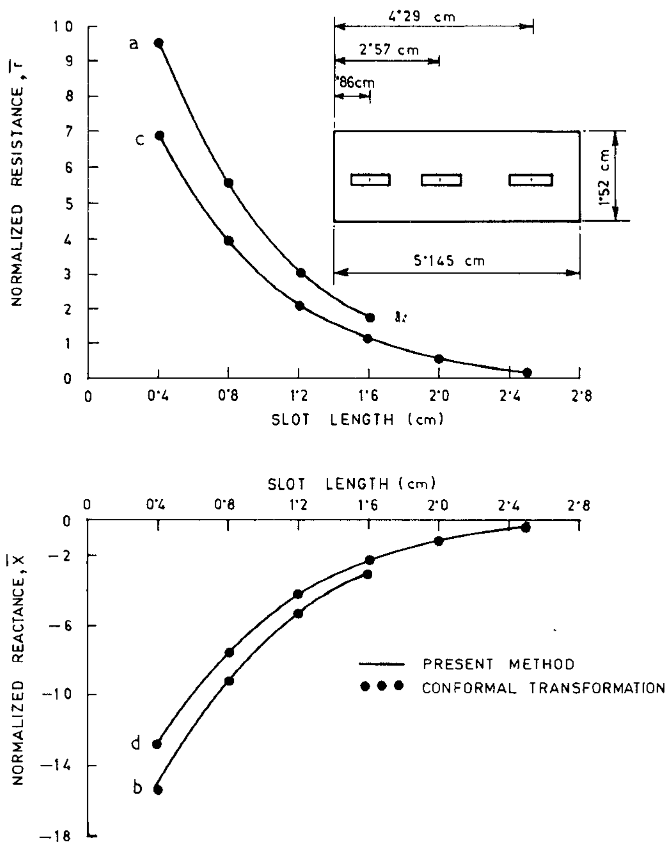

Fig. 6. Variation of normalized resistance and reactance seen by a stripline feeding a multimode guide as a function of slot length.

Curve	Description
a, b	$x_0 = 0.86$ cm, $x_0 = 4.29$ cm, and $y_0 = 0$
c, d	$x_0 = 2.57$ cm and $y_0 = 0.0$.

frequency, is computed and the results are presented as curve (a) in Fig. 5(a). The corresponding variation of coupling between a microstrip line and a rectangular waveguide is presented as curve (b) of Fig. 5(a).

Using (12) and (13) and the data of curves (c) and (f) of Fig. 4, the variation of coupling between a stripline and an S-band guide, as a function of frequency, is evaluated and the results are presented as curve (a) of Fig. 5(b). The corresponding results for coupling between a microstrip line and an S-band guide as a function of frequency is computed and the results on coupling are presented as curve (b) of Fig. 5(b).

The effect of the slot location in the y-direction on coupling has also been estimated at X-band for the case of coupling between stripline and the waveguide. The results on coupling as a function of frequency (X-band) for various locations of the slot in the y-direction have been presented in Fig. 5(c).

VI. Excitation of Multimode Guide by a Slot in the Ground Plane of Symmetric Stripline

The normalized impedances of three slots a', b', c' arranged in the cross section of the multimode guide, shown as the onset in Fig. 6, are evaluated. The locations of the centers of the slot are $x_0 = 0.86$ cm, 2.57 cm, and 4.29 cm, and $y_0 = 0.76$ cm for each x_0. The locations of the slots correspond to eigen excitations of the form $(1/2, 1, 1/2)$, $(\sqrt{3}/2, 0, -\sqrt{3}/2)$, and $(1, -1, 1)$ in the waveguide simulator, where these arrangements are used. For the multimode guide supporting TE_{10}, TE_{20}, TE_{30} modes, the waveguides dimensions are $a = 5.145$ cm, $b = 1.52$ cm. The normalized impedances are evaluated using (6), (10), and (11) for the above values of x_0 and y_0 and $\epsilon_1 = \epsilon_2 = 2.56$, $A/B = 25.0$, frequency $= 9.375$ GHz, $d = 0.1$ cm, $y_0 = 0.02$ mho, as a function of length of the slot. The results are presented in Fig. 6. The numerical results obtained from conformal transformation [6] are also presented in the same figure for the sake of comparison.

VII. Discussions

The investigations reported in this paper have thrown a new light regarding the realization of a transition between a stripline/microstrip line and a rectangular waveguide. The reactive stub is used to tune out the reactance at the position of the slot. Such a configuration can provide very strong coupling. It is found from the results presented in Figs. 5 and 6 that the values of coupling of the order of 0 dB can be achieved using the structure shown in Fig. 1. It is worthwhile to point out that, in the case of a symmetric T junction, the highest value of coupling is limited to 3 dB only.

It is found from the results presented in Fig. 5(a) that for a stub-terminated slot of length 2.055 cm, the coupling between a symmetric stripline and a single-mode X-band waveguide is nearly 0 dB over a frequency band of 9.0 to 9.6 GHz, centered at 9.3 GHz. For the same arrangement, the coupling is within 1 dB over a frequency range of about 2.5 GHz. For a microstrip line coupled to a single-mode X-band guide, the coupling is nearly 0 dB over a frequency range 0.54 GHz, centered at 11.5 GHz for a slot length equal to 2.09 cm. The coupling is found to be within 1 dB over a frequency range of about 2.5 GHz.

In the case of an S-band guide and a symmetric stripline, the coupling is nearly 0 dB over a frequency band of 2.9–3.2 GHz, and it is within 1 dB over a frequency range 0.74 GHz for a slot length equal to 5.14 cm. For coupling between a microstrip line and an S-band guide, the coupling is nearly 0 dB over a frequency band of 0.1 GHz, centered at 3.0 GHz, and it is within 1 dB over a frequency range of 0.46 GHz for a slot length equal to 6.818 cm.

In order to study the effect of slot location in the y-direction, (13) is evaluated for the values of $y_0/b = 0.1$, 0.2, 0.3, 0.4, and 0.5, and the results are plotted in Fig. 5(c). From the computed results, it is found that the coupling for $y_0/b = 0.1$ and $y_0 = 0.4$ are identical. Further, coupling for $y_0/b = 0.2$ and 0.3 are also found to be identical. As the slot is displaced from the symmetric location, it is observed that for frequencies higher than the resonant frequency, the coupling first increases with a change in displacement from the symmetric location and then decreases. For frequencies lower than the resonant point, the coupling decreases with a change in position of slot from a symmetric location and again increases. Results of Fig. 5(c) reveal that coupling varies between 0 and 0.5 dB over a frequency range of 8.375 GHz to 10.5 GHz for $y_0/b = 0.5$, 8.75 GHz to 11.125 GHz for $y_0/b = 0.1$, 0.4, and 9 GHz to 11.25 GHz for $y_0/b = 0.2$ and 0.3.

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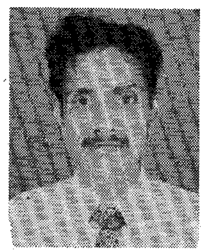

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