Analysis of Cascaded Sections of T Junctions Between Rectangular and Circular Waveguides

B. N. Das and P. V. D. Somasekhar Rao

Abstract —**This paper presents an analysis of the cascaded sections of a number of slot-coupled T junctions between rectangular and circular waveguides taking into account the mutual interactions of all possible modes generated by the discontinuities, as well as the effect of wall thickness. The formulation is based on solving a set of coupled integral equations resulting from the boundary conditions at the two interfaces of the waveguide sections representing the coupling slots. The integral equations are transformed into sets of matrix equations using the moment method with entire basis and testing functions. Numerical results on input VSWR and coupling are presented for the case of cascaded section of two air-filled T junctions for different frequencies and different values of interelement spacing.**

I. Introduction

The use of special types of T junctions for the suppression of cross-polarized radiation has been suggested in the literature [1], [2]. Conventional junctions [3] can also be used for the excitation of a large number of radiators. In order to produce a narrow beam, a number of such junctions are cascaded. The performance characteristics of cascaded junctions can be determined by following the methods suggested in the literature [4]–[6]. In these methods, interactions between the junctions have been taken into account considering the effect of only the dominant mode. In addition, the effect of the thickness of the waveguide wall, in which the slots are cut, has not been taken into account.

In the present paper, general formulas are derived for determining the performance characteristics of cascaded sections of slot-coupled T junctions between rectangular and circular waveguides, taking into account the effect of wall thickness and also the mutual interactions of all higher order modes generated because of the presence of discontinuities. A moment method with entire sinusoidal basis and testing functions [7], [8] is used for the determination of the amplitude coefficients of the field distribution in the aperture plane of the coupling slot. Expressions for the input reflection coefficient and the transmission and coupling coefficients into each junction are derived in terms of the amplitude coefficients.

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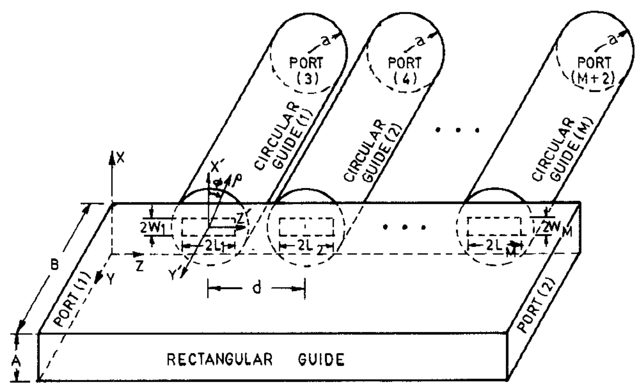

Fig. 1. Cascaded sections of T junctions between rectangular and circular waveguides.

Numerical results on coupling and input VSWR are presented for a cascaded section of two junctions between rectangular and circular waveguides as a function of frequency and also as a function of interelement spacing.

II. Analysis

Fig. 1 shows M cascaded sections of identical T junctions between rectangular and circular waveguides. The coupling elements between the exciting rectangular guide and the coupled circular guides are collinear longitudinal rectangular slots, of length $2L_J$ and width $2W_J$ $(J = 1,2,\cdots,M)$, centered in the narrow wall of the rectangular guide. The spacing between the symmetrical planes of successive junctions is equal to d. Excitation is applied to port (1) of the rectangular guide, and the other ports are assumed to be terminated in match loads.

The slots milled in a waveguide wall of finite thickness t are treated as short sections of rectangular waveguides (slot waveguides) [7], [8]. An expanded view of the geometry of the slot waveguide representation of the coupling slots is shown in Fig. 2. The rectangular waveguide–slot waveguide interface and the slot waveguide–circular waveguide interface of each junction are designated as the lower interface and the upper interface respectively.

Considering the fields scattered by the coupling slots in the junctions preceding and following any Jth slot waveguide, the field in the slot aperture at the lower interface of

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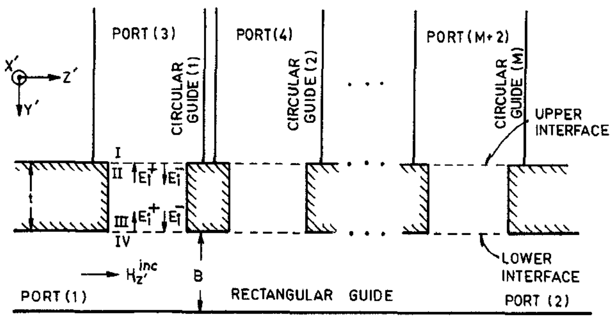

Fig. 2. Expanded view of the coupling slots represented as sections of rectangular waveguides.

the Jth slot waveguide is expressed as

$$\sum_{k=1}^{M} H_{Z'}^{rJk}(P_J;P_k'')$$

where $J=1,2,\cdots,M$ and the pair $(P_J;P_k'')$ represents the field and source points respectively at the Jth and kth slot apertures of Fig. 2.

A dominant mode incident field from port (1) of the rectangular waveguide will excite a number of modes in the slot waveguide [7], [8]. For an incident ith mode in the Jth slot waveguide, the boundary conditions at the two interfaces are of the form

$$H_{Z'}^{cJ}\left(E_i^{+(J)}e_i\right)+H_{Z'}^{cJ}\left(E_q^{-(J)}e_q\right)=E_i^{+(J)}e_iY_i-\sum_{q=1}^{N}E_q^{-(J)}e_qY_q \quad \text{at upper interface} \quad (1)$$

$$H_{Z'}^{rJ}\left(E_i^{-(J)}e_i\right)+H_{Z'}^{rJ}\left(E_q^{+(J)}e_q\right)+\sum_{\substack{k=1\\k\neq J}}^{M}H_{Z'}^{rJk}\left(E_Q^{\mathrm{Lo},(k)}e_Q\right)+H_{Z'}^{\mathrm{inc},J}=-E_i^{-(J)}e_iY_i+\sum_{q=1}^{N}E_q^{+(J)}e_qY_q \quad \text{at lower interface} \quad (2)$$

where $E_q^{\pm(J)}$ and $E_i^{\pm(J)}$ are the amplitude coefficients and the superscripts + and − indicate the directions of propagations shown in Fig. 2. $H_{Z'}^{\mathrm{inc},J}$ is the dominant mode longitudinal component of the incident magnetic field at the Jth slot in the rectangular waveguide. $E_Q^{(k)}$ denotes the amplitude coefficient and e_Q represents the Qth basis function ($Q=1,2,\cdots,N$) in the aperture field expansion of the Kth slot.

The slot field distribution for any Jth slot is expanded in terms of entire sinusoidal basis functions $e_q(Z')$ as

$$E_{X'}^{(J)}=\sum_{q=1}^{N}E_q^{(J)}e_q^{(Z')}=\sum_{q=1}^{N}E_q^{(J)}\sin\frac{q\pi}{2L_J}\{Z'-(J-1)d+L_J\}$$

$$\text{for}\left[\begin{matrix}(J-1)d-L_J\le Z'\le(J-1)d+L_J\\ -W_J\le X'\le W_J\end{matrix}\right]. \quad (3)$$

Here e_Q and e_i are of the same form as e_q, and $Y_g(g=q,i)$ is the modal admittance for the TE_{g0} mode in the slot guide [7], [8]. The summation over k ($k\neq J$) represents the mutual coupling effects due to all the other slots, the superscript "Lo" indicates the lower interface and $E_Q^{\mathrm{Lo}(k)}$ denotes the amplitude coefficient in the aperture field expansion at this interface for the kth slot. The quantities q, Q, and i vary from 1 to N, where N is the number of basis functions considered in the expansion of the electric field.

$H_{Z'}^{cJ}$ is the transverse component of the magnetic field in the Jth circular waveguide due to the electric field in the slot aperture at the upper interface, and $H_{Z'}^{rJ}$ is the longitudinal component of the magnetic field in the rectangular waveguide due to the electric field in the Jth slot aperture at the lower interface.

Equations (1) and (2) represent a pair of coupled integral equations for any Jth slot, and as J is varied from 1 to M, M pairs of such coupled integral equations are obtained. Taking the inner products of each pair of such equations with the corresponding testing functions $w_s^{(J)}$, given by

$$w_s^{(J)}=\sin\frac{s\pi}{2L}\{Z'-(J-1)d+L_J\} \quad (4)$$

and applying superposition for N modes in the slot waveguide, the integral equations are transformed into matrix equations of the form [7], [8]

$$[E^{-(J)}]_{\mathrm{II}}=[R^{cJ}][E^{+(J)}]_{\mathrm{II}} \quad \text{at upper interface}$$

$$[E^{+(J)}]_{\mathrm{III}}=[R^{rJ}][E^{-(J)}]_{\mathrm{III}}-[Y^{rJw}]^{-1}\{[h^{\mathrm{inc},J}]+[Y^{rJ1}][E]^{\mathrm{Lo},(1)}+\cdots+[Y^{rJk}][E]^{\mathrm{Lo},(k)}+\cdots+[Y^{rJM}][E]^{\mathrm{Lo},(M)}\} \quad (5)$$

$$\text{for } k\neq J \text{ at lower interface} \quad (6)$$

where

$$[R^{cJ}]=[Y^{cJw}]^{-1}[h^{cJw}] \quad (7)$$

$$[R^{rJ}]=[Y^{rJw}]^{-1}[h^{rJw}]. \quad (8)$$

The elements of the matrices $[Y^{rJw}]$, $[h^{rJw}]$ and $[Y^{cJw}]$, $[h^{cJw}]$ appearing in the above equations are of the same form as those of [8, eqs. (24)–(26) and (28)–(31)]. Expressions for the elements of the column matrix $[h^{\mathrm{inc},J}]$ and the square matrix $[Y^{rJk}]$ ($k\neq J$) are derived in the following section.

In the case where all the T junctions are identical ($2L_1=2L_2=\cdots=2L_J=2L$ and $2W_1=2W_2=\cdots=2W_J=2W$), the following simplifications can be used for the analysis:

$$[Y^{gJw}]=\cdots=[Y^{gkw}]=\cdots=[Y^{gMw}]=[Y^{g1w}] \quad (9)$$

$$[h^{gJw}]=\cdots=[h^{gkw}]=\cdots=[h^{gMw}]=[h^{g1w}] \quad (10)$$

and therefore,

$$[R^{gJ}]=\cdots=[R^{gk}]=\cdots=[R^{gM}]=[R^{g1}] \quad (11)$$

where $g=r$ and c.

From (5)–(11) and the relations between the incident and reflected waves at the lower and upper interfaces given by [8, eqs. (15) and (16)], the amplitude coefficients for the total electric field at the two interfaces of the slot waveguide are obtained, using the procedure followed in [8], as

$$[E]^{\mathrm{Lo},(J)}=[\eta][\theta] \quad (12)$$

$$[E]^{\mathrm{Up},(J)}=[\zeta][\theta] \quad (13)$$

where

$$[\eta]=\{[U]+[B][R^{c1}][B]\}\{[R^{r1}][B][R^{c1}][B]-[U]\}^{-1}\cdot[Y^{r1w}]^{-1} \quad (14)$$

$$[\zeta]=\{[B]+[R^{c1}][B]\}\{[R^{r1}][B][R^{c1}][B]-[U]\}^{-1}\cdot[Y^{r1w}]^{-1} \quad (15)$$

and

$$[\theta]=[h^{\text{inc},(J)}]+[Y^{rJ1}][E]^{\text{Lo},(1)}+\cdots+[Y^{rJk}][E]^{\text{Lo},(k)}+\cdots+[Y^{rJM}][E]^{\text{Lo},(M)}\} \quad \text{for } k\neq J. \quad (16)$$

The matrix $[B]$ appearing in (14) and (15) is an $N\times N$ diagonal matrix, whose diagonal elements are presented in [8].

Rearranging the terms, the above set of equations can be written as

$$[\alpha][E]^{\text{Lo}}=[h^{\text{inc}}] \quad (17)$$

where $[E]^{\text{Lo}}$ and $[h^{\text{inc}}]$ are column matrices given by

$$[E]^{\text{Lo}}=\begin{bmatrix}E^{\text{Lo},(1)}\\E^{\text{Lo},(2)}\\\vdots\\E^{\text{Lo},(M)}\end{bmatrix} \qquad [h^{\text{inc}}]=\begin{bmatrix}-h^{\text{inc},1}\\-h^{\text{inc},2}\\\vdots\\-h^{\text{inc},M}\end{bmatrix}.$$

The elements $E^{\text{Lo},(J)}$ and $h^{\text{inc},J}$ $(J=1,2,\cdots,M)$ are also column matrices, each containing N elements.

The elements of the $M\times M$ square matrix $[\alpha]$, which are themselves square matrices of order $N\times N$, are given by

$$[\alpha_{Jk}]=\begin{Bmatrix}-[\eta]^{-1} & \text{for } k=J\\ [Y^{rJk}] & \text{for } k\neq J\end{Bmatrix}. \quad (18)$$

Therefore, the amplitude coefficients for the electric fields at the lower interface of each coupling slot are obtained as

$$[E]^{\text{Lo}}=[\alpha]^{-1}[h^{\text{inc}}]. \quad (19)$$

The amplitude coefficients for the electric fields at the upper interface are expressed in terms of those of the lower interface by (13), (15), and (16).

A. Expressions for the Elements of the Matrices $[Y^{rJk}]$ and $[h^{\text{inc},J}]$

The elements of the square matrix $[Y^{rJk}]$ and the column matrix $[h^{\text{inc},J}]$ are respectively given by the inner products

$$Y_{qs}^{rJk}=\iint_{J\text{th slot}} H_{Z'}^{rJk}(P_J;P_k'')w_s^{(J)}\,dZ'\,dX' \quad (20)$$

$$h_s^{\text{inc},J}=\iint_{J\text{th slot}} H_{Z'}^{\text{inc},J}w_s^{(J)}\,dZ'\,dX'. \quad (21)$$

For an electric field distribution in the aperture plane at the lower interface of the kth slot of the form given in (3), expressions for the longitudinal component of the magnetic field $H_{Z'}^{rJk}$ for the forward-scattered $(k<J)$ and backward-scattered $(k>J)$ waves in the rectangular waveguide are obtained following the method suggested in the literature [9]. Using (3) for the kth slot, [8, eq. (22)], [9, eqs. (7–34) and (7–31)], and integrating, respectively, the first and second terms within the square brackets of [9, eq. (7–34)] from $(k-1)d-L$ to $(k-1)d+L$, the forward- and backward-scattered fields in the rectangular waveguide are determined. Substituting the resultant expressions and (4) in (20) and carrying out the integration over the Jth slot aperture, the elements Y_{qs}^{rJk} are obtained as

$$Y_{qs}^{rJk}=\frac{1}{j\omega\mu}\sum_m\sum_n\frac{\epsilon_m\epsilon_n}{2AB\gamma}\left\{2W\cos(m\pi/2)\frac{\sin(m\pi W/A)}{(m\pi W/A)}\right\}^2\cdot(K^2+\gamma^2)\sum_{q=1}^{N}E_q^{\text{Lo},(k)}\frac{q\pi/2L}{\gamma^2+(q\pi/2L)^2}\frac{s\pi/2L}{\gamma^2+(s\pi/2L)^2}$$
$$\begin{bmatrix}(e^{\gamma L}-e^{-\gamma L}\cos q\pi)(e^{-\gamma L}-e^{\gamma L}\cos s\pi)e^{\gamma(J-k)d} & \text{for } J<k\\(e^{-\gamma L}-e^{\gamma L}\cos q\pi)(e^{\gamma L}-e^{-\gamma L}\cos s\pi)e^{\gamma(k-J)d} & \text{for } J>k\end{bmatrix}. \quad (22)$$

For an orthonormalized dominant mode incident wave in the rectangular waveguide, the expression for H_Z^{inc} is of the form [8], [10]

$$H_Z^{\text{inc}}=\frac{1}{j\omega\mu}\frac{\pi}{B}\sqrt{\frac{2}{AB}}\cos\frac{\pi Y}{B}e^{-j\beta Z}. \quad (23)$$

Using (23) and (4) in (21) and carrying out the integration over the aperture plane of the Jth slot, the elements $h_s^{\text{inc},J}$ are obtained as

$$h_s^{\text{inc},J}=\frac{1}{j\omega\mu}\frac{\pi}{B}\sqrt{\frac{2}{AB}}\frac{2W(s\pi/2L)}{(s\pi/2L)^2-\beta^2}e^{-j\beta(J-1)d}(e^{j\beta L}-e^{-j\beta L}\cos s\pi). \quad (24)$$

B. Expressions for Reflection, Transmission, and Coupling Coefficients

The reflection coefficient seen by the matched generator at port (1) of the rectangular guide of Fig. 1 is defined as

$$\Gamma=\frac{\sum_{k=1}^{M}H_Z^{\text{ref},(k)}}{H_Z^{\text{inc}}} \quad (25)$$

where $H_Z^{\text{ref},(k)}$ is the dominant mode reflected wave, due to the electric field at the lower interface of the kth slot aperture.

For an aperture field distribution at the lower interface of the kth slot of the form given in (3), the dominant mode longitudinal component of the magnetic field reflected into port (1) of the rectangular waveguide is obtained from the backscattered field $H_{Z'}^{rJk}(k>J)$ evaluated in the above section, by substituting $m=0$, $n=1$, and $\gamma=j\beta$. Using the resulting expression and (23) in (25), the reflection coefficient seen by port (1) at the reference cross-sectional plane passing through the center of the first slot is expressed as

$$\Gamma=\sum_{k=1}^{M}\Gamma^{(k)}=\sum_{k=1}^{M}\frac{\pi W}{B\beta}\sqrt{\frac{2}{AB}}\sum_{q=1}^{N}E_q^{\text{Lo},(k)}\frac{q\pi/L}{(q\pi/2L)^2-\beta^2}\cdot e^{-j\beta(k-1)d}\begin{bmatrix}-j\cos\beta L & q \text{ odd}\\ \sin\beta L & q\text{ even}\end{bmatrix}. \quad (26)$$

The VSWR seen by the exciting rectangular waveguide is therefore given by

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}. \tag{27}$$

The transmission coefficient from port (1) to port (2) of the rectangular waveguide is defined as

$$T = 1 + \frac{\sum_{k=1}^{M} H_Z^{\text{tr},(k)}}{H_Z^{\text{inc}}} \tag{28}$$

where $H_Z^{\text{tr},(k)}$ is the dominant mode forward-scattered wave at port (2) of the rectangular waveguide caused by the aperture field at the lower interface of the kth slot.

Substituting (23) and the expression for the dominant mode longitudinal component of the forward-scattered magnetic field H_Z^{rJk} derived in the earlier section in (27), the transmission coefficient into port (2) at the cross-sectional plane passing through the centre of the Mth slot is given by

$$\begin{aligned} T &= 1 + \sum_{k=1}^{M} T^{(k)} \\ &= 1 + \sum_{k=1}^{M} \frac{\pi W}{B\beta}\sqrt{\frac{2}{AB}} \sum_{q=1}^{N} E_q^{\text{Lo},(k)} \frac{q\pi/L}{(q\pi/2L)^2 - \beta^2} \\ &\quad \cdot e^{j\beta(k-1)d} \begin{bmatrix} -j\cos\beta L & q \text{ odd} \\ -\sin\beta L & q \text{ even} \end{bmatrix}. \end{aligned} \tag{29}$$

The amplitude coupling coefficient from port (1) of the feed waveguide to any port $(k+2)$ of the kth circular waveguide is defined as [8]

$$S_{k1} = \vartheta_{11}^{e,(k)} = \sum_{q=1}^{N} E_q^{\text{Up},(k)} V_{11,q}^{e} \tag{30}$$

where $\vartheta_{11}^{e,(k)}$ is the dominant mode modal voltage of the coupled wave in the kth circular waveguide, and $V_{11,q}^{e}$ is obtained from [8, eq. (30)] by substituting $n=1$, $p=1$, and $r=q$.

Therefore, the coupling from port (1) to port $(k+2)$ of the configuration shown in Fig. 1 is given by

$$\begin{aligned} C_{k1} &= 10\log\left\{\frac{|S_{k1}|^2}{Z_{11}} Z_0\right\} \\ &= 10\log\left\{\frac{\left|\sum_{q=1}^{N} E_q^{\text{Up},(k)} V_{11,q}^{e}\right|^2}{Z_{11}} Z_0\right\} \end{aligned} \tag{31}$$

where Z_0 and Z_{11} are the characteristic wave impedances of the dominant mode in the rectangular and circular waveguides respectively.

III. Numerical Results

Using (12)–(19), (7)–(11), (22), (23), and the expressions for the elements of the matrices derived in [8], the amplitude coefficients at the two interfaces of each slot waveguide are evaluated for a cascaded section of two T junctions ($M=2$) for $2L = 1.69$ cm, $2W = 0.107$ cm, $A = 1.016$ cm, $B = 2.286$ cm, and $a = 1.185$ cm over the frequency range 8.4 to 9.6 GHz. The computations are carried out for both $t = 0$ and $t = 0.127$ cm for different values of N and for d ranging from 2.4 cm to 4.8702 cm (λ_g at $f = 9.0$ GHz).

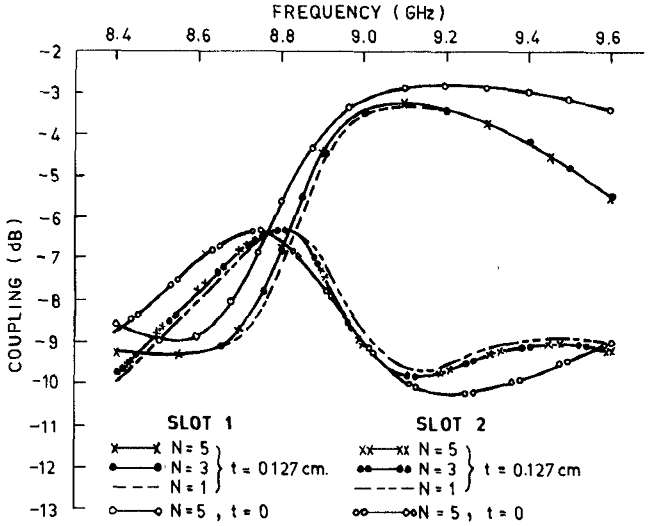

Fig. 3. Variation of coupling with frequency for $M=2$, $2L = 1.69$ cm, $2W = 0.107$ cm, and $d = 2.8$ cm.

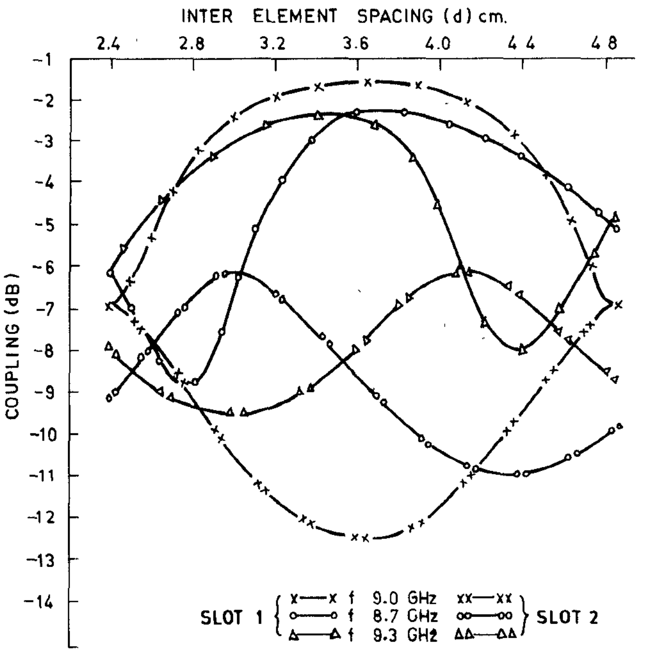

Fig. 4. Variation of coupling with interelement spacing for $M=2$, $2L = 1.69$ cm, $2W = 0.107$ cm, $N = 5$, and $t = 0.127$ cm.

Substituting the numerical values of $E_q^{\text{Up},(1)}$ and $E_q^{\text{Up},(2)}$ in (31), the variations of coupling from port (1) of the rectangular waveguide to port (3) and port (4) of the circular waveguides with frequency are evaluated for $d = 2.8$ cm, $t = 0$, and $t = 0.127$ cm, and results are presented in Fig. 3. The computed results on variations of coupling as a function of interelement spacing are shown in Fig. 4 for different frequencies and for $N = 5$ and $t = 0.127$ cm.

The theoretical results on the variation of the VSWR with frequency computed using (12), (14), (26), (27), and (29) are presented in Fig. 5 with d as a parameter.

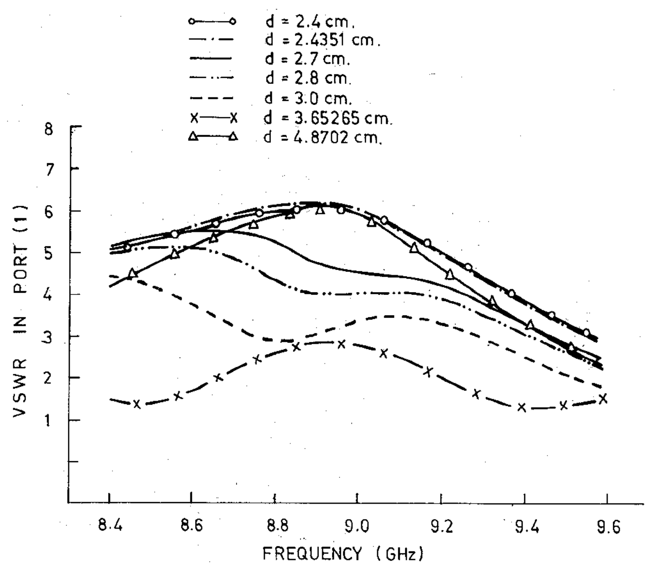

Fig. 5. Variation of VSWR seen by port (1) of the rectangular waveguide with frequency for $M=2$, $2L=1.69$ cm, $2W=0.107$ cm, $N=5$, and $t=0.127$ cm.

Following the procedure described in [8, section III], the elements of the scattering matrix of a cascaded section are found and from the results its unitary property is verified. Further, for $d=0$, $M=1$ and all expressions reduce to those of [8], in which case agreement between theoretical and experimental results has been presented in [8, fig. 5].

IV. Discussions

The results presented above reveal many interesting aspects of cascaded sections of T junctions between rectangular and circular waveguides. In the particular case of cascaded sections of two junctions, when $d=\lambda_g/2$ and its multiples, the couplings into the two circular waveguide ports are almost identical and the VSWR is high. The value of coupling is reduced to 6.9 dB in place of 3.1 dB for an isolated T junction [8] and the VSWR is of the order of 6.2. For other values of d, the VSWR is less and the couplings into the two ports are different, being higher in the first T arm and lower in the second. When $d=3\lambda_g/4$ and its multiples, the coupling into port (3) is maximum (1.5 dB), while that into port (4) is minimum (12.5 dB). The corresponding VSWR is minimum and its maximum value is about 2.85.

The amplitude coefficients are found to be functions of d as well as of frequency. This variation of complex amplitude coefficients, together with the phase change resulting from path differences and also from the individual junctions, modifies the reflection and transmission characteristics of the cascaded sections of T junctions.

The evaluation of numerical results requires inversion of matrices of order 10×10 in view of the fact that convergence is obtained for $N=5$. If the convergence had been obtained for higher values of N, the solution of the problem would have required inversion of the matrices of still higher order, even for these cascaded sections of two junctions. Evaluation of the electrical parameters of interest for cascaded sections of M junctions requires inversion of matrices of order $(M\times N)\times(M\times N)$, which can be carried out through partitioning of matrices [11].

The analysis presented in this paper is quite general and can be used for the computation of the performance characteristics of cascaded sections of any number of similar or dissimilar junctions. The discussion presented in the last part of Section III, which shows that the unitary property of the scattering matrix is satisfied, justifies of the validity of the analysis and shows a method of verifying the results. The nature of variation of the numerical results is also expected from physical considerations.

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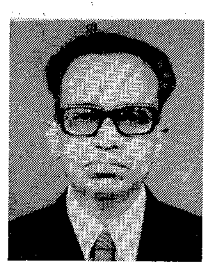

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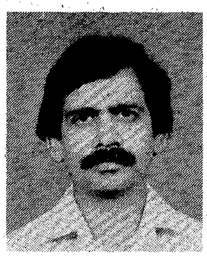

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