A Generalized Theory of Tapered Transmission Line Matching Transformers and Asymmetric Couplers Supporting Non-TEM Modes

PROTAP PRAMANICK, SENIOR MEMBER, IEEE, AND PRAKASH BHARTIA, FELLOW, IEEE

Abstract —This paper presents a generalized Fourier transform pair for the analysis and synthesis of tapered transmission lines supporting a non-TEM mode. The Fourier transform pair first pointed out by Bolinder and subsequently used by Klopfenstein and others, for TEM lines, can be shown to be a special case of the present transform pair. A step-by-step synthesis method has been described for exact designs of matching transformers and asymmetric couplers. The theory is verified with the design of two Ka-band finline tapers and a C-band microstrip coupler.

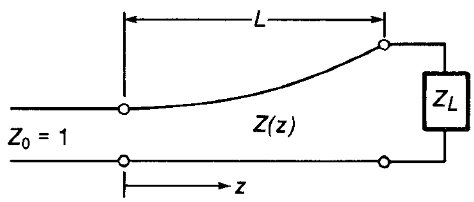

Fig. 1. Tapered transmission line.

I. Introduction

Tapered transmission lines are useful in the design of matching networks, filters, couplers circulators, etc. The theory for a tapered transmission line supporting a TEM mode is well established [1]–[3]. Analysis of tapered transmission lines supporting TEM modes deals with a constant propagation constant along the taper. Since the propagation constant varies along the length of a non-TEM transmission line taper, the analysis of such tapers becomes involved. Lund in 1950 [4] and Bolinder in 1951 [5] showed how the analysis of such tapered lines can be carried out in terms of electrical length, instead of physical length. However, so far no integral transform pair has been available for directly relating the frequency response and the impedance profile of a taper.

Microstrip lines support a quasi-TEM mode at lower frequency bands and a complete hybrid mode at higher frequency bands. Despite the quasi-TEM nature of the supported mode, the propagation constant of a tapered microstrip line varies along its length. Tapered microstrip has been analyzed by Pramanick and Bhartia [6] by solving a pair of complex nonlinear differential equations. A similar technique has been applied to unilateral finline, for exponential cosine-squared and parabolic tapers, which support purely non-TEM modes [7]. Schieblich *et al.* [8] and Hinken [9] reported a synthesis method for optimum Chebyshev unilateral and antipodal finline tapers in terms of electrical length. This method carefully avoids the controversial definition problem of the characteristic impedance of a non-TEM transmission line, by synthesizing the taper in terms of a mode coupling coefficient in structures supporting TE mode. An apparent lack of generality prevents it from being applied to other transmission lines. Moreover, the method is based on certain simplifying assumptions. So far there has been no rigorous generalized theory for designing an optimum Chebyshev dispersive tapered transmission line. This paper presents a generalized Fourier transform pair, by treating the tapered line in terms of the electrical length. The transform pair is mathematically rigorous and simple enough to implement even on a desktop computer for designs of many useful dispersive transmission line tapers. The theory is supported by the designs of two finline Ka-band tapers and a C-band microstrip asymmetric coupler.

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P. Pramanick is with COM DEV Ltd., Cambridge, Ont., Canada.
P. Bhartia is with the Department of National Defence, Ottawa, Ont., Canada K1A 0K2
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II. Theory

Consider the schematic representation of a tapered transmission line network in Fig. 1. The frequency response $F(u)$ and the taper impedance profile $g(p)$ for such a line can be related by the following Fourier transform pair [3]:

$$F(u)=\int_{-\pi}^{\pi} e^{-jpu} g(p)\,dp \tag{1}$$

$$g(p)=\frac{1}{2\pi}\int_{-\infty}^{\infty} e^{jpu} F(u)\,du \tag{2}$$

where

$$g(p)=\frac{d}{dp}\ln(\bar{Z}(p))$$

$$p=2\pi\left\{\frac{z}{L}-\frac{1}{2}\right\}$$

$$\bar{Z}(p)=Z(p)/Z_0 \tag{3}$$

and

$$u = \frac{\beta L}{\pi} \tag{4}$$

where L is the length of the taper and β is the phase constant. The line is assumed to support a purely TEM mode, and the phase constant β remains constant along the line.

If we treat the taper in terms of the electrical angle, then the variables p and u become

$$\bar{p} = 2\pi\left\{\frac{\beta_0 z}{\beta_0 L} - \frac{1}{2}\right\} \tag{5}$$

$$\bar{u} = \frac{\beta L}{\pi} \tag{6}$$

where β_0 is the phase constant at the cutoff frequency of the taper.

The above Fourier transform pair can be generalized for non-TEM lines in the following way:

$$F(\bar{u}) = \int_{-\pi}^{\pi} \bar{e}^{j\bar{p}\bar{u}} g(\bar{p})\, d\bar{p} \tag{7}$$

$$g(\bar{p}) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{j\bar{p}\bar{u}} F(\bar{u})\, d\bar{u} \tag{8}$$

where

$$\bar{p} = 2\pi\left\{\frac{\int_0^z \beta_0(\tau)\, d\tau}{\int_0^L \beta_0(z)\, dz} - \frac{1}{2}\right\} \tag{9}$$

and

$$\bar{u} = \frac{1}{\pi}\int_0^L \beta(z)\, dz \tag{10}$$

where $\beta_0(z)$ is the propagation constant at a specified cutoff frequency f_0 of the taper. For β_0 independent of z, the transform pair (7) and (8) reduces to that of Bolinder [5] as in (1) and (2). The taper profile $g(\bar{p})$ can now be obtained given the frequency response $F(\bar{u})$ and using the Fourier transform pair (7) and (8). Such a method is valid for any frequency response for which the inverse Fourier transform gives a physically realizable taper profile. The condition for realizability is given by

$$\left|\int_{-\infty}^{\infty} g(\bar{p})\, d\bar{p}\right| < \infty. \tag{11}$$

On the other hand, given a physically realizable taper profile $g(\bar{p})$, one can always obtain the frequency response $F(\bar{u})$ using the generalized Fourier transform pair (7) and (8).

In practice most cases require synthesis of tapers rather than their analysis. It is well known that a Chebyshev taper offers the optimum electrical performance. The frequency response for such a taper using a TEM transmission line is given by [10]:

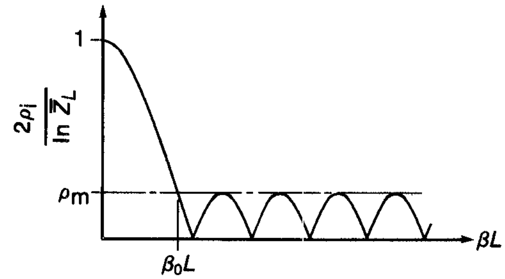

Fig. 2 Reflection coefficient characteristics for a Chebyshev taper.

$$\Gamma_i(u) = \frac{1}{2}e^{-j\pi u}F(u) \tag{12}$$

where (see Fig. 2)

$$F(u) = \ln(\bar{Z}_L)\frac{\cos L\sqrt{(\beta^2 - \beta_0^2)}}{\cosh(\beta_0 L)} \tag{13}$$

$$\rho_m = \frac{1}{2}\ln(\bar{Z}_L)/\cosh(\beta_0 L) \tag{14}$$

$$\rho_i = |\Gamma_i(u)| \tag{15}$$

$$\bar{Z}_L = Z_L/Z_0 \tag{16}$$

and u is defined in (4).

For a dispersive line, (12) assumes the form

$$\Gamma_i(\bar{u}) = \frac{1}{2}\bar{e}^{j\pi\bar{u}}F(\bar{u}) \tag{17}$$

and

$$F(\bar{u}) = \frac{1}{2}\ln(\bar{Z}_L)\frac{\cos\left\{\pi(\bar{u}^2 - \bar{u}_0^2)^{1/2}\right\}}{\cosh(\pi\bar{u}_0)}. \tag{18}$$

From (18) and (8), evaluating the inverse Fourier transform and subsequent integration yields the taper profile given by

$$\ln(Z(\theta)/Z_0) = \frac{1}{2}\ln(Z_L/Z_0) + \frac{(\pi\bar{u}_0)^2\ln(Z_L/Z_0)}{2\cosh(\pi\bar{u}_0)}\Phi\left(\frac{2\theta}{\pi\bar{u}_0}, \pi\bar{u}_0\right) \quad \text{for } -\frac{\pi\bar{u}_0}{2} < \theta < \frac{\pi\bar{u}_0}{2} \tag{19}$$

and

$$Z(\pi\bar{u}_0/2)/Z_0 = \exp\left\{\frac{\ln(Z_L/Z_0)}{2\cosh(\pi\bar{u}_0)}\right\} \tag{20}$$

$$Z(-\pi\bar{u}_0/2)/Z_0 = \exp\left\{\ln(Z_L/Z_0) - \frac{\ln(Z_L/Z_0)}{2\cosh(\pi\bar{u}_0)}\right\} \tag{21}$$

where

$$\theta = \int_0^z \beta_0(\tau)\, d\tau - \pi\bar{u}_0/2 \tag{22}$$

and the function $\Phi(\theta/\pi\bar{u}_0, \pi\bar{u}_0)$ is defined to be

$$\Phi\left(\frac{\theta}{\pi\bar{u}_0}, \pi\bar{u}_0\right) = \frac{1}{\pi\bar{u}_0}\int_0^\theta \frac{I_1\left[\sqrt{\left\{1-\left(\frac{x}{\pi\bar{u}_0}\right)^2\right\}}\pi\bar{u}_0\right]}{\pi\bar{u}_0\sqrt{\left\{1-\left(\frac{x}{\pi\bar{u}_0}\right)^2\right\}}}\, dx \tag{23}$$

where I_1 is the modified Bessel function.

III. Design Steps

The design procedure for a matching transformer can be summarized in the following steps:

1) Set $z = 0$.

2) Determine the electrical length $\pi\bar{u}_0$ of the taper from the given ripple level RL in dB, using

$$\pi\bar{u}_0 = \ln\left(R^2 + \sqrt{R^2 - 1}\right) \tag{24}$$

where

$$R = \frac{1}{2}\ln(Z_L/Z_0)/\rho \tag{25}$$

and

$$\rho = 10^{(-\mathrm{RL}/20)}. \tag{26}$$

3) Given Z_L and Z_0, determine $Z(L/2)$ and $Z(-L/2)$ using (20) and (21) respectively.

4) Use a suitable synthesis scheme to obtain the corresponding physical parameter of the transmission line (for example, fin gap in finline or strip width in microstrip).

5) Approximate (22) over a small length Δz by

$$\theta(z = \Delta z) = \beta_0(z)\,\Delta z - \pi\bar{u}_0/2 \tag{27}$$

where $\Delta Z = \lambda/N$, λ is the design wavelength, and N can be chosen arbitrarily depending upon the required accuracy of the design. $N = 40$ is reasonable. $\beta_0(z)$ is the propagation constant corresponding to the impedance $Z(-\pi u_0/2)$. $\beta_0(z)$ is obtained by using a suitable analysis technique. It is assumed that $\beta_0(z)$ has negligible variation over Δz.

6) Initialize z to zero. The corresponding value of θ is $-\pi\bar{u}_0/2$ (from (27)).

7) Using $\pi\bar{u}_0$ and $\theta(z = \Delta z)$ in (19), obtain $Z(\Delta z)/Z_0$.

8) Using synthesis and the subsequent analysis technique, obtain $\beta_0(\Delta z)$.

9) Replace z by $z + \Delta z$ in step 1 and repeat the above steps until the physical parameter corresponding to $Z(\pi\bar{u}_0/2)$ is reached.

10) One could also choose the electrical length of the taper directly, which alternatively fixes the passband ripple.

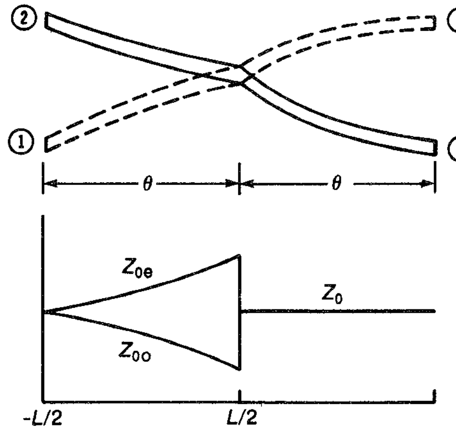

Fig. 3 A symmetric coupled line directional coupler.

In step 7, the function Φ can be approximated using Grossberg's [11] method as

$$\Phi(x, A) = \sum_{n=0}^{\infty} a_n b_n \tag{28}$$

with

$$a_0 = 1$$
$$b_0 = x/2$$
$$a_n = \frac{A^2}{4n(n+1)}a_{n-1}$$
$$b_n = \frac{x}{2}\,\frac{(1-x^2)^n + 2nb_{n-1}}{2n+1}.$$

A maximum of 20 terms are required to accurately evaluate (28).

Design of Asymmetric Coupler

The stripline TEM coupler (shown schematically in Fig. 3) that performs as a magic T or 180° hybrid over a semi-infinite frequency band above a lower cutoff frequency is well known [12]–[14]. The spacing between the pair of coupled lines is tapered so as to act as an impedance transformer for the even and the odd modes, with coupler action due to the reflection caused by the abrupt step between the coupled and uncoupled lines.

The design of a 180° asymmetric coupling using inhomogeneous transmission lines, such as microstrip, is performed using the above theory. It is based on choosing either the cutoff electrical length $\pi\bar{u}_0$ or the passband ripple.

The design steps for such a coupler are as follows:

1) Given the coupling coefficient at infinite frequency C_∞, determine the even-mode characteristic impedance of the coupled line:

$$Z_{0e}(0) = Z_0\frac{1 + C_\infty}{1 - C_\infty}. \tag{29}$$

2) Determine the odd-mode impedance from

$$Z_{0e}(0)\,Z_{0o}(0) \cong Z_0^2 \tag{30}$$

where Z_0 is the system impedance.

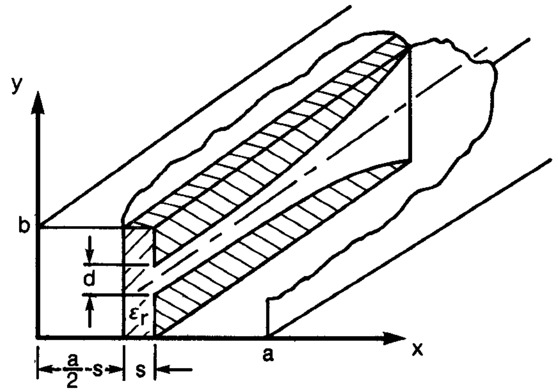

Fig. 4. Cutaway section of a finline taper.

3) Using $Z_{0e}(0)$ and $Z_{0o}(0)$ determine the physical parameters of the coupled lines using a suitable synthesis technique.

4) Using analysis techniques determine the corresponding even- and odd-mode phase constants $\beta_{0e}(0)$ and $\beta_{0o}(0)$ respectively. Use

$$\beta_0(0) \cong \frac{1}{2}(\beta_{0e}(0)+\beta_{0o}(0)) \tag{31}$$

or use the Dell–Imagine [15] equation:

$$\beta_0(0) = \frac{Z_{0e}\beta_{0e}(0)+Z_{0o}\beta_0(0)}{Z_{0e}+Z_{0o}}. \tag{32}$$

5) Follow steps 6 to 10 in taper transformer design until $Z_{e0} \cong Z_{0o} \cong Z_0$ at $\theta = \pi\bar{u}_0/2$ is reached.

IV. Application to Unilateral Finline Taper Design

The above theory can be applied to the exact design of a unilateral finline Chebyshev taper, shown in Fig. 4. The taper matches two different fin gaps. Hence an absolute value of the fin gap impedance is not required. As a result, we can synthesize the taper in terms of the wave impedance. Such an impedance definition of finline taper design has also been used by Beyer [16]. It is given by

$$z(f_0) = \frac{\eta_0}{\sqrt{k_e-(f_{ca}/f_0)^2}} \tag{33a}$$

or, in terms of wavelength,

$$z(\lambda_0) = \frac{\eta_0}{\sqrt{k_e-(\lambda_0/\lambda_{ca})^2}} \tag{33b}$$

where k_e is the equivalent dielectric constant of the finline and λ_{ca} is the cutoff wavelength of the corresponding homogeneous air-filled ridged waveguide [17], [18]. The parameter $\eta_0 = 120\pi$ is the free-space impedance.

Inverting (33) for thin, low-dielectric-constant substrates used in finlines gives the fin gap corresponding to $z(f_0,\theta)$ as

$$d(f_0,\theta) = \frac{2b}{\pi}\sin^{-1}\cdot\exp(-x) \tag{34}$$

where

$$x = \left\{-p+(p^2-4q)^{1/2}\right\}/2$$
$$p = (a_x b_x - \kappa(f_0,\theta))a_x$$
$$q = (b_x - J - \kappa(f_0,\theta))/(a_x N)$$
$$N = \left(\frac{4}{N}\right)(b/a)(1+0.2\sqrt{b/a})$$
$$a_x = (\epsilon_r-1)(S/a)a_1$$
$$b_x = 1.+(\epsilon_r-1)(S/a)b_1$$
$$a_1 = 0.4021\{\ln(a/S)\}^2 - 0.7685\ln(a/S)+0.3921$$
$$b_1 = 2.42\sin(0.556\ln(a/S))$$
$$J = 0.25(\lambda_0/b)^2(b/a)^2$$
$$\kappa(f_0,\theta) = \{\eta_0/z(f_0,\theta)\}^2.$$

Once $d(f_0,\theta)$ is defined, $\beta_0(\theta)$ and $z_0(f_0,\theta)$ are obtained by using the equations in [17] and [18].

V. Experimental Results

In order to support the validity of the theory developed herein, unilateral finline Chebyshev taper transformers were designed and tested at *Ka*-band. Figs. 5 and 6 show the computed fin gap and wave impedance profiles of unilateral finline tapers, where d_1 is the smallest fin gap and d_2 is the largest fin gap in the tapers. Figs. 7 and 8 show the experimental results of two unilateral finline tapers on 0.127 mm RT Duroid 5880 and 0.025 4 mm Cuflon substrates. The results agree closely with theory. Several other such tapers with ripple values lower than −30 dB have been tested. However, it is virtually impossible to get a matching better than −35 dB in practical situations. Such a phenomenon has also been observed by Scheiblich *et al.* [8]. The insertion losses of the tapers were within 0.2 dB.

Comparison of Figs. 7 and 8 shows the effects of finite substrate thickness on the passband ripple. The Cuflon substrate, being thinner than the RT Duroid substrate, gives better matching in the passband.

A general computer program has been developed for synthesizing unilateral finline tapers. Closed-form design equations of Pramanick and Bhartia [17], [18] are used to compute the phase constants, wave impedances, and fin gaps in the taper. This has made the program extremely fast. Typical computation time for synthesizing a taper is 1.70 s of CPU time on a CYBER 180/830 system. A desktop version of the program is also available.

VI. Application to Microstrip Asymmetric Coupler Design

In order to support the validity of the theory developed herein, a microstrip asymmetric coupler was designed and analyzed at *C*-band. Fig. 9 shows the even- and the odd-mode impedance profiles of a 14 dB coupler at 5 GHz. The figure also shows the gap and the width profiles of the coupler on a 25 mil Epsilum 10™ substrate. The coupler

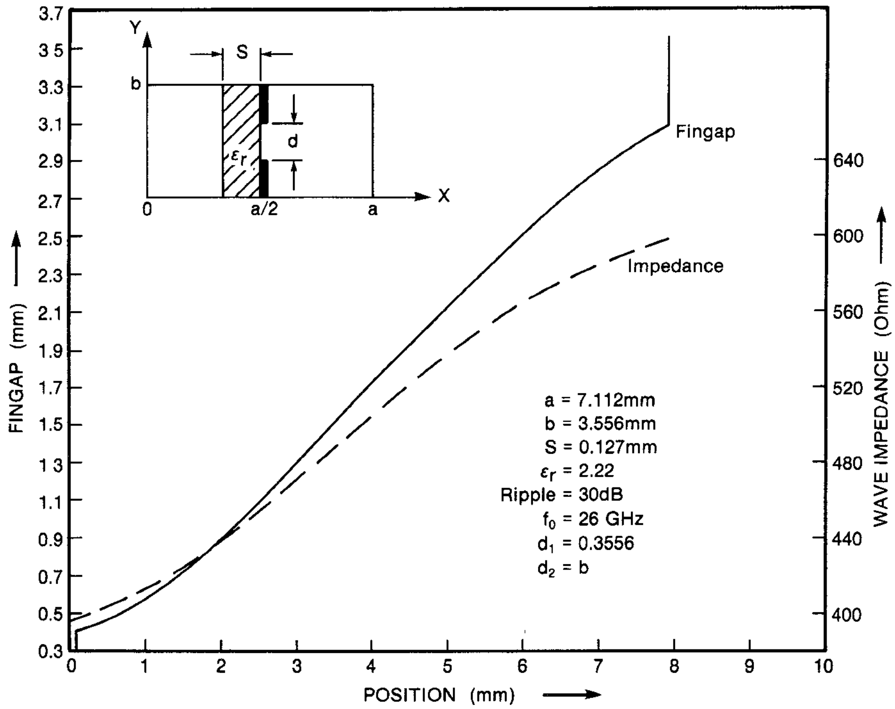

Fig. 5. Profile of finline taper at *Ka*-band.

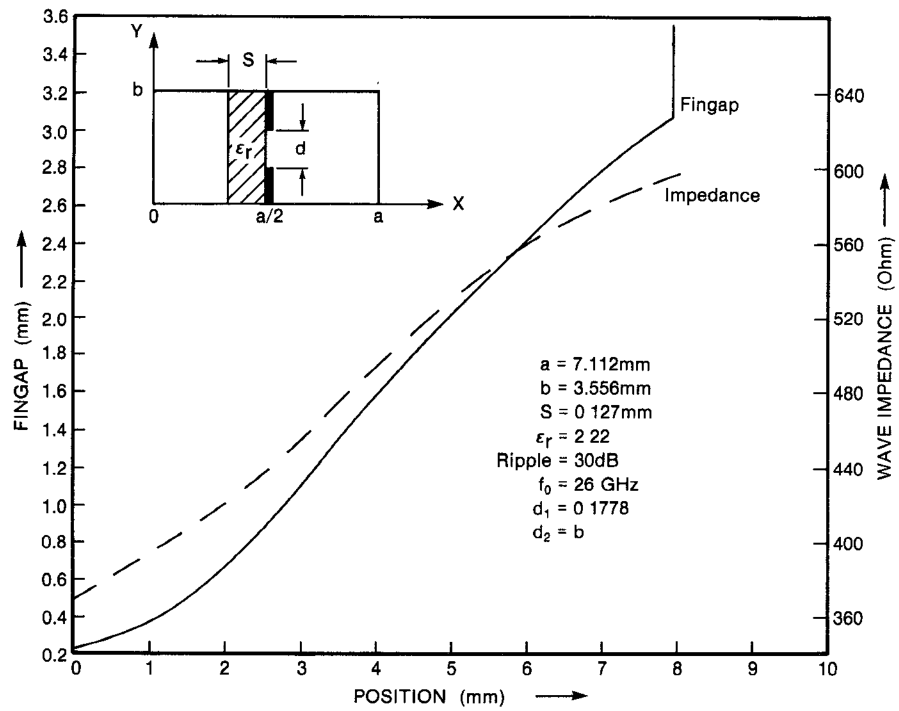

Fig. 6. Profile of finline taper at *Ka*-band.

was subsequently analyzed on TOUCHSTONE™ by dividing it into a large number of short coupled microstrip sections. The computed response is shown in Figs. 10 and 11. Computation shows that the bends at the most tightly coupled end of the coupler have virtually no effect on the coupling and phase response. However, they influence the input match, as shown in Fig. 10. Therefore, adequate care should be taken while designing the bends. This shows that in principle a coupler can be designed using the modified Fourier transform. However, such a microstrip coupler will have very poor directivity unless compensation techniques are used [19].

VII. Conclusion

A generalized Fourier transform pair has been presented for the analysis and synthesis of dispersive taper transmission lines. Based on the theory, computer algorithms have

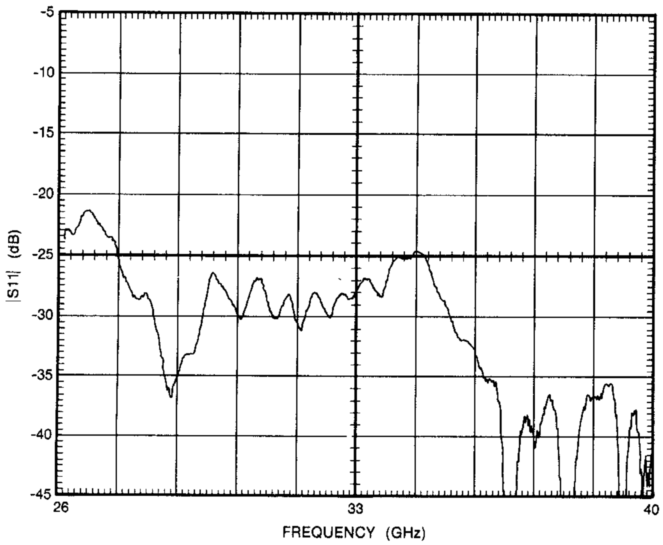

Fig. 7. Measured performance of *Ka*-band taper. Ripple = −30 dB; cutoff frequency = 26 GHz. $S = 127\,\mu$m, $\epsilon_r = 2.22$, $d_1 = 0.3556$, $d_2 = b$ (WR-28, housing), centered fin gap

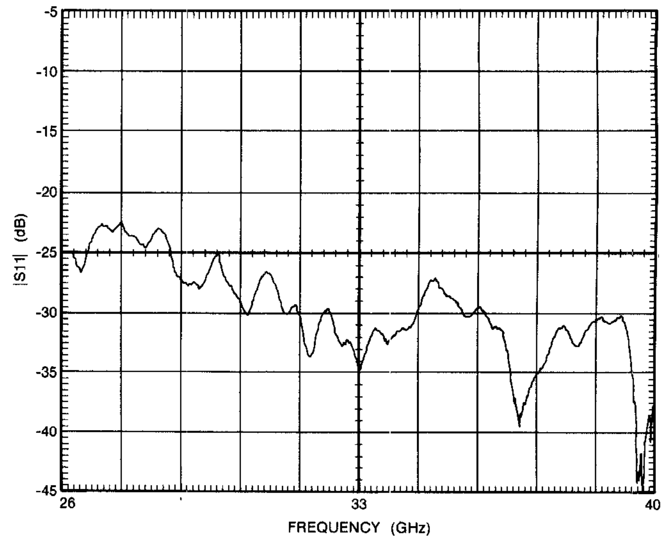

Fig. 8. Measured performance of *Ka*-band taper. Ripple = −30 dB; cutoff frequency = 26 GHz. $S = 25.4\,\mu$m, $\epsilon_r = 2.1$, $d_1 = 0.3556$ $d_2 = b$ (WR-28, housing), centered fin gap.

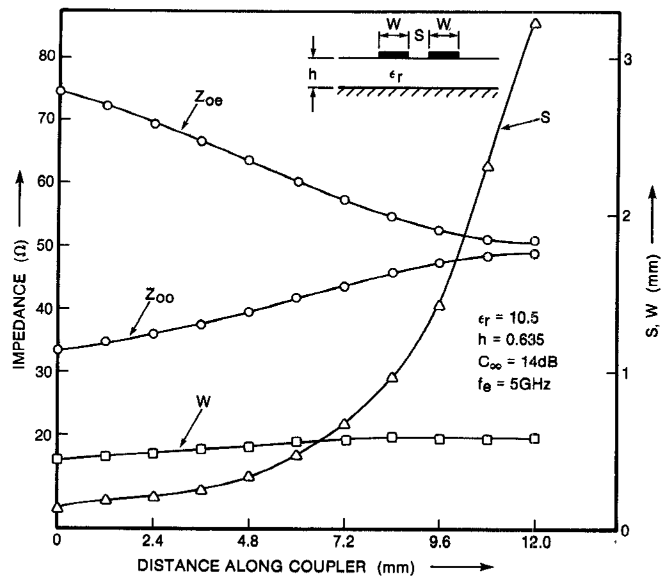

Fig. 9. Impedance profile of 14 dB coupler.

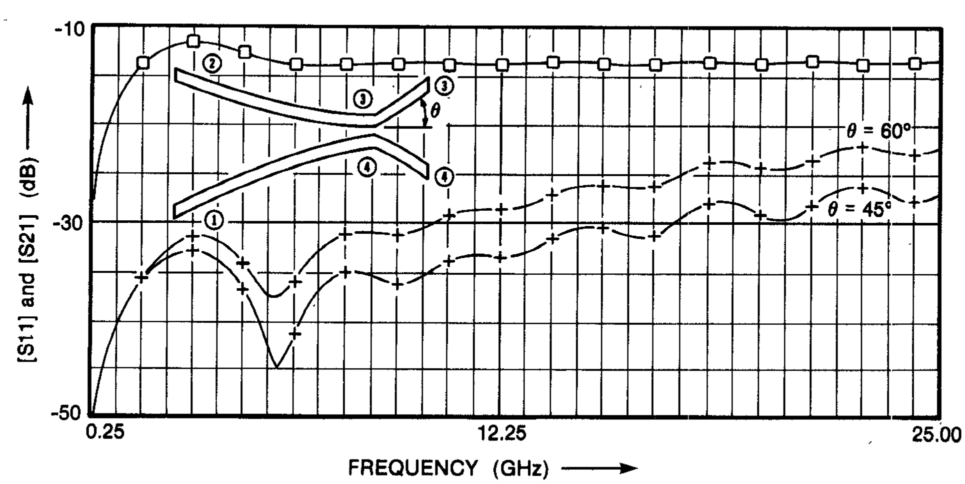

Fig. 10. Coupling input match response of 14 dB coupler: ——□—— ([S21]); ——+—— ([S11]).

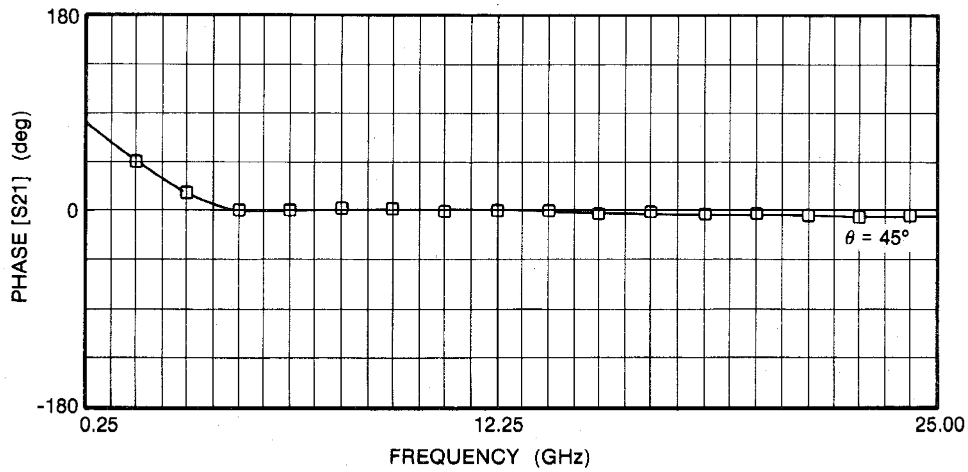

Fig. 11. Phase response of microstrip coupler.

been developed for the synthesis of various transmission line tapers and couplers. Experimental results on *Ka*-band unilateral finline tapers and theoretical results on *S*-band microstrip couplers are presented in support of the theory. The method will be useful in the design and analysis of many other tapered transmission lines.

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Protap Pramanick (S'82–M'84–SM'88) obtained the B. Tech (Hons.) degree in electronics and communication engineering from the Indian Institute of Technology in 1977 and the Ph.D. degree in electrical engineering from the Indian Institute of Technology, Kanpur, India, in 1982.

In September 1982, he joined the Department of Electrical Engineering, University of Ottawa, as a postdoctoral fellow. In December 1984, he joined the Canadian Marconi Company, Ottawa, as a member of the Microwave Group, Avionics Division. Since April 1986, he has been with the Satellite Division of COM DEV Limited in Cambridge, Ont., as a Senior Member of the technical staff. His main fields of interest include microwave measurements and microwave and millimeter-wave integrated circuits.

Dr. Pramanick has published over 40 papers, seven of which appear in the book *E-Plane Integrated Circuits* (Artech House, 1987) and one in *Microwave Integrated Circuits* (Artech House, 1985). He coedited the book *E-Plane Integrated Circuits* (Artech House, 1987) and contributed to the books *Topics in Millimeter Wave Technology* (Academic Press, 1988) and *Microwave Solid State Circuit Design* (Wiley Interscience, 1988). He serves on the editorial review board of IEEE Transactions on Microwave Theory and Techniques.

Prakash Bhartia (S'68–M'71–SM'76–F'89) obtained the B. Tech (Hons.) degree from Bombay in 1966 and the M.Sc. and Ph.D. degrees from the University of Manitoba in 1968 and 1971 respectively.

He served as a Research Associate at the University of Manitoba (1971–1973), as Associate Professor and Assistant Dean of Engineering at the University of Regina (1973–1977) and joined the Defence Research Establishment Ottawa in 1977. Over the years he has worked as a bench scientist and held the positions of MSAT Military EHF Payload manager, and Section Head for Navigation and EMC/EMP. In 1985, he was appointed Director Research and Development Air and subsequently spent a year at the National Defence College. In 1986 he was appointed Director of Research Communications and Space and in 1989, Director of Underwater Acoustics Division at the Defence Research Establishment Atlantic.

Dr. Bhartia has published extensively on many topics, with over a hundred papers to his credit. He coauthored the texts *Microstrip Antennas*, *Millimeter Wave Engineering and Applications*, *E-Plane Integrated Circuits*, and *Microwave Solid State Circuit Design*, and contributed chapters to other texts. He holds a number of patents. Dr. Bhartia is a Fellow of IETE and a member of many other technical societies. He served as Associate Editor of the *Journal of Microwave Power* and currently serves on the editorial review boards of a number of journals.