COMPUTER AIDED DESIGN OF MICROSTRIP TAPER LINES

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ABSTRACT

This work presents an accurate computer aided design (CAD) for microstrip taper lines in the microwave range of frequency. This CAD considers all design parameters affecting the characteristics of the line for different terminal impedances. The CAD takes into consideration the dispersion of effective permittivity at high frequency, different substrates materials, different shape ratios (w/h) and metalization thickness. The CAD is designed based on accurate formulas to obtain the matching requirements for any section. Evaluation of the reflection coefficient takes into account the variation of effective permittivity with line width and frequency, and then a modified reflection pattern is applied to obtain the optimum bandwidth for the tapered line. Restrictions for accurate calculations of the effective permittivity and the characteristic impedance at high frequency are underlined.

INTRODUCTION

Microstrip tapered lines are of great importance for MICs. Matching between two different terminal impedances in an integrated circuit must be smooth in a gradual way. Impedance variation from terminal impedance Z_1 to the other terminal Z_2 can be exponential [1], linear [2], parabolic [3], hyperbolic [4] or according to Wills Sinha formulas [5]. Gradual change in impedance from one terminal to the other results in a general variation of the shape ratio (w/h) along the line as shown in Fig.1. In the previous work [6] the effective permittivity (ε_{eff}) and the propagation constant (β) are assumed to be constant along the taper line using the approximation of uniform transmission line. In fact ε_{eff}, β and the characteristic impedance (Z) are functions in both frequency and position along the taper line. The reflection pattern was previously calculated using

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Riccati equation for small reflection as given by Pramanick and Bhartia [7], assuming that both β and ε_{eff} are constant average values. This work presents accurate dispersion analysis of the taper line based on the fact that β, ε_{eff} and Z are functions of position and frequency. Accurate reflection formulas are used to construct the frequency dependent reflection pattern. The study included all types of taper section on different substrate materials.
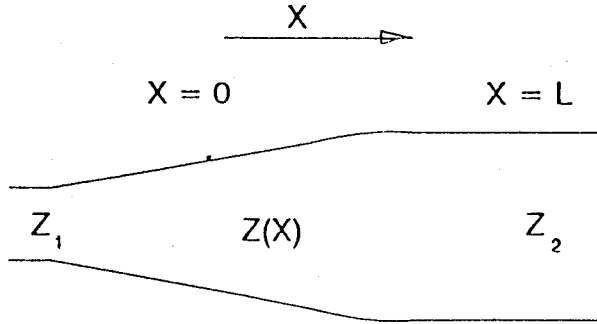

Fig. 1. Taper matching circuit.

ANALYSIS AND DESIGN OF THE TAPER LINE

Different matching sections with different ranges from 25Ω to 100Ω are designed using linear, exponential and Willis - Sinha formulae. The impedance profiles at any length X are given respectively by:

$$Z_0(x) = Z_1 + (Z_2-Z_1) \frac{X}{L} \tag{1}$$

$$Z_0(x) = Z_1 \exp[\frac{X}{L} \ln(\frac{Z_2}{Z_1})] \tag{2}$$

$$Z_0(x) = Z_1 \exp\{[\frac{X}{L} - \frac{0.2405}{2\pi} \sin(\frac{2\pi X}{L})]\ln(\frac{Z_2}{Z_1})\} \tag{3}$$

where L is the total line length. The geometric profile of the line(i.e. obtaining the line width to the substrate height (w/h)) are calculated from the equations given in [8]. Accurate calculations of the metalization thickness (t) effect is given by Hamerstad and Jenson [9] in which they use a corrected shape ratio U_r such that:

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$$Z_0(w/h,t,\varepsilon_r) = \frac{Z_0(U_r)}{\sqrt{\varepsilon_e(U_r,\varepsilon_r)}} \tag{4}$$

$$\varepsilon_{eff}(w/h,t,\varepsilon_r) = \varepsilon_e(U_r,\varepsilon_r)\left[\frac{Z_0(u_1)}{Z_0(u_r)}\right]^2 \tag{5}$$

where:

$$Z_0(U_r) = \frac{\eta_0}{2\pi}\ln\left[\frac{F(U_r)}{U_r} + \sqrt{1+\left(\frac{2}{U_r}\right)^2}\right] \tag{6}$$

$$F(u_r) = 6 + (2\pi - 6)\exp\left[-\left(\frac{30.666}{U_r}\right)^{0.7528}\right] \tag{7}$$

$$\text{and} \quad \varepsilon_e(U_r,\varepsilon_r) = \frac{\varepsilon_{r+1}}{2} + \frac{\varepsilon_{r-1}}{2}\left[1+\frac{10}{U_r}\right]^{-f} \tag{8}$$

where $f = a(U_r).b(\varepsilon_r)$ (9)

$$a(U_r) = 1 + \frac{1}{49}\ln\left[\frac{U_r^4 + \left(\frac{U_r}{52}\right)^2}{U_r^4 + 0.432}\right] + \frac{1}{18.7}\ln\left[1+\left(\frac{U_r}{18.1}\right)^3\right] \tag{10}$$

$$b(\varepsilon_r) = 0.564\left(\frac{\varepsilon_r - 0.9}{\varepsilon_r + 3}\right)^{0.053} \tag{11}$$

$$U_r = (w/h) + \Delta U_r \tag{12}$$

$$U_1 = (w/h) + \Delta U_1 \tag{13}$$

$$\Delta U_1 = \frac{(t/h)}{\pi} \ln\left[1 + \frac{4e}{(t/h)\coth^2\sqrt{6.517(w/h)}}\right] \tag{14}$$

$$\Delta U_r = \frac{1}{2}\left[1 + \left(\cosh\sqrt{\varepsilon_{r-1}}\right)^{-1}\right]\Delta U_1 \tag{15}$$

In the literature the characteristic impedance and the effective permittivity of microstrip lines are calculated using several formulae [8], but accurate calculations considering the effect of metalization thickness (t) is given in [9]. The accuracy of the model for characteristic impedance is better than 0.01% for $U_r \leq 1$ and 0.03% for $U_r \leq 1000$, and the accuracy for effective permittivity is better than 0.2% for $\varepsilon_r \leq 128$ and $0.01 \leq U \leq 100$.

Figs. 2-4 illustrate the relation between w/h and the position along the matching section for different impedance ranges. Fig.5 shows the conductor thickness effect on the geometric profile of the line.
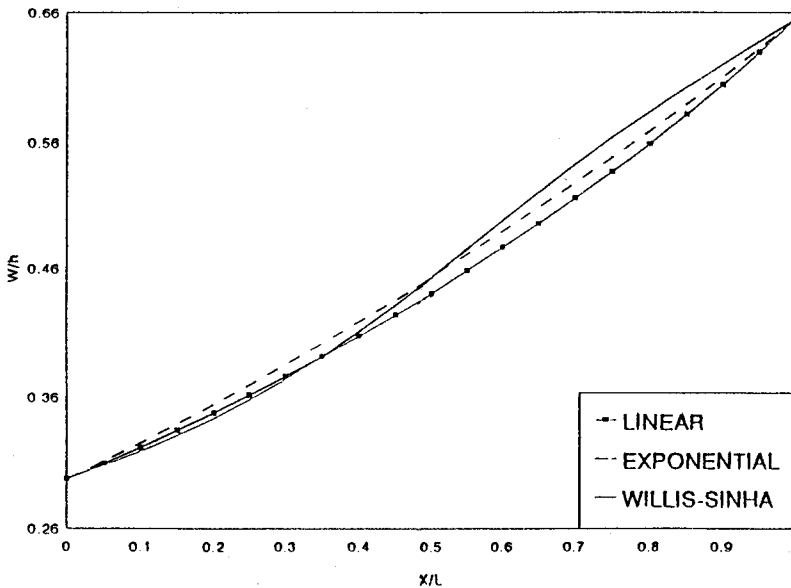

Fig. 2. Geometric profile of different types of taper lines when $Z_1=100\Omega$, $Z_2=75\Omega$, Teflon substrate, $\varepsilon_r=6.0$ & f=2 GHz.
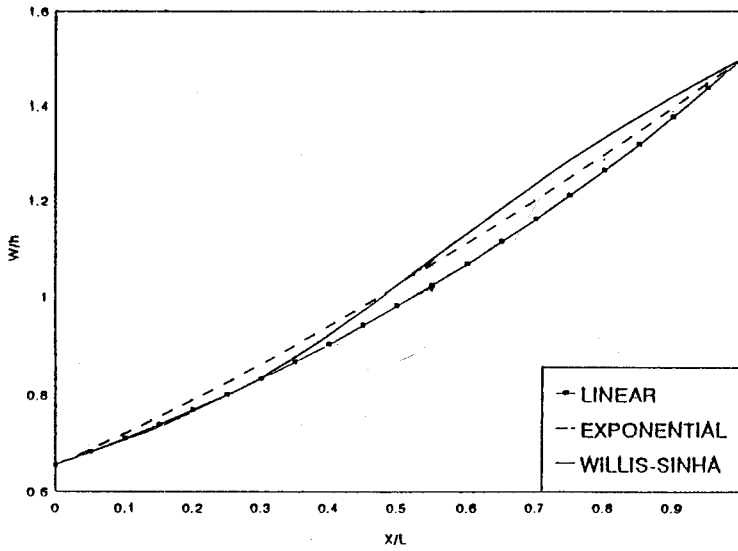
Fig. 3. Geometric profile of different types of taper lines when Z_1=75Ω, Z_2 = 50Ω, Teflon substrate, ε_r=6.0 & f = 2GHz.
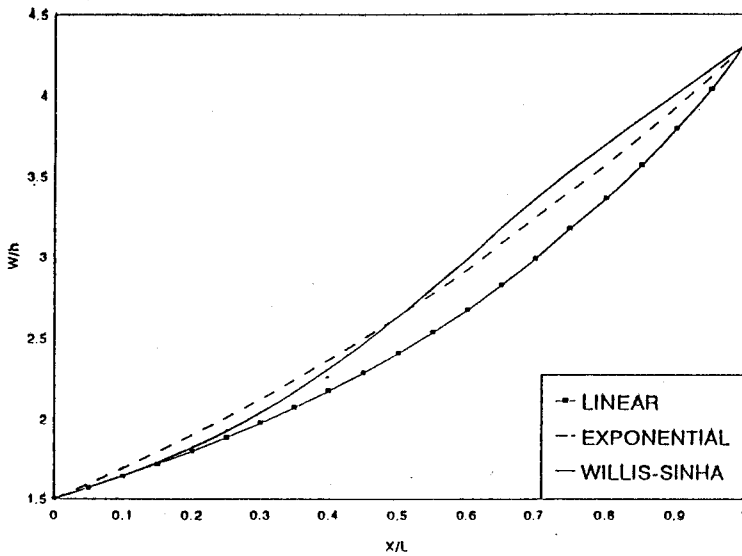

Fig. 4. Geometric profile of different types of taper lines when Z1=50Ω, Z_2 = 25Ω, substrate Teflon, ε_r=6.0 & f = 2GHz.
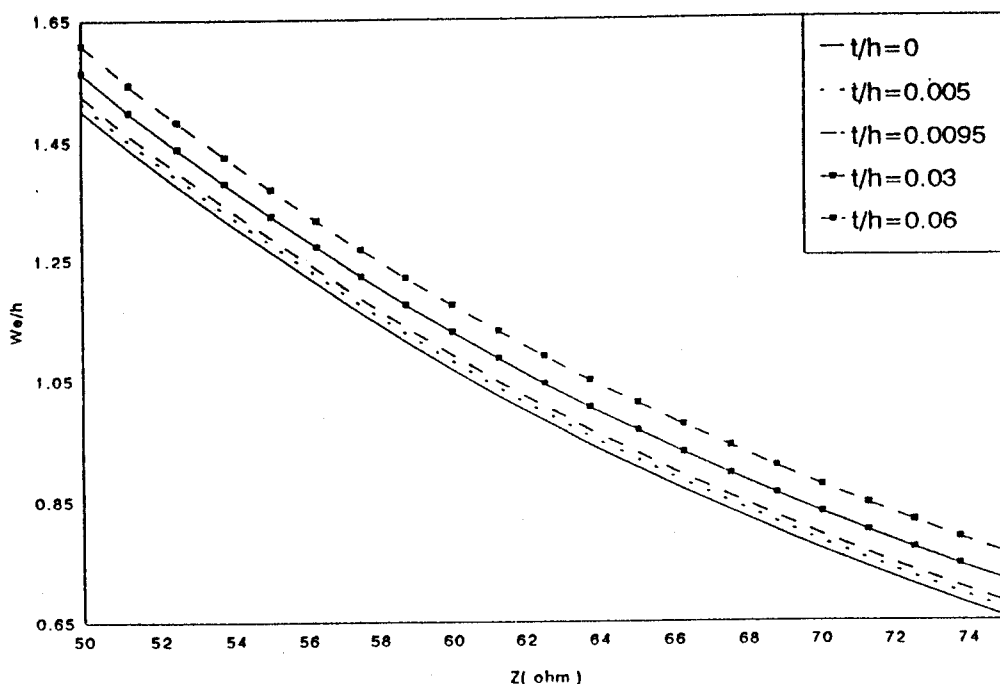
Fig. 5. Effect of conductor thickness on geometric profile of taper line when
$Z_1=75\Omega$, $Z_2 = 50\Omega$, $\varepsilon_r=6.0$ & $f = 2GHz$.

Substrate material is another controlling parameter for both the shape ratio and the impedance profile. If it is required to match between two different impedances with a specified line width, figs.6 and 7 help to choose the dielectric material which must be used for this special matching section. Different material substrates with ε_r ranging from 1.5 to 16 are shown in these graphs to illustrate how impedance profiles change with substrate permittivity. It is worth mentioning that in Fig.7 when matching between impedance's from 25 Ω to 50 Ω using substrates with dielectric constant $\varepsilon_r < 3$, unsmooth profiles are obtained specially when $\varepsilon_r = 2$ and 1.5. Unsmooth profile causes an increase in the signal reflections along the matching section. Hence for optimum design when the range of impedance varies form 25 to 50 ohms substrates with relatively high dielectric constants must be selected ($\varepsilon_r > 3$).

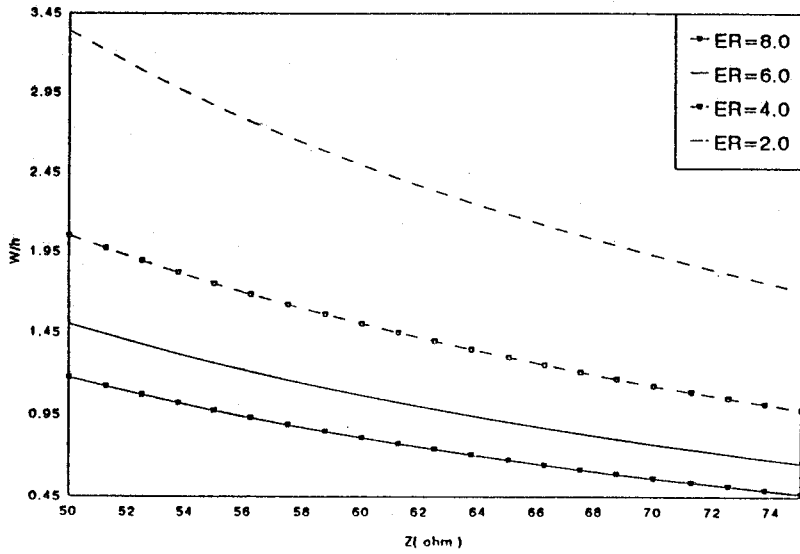**Fig. 6. Effect of relative permittivity on geometric profile of taper line when $Z_1=75\Omega$, $Z2 = 50\Omega$, $\varepsilon_r=6.0$ & f = 2GHz for different substrate materials.**
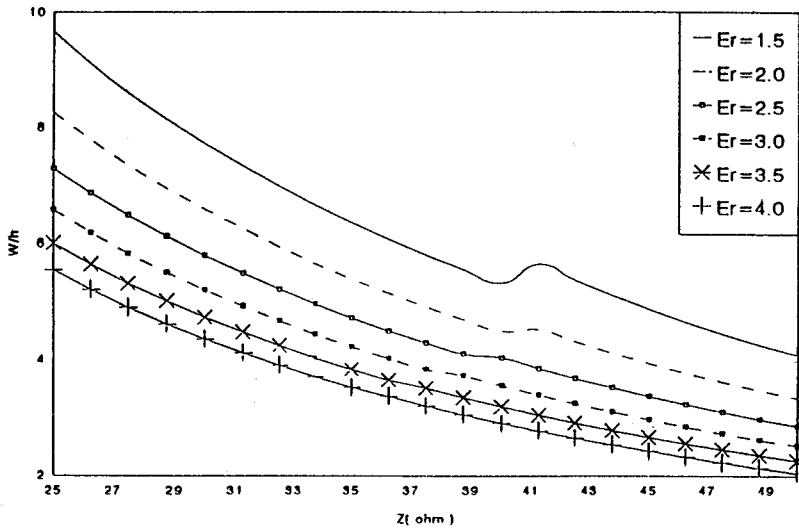

Fig. 7. Geometric profile of taper line when $Z1=50\Omega$, $Z_2 = 25\Omega$, f = 2GHz for different substrate materials.

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DISPERSION CHARACTERISTICS OF THE TAPER LINE.

The microstrip section is designed to operate for a certain bandwidth. But the changes in frequency cause variation in the effective dielectric constant and in the characteristic impedance through the line according to the relations in [9]:

$$\varepsilon_{eff}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}(0)}{1 + G(f/f_p)^2} \tag{16}$$

where:

$$f_p = \frac{Z_0}{2\mu_0 h} \tag{17}$$

$$G = \frac{\pi^2}{12} \frac{\varepsilon_r - 1}{G_{eff}(0)} \sqrt{\frac{2\pi z_0}{\eta_0}} \tag{18}$$

$$Z_0(f) = Z_0(0) \sqrt{\frac{\varepsilon_{eff}(0)}{\varepsilon_{eff}(f)} \frac{\varepsilon_{eff}(f) - 1}{\varepsilon_{eff}(0) - 1}} \tag{19}$$

where Z_o is the characteristic impedance of the line section under consideration, μ_o and η_0 is the free space permeability and impedance respectively, while h is the substrate height. Figs.8-10 illustrate the variation of the effective dielectric constant and impedance with frequency. In these graphs the impedance increases with frequency when using the relations given by equations (4) to (19). In figs.11-12 the impedance decreases with frequency when applying Getsinger's relation [10]. This is due to using different definitions of the characteristic impedance as explained by Getsinger [11]. For the case when $Z_o = 100\Omega$, with different substrates (ε_r=10 to 16), the impedance profiles are different as shown in fig.13 which indicates and emphasizes that the range of (w/h), must be restricted by both the frequency range and ε_r value, these limits are:

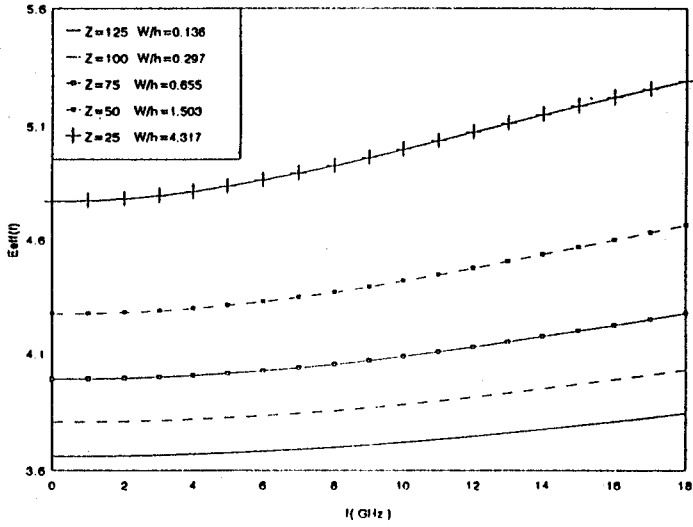$0.19 < w/h < 20$, $\varepsilon_r < 16$ and $f < 18GHz$ (20)

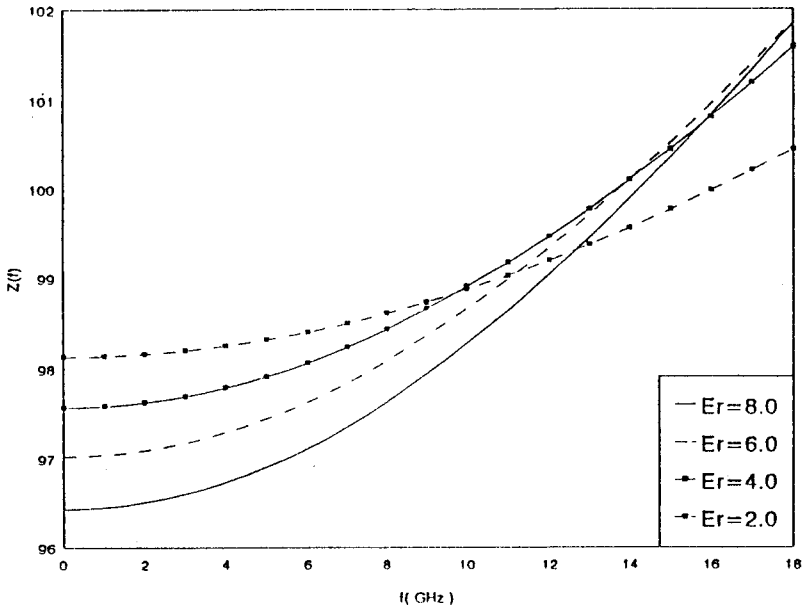**Fig. 8. Dispersion of permittivity when ε_r=6.0.**

Fig. 9. Dispersion of impedance when Z= 100Ω.
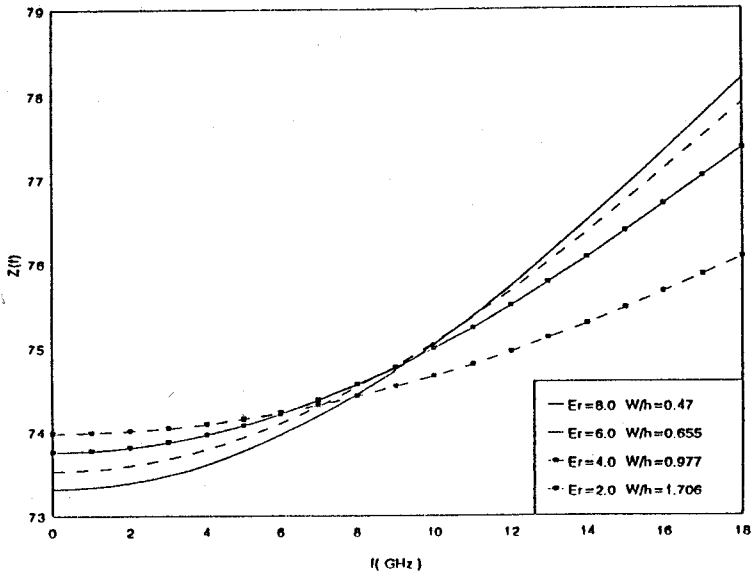
Fig. 10. Dispersion of impedance when Z= 75Ω.
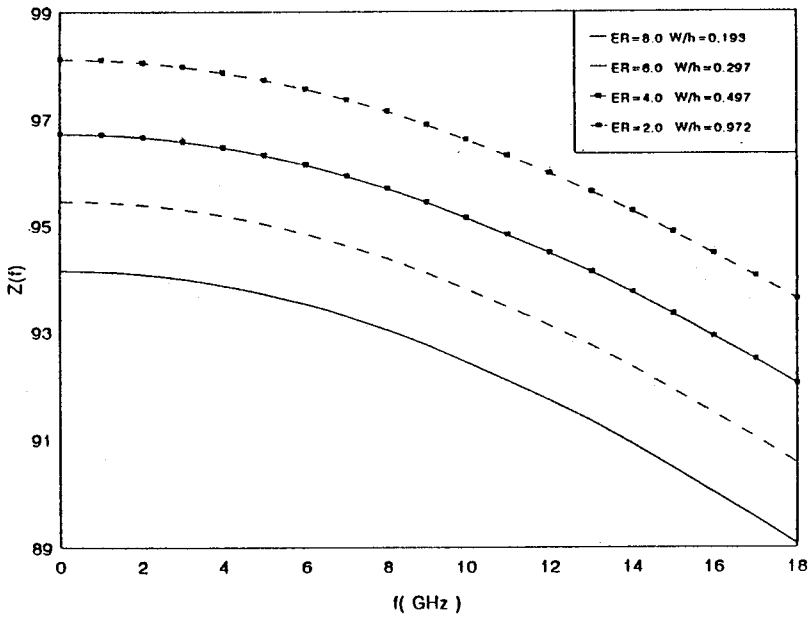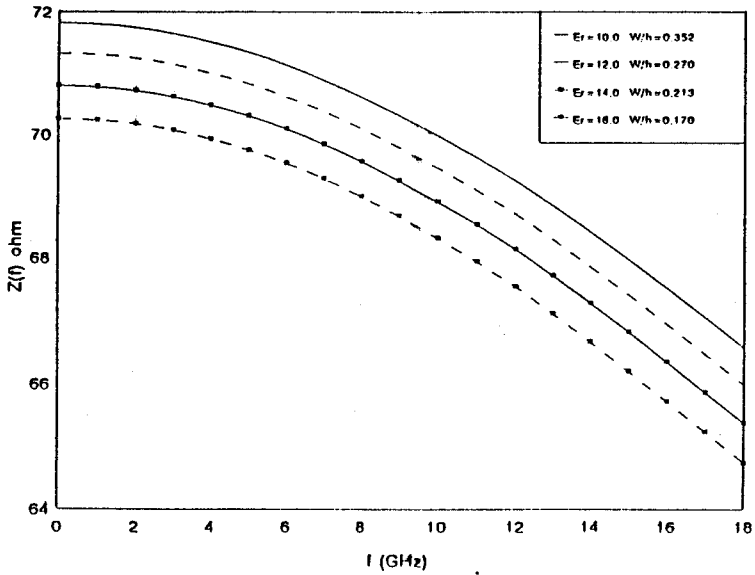

Fig. 11. Dispersion of impedance when Z= 100Ω.
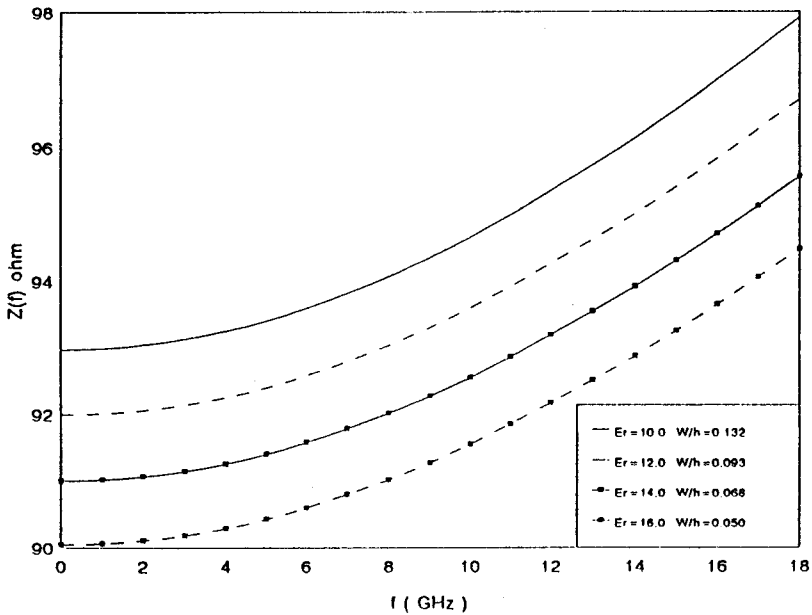
Fig. 12. Dispersion of impedance when Z= 75Ω

Fig. 13. Dispersion of impedance when Z= 100Ω

REFLECTION PATTERN

The propagating waves along the taper line suffers from continuous reflections due to variations in section impedance Z (x). Applying the small reflections theorem [1], the modified total reflection coefficient is given by:

$$\Gamma(f,x) = \frac{1}{2}\int_0^L \exp[-2\beta(f,x)x]\frac{d}{dx}\Big[\ln Z_0(f,x)\Big]dx \qquad (21)$$

where L is the total line length, Zo(f,x) and β(f,x) are respectively, the impedance profile and the propagation constant along the line. Fig.14 illustrates the reflection pattern where $|\Gamma|/\rho o$ is the normalized reflection coefficient while ρo is the reflection coefficient between Z_1 and Z_2 without using the matching section .
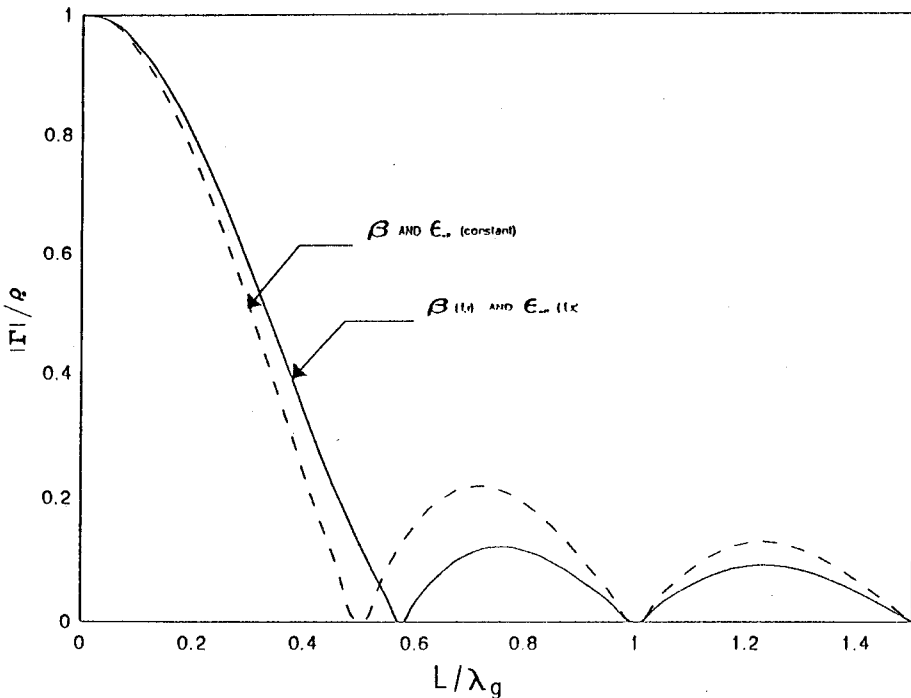

Fig. 14. Reflection pattern when Z_1=75Ω, Z_2=50Ω ε_r=2, f_0 (center frequency) =2GHz, (Exponential taper line).

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OPTIMIZATION OF BAND WIDTH

For a fixed length of taper line which is usually $\lambda_g/2$ length, (λ_g is the wavelength at center frequency), varying the frequency will greatly affect the reflection coefficient. Frequency changing will cause variations in β, ε_{eff} and consequently in Zo. Hence there must be an optimum range of frequency at which the line can operate with minimum reflections. Using the established curves directly, for example when $\varepsilon_r=8$, $Z_1=100\Omega$ and $Z_2=75\Omega$, figs.9 and 10 are used to evaluate the optimum bandwidth for the taper line. For $Z_1=100\Omega$, impedance deviation of $\pm2\%$ at $f_1=7.6$ GHz and $f_2=18$ GHz, While for $Z_1=75\Omega$, impedance deviation of $\pm2\%$ corresponds to $f_1=6$ GHz and $f_2=15.3$ GHz. Hence the optimum common range of frequency for $Z_1=100$, $Z_2=75\Omega$ with minimum impedance variation when $f_1=7.6$ GHz and $f_2=15.3$ GHz, when the center frequency is 11.5 GHz. Table (1) illustrate the optimum bandwidth range for other cases when the maximum error is $\pm2\%$.

Table 1 Optimum bandwidth ranges for same cases when the error is $\pm 2\%$

ε_r	2	4	6	8	10	12	14	16
$Z_1 = 125\Omega$ and $Z_2= 100\Omega$								
f_1(GHz)	4.2	9.9	12.8	14.9	16.9			
f_2 (GHz)	18	18	18	18	18			
$Z_1 = 100\Omega$ and $Z_2= 75\Omega$								
f_1 (GHz)	16.5	16.5	5.3	7.6	9.2	10.7	12.1	
f_2 (GHz)	18	17	15.7	15.3	15	15	15.1	
$Z_1 = 75\Omega$ and $Z_2= 50\Omega$								
f_1 (GHz)	16.5	16.5	16.5	16.5	16.5	2.5	4.1	5.3
f_2 (GHz)	18	14	12.7	12.3	12	11.7	11.5	11.4
$Z_1 = 50\Omega$ and $Z_2= 25\Omega$								
f_1 (GHz)	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
f_2(GHz)	14.7	10.7	9.5	8.8	12	7	6.9	6.9

CONCLUSIONS

This CAD is a design guide which provides the designer with all tools for complete and accurate microstrip taper line, using any dielectric substrate material and for matching between any two practical terminal impedances. This CAD can be used for directly manufacturing the required taper line. The frequency response of the characteristic impedance gives light on the optimum range of operating frequency when matching between any two different terminal impedances. Effect of metalization thickness is considered and the optimum conditions for applying the used formula are obtained by equation (20). Frequency dependent reflection pattern is constructed for the first time using the modified equation (21).

REFERENCES

1. **R.E.Collin**, Foundation for Microwave Engineering, Mc Graw Hill, 1990. Page 370

2. **Rustogi, O. P.**, "IEEE Transaction, Microwave Theory and Tech. 17, 166; 1969.

3. **Yang, R. F. H.**, Proc. IRE, 43, P. 1010, 1955.

4. **Scott, H. J.**, Proc. IRE 41, P. 1654, 1953.

5. **Willis, J. and Sinha, N. K.**, Proc. IEE, 103B P. 166, 1956.

6. **Ching-Wen Hsue**, "Time Domain Scattering Parameters of an Exponential Transmission Line," IEEE Trans. MTT, vol. 39, pp. 1891-1895, Nov. 1991.

7. **Pramanick P. and Bhartia P.**, "A Generalized Theory of Tapered Transmission Line Matching Transformers and Asymmetric Couplers Supporting non-TEM modes, IEEE Trans. MTT, vol. 37, pp. 1184-1191, Aug. 1989.

8. **T.C. Edwards,** Foundation for Microstrip Circuit Design, John Willy and Sons Ltd 1981.

9. **Hammerstad E. and Jenson F.**, "Accurate modal for Microstrip Computer Aided Design," Proc. IEE, vol. 18, pp. 407-409, Nov.1980.

10. **Getsinger W.J.,** "Microstrip Characteristic Impedance," IEEE Trans. Microwave Theory Tech. (MTT), vol. 27,pp. 293-297, Feb. 1979.

11. **Getsinger W.J.,** "Measurement and Modeling of the Apparent Characteristic Impedance of Microstrip," IEEE Trans. MTT, vol. 31, No-8, Aug.1983.