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A Conformal Mapping approach to various Coplanar Waveguide Structures

¹Nataraj Boothalingam and ²Porkumaran Karantharaj

¹Department of ECE, Sri Ramakrishna Engineering College, Coimbatore, Tamil Nadu, India.

²Principal, Dr. NGP Institute of Technology, Coimbatore, Tamil Nadu, India.

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ABSTRACT

This paper presents a quasi-static TEM analysis of various coplanar waveguide structures using conformal mapping to compute their capacitance, effective dielectric constant, phase velocity and characteristic impedance. A few tapered coplanar waveguide structures are discussed for millimeter wave applications. The numeric and simulation results are presented for the various coplanar waveguide structures and show S_{11} greater than 11dB and attenuation S_{21} less than 0.45dB. The phase also varies for different structures ranging from 120° to 128° for same lengths. These types of coplanar designs can be used in phase shifters and varactors with reduction in lengths.

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INTRODUCTION

The quasi-static analysis of microwave transmission lines can be done using conformal mapping, mostly preferred among the other techniques. This technique gives the exact evaluation of line capacitance, line inductance, effective dielectric constant, phase velocity and characteristic impedance of the line. The conformal transformation method is mostly used in the analysis of coaxial structures, strip lines and coplanar waveguides (CPWs) to get the closed form expression for the line parameters in the form of complete elliptic integrals. The conformal mapping's validity relies on the assumption that the propagation mode is quasi-static, i.e., pure TEM mode. Monolithic microwave integrated circuits (MMICs) and electro-optic devices require finite thickness CPWs which led to solution in terms of accurate analytic approximations.

C.P. Wen in 1969 introduced CPW and described its benefits for circuit miniaturization and component integration. The CPW configuration consists of a center conductor strip on top of a dielectric substrate with two ground conductors at a distance G on either side, as shown in Figure 1. The inductance associated with ground is reduced, since the ground is at the same level as the signal line, CPW shows lower dispersion than microstrip, more suitable for some broadband applications. There are a variety of disadvantages to CPW. Packaging may also be more challenging than packaging a microstrip circuit since adding a metal plane at the back of the substrate causes additional parallel-plate waveguide modes which must be dealt with, typically by using a thinned substrate and a significant number of substrate vias for parallel-plate mode suppression.

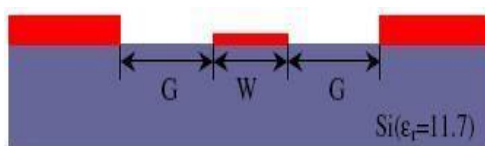


Fig. 1: Layout of the coplanar waveguide

Circuit Parameters of Equivalent Circuit For Cpw:

The equivalent circuit of CPW transmission line has series line inductance L_t and shunt line capacitance C_t , as shown in Figure 2. Using conformal mapping approach, the per unit length capacitance can be computed.

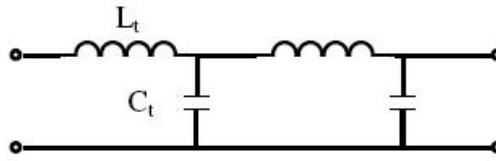


Fig. 2: Equivalent circuit of the coplanar waveguide

The line capacitance is computed using conformal mapping method using two boundary conditions: CPW in the absence of all dielectrics and CPW exist only in a dielectric layer with thickness of h_1 and relative dielectric constant of ϵ_{r1} . The line capacitance can be computed as the sum of two capacitances obtained from the two boundary conditions (Chen, E., *et al.* 1997).

The capacitance C_{nd} under no dielectric condition is solved using conformal mapping, as shown in Figure 3., is given by (Ghione, G., *et al.* 1984, Simons, R. N., 2001)

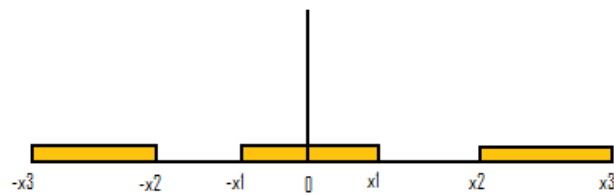


Fig. 3: Configuration of CPW under no dielectric condition

$$C_{nd} = 4\epsilon_0 \frac{K'(k)}{K(k)} \quad (1)$$

where K is the complete elliptical integral of the first kind, and $K'(k) = K(k')$. The variables k and k' are given as

$$k = \frac{x_3}{x_2} \sqrt{\frac{x_2^2 - x_1^2}{x_3^2 - x_1^2}} \quad (2)$$

$$k' = \sqrt{1 - k^2} \quad (3)$$

The capacitance C_d configuration is shown in Figure 4., in which the field exists only in a dielectric layer with thickness of h_1 and relative dielectric constant of $\epsilon_{r1}-1$.

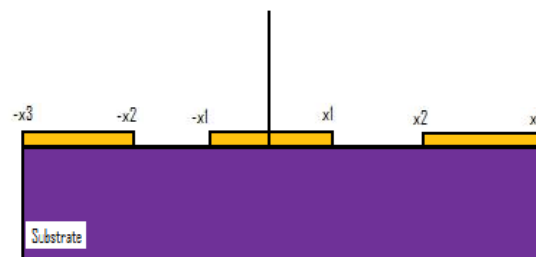


Fig. 4: Configuration of cpw under dielectric condition

$$C_d = 2\epsilon_0(\epsilon_{r1} - 1) \frac{K'(k_1)}{K(k_1)} \quad (4)$$

where

$$k_1 = \frac{\sinh(\frac{\pi x_3}{2h_1})}{\sinh(\frac{\pi x_2}{2h_1})} \sqrt{\frac{\sinh^2(\frac{\pi x_2}{2h_1}) - \sinh^2(\frac{\pi x_1}{2h_1})}{\sinh^2(\frac{\pi x_3}{2h_1}) - \sinh^2(\frac{\pi x_1}{2h_1})}} \quad (5)$$

$$k_1' = \sqrt{1 - k_1^2} \quad (6)$$

The CPW line capacitance is the sum of capacitance under no dielectric condition C_{nd} and capacitance under dielectric condition C_d with thickness h_1 .

$$C_t = C_{nd} + C_d \quad (7)$$

Once line capacitance C_t is obtained, per unit length inductance can be obtained using (Barker, S., Rebeiz, G., 1998)

$$L_t = \frac{1}{c^2 C_t} \quad (8)$$

where c is the speed of light in vacuum.

The line parameters effective dielectric constant ϵ_{eff} , phase velocity v_{ph} , and characteristic impedance Z_0 , of a transmission line are given as

$$\epsilon_{eff} = \frac{C_t}{C_{nd}} \quad (9)$$

$$v_{ph} = \frac{c}{\sqrt{\epsilon_{eff}}} \quad (10)$$

$$Z_0 = \frac{1}{C_t v_{ph}} \quad (11)$$

The complete elliptical integrals of the first kind using the approximations given by (Hilberg, W., 1969, Veyres, C., *et al.* 1980) and is given as

$$\frac{K(k)}{K'(k)} \approx \frac{2}{\pi} \ln \left(2 \sqrt{\frac{1+k}{1-k}} \right) \quad \text{for} \quad 1 \leq \frac{K}{K'} \leq \infty \quad \text{and} \quad \frac{1}{\sqrt{2}} \leq k \leq 1 \quad (12)$$

$$\frac{K(k)}{K'(k)} \approx \frac{\pi}{2 \ln \left(2 \sqrt{\frac{1+k'}{1-k'}} \right)} \quad \text{for} \quad 0 \leq \frac{K}{K'} \leq 1 \quad \text{and} \quad 0 \leq k \leq \frac{1}{\sqrt{2}} \quad (13)$$

Tapered Coplanar Waveguide:

A 7940 μm long CPW conductors are deposited on a 425 μm high resistivity silicon substrate having relative dielectric constant of 11.7 and $\tan\delta=0.008$. The center conductor width and slot width is 80 μm and 45 μm respectively. The layout of conventional CPW and single section of various tapered CPW chosen for analysis is shown in Figure 5(a)-(g) respectively. These tapered CPWs are analyzed using conformal mapping.



Fig. 5: (a). Conventional CPW

Fig. 5: (b). Step Tapered CPW



Fig. 5: (c). Step ground tapered CPW

Fig. 5: (d). Linear tapered CPW



Fig. 5: (e). Linear ground tapered CPW

Fig. 5: (f). Bow-Tie tapered CPW

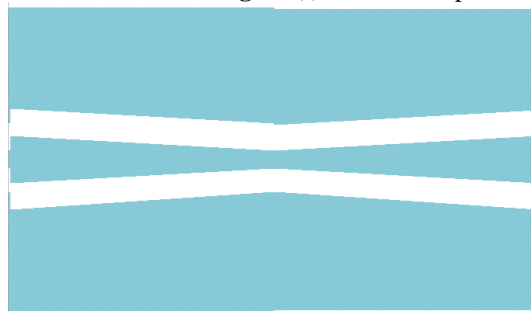


Fig. 5: (g). Bow-Tie ground tapered CPW

A 7940 μm long CPW is divided into 11 sections each of 750 μm long. All the tapered and ground tapered CPW center conductor width has 5 steps ranging from 80 μm to 30 μm for each section. A step tapered CPW showing 3 sections among 11 sections taken for analysis is shown in Figure 6. Table. 1-4 shows the parameters obtained from analysis using conformal mapping technique.



Fig. 6: A step tapered CPW having 3 sections

Table 1: Analysis for conventional CPW

W/ G	C_t (x 10^{-10} F)	ϵ_{eff}	V_{ph} (x 10^6 m/s)	$Z_0(\Omega)$
80/45	1.6555	6.3454	119.0945	50.71

Table 2: Analysis for step tapered CPW

W/ G	C_t (x 10^{-10} F)	ϵ_{eff}	V_{ph} (x 10^6 m/s)	$Z_0(\Omega)$
80/45	1.6555	6.34570	119.0916	50.71
70/50	1.5458	5.9251	123.2416	54.315
60/55	1.4398	5.5188	127.702	58.316
50/60	1.3343	5.1144	132.654	62.927
40/65	1.2266	4.7015	138.359	68.453
30/70	1.1127	4.2649	145.266	75.463

Table 3: Analysis for step ground, linear and bow-tie tapered CPW

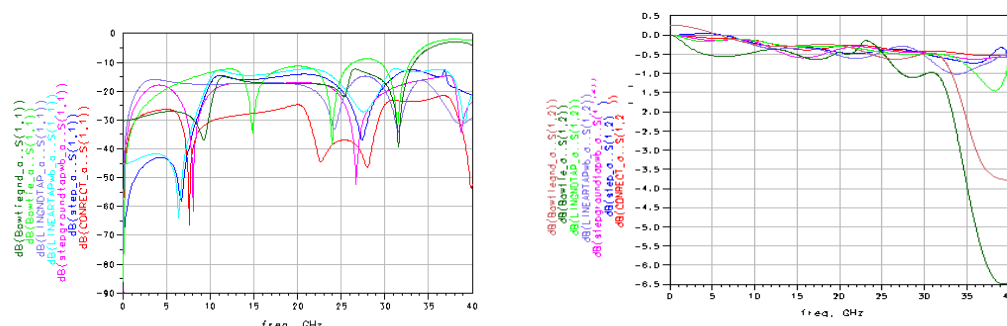
W/ G	C_t (x 10^{-10} F)	ϵ_{eff}	V_{ph} (x 10^6 m/s)	$Z_0(\Omega)$
80/45	1.6555	6.3457	119.0916	50.71
70/45	1.5458	5.925	123.2472	52.59
60/45	1.4398	5.5188	127.7023	54.85
50/45	1.3343	5.1144	132.6550	57.68
40/45	1.2266	4.70159	138.3562	61.35
30/45	1.1127	4.2649	144.2669	66.40

Table 4: Analysis for linear and bow-tie tapered CPW

W/ G	C_t (x 10^{-10} F)	ϵ_{eff}	V_{ph} (x 10^6 m/s)	$Z_0(\Omega)$
80/45	1.6555	6.3457	119.091	50.71
75/47.5	1.5998	6.1321	121.148	52.4814
70/50	1.5458	5.9251	123.246	54.3156
65/52.5	1.4926	5.7212	125.423	56.2533
60/55	1.4398	5.5188	127.702	58.3168
55/57.5	1.3871	5.3168	130.105	60.5308
50/60	1.3343	5.1144	132.655	62.92
45/62.5	1.2810	4.9101	135.386	65.549
40/65	1.2266	4.7015	138.357	68.453
35/67.5	1.1708	4.4877	141.615	71.7197
30/70	1.127	4.2649	145.266	75.4635

Results:

The analysis results shows that using tapered CPWs the characteristic impedance and phase velocity increases rapidly. The change in characteristic impedance and phase velocity increases the phase shift compared to conventional CPW. These CPWs are designed and simulated using ADS and the corresponding S-parameters are obtained for 20GHz frequency. The results are shown in Figure 7 (a) - (c). Table 5 shows the S-parameter values for all the CPW designs. The simulated results shows S_{11} greater than 11dB and S_{21} less than 0.45dB and phase varies from 120° to 128° for same coplanar lengths. It is inferred that step ground tapered waveguide produces more phase than the other designs.

**Fig. 7:** (a) S_{11} (dB) of various CPW designs Figure 7(b) S_{12} (dB) of various CPW designs

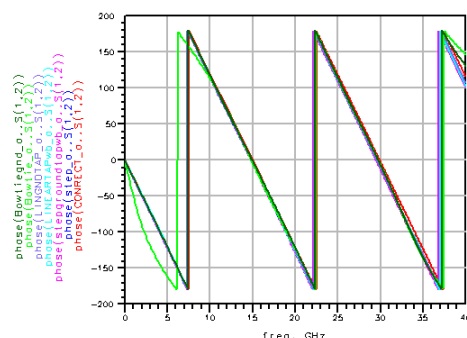


Fig. 7: (c) S_{12} (phase) of various CPW designs

Table 5: S-parameter of various CPW designs

Coplanar Waveguide Types	S_{11} (dB)	S_{12} (dB)	S_{12} (phase)
Conventional CPW	-24.64	-0.29	-120.86
Step Tapered CPW	-14.17	-0.45	-126.86
Step Ground Tapered CPW	-17.13	-0.36	-128.15
Linear Tapered CPW	-12.50	-0.54	-126.54
Linear Ground Tapered CPW	-17.71	-0.29	-125.32
Bow-Tie Tapered CPW	-11.30	-0.45	-122.91
Bow-Tie Ground Tapered CPW	-17.37	-0.27	-121.16

Conclusion:

From Table 5, the CPWs show very low loss and comparing the phase shift of each CPW, the step tapered CPW produces high phase shift (128°) among the other CPW structure designs. The use of step tapered and step ground tapered coplanar waveguides provides an increase in phase shift compared to conventional CPW. These structures can be used in designing a tunable MEMS phase shifter by placing a capacitive membrane above the center conductor of the CPW so that the phase shift per unit length can be improved compared to conventional CPW with very low insertion loss and high isolation. Also, these types of transmission lines can be implemented for tunable MEMS filter and varactor designs.

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