Analysis and Modeling of various Tapered Coplanar Waveguide

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Abstract. This paper proposes the analysis of investigations on various tapered Coplanar Waveguide (CPW) structures to achieve increase in phase shift per unit length and the reduction in line length. The analysis of the tapered CPW is important in order to obtain the characteristic impedance and phase velocity of the transmission line. The step tapered CPW structures proposed have the center conductor, the gap/ground or both the widths varying having constant characteristic impedances for a fixed line length. The conformal mapping method is applied to the proposed tapered CPW structures to obtain the electrical parameters of the transmission line. The obtained impedance can be utilized in the design of RF circuits such as phase shifter using MEMS bridges.

Keywords- Coplanar Waveguide, Conformal Mapping, Quasi-TEM.

INTRODUCTION

Transmission lines are used to carry alternating current (AC) and radio frequency (RF) signals. The energy radiates off the lines as waves causing power losses and reflects in the cable and returns back towards the source. The construction of the lines uses precise conductor spacing, dimensions and impedance matching, which carry electromagnetic signals with reflections being minimal and low power loss. Microwave signals are electromagnetic waves having frequencies, ranging from 300 MHz to 300GHz corresponding to wavelengths 1m to 1mm. To conduct energy at high frequencies, the wavelength becomes much smaller than the dimensions of the transmission lines. The wavelength is comparable to the device dimension leading to many issues in the design of microwave components. The selection of transmission line used in Monolithic Microwave Integrated Circuits (MMIC) is an essential part of the design process. This paper analyzes the transmission line equations and describes the proposed tapered coplanar waveguide structures electrical parameters using conformal mapping analysis.

Transmission lines are analyzed using their lumped element model or distributed element model. Maxwell’s equations are applied to all types of transmission lines to analyze the electromagnetic behavior at all frequencies. When the electrical length is comparable to that of the operating wavelength of the circuit, lumped element components represent the electrically smaller section of a transmission line. In such cases, the circuit parameters are considered to be frequency independent parameters [1]. At high frequencies the electrical length is relatively larger which needs wave equations in the analysis of circuits [2]. The distributed models are often used in the analysis of micro-scale circuits such as Integrated Circuits (IC). Figure 1 represents the equivalent lumped element model circuit of a section of transmission line having inductance (L) and capacitance (C).
The most commonly used transmission media for microwave integrated circuits is the planar transmission lines. This section gives a preview of the most commonly used planar transmission line for Printed Circuit Boards (PCB), ICs and MMICs. The first planar line was the strip transmission line consisting of a thin strip conductor sandwiched between two dielectric sheets with conductive plating on the two outer sides supporting TEM wave propagation. The advantage of striplines are emissions by adjacent planes, highly scalable used in multilayer interconnects and immunity to crosstalk. The limitation is that striplines needs multilayers for signal transmission and power sources [4]. Microstrip consists of a substrate having high dielectric constant with a strip conductor on one side and a conducting layer on the opposite side to confine the electromagnetic fields near the strip conductor. Microstrip cannot propagate true TEM wave due to the inhomogeneous dielectric materials. Cohn [5] introduced slotline, an alternative to microstrip line has a slot conducting layer on one side of the dielectric substrate. Frankel et al [6] demonstrated good signal propagation of very fast pulses in coplanar stripline, the width of the coplanar strips can be varied to control resonance. The limitation reported by Goverdhanam et al [7] is susceptible to crosstalk from neighboring circuits, due to lack of shielding. Coplanar Waveguide (CPW) transmission line was proposed by Wen [8] which has all the conductors on the one side of the dielectric substrate with no metallization on the reverse side. The structure has a strip conductor separated by a slot on either side from two adjacent ground planes. The CPW design was later modified by many researchers to obtain good attenuation and dispersion characteristics. Yoon et al [9], Wu et al [10] modified the structure of CPW by having center strip conductor elevated, so that dielectric interface discontinuities are reduced. The geometrical model of CPW consists of three strip conductors placed adjacent on the top of the dielectric substrate, central strip being the signal line and the other two on either side being the semi-infinite ground planes. Figure 2 illustrates the conventional CPW geometry and electromagnetic field distributes in CPW. The two coplanar slots act as perfect magnetic walls.

The advantages and use of CPW transmission line in RF MEMS applications paved way for the study and analysis of different modified CPW structures proposed in this paper.
1. QUASI-STATIC ANALYSIS OF THE PROPOSED CPW

The characteristics of coplanar waveguide is analyzed using conformal mapping technique, transforming the geometry of the PCB into another conformation, whose properties make the computations straightforward. The electrical parameters are computed and the equivalent circuit of CPW transmission line at high frequency has series line inductance \( L_t \) and shunt line capacitance \( C_t \) is shown in figure 3. The per unit length capacitance is found to compute the characteristics of CPW.

![Figure 3. Equivalent circuit of the Coplanar Waveguide](image1)

The conformal mapping approach computes the line capacitance under two boundary conditions with the line with no dielectrics and the line with a dielectric layer of thickness \( h_1 \) and relative dielectric constant \( \Sigma_{r1} \). The line capacitance of the coplanar waveguide is the addition of two capacitances obtained from the two boundary conditions without the dielectric substrate and with dielectric substrate[11].

The capacitance \( C_{nd} \) under no dielectric condition boundary condition of the CPW structure [12,13] shown in Figure 4 and given by equation (1)

![Figure 4. CPW with only conductor and no dielectric substrate](image2)

\[
C_{nd} = 4\varepsilon_0 \frac{K'(k)}{K(k)}
\]

\[
k = \frac{x_c}{x_t} \sqrt{\frac{x_t^2 - x_0^2}{x_c^2 - x_0^2}} \quad \text{and} \quad k' = \sqrt{1 - k^2} \quad k'' = \sqrt{1 - k'^2}
\]

Figure 5 illustrates the capacitance \( C_d \) configuration with the dielectric layer existing on a conductor with \( h_1 \) thickness, \( \Sigma_{r1} \) represented by equation (3)
The line capacitance of the coplanar waveguide is given in the equation (5) as

$$C_t = C_{nd} + C_d$$

Once line capacitance $C_t$ is obtained, per unit length inductance $L_t$ can be obtained using equation (6)

$$L_t = \frac{1}{c^2 C_t}$$

The electrical parameters of a CPW transmission line is given as

$$\varepsilon_{\text{eff}} = \frac{C_{ph}}{C_{nd}}$$

$$\sqrt{\varepsilon_{\text{eff}}} = \frac{c}{\sqrt{\varepsilon_{\text{eff}}}}$$

$$Z_0 = \frac{1}{\varepsilon_{\text{eff}} \sqrt{\varepsilon_{\text{eff}}}}$$

2. **TAPERED CPW STRUCTURES ANALYSIS**

2.1 **CONVENTIONAL CPW STRUCTURE**

The conventional CPW transmission line has the centre conductor width of 80µm, gap width of 45µm and ground width of 170µm. The CPW metal with gold conductor of 1µm thickness is deposited on a high resistive silicon substrate of 425µm thickness having 11.7 dielectric constant and 0.008 loss tangent (tan $^\text{TM}$), as shown in Figure 6.
2.2 PROPOSED STEP TAPERED CPW STRUCTURES

The tapered waveguide proposed consists of variations in either the center conductor or the gap width of the CPW line. The characteristic impedance of the line varies with respect to the variation in center conductor or the gap width. The 7.94mm long CPW transmission line is divided into 11 tapered sections, each section has length 750µm. In the proposed first design, the sections having spacing of 750µm has center conductor width tapered into 5 sections each of 150µm long and the signal line width varying from 80µm to 40µm in the step size of 10µm, as shown in Figure 7.

Figure 7. A section of 2D-model of step tapered CPW design 1

The second design proposed has a constant conductor width of 80µm and the gap width varying from 45µm to 25µm in the step size of 5µm, as illustrated in Figure 8. The ground width is varying from 170µm to 190µm for step size of 5µm.

Figure 8. Step tapered CPW design 2

Figure 9 depicts the third design, having constant conductor width and the gap width varying between 45µm to 65µm. The ground width taper decreases from 170µm to 150µm.
The fourth design has a constant gap width and the conductor width varying from 80µm to 40µm, as shown in Figure 10. Ground width taper vary from 170µm to 190µm.

The fifth design has both the center conductor, gap width and ground width varying from 80µm to 40µm, 45µm to 85µm and 170µm to 150µm respectively, as shown in Figure 11.

3. RESULT AND DISCUSSION

The effective analysis of the proposed tapered CPW structures to obtain the electrical parameters is demonstrated using computer simulations in MATLAB and the parameters are obtained with respect to the variation in CPW conductor widths and are tabulated. The table illustrates the obtained line parameters of the CPW transmission line. From the Table 1, the conventional CPW has a constant
characteristic impedance of 50.78 \( \Omega \) throughout the line. A constant phase velocity of 119 x 106 m/s is obtained for the conventional CPW design and the phase velocity can be varied by adding circuits to the CPW transmission line.

**Table 1.** Calculated electrical parameters for conventional CPW line

| Coplanar Waveguide Types | W/G (µm)  | \( C_{CPW} \times 10^{-10} \) (F) | \( \varepsilon_{eff} \) | \( v_{ph} \times 10^6 \) (m/s) | \( Z \) (\( \Omega \)) |
|--------------------------|-----------|----------------------------------|-------------------|-------------------------------|-----------------|
| Conventional CPW         | 80/45     | 1.656                            | 6.345             | 119.09                        | 50.78           |

From the Table 2, the five steps tapered coplanar waveguide designs have impedances varying from 50.78 \( \Omega \) to 68.51 \( \Omega \), 50.78 \( \Omega \) to 42.55 \( \Omega \), 50.78 \( \Omega \) to 57.16 \( \Omega \), 50.78 \( \Omega \) to 61.26 \( \Omega \), and 50.78 \( \Omega \) to 74.48 \( \Omega \) in five steps, respectively. The electrical parameters for the different step CPW conductor widths are obtained and are listed in Table.2.

**Table 2.** Calculated electrical parameters for step tapered CPWs

| CPW Types               | W/G (µm)  | \( C_{CPW} \times 10^{-10} \) (F) | \( \varepsilon_{eff} \) | \( v_{ph} \times 10^6 \) (m/s) | \( Z \) (\( \Omega \)) |
|-------------------------|-----------|----------------------------------|-------------------|-------------------------------|-----------------|
| Step Tapered CPW Design 1 | 80/45     | 1.656                            | 6.345             | 119.09                        | 50.78           |
|                         | 70/50     | 1.546                            | 6.345             | 119.10                        | 54.36           |
|                         | 60/55     | 1.440                            | 6.345             | 119.10                        | 58.37           |
|                         | 50/60     | 1.335                            | 6.345             | 119.10                        | 62.98           |
|                         | 40/65     | 1.227                            | 6.345             | 119.09                        | 68.51           |
| Step Tapered CPW Design 2 | 80/45     | 1.656                            | 6.345             | 119.09                        | 50.78           |
|                         | 80/40     | 1.717                            | 6.345             | 119.10                        | 48.96           |
|                         | 80/35     | 1.789                            | 6.345             | 119.09                        | 47.00           |
|                         | 80/30     | 1.874                            | 6.346             | 119.09                        | 44.88           |
|                         | 80/25     | 1.976                            | 6.347             | 119.08                        | 42.55           |
| Step Tapered CPW Design 3 | 80/45     | 1.656                            | 6.345             | 119.09                        | 50.78           |
|                         | 80/50     | 1.602                            | 6.344             | 119.11                        | 52.50           |
|                         | 80/55     | 1.553                            | 6.343             | 119.11                        | 54.12           |
|                         | 80/60     | 1.510                            | 6.342             | 119.12                        | 55.68           |
|                         | 80/65     | 1.470                            | 6.342             | 119.12                        | 57.16           |
| Step Tapered CPW Design 4 | 80/45     | 1.656                            | 6.345             | 119.09                        | 50.78           |
|                         | 70/45     | 1.598                            | 6.345             | 119.10                        | 52.59           |
|                         | 60/45     | 1.534                            | 6.345             | 119.09                        | 54.82           |
|                         | 50/45     | 1.460                            | 6.346             | 119.08                        | 57.61           |
The step tapered CPW Design 1 proposed has five step structures in the center conductor and are analyzed to have characteristic impedances of 50.78, 54.36, 58.37, 62.98 and 68.51, respectively. The second step tapered design has characteristic impedances of 50.78, 48.96, 47, 44.88 and 42.55, respectively for the five step tapers proposed of a length of 750µm. The design 3 proposed has a constant center conductor width and decreasing ground width of step size 5µm having characteristic impedances of 50.78, 52.50, 54.12, 55.68 and 57.16, respectively. The characteristic impedances of the step tapered CPW design 4 is derived and have 50.78, 52.59, 54.82, 57.61 and 61.26, respectively for the five sections. The fifth step tapered design proposed has characteristic impedances values of 50.78, 56.04, 61.56, 67.60 and 74.48, respectively. The effective dielectric constant and the phase velocity of the proposed step tapered CPW designs are also derived.

4. CONCLUSION

The electrical parameters of the proposed tapered CPW structures are obtained using conformal mapping method and are observed that the tapered structures have an impedance change at the tapered points. Compared with the conventional CPW structure, the proposed tapered design exhibits a variation in impedance at the sample points used for the analysis. The variation in phase velocity leads a thought to use the tapered CPW structures in phase shifter application. The impedances obtained can used in the design of RF MEMS phase shifter using periodically loaded tapered impedance transmission line.

References

[1] Rabaey, JM, Chandrakasan, AP, Nikoli, B.: Digital Integrated Circuits: A Design Perspective, Pearson Education, NJ, (2003)
[2] Pozar, DM.: Microwave Engineering, 3rd edn, John Wiley, NJ, (2005)
[3] Ramo, S, Whinnery, J, Van Duzer, T.: Fields and Waves in Communication Electronics, 3rd edn.John Wiley & Sons, (1993)
[4] Cohn, SB.: Characteristic Impedance of Shielded Strip Transmission Line. IRE Transactions on Microwave Theory and Techniques, 2, 52-55 (1954).
[5] Cohn, SB.: Slot Line - An Alternative Transmission Medium for Integrated Circuits. Proceedings of the G-MTT International Microwave Symposium, pp. 104-109 (1968).
[6] Frankel, MY, Gupta, S, Valdmanis, J, Mourou, GA.: Terahertz attenuation and dispersion characteristics of coplanar transmission lines. IEEE Transactions on Microwave Theory and Techniques, 39(6), 910-916, (1991).

[7] Goverdhanam, K, Katehi, LPB & Cangellaris, A.: Applications of multiresolution based FDTD multigrid. IEEE MTT-S International Microwave Symposium Digest, 1, 333-336 (1997).

[8] Wen, CP.: Coplanar Waveguide: A Surface Strip Transmission Line suitable for Nonreciprocal Gyromagnetic Device Applications. IEEE Transactions on Microwave Theory and Techniques, 17(12), 1087-1090 (1969).

[9] Yoon, SJ, Jeong, SH, Yook, JG, Kim, YJ, Lee, SG, Seo, OK, Lim, KS & Kim, DS.: A novel CPW structure for high-speed interconnects. IEEE MTT-S International Microwave Symposium Digest, 2, 771-774 (2001).

[10] Wu, Ke, Yu, M & Vahldieck, R.: Rigorous analysis of 3-D planar circuit discontinuities using the space-spectral domain approach (SSDA). IEEE Transactions on Microwave Theory and Techniques, 40(7), 1475-1483 (1992).

[11] Chen, E, Chou, SY.: Characteristics of coplanar transmission lines on multilayer substrates: modeling and experiments. IEEE Transactions on Microwave Theory and Techniques, 45(6), 939-945 (1997).

[12] Ghione, G, Naldi, C.: Analytical Formulas for Coplanar Lines in Hybrid and Monolithic MICs. Electronics Letters, 20(4), 179-181 (1984).

[13] Nataraj, B, Porkumaran, K.: RF Phase Shifter using MEMS Switches on a tapered Coplanar Waveguide. Songklanakarin Journal of Science and Technology, 34(6), 645-651 (2012).

[14] Simons, RN.: Coplanar Waveguide Circuits, Components and Systems, John Wiley and Sons (2001).

[15] E. Ramprasath, P. Manojkumar and P. Veena, "Induction motor analysis using labview", Proceeding on International Conference on Electrical Engineering and Technology, vol. 2, no. 5, pp. 498, 2015.

[16] Nataraj B, Porkumaran K.: Conformal Mapping Analysis of Various Coplanar Waveguide Structures. ICTACT Journal on Communication Technology, 3(2). (2012).

[17] Nataraj, B, Porkumaran, K.: Investigation of using tapered Coplanar Waveguide in RF MEMS phase shifter. UPB Scientific Bulletin Series C, 75(1), (2013).