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CONFORMAL MAPPING ANALYSIS OF VARIOUS COPLANAR WAVEGUIDE STRUCTURES

B. Nataraj[1] **and K. Porkumaran**[2]
[1]*Department of Electronics and Communication Engineering, Sri Ramakrishna Engineering College, India*
E-mail: bnatarajpillai@gmail.com
[2]*Dr. NGP Institute of Technology, India*
E-mail: porkumaran@gmail.com

Abstract
A conformal mapping analysis of various coplanar waveguide structures is presented on silicon substrate. The analysis is based on quasi-TEM analysis which is used in formulating the electrical parameters of a transmission line. Different coplanar structure configurations are investigated. Simulation results are presented for coplanar waveguides etched on the surface of a rectangular silicon substrate. Calculated electrical parameters like line capacitance, characteristic impedance, effective dielectric constant and phase velocity and simulated results shows tapered waveguides are more suitable for tunable devices like MEMS phase shifters, varactor designs. The results shows return loss of conventional CPW designs varying from 32 dB at 1 GHz to a value of 52 dB at 40 GHz. The loss of Bow-tie and Bow-tie ground tapered configurations are above 29 dB at 1dB and above 39 dB at 32 GHz. The insertion loss obtained from simulation of the 3 coplanar waveguide designs is less than 1 dB upto 30GHz.

Keywords:
Coplanar Waveguide, TEM, MEMS, Phase Shifters, Varactors

1. INTRODUCTION

The high-speed electronic devices operate successfully at frequencies above 100 GHz. For frequencies higher than 100 GHz monolithic circuits encounter high attenuation, dispersion and multi-mode propagation [1]. These problems are due to the underlying high permittivity substrate. An obvious solution to these problems is to remove the underlying substrate and to fabricate planar transmission lines on thin dielectric membrane. At these high frequencies, planar transmission lines have to be used for device connection and signal distribution to retain the signal fidelity [2]. Among all the types of transmission lines, coplanar transmission lines, coplanar waveguides (CPW), are most promising due to their integration capability with electronic devices and fabrication compatibility with modern ultra-large scale integration (ULSI) processing. Coplanar lines are important components in the ultra fast signal characterization [3], [4] and monolithic microwave integrated circuits [5], [6].

The transmission line analysis are carried out by either full-wave or quasi-static analysis. The full-wave analysis requires time-consuming numerical calculations, and quasi-static analysis, which provides analytic formulas, is generally preferred in transmission-line design. The first analytic formulas for calculating quasi-static wave parameters of CPW's have been given by Wen, obtained using conformal mapping [7]. However, Wen's formulas are based on the assumption that the substrate thickness is infinitely large and the ground wires of the CPW's are infinitely wide [8], [9]. Veyres and Fouad Hanna have extended the application of conformal mapping to CPW's with finite dimensions and substrate thicknesses [10]. Their formulas have been proven experimentally to be quite accurate by several authors [11], [12]. Fouad Hanna also has derived analytic formulas for CPS's on substrates with finite thicknesses. His results, however, have a good accuracy only if the thicknesses of substrates are larger than the line dimensions, but diverge otherwise. To solve this problem, Ghione et al. have obtained more generalized formulas using the duality principle that the phase velocities of complementary lines are equal [11].

MEMS technology has emerged as a key approach for building low-loss mm-wave components. Radio Frequency (RF) MEMS concepts have been implemented in the development of low-loss RF switching devices and variable capacitors using CPW. Low-loss MEMS CPW switching devices have been used to realize conventional switched – line phase shifter circuits with significantly lower loss. Microwave switches have been fabricated in both series and shunt configurations. In the series configuration with the MEMS switch actuated, the signal path is completed, whereas in shunt configuration, the signal path is shorted to ground with the switch actuated. MEMS switch designs have been very similar to standard p-i-n diode or FET switch networks, with the active device replaced by the MEMS switch. With decrease in size to micro-scale, force, size and boundary conditions should be considered for the design of MEMS structures [13]. In Micro/nano-scale fabrication techniques, any ideal boundary condition could not be applied and boundary support conditions are to be theoretically validated.

Lakshminarayanan and Weller [14] proposed a distributed MEMS phase shifter using tapered coplanar waveguide. The use of MEMS CPW switches for the design of tunable filter for X-band was reported [15]. Frequency is tuned using MAM fixed-fixed shunt switches producing variable capacitances for the band pass filter. The loss obtained is less than 0.7 dB for X-band. Chen and Chou [2] presented the characteristics of coplanar waveguide on a multilayer substrate. Simons [16] presented the various analysis and synthesis methods for various coplanar transmission lines for use in RF applications.

2. COPLANAR WAVEGUIDE ANALYSIS

CPW transmission line consists of a center conductor strip and two ground conductor planes with variable widths, placed on the same side of a dielectric substrate, as shown in Fig.1. In practice, the back of the substrate is often in contact with a metal package, coated with metal, or metalized. Since the ground is at the same level as the signal line, the inductance associated with accessing ground is significantly reduced. The characteristic impedance of the transmission line is determined by both *W* and *S*. The equivalent circuit of the CPW with per unit length Inductance and capacitance are shown in Fig.2.

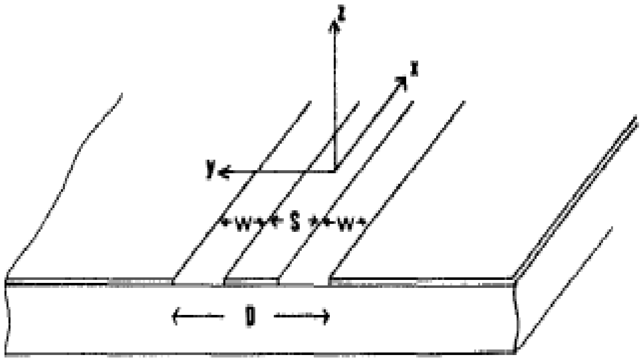

Fig.1. Structure of the CPW transmission line

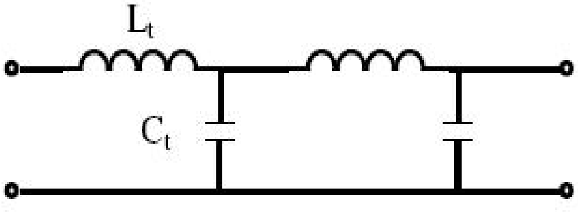

Fig.2. Equivalent Circuit of the CPW

The effective dielectric constant ε_{eff}, phase velocity ν_{ph}, and characteristic impedance Z_0, of a transmission line are given as, [2]

$$\varepsilon_{eff} = \frac{C_{CPW}}{C_0} \tag{1}$$

$$\nu_{ph} = \frac{c}{\sqrt{\varepsilon_{eff}}} \tag{2}$$

$$Z_0 = \frac{1}{C_{CPW}\nu_{ph}} \tag{3}$$

where, c is the speed of light in free space, C_{CPW} is the line capacitance of the transmission line, and C_0 is the line capacitance of the transmission line when no dielectrics exist. To obtain the quasi-static wave parameters of a transmission line, we only have to find the capacitances C_{CPW} and C_0.

The Veyres – Fouad Hanna approximation [10] is used in our case, in which the line capacitance of the CPW shown in Fig.2. can be written as the sum of two line capacitances, i.e.,

$$C_{CPW} = C_0 + C_1 \tag{4}$$

C_0 is the line capacitance of the C_{PW} in the absence of all dielectrics and this boundary problem can be solved using conformal mapping, which gives,

$$C_0 = 4\varepsilon_0 \frac{K^{'}(k)}{K(k)} \tag{5}$$

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

$$k = \frac{x_c}{x_b}\sqrt{\frac{x_b^2 - x_a^2}{x_c^2 - x_a^2}} \tag{6}$$

$$k^{'} = \sqrt{1-k^2} \tag{7}$$

The configuration of C_1, in which the electrical field exists only in a dielectric layer with thickness of h_1 and relative dielectric constant of ε_{r1}-1.

$$C_1 = 2\varepsilon_0(\varepsilon_{r1} - 1)\frac{K'(k_1)}{K(k_1)} \tag{8}$$

where,

$$k_1 = \frac{\sinh(\frac{\pi x_c}{2h_1})}{\sinh(\frac{\pi x_b}{2h_1})}\sqrt{\frac{\sinh^2(\frac{\pi x_b}{2h_1}) - \sinh^2(\frac{\pi x_a}{2h_1})}{\sinh^2(\frac{\pi x_c}{2h_1}) - \sinh^2(\frac{\pi x_a}{2h_1})}} \tag{9}$$

$$k_1^{'} = \sqrt{1-k_1^2} \tag{10}$$

The complete elliptical integrals of the first kind using the approximations given by Hilberg is given as,

$$\frac{K(k)}{K^{'}(k)} \approx \frac{2}{\pi}\ln(2\sqrt{\frac{1+k}{1-k}}) \text{ for } 1 \le \frac{K}{K^{'}} \le \infty \text{ and } \frac{1}{\sqrt{2}} \le k \le 1 \tag{11}$$

$$\frac{K(k)}{K^{'}(k)} \approx \frac{\pi}{2\ln(2\sqrt{\frac{1+k^{'}}{1-k^{'}}})} \text{ for } 0 \le \frac{K}{K^{'}} \le 1 \text{ and } 0 \le k \le \frac{1}{\sqrt{2}} \tag{12}$$

3. TAPERED COPLANAR WAVEGUIDE

A 7940 μm long C_{PW} conductors are deposited on a 425μm high resistivity silicon substrate having relative dielectric constant of 11.7 and tanδ=0.008. The center conductor width and slot width is 80μm and 45μm respectively. The layout of conventional C_{PW} and single section of various tapered C_{PW} chosen for analysis is shown in Fig.3, Fig.4 and Fig.5 respectively. These tapered CPWs are analyzed using conformal mapping.

Fig.3. Conventional CPW

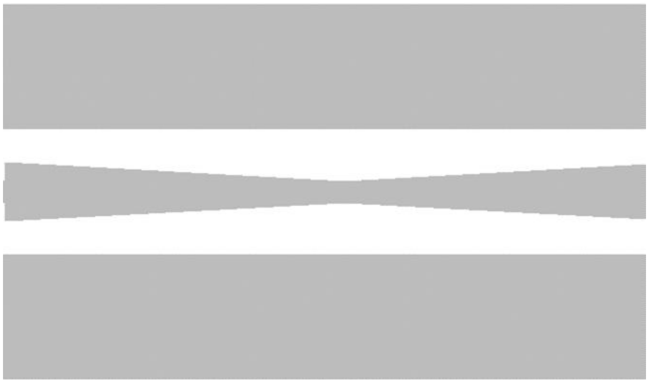

Fig.4. Bow-Tie Tapered CPW

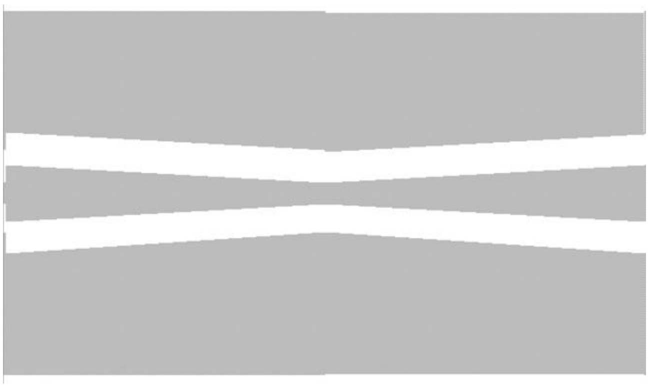

Fig.5. Bow-Tie Ground Tapered CPW

Fig.6. A Bow-Tie tapered CPW having 2 sections

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 ranging from 80µm to 30µm for each section. A step tapered CPW showing 2 sections among 11 sections taken for analysis is shown in Fig.6.

4. SIMULATION RESULTS

From the conformal mapping analysis, the electrical parameters like line capacitance, effective dielectric constant, phase velocity and characteristic impedance obtained for the conventional coplanar waveguide is 0.1655 pF, 6.3454, 119.1 x 10^6 m/s and 50.7 Ω respectively and for the tapered waveguide having the varying width has line capacitance varying from 0.1655 to 0.1127 pF, effective dielectric constant being 6.3454 to 4.264, phase velocity varies from 119.1 x 10^6 to 145.3 x 10^6 m/s, and impedance 50.7 Ω to 75 Ω. The geometries of these waveguides are implemented simulated using Agilent’s ADS. We performed quasi- static electromagnetic calculations for these waveguide structures over the frequency range upto 40GHz. The s-parameters obtained from the simulation are shown in Fig.7 and Fig.8.

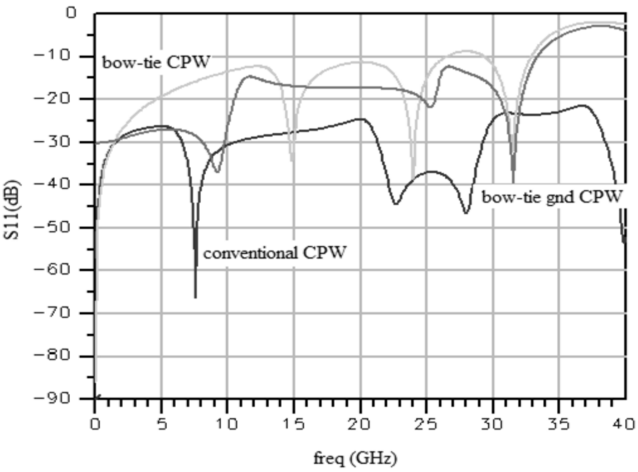

Fig.7. Return Loss (S11 dB) of 3 CPW designs

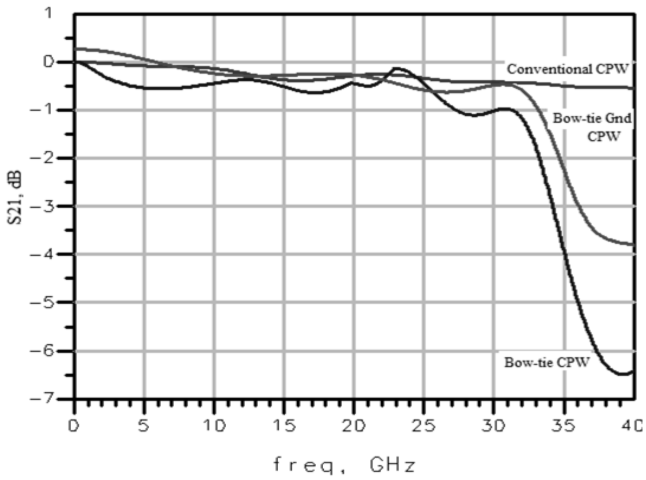

Fig.8. Insertion Loss (S21 dB) of 3 CPW designs

The simulated results shows return loss of conventional CPW designs varying from 32 dB at 1 GHz to a value of 52 dB at 40 GHz. The loss of Bow-tie and Bow-tie ground tapered configurations are above 29 dB at 1dB and above 39 dB at 32 GHz. The insertion loss obtained from simulation of the 3 coplanar waveguide designs is less than 1 dB upto 30GHz.

5. CONCLUSION

We have presented various coplanar waveguide designs formed on a silicon substrate. The value of insertion loss of the CPWs presented here is better than the other waveguides reported. The electromagnetic simulations with Agilent's ADS software show that the overall expected performance of the proposed CPWs will be excellent over a wide range of frequencies and can be implemented better to operate the given CPW structure with less radiation losses. The CPW technology is extensively applied for 3G, Wi-Fi, WiMAX, CPW UWB Antenna and next generation wireless applications easily. It can also been widely used in the design of microwave/millimeter-wave circuits, IC Interconnects, and other wireless antennas.

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