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Design of various Coplanar Waveguide RF MEMS Phase Shifters

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ABSTRACT

This paper presents the modeling and analysis of Radio Frequency (RF) Microelectromechanical System (MEMS) phase shifter using various structures of transmission lines. The proposed phase shifter designs consists of various structures of coplanar waveguide (CPW) loaded with MEMS switches. The loading of MEMS switches contributes a phase change which had been proven effective for the design of phase shifter with low loss, low parasitic and high linearity. The shunt switch's capacitance is varied by applying an analog bias voltage across the center conductor of the CPW line and MEMS bridge, which in turn varies the characteristic impedance of the transmission line, producing the phase shift. Periodic loading of transmission line with MEMS bridges produces increased phase change, resulting in more phase shift compared with the non-biased condition. The results presents a comparison between RF MEMS phase shifter design with a conventional phase shifter with new structures of CPW lines, with increased per unit length phase shift. The proposed phase shifter design can operate up to 15GHz with a measured return loss below −12 dB and with a loss less than 1dB/phase shift at 10 GHz.

Keywords

RF, MEMS, CPW, Phase Shifter, Insertion loss, Return loss

Introduction

Phase shifter is a two-port device controlling the relative phase of each element used in applications such as RADAR, steerable communication link and in highly linear amplifiers. The ideal phase shifters will have zero insertion loss but practically it will vary with each phase state. PIN diode phase shifter, FET phase shifter and MEMS phase shifter are the different types of planar phase shifters among which the first two types were used earlier having high loss and intermodulation distortion. With the invention of MEMS technology, MEMS phase shifter designs had greater advantages with small size, uses low current, wide band frequency operation, low insertion loss etc. The reduction in loss in a phased array application can reduce considerable amount of weight, cost and heat dissipation problems since the design requires only few amplifiers to drive the phase shifters. With a design of RF MEMS switches with low loss, low-loss phase shifter designs using these switches are possible. The development in RF MEMS technology had proved way for high performance in millimeter-wave switches, phase shifters, varactors, filters, low-noise amplifiers, etc. which are the most essential components in RADAR and wireless communication systems. The distributed MEMS transmission line (DMTL) consists of a CPW line periodically loaded with MEMS bridges have better performance since CPWs are planar lines. The main advantage of using CPW lines is it eliminates viaholes used in microstrip lines which produces high losses, simplifying the fabrication and integration process with other components. The analog control bias voltage applied between the center conductor of the CPW and the MEMS bridge produces an electrostatic force pulling the MEMS switch downwards. The gap between the center conductor and the bridge acts as a variable capacitance and when the bridge gets activated the bridge capacitance varies and this in turn changes the characteristic impedance of the transmission line. The change in characteristic impedance of the line changes the phase velocity of the DMTL producing a true time delay phase shifts. This paper proposes six different phase shifter designs on a distributed coplanar waveguide MEMS transmission line. The main objective of the phase shifter design is to optimize with low cost, size, per dB loss per unit

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length and improve the phase shift per unit length. More number of switches increases the phase shift per unit length but also increases the insertion loss. Optimization had to be done to fix the number of switches required for the phase shifter design. The existing MEMS switches designs had demonstrated with low loss and parasitic for frequencies upto 60GHz. When the MEMS switch is activated, the shunt capacitance produces a RF short and the capacitance increases by a factor of 20- 100. Low dc power consumption, large down-state to up-state capacitance ratios, low intermodulation products and easy fabrication on any substrates are the key advantages which makes MEMS switches used for many applications.

Design of RF MEMS Phase Shifter

Distributed MEMS Transmission Line(DMTL)

Distributed MEMS transmission line consists of a high impedance coplanar waveguide (CPW) periodically loaded with MEMS bridges. The configuration of DMTL is shown in figure 1 which is periodically loaded with MEMS bridges. The parameters considered in DMTL are W the center conductor width of CPW, G the gap between the center conductor and the ground plane, L the length of the CPW, h represents the thickness of the dielectric material, t the thickness of the conductor, g_0 the height between the center conductor and the MEMS bridge, s, the spacing between the successive MEMS bridges, w the width of the MEMS bridge and l the length of the MEMS bridge. Figure 2 shows the 3-dimensional layout of CPW and Figure 3 shows the equivalent circuit of the CPW and the DMTL.

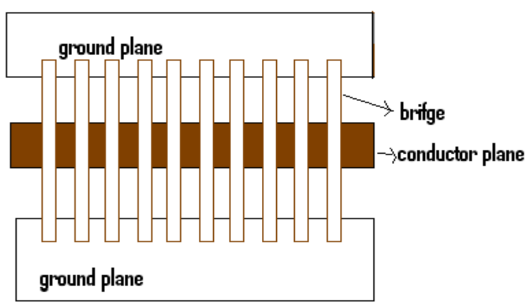

Figure 1. Distributed MEMS Transmission Line

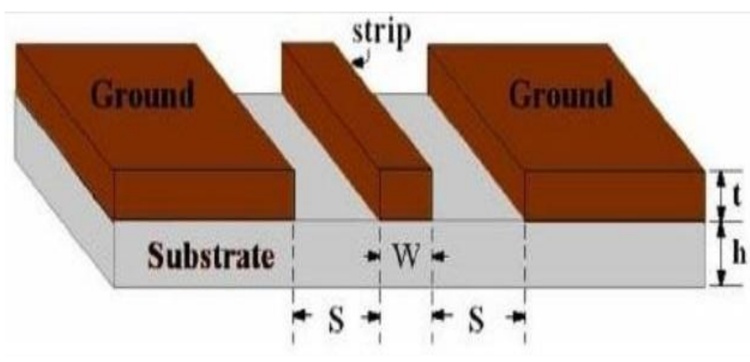

Figure 2. Structure of Coplanar Waveguide

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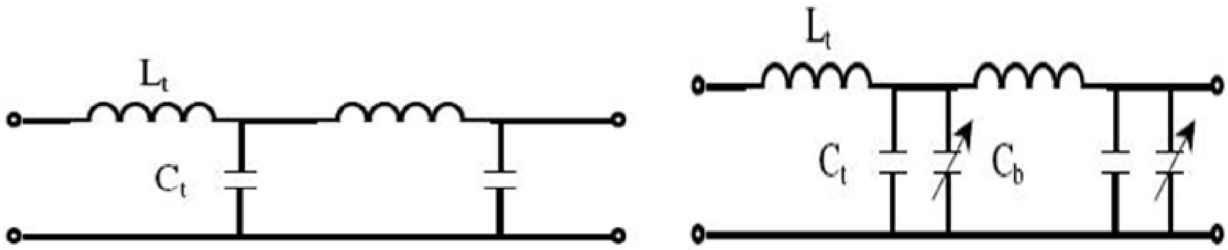

Figure 3. Equivalent circuit of the CPW and the DMTL.

The parameters in the equivalent circuit consists of L_t – the per unit length inductance of the unloaded CPW line, C_t – per unit length capacitance of the unloaded CPW line, C_b – the bridge capacitance which load the CPW line. The per unit length inductance L_t and per unit length capacitance C_t is given by

$$C_t = \frac{\sqrt{\varepsilon_{eff}}}{cZ_0} \quad (1)$$

$$L_t = C_t Z_0^{\ 2} \quad (2)$$

where c is the velocity in free space, Z_0 is the characteristic impedance of the unloaded transmission line and ε_{eff} is the effective dielectric constant of the CPW. The loaded line characteristic impedance Z_l and phase velocity v_l are given by

$$Z_l = \sqrt{\frac{L_t}{C_t + C_b/s}} \quad (3)$$

$$v_l = \sqrt{\frac{1}{L_t(C_t + C_b/s)}} \quad (4)$$

The unloaded line is designed to have high characteristic impedance such that while loading the line the characteristic impedance is 50Ω. The frequency at which the characteristic impedance becomes zero is the Bragg frequency, where the entire power reflects back.

The phase shift and the loss of the loaded line must be determined to find the optimal width of the center conductor and the unloaded impedance. The DMTL phase shift is given in terms of loaded-line impedance values at the up- and down-state as

$$\Delta\varphi = \omega\sqrt{L_t C_t}\left(\sqrt{1 + \frac{C_{lu}}{sC_t}} - \sqrt{1 + \frac{C_r C_{lu}}{sC_t}}\right) \quad (5)$$

$$\Delta\varphi = \frac{\omega Z_0 \varepsilon_{eff}}{c}\left(\frac{1}{Z_{ld}} - \frac{1}{Z_{lu}}\right) \quad (6)$$

Design of RF MEMS Phase Shifter using various CPW Structures

Different structures of CPW transmission lines are designed on a high resistive quartz substrate having varying impedances throughout the line. On these CPW lines, 10 MEMS bridges are periodically placed on a 30mm line. The layout is shown in figure 4. The thickness of the quartz substrate is 500μm and the thickness of the conductor is 1μm. The MEMS bridge is place 3μm

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above the CPW center conductor. An analog control voltage applied on the center conductor produces an electrostatic force which actuates the MEMS bridge and varies the gap between the center conductor and bridge. The change in gap height produces change in bridge capacitance which varies the phase velocity of the line and hence the phase shift. The bridge heights are varied from 3µm to 1µm and phase shifts are measured. Figure 5 shows the layout of MEMS phase shifter designs on various coplanar waveguide structures.

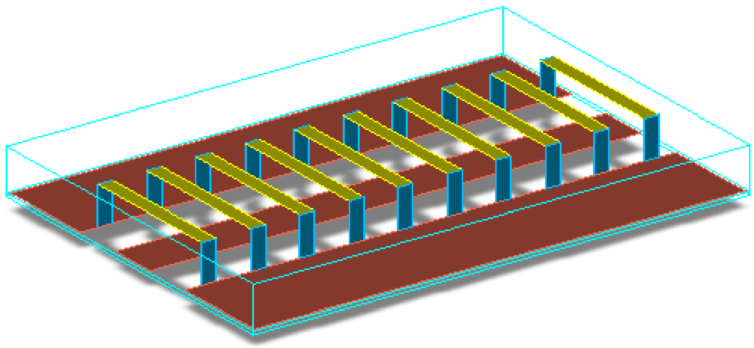

Figure 4. 3-Dimensional Layout of RF MEMS phase shifter on a conventional CPW.

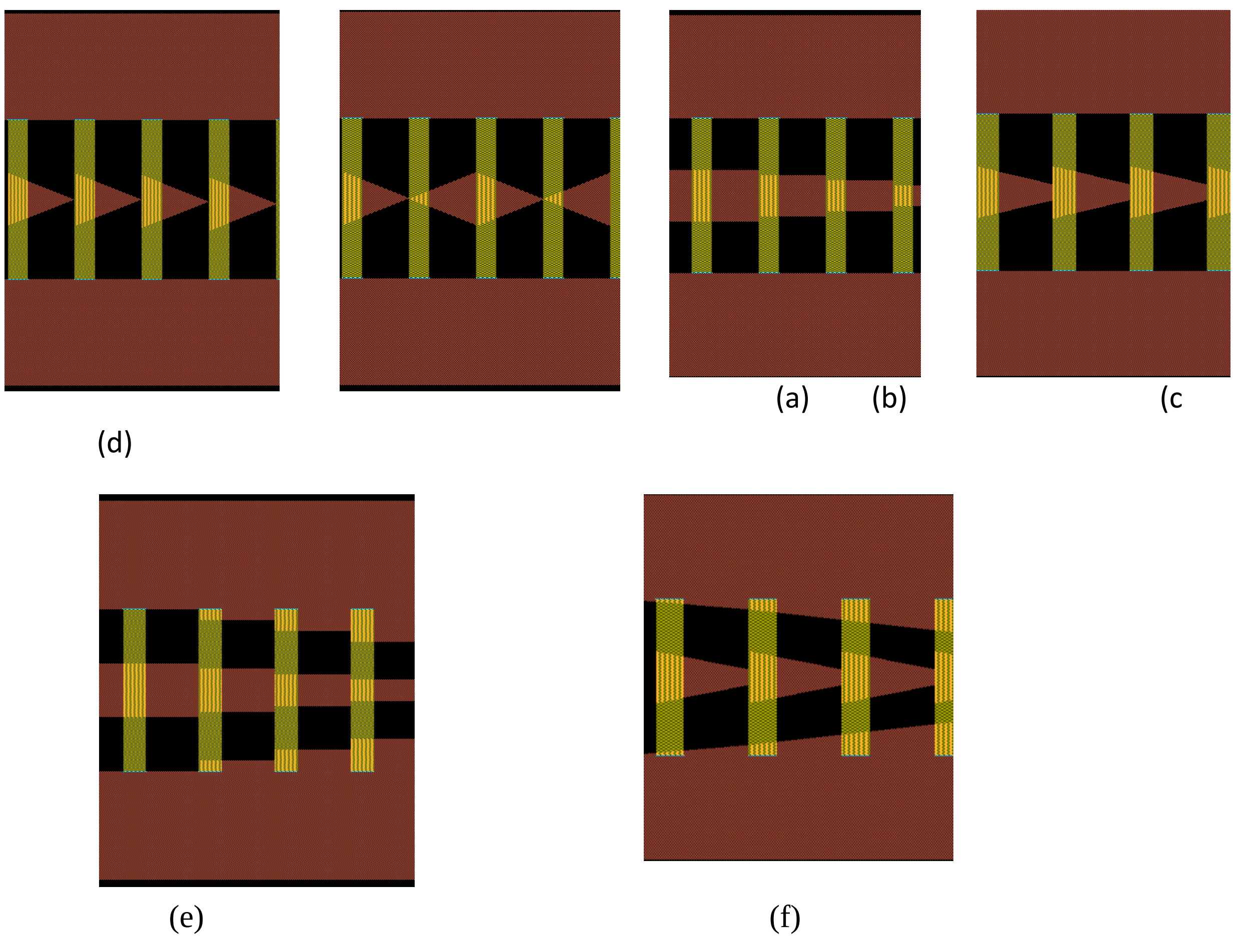

Figure 5(a-f). Layout of RF MEMS phase shifters on different CPW structures

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Results and Discussions

The layout of the proposed structures of CPW based MEMS phase shifter designs are simulated using Advanced Design System. The conventional CPW MEMS phase shifter design gives an insertion loss less than -2 dB and high return loss of -12.5dB upto frequency range of 15GHz. As the proposed structures have varying characteristic impedance across the line, the the proposed phase shifter designs will have an increased phase shift per unit length compared with the conventional CPW phase shifter design. The simulation results of S12 (phase) of various tapered CPW phase shifter designs are shown in figure 6. The S_{12} (dB), S_{11} (dB) and S_{12} (phase) for the simulated results of various CPW phase shifter designs are shown in Table 2.

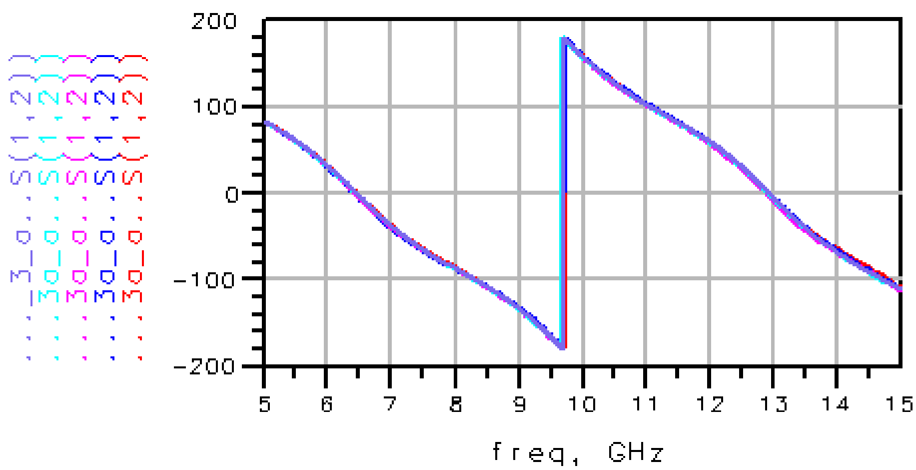

Figure 6a. S12 (phase) of various CPW phase shifter designs at 3µm bridge height (Up state).

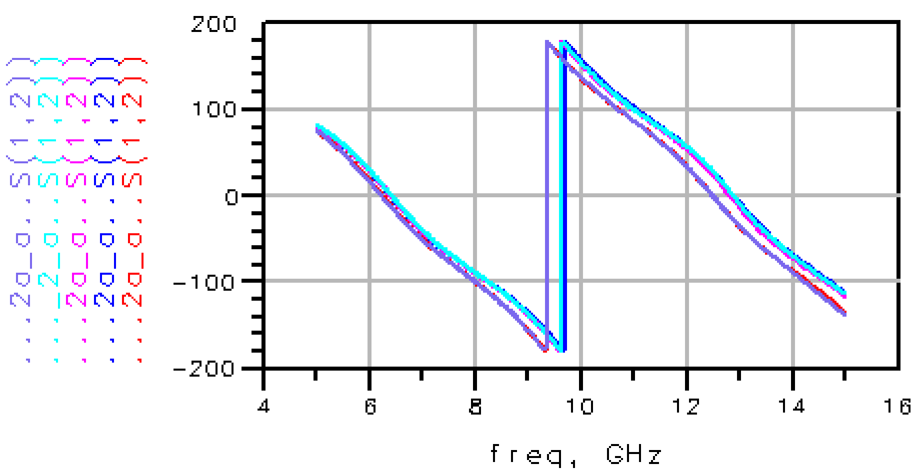

Figure 6b. S12 (phase) of various CPW phase shifter designs at 2µm bridge height (Down state).

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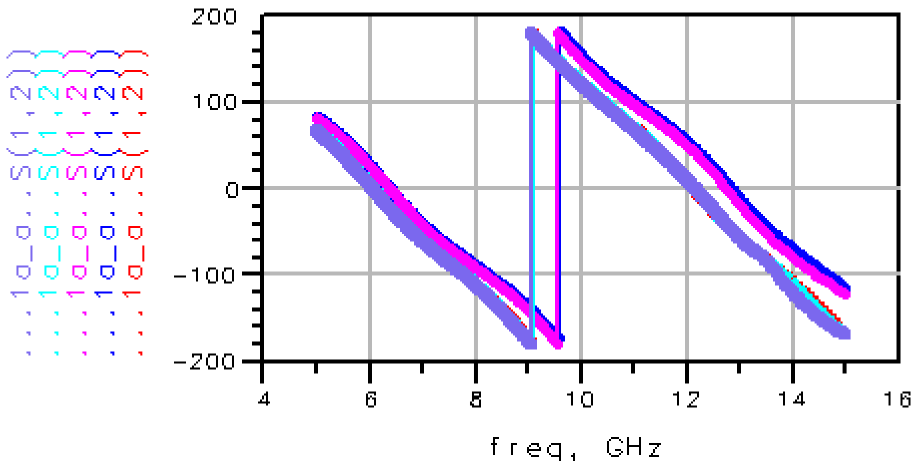

Figure 6c. S12 (phase) of various CPW phase shifter designs at 1.5μm bridge height (Down state).

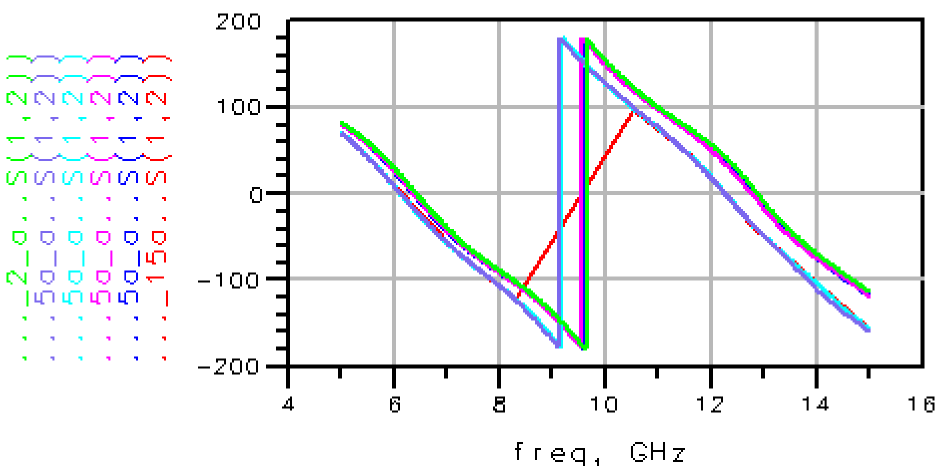

Figure 6d. S12 (phase) of various CPW phase shifter designs at 1μm bridge height (Down state).

Table 2. Simulated parameters of RF MEMS phase shifter designs in different CPW structures

Type of CPW MEMS Phase Shifter	Position of MEMS Bridge (μm)	S_{11}(dB)	S_{12}(dB)	S_{12}(°)
Linear tapered CPW	3	-11.94	-0.28	157.50
	2	-10.82	-0.55	154.06
Linear taper with ground taper	3	-12.12	-0.27	156.99
	2	-7.86	-0.94	136.13
	1.5	-7.07	-1.71	126.16
	1	-6.54	-1.08	121.13
Bow_tie Tapered	3	-0.17	-10.05	157.28

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CPW	2	-0.47	-9.86	157.37
	1.5	-0.62	-9.39	152.57
	1	-0.50	-9.36	151.94
Step tapered Conductor CPW	3	-5.67	-0.29	158.08
	2	-6.29	-1.00	135.70
	1.5	-6.66	-1.16	125.96
	1	-11.88	-1.41	119.72
Step taper in both conductor and Ground	3	-12.48	-0.22	157.93
	2	-7.63	-0.86	136.09
	1.5	-6.75	-1.03	126.75
	1	-6.24	-1.91	121.69
Cascaded Tapered CPW	3	-11.59	-0.31	154.78
	2	-10.63	-0.39	151.64
	1.5	-9.85	-0.47	148.66
	1	-9.48	-0.49	147.76

Conclusion

RF MEMS phase shifter designs on various CPW structures is presented and results are analyzed. The increase in phase shift per unit length is inferred for the results paving way for these phase shifters be usied in phased array antenna and wireless communication applications reducing the size and length of the phase shifter. High resolution phase shifter can be obtained by optimizing the width and gap of the coplanar waveguide structures. The loss obtained form these designs are comparatively low from other designs proposed earlier. So, this paper presents a RF MEMS DMTL phase shifter with low loss, higher phase shift per unit length and an structure to integrate easily into any RF circuits.

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