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DESIGN AND MODELING OF RF MEMS PHASE SHIFTERS USING VARIOUS STRUCTURES OF COPLANAR WAVEGUIDES

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Abstract - *Design and Modeling of RF MEMS Phase Shifters using various structures of CPW are presented. This paper presents six different designs for RF MEMS phase shifters that are based on characteristic impedance of coplanar waveguide (CPW) distributed Micro Electro Mechanical Systems (MEMS) transmission line (DMTL), which are loaded with different designs/structures of conductor and number of shunt capacitive switches. The design operates up to Ku band with a measured return loss below −12 dB and an average loss of less than 1dB/phase shift of 150◦ at 10 GHz. MEMS concept have been successfully applied in the development of RF switches and variable capacitors and have proven to be effective for the phase shifter design due to low-loss, low parasitic and high linearity. The distributed RF-MEMS phase shifter consists of a varying length of high impedance coplanar waveguide transmission line that is capacitively loaded by periodic placement of discrete MEMS capacitors. With the varying structure of conductors ,the characteristic impedance and hence the phase velocity is changed and when a DC voltage is applied on the line, the electrostatic force between the beam and the underlying conductor snaps down the beam, which increases the net capacitance and results in a phase shift relative to the non biased condition. The comparison result of new design with the conventional RF MEMS phase shifter is also presented here. It shows that, with the new design, increased per unit length (PUL) phase shift is achievable.*

Key Words: *Phase shifter, coplanar waveguide (CPW), RF MEMS, Capacitive shunt switch*

1. INTRODUCTION

Phase shifter is a key component of phased array antenna. As the two-port key element of a phased array antenna system, the phase shifter gives the role to change the phase of the input signal ideally without the insertion loss, but practically it has the insertion loss variation according to each phase state. The planar integrated digital phase shifter can be roughly classified into three groups: the MEMS phase shifter, the FET phase shifter, and the PIN diode phase shifter. MEMS phase shifter has the advantages of small volume, small current, wide frequency band, low insertion loss, and so on. Decreasing the loss for an array of phase shifters can drastically reduce cost, weight, and heat dissipation problems by requiring fewer amplifiers to drive the phase shifters. RF MEMS technology provides an option of using an extremely low-loss switch in phase shifter designs in order to drastically reduce insertion loss throughout a phase shifter.

Current development in radio frequency (RF) micro electromechanical systems (MEMS) has greatly improved the performance of the millimeter wave switches and phase shifters, which are essential for modern radar and telecommunication systems. Low loss and less measurable intermediation distortion are two main advantages of MEMS over field effect transistor (FET) or p-i-n diodes. In addition, the DMTL phase shifters demonstrated in this work have better performance on simple coplanar waveguide (CPW) transmission lines because CPW based phase shifters are uniplanar. This is one of the main advantages as only one side of the substrate is used; eliminating the need for via-hole process and simplifying the fabrication and integration process with other components. When a single analog control bias voltage is applied to the center conductor, the bridges will be pulled closer to the center conductor, which in turn increases the loading capacitance in the switch, besides varying the propagation characteristics and decreasing the phase velocity of the DMTL. The resulting change in the phase velocity of the DMTL produces the TTD phase shifts. This paper analyzes six different designs of DMTL phase

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shifters based on varying structure CPW transmission lines and the objective is to optimize the designs with low cost and size, and maximize phase shift per dB loss per unit length by varying the impedance size of the transmission lines and the number of switches developed on silicon wafer.

RF MEMS capacitive membrane switches have already demonstrated low loss and low parasitics at frequencies through 40 GHz. A shunt capacitive MEMS switch consists of a thin metal membrane "bridge" suspended over the center conductor of a CPW (Coplanar Waveguide) or micro strip line and fixed at both ends to the ground conductors of the CPW line. When the switch is pulled down to the center conductor, the shunt capacitance increases by a factor of 20-100, presenting an RF short. The MEMS switch has very little DC power consumption (*μ*J during the switching process), allows for large down-state to up-state capacitance ratios (*Cd*/*Cu* = 20-100), has very low inter modulation products, and can be fabricated on almost any substrate.

2. DESIGN

2.1 The Architecture of the DMTL phase shifter

The DMTL phase shifter consists of a high impedance (>50) CPW transmission line and MEMS shunt switches that are loaded by the periodic placement of variable capacitance. The configuration of the MEMS shunt switch over the CPW transmission line is shown in Fig. 1. W is the center conductor width, G is the gap width, g0 the bridge height, S the periodic spacing of the MEMS bridges on the CPW line, w and l are the width and length of the MEMS bridge, respectively.

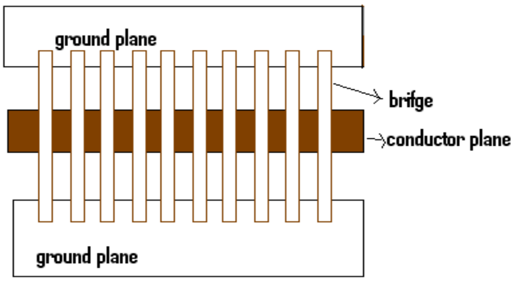

Fig -1: DMTL phase shifter

2.2 Loss versus impedance

An equivalent circuit of the MEMS bridge over the transmission line is shown in Fig. 2, which consists of variable shunt capacitor, Cb of bridge, the per unit length capacitance,Ct and the inductance, Lt of the unloaded CPW transmission line is given by

$$C_t = \frac{\sqrt{\in_{reff}}}{cZ_0} \qquad L_t = c_t Z_0^2 \tag{3}$$

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

$$Z_1 = \sqrt{\frac{L_t}{C_t + C_b / s}} \qquad v_1 = \frac{1}{\sqrt{L_t(C_t + C_b / s)}} \tag{4}$$

The loaded line is designed such that $Z_l \approx 50$ by choosing an unloaded line impedance of $Z_0 > 50$

The Bragg frequency is the frequency at which the characteristic impedance of the line goes to zero, where entire power reflects back. In the case of the DMTL, the up-state inductance–capacitance (LC) resonant frequency of the MEMS bridges is very high (300–600 GHz). As a result, the operation is generally limited by the Bragg frequency f_{Bragg} of the loaded line. The Bragg frequency is given by

$$f_{Bragg} = \frac{1}{\sqrt{\pi s \quad L_t(c_{t+}c_b / s)}} \tag{5}$$

In order to determine the width of the optimal center conductor and the associated unloaded line impedance, both the phase shift and the loss contributed by the loaded line against center conductor width must be determined. The phase shift of the DMTL is determined by the impedance change, which also determines the reflection coefficient of the phase shifter. The phase shift φ of this slow wave structure can be calculated by

$$\Delta\phi = \omega\sqrt{L_t C_t}\left(\sqrt{1+\frac{C_{lu}}{sC_t}} - \sqrt{1+\frac{C_r C_{lu}}{sC_t}}\right) \tag{6}$$

By substituting the Eqs. (3) and (4), into (6),the following expression is derived as

$$\Delta\phi = \frac{\omega Z_0 \in_{reff}}{c}\left(\frac{1}{Z_{ld}} - \frac{1}{Z_{lu}}\right) \tag{7}$$

where Z_{lu} and Z_{ld} are the loaded-line impedance values at the up- and down-state, respectively. The effective capacitance seen by the DMTL at the up-state is C_{lu}, at the down-state is C_{ld} and C_r is capacitance ratio. The impedance varies when the loss of the transmission line is changed due to a change in the amount of capacitance on the transmission line. In order to achieve the maximum amount of phase shift for the minimum amount of insertion loss, the attenuation constant α for the unloaded CPW transmission line can be expressed as

$$\alpha = \beta \frac{8.86\times10^2 R_s\sqrt{\epsilon_{reff}}}{4\eta_0 SK(k)K(k')(1-k^2)} \times \left[\begin{array}{l} \frac{2S}{W}\left\{\pi+\ln\left(\frac{4\pi W(1-k)}{t(1+k)}\right)\right\} \\ +2\left\{\pi+\ln\left(\frac{4\pi S(1-k)}{t(1+k)}\right)\right\} \end{array} \right] \quad (8)$$

$$\alpha_1 = \alpha\frac{Z_0}{Z_{ld}} \quad (9)$$

$$R_s = \sqrt{\frac{\pi f \mu_0}{\sigma}}$$

where αl is the loaded line attenuation constant, R_s the surface resistance, t the metal thickness, β the correction of multiplicative factor, η_0 the characteristic impedance of free space, f the frequency, W the width of the CPW center conductor, G the width of the CPW gap, σ the conductivity of the metal, K the modulus of elliptical integral, k the complementary modulus of k for the elliptical integral, K(k) and K(k) are the complete elliptic integral of the first kind of modulus k , respectively.

Another important factor which required careful consideration is the radiation loss. It is present in an unloaded CPW line on a thick dielectric substrate. This is because the wave velocity of the transmission line being greater than the phase velocity of the waves in the dielectric. The loaded line is built on low dielectric constant substrates (quartz), the wave velocity of the transmission line is slower than the phase velocity in the dielectric and radiation loss cannot occur. Thus, the line loss per unit length on silicon substrate is higher than that on quartz substrate. It is also important to select the input and output port feed lines to match the dimensions and minimize the radiation loss in these lines.

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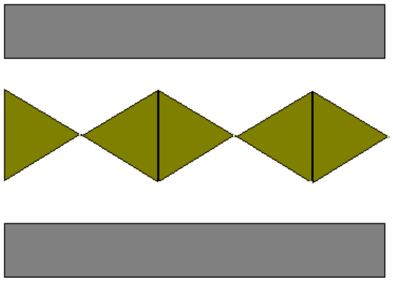
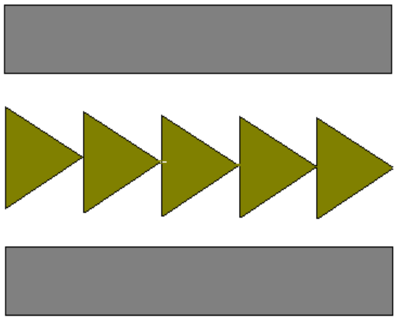
2.3 Design of CPW transmission line

Six types of CPW transmission lines are designed with different impedances on high resistivity quartz substrate. Six types of CPW transmission line are shown in figure 2. In general, these CPW transmission lines differ in terms of their impedances. In each of the design there are 10 shunt capacitance switches, equally spaced and placed above a 30 mm transmission line. The simulated comparison results of the various phase shifters which are designed using advanced design system (ADS) system software are shown in table 1. From this, we can infer that as the characteristic impedance changes there is a change in phase shift and more superior performance than the conventional RF MEMS phase shifter in terms of low insertion loss of −2 dB and high return loss of −12 dB.



a) Bowtie structure



b)Cascaded structure

c) Step structure

e)Tapered structure

d)Ground Step structure

f) Ground tapered structure

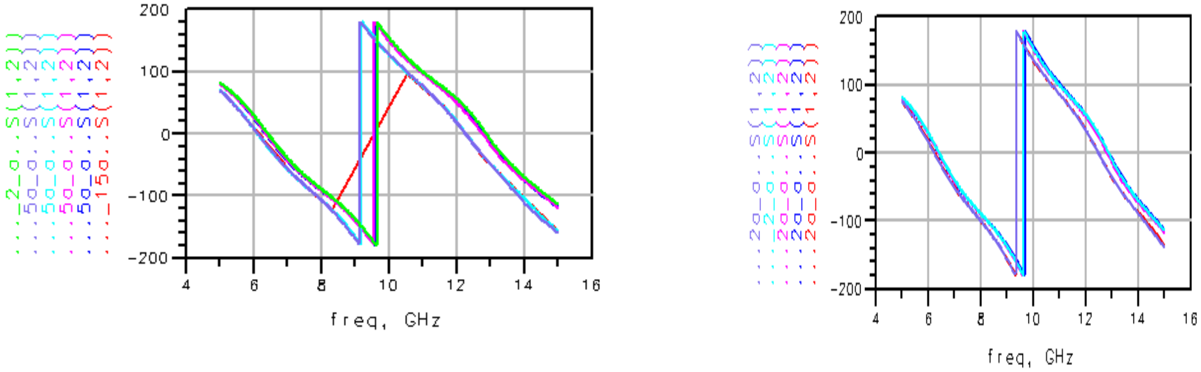
figure 2: structures of transmission lines

Bridge_Height	S12 PHASE		
	conductor shape		
	Rectangular	**Step Change**	**StepChange_Ground**
1um	112.71692	119.722224	121.698714
1.5um	119.00991	125.965167	126.757252
2um	122.94135	135.700342	136.095021
2.5um	147.10742	157.837719	152.205758
3um	151.43682	158.088882	157.930765

Table 1: simulation result- comparison of phase shifters having different structures

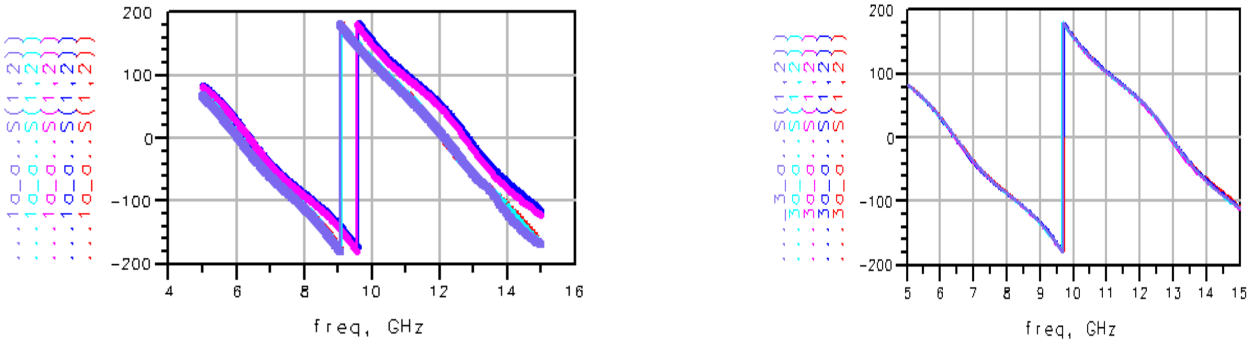
3 SIMULATION RESULT

The simulated results of the various phase shifters which are designed using advanced design system (ADS) software are shown in table 2. From this, we can infer that, as the structure changes , the characteristic impedance also changes, and hence there is a change in phase shift and more superior performance than the conventional RF MEMS phase shifter in terms of low insertion loss of −2 dB and high return loss of −12 dB at ku band frequencies. And also from the result it is clear that the per unit length phase shift is higher than that of the conventional CPW. The graph of the simulated result of different RF MEMS phase shifter using ADS software is shown as follows.



a) Bridge gap of 1um

b) Bridge gap of 2um



c) Bridge gap of 1.5um

d) Bridge gap of 3um

Figure 3: Simulation result of phase shifters having different structures

structure	bridge_height	s12 phase	s11(dB)	s12(dB)
linear_taper	2um	154.063421	-10.822135	-0.558244
	3um	157.508884	-11.941934	-0.287863
linear taper_gnd taper	1um	121.131514	-6.54432	-1.08944
	1.5um	126.164796	-7.07157	-1.714214
	2um	136.130192	-7.861729	-0.944581
	3um	156.998811	-12.129	-0.275291
cascaded_taper	1um	147.75713	-9.486	-0.496642
	1.5um	148.659143	-9.850302	-0.478495
	2um	151.640347	-10.632158	-0.396667
	3um	154.7871	-11.586033	-0.316079
bow_tie	1um	151.947095	-9.363707	-0.508205
	1.5um	152.5761	-9.395337	-0.624034
	2um	157.3702	-9.864559	-0.474701
	3um	157.28001	-10.050017	-0.176686
step change_conductor	1um	119.722224	-5.672494	-1.411544
	1.5um	125.965167	-6.299098	-1.167476
	2um	135.700342	-6.663151	-1.009067
	3um	158.088882	-11.886014	-0.292134
step change_both conductor and gnd	1um	121.698714	-6.242167	-1.911422
	1.5um	126.757252	-6.754217	-1.030961
	2um	136.095021	-7.639718	-0.863089
	3um	157.930765	-12.484179	-0.228606

Table 2: Simulation result of phase shifters having different structures

IV CONCLUSION

In this paper, the RF MEMS phase shifter based on capacitance shunt switch is designed and simulated. We improve the distributed MEMS phase shifter design by using multi-structured configuration of conductor to enable multiple phase shifts in a single RF MEMS structure. With these techniques, we could achieve higher resolutions, larger per unit length phase shift and lower loss phase shifters with smaller device sizes. They remain linear in maintaining return loss ($S11\leq-12$ dB) up to Ku band . The driving voltage reduces the height of the switches, thereby increases the capacitive loading and decreases the phase velocity. As a result, the advantages of the DMTL phase shifters in Ku band are lower insertion loss, higher phase shift and easier integration into RF circuit and systems for different military and commercial applications.

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