Distributed MEMS Phase Shifters on Silicon Using Tapered Impedance Unit Cells

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ABSTRACT

This paper presents results for one bit distributed coplanar waveguide (CPW) MEMS phase shifters that are designed to operate from 5-40GHz on high resistivity silicon. The periodically loaded structures use 11 MEMS capacitors interconnected with tapered impedance transmission line. The phase shift of a one bit configuration is approximately 150°/dB at 25GHz and 211°/dB at 35GHz. The return loss in the up and down state is greater than 10dB from 10–35GHz.

I. INTRODUCTION

Phase shifters are integral components in modern radar and communication systems. Traditional electronic phase shifters use active devices as a switching elements to achieve the desired phase shift. Micro–Electro–Mechanical Systems (MEMS) concepts have been successfully applied in the development of RF switches and variable capacitors and have proven to be a effective for phase shifter design due to low–loss, low parasitics, and high linearity.

The distributed MEMS phase shifter usually consists of a uniform length of high impedance coplanar waveguide (CPW) transmission line that is capacitively loaded by periodic placement of discrete MEMS capacitors. When a DC voltage is applied on the line, the electrostatic force between the beam and the underlying conductor snaps down the beam (down state), which increases the net capacitance and results in a phase shift relative to the non – biased condition (up state).

II. BACKGROUND

The distributed MEMS transmission line (DMTL) was initially reported by Barker et al., [1] designed from 6-60GHz with very good return loss (S11<-15dB in the up and down state). The authors showed two designs with a length of approximately 5.2mm and 10.8mm, respectively, for two different spacings (306μm and 640μm with 16 MEMS capacitors). The phase shift was approximately 118°/2–dB of insertion loss for a 300μm ground – ground spacing. Further improvements in return loss and insertion loss were presented in [2]. In this work, larger ground – ground spacing (900um) was used to achieve a phase shift of 90°/dB at 60GHz. [2]. The designs presented [1,2] were fabricated on quartz substrate.

Similar phase shifter design on glass ($\varepsilon r \approx 5.7$) were presented in [3]. Here, a phase shift of 154°/dB at 25GHz was achieved with a return loss greater than 10dB. In this work, a fixed - variable series capacitor configuration was used to achieve capacitance ratios between the down and up state of 7.5

In this paper, work on improving the per unit length phase shift using tapered transmission lines is presented. The phase shifters were fabricated on high resistivity silicon and designed to operate from 5–40GHz. Experimental results for three phase shifter designs are presented and a phase shift of 240°/dB at 35GHz is demonstrated. The return loss in the up and down state is typically less than 10dB from 10-35GHz. The overall length of the phase shifters is approximately 8mm and the total phase shift at 35GHz ranges from 338° to 393°.

In the following sections, the fabrication and design of MEMS phase shifters are described followed by a summary of experimental results.

III. FABRICATION AND DESIGN

The MEMS phase–shifter is fabricated on a 425μm high resistivity silicon substrate (ε_r=11.7, tanδ=0.008). Lift–off processing is used to define metal lines to a thickness of 1μm (Cr/Ag/Cr/Au). The width of the center conductor and the slot is 80μm and 45μm. A 0.5μm thick Si_3N_4 is deposited using RF magnetron sputtering on top of the metal layer. Next, the pedestal areas are patterned with photoresist and a 3μm thick gold pedestal is electroplated. A 1μm thick Cr/Al layer is coated on top the sacrificial photoresist layer and subsequently etched to form the capacitor beam geometry. The sacrificial photoresist is removed and a critical point drying system is used to release the MEMS capacitors.

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The phase shifter presented herein consists of an 8mm long CPW transmission line that is periodically loaded with 11 shunt MEMS capacitors, each spaced by 750μm. The width was 40μm, making the total length of the phase shifter approx 8mm (Figure 1). To maintain a return loss of atleast 10dB, a down state capacitance less than 0.1pF is needed in each capacitor. In this work, the topology suggested in [3] that employs a fixed capacitance in series with the variable capacitance was used, as shown in Figure 2. The capacitance ratios that were realized are shown in Table 1. The beam characteristics and measured actuation voltage are shown in Table 2. The factors that affect the actuation voltage are the beam length and the area of actuation.

One of the goals in this paper was to investigate methods to improve per unit length phase shift. The use of a uniform high impedance line (Z_0>70Ω) would provide an increase in the phase shift at the expense of return loss. An alternative method used here was to introduce tapered impedance sections as shown in Figure 3. The characteristics of three designs are as follows:

- In Design 1, the impedance of a distributed line between two adjacent MEMS capacitor is increased in steps of 10Ω from 50Ω to 90Ω making it a 5–section stepped impedance transformer. Each impedance section is 150μm long and the overall length of connecting sections is maintained at 750μm.
- In Design 2, a linear taper from 50Ω to 120Ω is used.
- In Design 3, the impedance varies from 40Ω to 90Ω in a bow – tie configuration.

In all designs, the feed lines have a center conductor width of 80μm and the slot width of 45μm, respectively.

III. EXPERIMENTAL RESULTS

Measurements were performed from 5–40GHz using a Wiltron 360B vector network analyzer and 150μm GGB microwave probes. A Thru–Reflect–Line (TRL) calibration was performed using calibration standards fabricated on the wafer. A high voltage bias tee was used to supply voltage through the RF probe to avoid damaging the VNA test port.

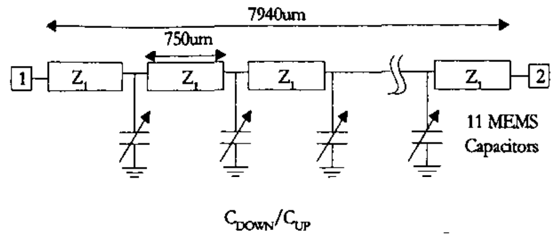

Figure 1- Schematic representation of the 11-section phase shifter.

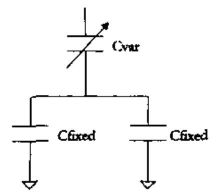

Figure 2- Schematic representation of the MEMS capacitor used in achieving low down state capacitance per [3].

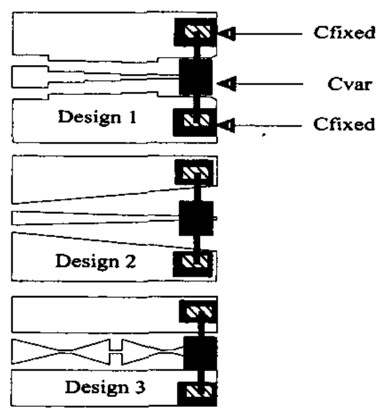

Figure 3- Schematic of the unit cell design used in the MEMS phase shifter.

Table 1- Capacitance ratios used in the design of the MEMS phase shifters.

	C_{up} [pF]	C_{down} [pF]	C_{ratio} [C_{down}/C_{up}]
$Cratio_a$	$4.6*10^{-3}$	0.132	28.6
$Cratio_b$	$2.6*10^{-3}$	0.081	31.1
$Cratio_c$	$6.6*10^{-3}$	0.0747	18.6

Table 2- Characteristics of the beams used in this work

	Actuation Area [μm²]	Beam Length [μm]	Actuation Voltage [V]
$Cratio_a$	1600	615	59V

$Cratio_b$	2400	915	37V
$Cratio_c$	900	615	69V

Figure 4 shows the comparison of the measured phase shift of the three designs presented herein. Also shown are circuit simulation results for an equal length phase shifter that uses uniform width 70Ω interconnect line. It is seen that the phase shift increases linearly with frequency up to 30GHz. The non–linearity seen at frequencies above 30GHz for designs 2 and 3 may be due to a higher down state impedance resulting in a lower Bragg's frequency limit [4].

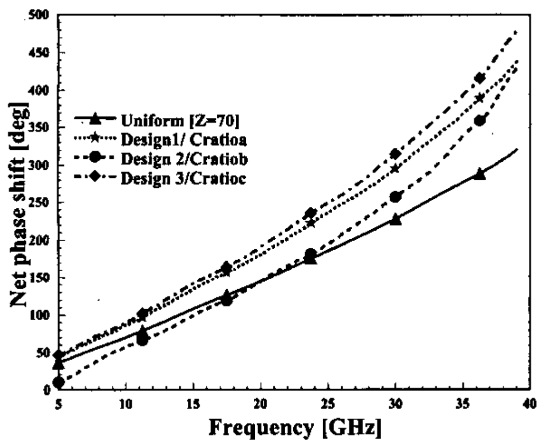

Figure 4- Comparison of the phase shift between a uniform line phase shifter verses the measured response of the tapered designs presented herein.

Figure 5 shows the measured S11 in the up state for the three fabricated designs. It is seen that the S11 for design 1 is less than -10dB upto 30GHz. Designs 2 and 3 have S11 below -10dB from 8-35GHz and 8-28GHz, respectively.

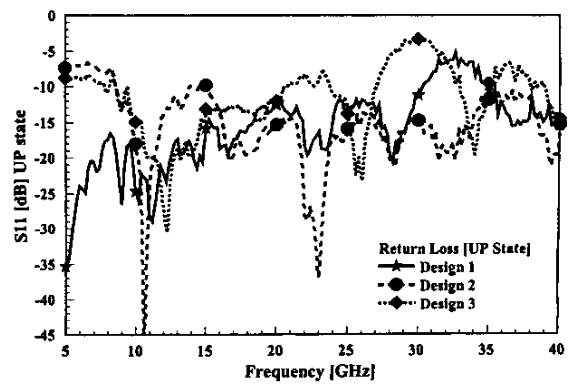

Figure 5- Comparison of measured S11[dB] in the up state for the three designs in Figure 2.

In Figure 6 the down state S11 is shown. Design 1 has S11 less than −10dB from 8 – 30GHz. Designs 2 and 3 have S11 below −10dB from 5 – 30GHz.

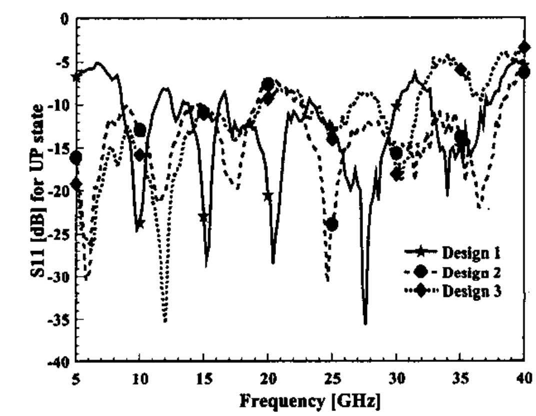

Figure 6- Comparison of measured S11 [dB] in the down state for the three designs in Figure 2.

The insertion loss in the up and down states is shown in Figure 7 and 8, respectively. The insertion loss for designs 1 thru 3 in the up state is approximately 1.6, 1.4, and 1.7dB at 35GHz and the down state is 1.7, 1.4, and 3 dB, respectively. The ripple present in Figures 5 thru 8 is partly attributable to calibration errors resulting from the bias tee networks.

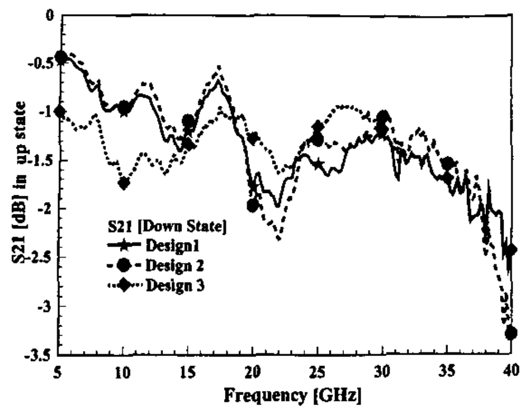

Figure 7- Comparison of measured S21 [dB] in the up state for the three designs in Figure 3.

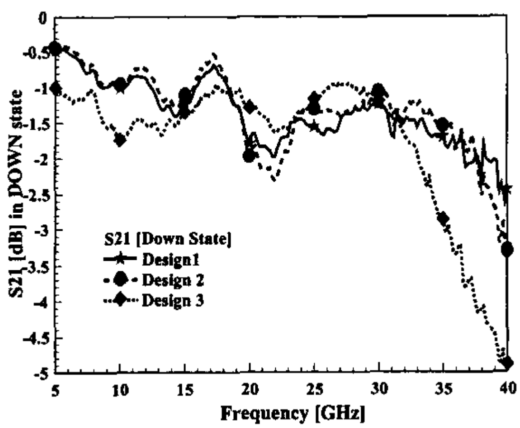

Figure 8- Comparison of measured S21 [dB] in the down state for the three designs in Figure 3.

IV. SUMMARY

In this paper, experimental results for distributed MEMS phase shifters designed on silicon are presented. By connecting a section of tapered impedance transmission line between adjacent MEMS capacitors, the phase shift for the three design varies from 142°/dB to 208°/dB at 25GHz and from 134°/dB to 242°/dB at 35GHz. This compares favorably with 154°/dB at 25GHz presented in [3]. Furthermore, the phase shift per unit length of approximately 40°/mm exceeds the values of 20-30°/mm reported in [1–3]. The modeling and analysis of the design presented herein is in progress.

ACKNOWLEGDEMENTS

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