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A new structure for reducing the number of MEMS switches used in six-bit DMTL phase shifters

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Abstract. In this paper, a new structure is proposed for a six-bit DMTL phase shifter in which the number of micro-electro mechanical system (MEMS) switches is reduced from 63 to 29. This is done through designing three different kinds of MEMS switches, which are capable of doing different phase shifts, instead of using identical switches. The reduction of the number of switches results in decreasing the die-size of the phase shifter and as a result in amount of loss and the production cost. In order to match the proper impedance along CPW line, all three kinds of the MEMS switches have been designed so that their impedances in up and down states are identical. The structure is calculated and simulated at 16 GHz using HFSS and COMSOL softwares. According to calculation and simulation results, for all phase states, the return loss is better than –11.4 dB and maximum phase error is 1.7 °. Although three different structural switches are used, the pull-in voltages and switching times are all identical. The total structure size is $1.6 \times 21\,\mathrm{mm}^2$ and the surface micromachining process is proposed for the phase shifter fabrication.

Key words. Micro-electro mechanical system, phase shifter, shunt capacitive switch, actuation voltage, switching time.

1. Introduction

Phase shifters are one of the prominent components of Phased Array Antenna Systems. Phased Array Antenna Systems have widespread application in military industry, remote communication and radar [1–3]. Today phase shifters are produced through usage of ferrite materials, field effect transistors, p-i-n diodes, and micro-electro mechanical systems (MEMS) technology [4]. Among these, phase shifters which are produced using MEMS switches [5] have gained widespread acceptance because of their low loss in Radio Frequency (RF).

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There are mainly four kinds of MEMS phase shifters [4]: reflect line [6], loaded line [7], switched line [8–10] and distributed MEMS transmission line (DMTL) [11–13]. According to their applications each of them has its own advantages and disadvantages. DMTL phase shifters are produced using shunt capacitive switches which are located periodically on coplanar wave guide (CPW) or micro strip transmission lines.

In DMTL phase shifters a DC bias voltage is applied to shunt capacitive switches of a number of required bits and the capacitance between switches and line changes hence the impedance of line alters, by varying the line impedance the phase of signal passing though the CPW line alters.

In [11], the designed two-bit Ka band DMTL phase shifter, the structure consists of a high impedance line capacitively loaded by the periodic placement of series MEMS switches and MIM or MAM capacitors. The structure is fabricated with 21 MEMS switches in which 7 of switches are devoted to the first bit and rest of them to the second one. The distance between switches is 400 μm . Each switch is capable of 12.857 ° phase shift, 90 and 180 degrees is shifted by turning the first and second bit's switches on, respectively.

A lot of switches are used in high accuracy DMTL phase shifters. Usually 63 identical MEMS switches with shift phase of 5.625 ° are used in a six-bit DMTL phase shifter (1×.5625 °/ 2×5.625 °/ 4×5.625 °/ 8×5.625 °/ 16×5.625 °/ 32×5.625 °). It is probable that one of the switches becomes defective during fabrication process and does not work properly. Also, an increase in number of the switches used in the phase shifter results in an increase in length of the phase shifter and as a result an increase in loss and production cost. In designing a six-bit DMTL phase shifter decreasing number of switches which leads to a smaller size is a very prominent issue for designers.

In [12] a new structure is presented for a six- bit DMTL phase shifter for Ka band which contains just 32 switches instead of 63 switches. They have presented a new switch which is capable of altering the phase of signal for two different values (5.625 ° and 11.25 °). These switches require two different actuation voltages for each state.

In this paper, a new structure for a 6 bit phase shifter in Ku band is proposed. Three different switches have been used for 5.625, 11.25 and 12.857 degrees phase shifts. Doing this, number of switches is reduced from 63 to 29. Number and kind of switches which are used in the first to sixth bit are, respectively, as follows: 1×.5625 °/ 1×11.25 °/ 2×11.25 °/ 4×11.25 °/ 7×12.857 °/ 14×12.857 °. Identical actuation voltages and identical switching times are used for all switches and a simple fabrication process has been proposed which will be discussed in details in the following sections.

2. Structure of the proposed phase shifter

The DMTL phase shifter consists of a high impedance (>50 Ω) CPW transmission line and MEMS shunt switches that are loaded by periodic placement of variable capacitance [8]. Shunt capacitive switches with predefined spacing are called unit

cells. Electrical model of the unit cell is depicted in Fig. 1, which consists of variable shunt capacitor, C_{b} of the bridge, per unit length capacitance, L_{t} and C_{t} are the per unit inductance and capacitance of the unloaded line with impedance Z_0 respectively. Also there is a line loaded with MEMS switches in series with lumped element capacitors (C_{s}).

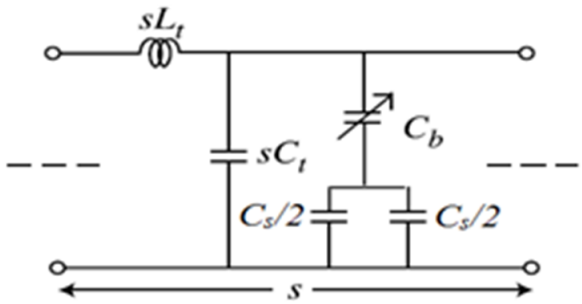

Fig. 1. The lumped model of a DMTL constructed using a CPW line

The phase shift of the distributed MEMS phase shifter can be expressed as [13, 14]

$$\Delta\emptyset = \omega\sqrt{L_{\mathrm{t}}C_{\mathrm{t}}}\left(\sqrt{1+\frac{C_{\mathrm{bdown}}}{SC_{\mathrm{t}}}}-\sqrt{1+\frac{C_{\mathrm{bup}}}{SC_{\mathrm{t}}}}\right), \tag{1}$$

The proposed DMTL phase shifter is composed of a CPW line and 29 shunt capacitive switches which are depicted in Fig. 2.

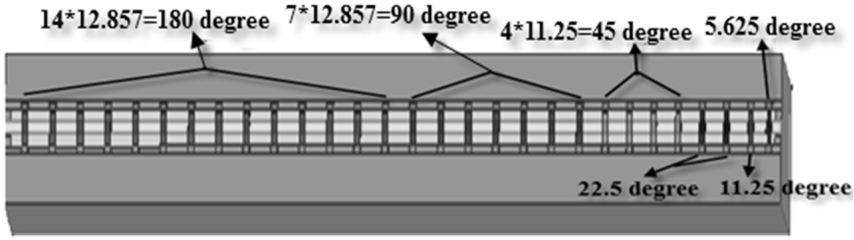

Fig. 2. Total structure of a six-bit phase shifter with 29 switches

Each switch in Fig. 2 is a fixed-fixed beam in up and down states. There is a series capacitor between anchors of the bridges and ground $C_{\mathrm{s}}/2$). The equivalent capacitors of $C_{\mathrm{s}}/2$ and bridge capacitance in up and down states are named C_{up} and C_{down}, respectively. It is worthy to note that in down state the bridge capacitance increases to picofarad (pF) range and the equivalent becomes C_{s}. In the proposed design, there is one MEMS switch with 5.625° shift phase for the first bit, seven MEMS switches with 11.25° shift phases for the second to fourth bits, and twenty one MEMS switches with 12.857° shift phases for the fifth and sixth bits. In Fig. 3, all three kinds of the designed switches for 5.625°, 11.25° and 12.857°, the shift phases are shown in both up and down states.

The switches in phase shifter in up and down states vary the impedance of the

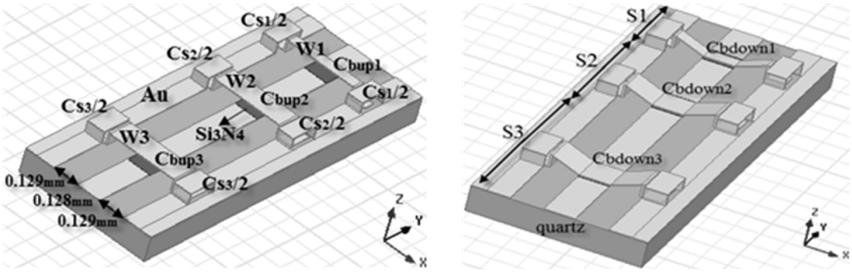

Fig. 3. 3D view of switches in up and down states

line, which changes the return loss of the CPW. Impedance mismatch in DMTL phase shifter leads to return loss, if R_{Lmax} is named maximum return loss, the governing equation for reflection coefficient being

$$\Gamma_{\mathrm{in}} = 10^{\frac{R_{\mathrm{Lmax}}}{20}}\,, \tag{2}$$

In ideal conditions the return loss has to be less than –10 dB, $S_{11} \leq -10\,\mathrm{dB}$). To achieve this criteria, the return loss of each switch is considered to be –16 dB, ($R_{\mathrm{Lmax}} = -16\,\mathrm{dB}$). So the impedances of the switch in up and down states can be calculated through the following equations [13]:

$$\Gamma_{\mathrm{in}} = 10^{-\frac{16}{20}} = 0.1585\,, \tag{3}$$

$$Z_{\mathrm{Lup}} = 50\sqrt{\frac{1+\Gamma_{\mathrm{in}}}{1-\Gamma_{\mathrm{in}}}} = 58.67\,, \tag{4}$$

$$Z_{\mathrm{Ldown}} = 50\sqrt{\frac{1-\Gamma_{\mathrm{in}}}{1+\Gamma_{\mathrm{in}}}} = 42.61\,. \tag{5}$$

So the line impedance in up state must be less than 59 Ω and for down state has to be higher than 42 Ω. In this work the up and down impedances for all designed switches are considered to be 58.14 and 43 Ω, respectively. This results in a proper impedance matching in length of CPW line and among the switches. The phase shift by each switch and distance between them is formulated in in the equations

$$\Delta\emptyset = \frac{s\omega Z_0\sqrt{\varepsilon_{\mathrm{r,eff}}}}{c}\left(\frac{1}{Z_{\mathrm{Lup}}} - \frac{1}{Z_{\mathrm{Ldown}}}\right)\ \frac{\mathrm{degree}}{\mathrm{section}}\,, \tag{6}$$

$$s = \frac{Z_{\mathrm{Ldown}}C}{\pi f_{\mathrm{B}} Z_0\sqrt{\varepsilon_{\mathrm{r,eff}}}}\ \mathrm{meters}\,, \tag{7}$$

where S is the spacing between switches or length of unit cells, C is speed of light (3×10^8 m/s, and $\varepsilon_{\mathrm{r,eff}}$ is effective dielectric constant. By substituting $Z_{\mathrm{Lup}} \times Z_{\mathrm{down}} =$

2500. Equation (1) is now rewritten as equation:

$$\Delta\emptyset = \frac{360 f_0}{f_{\mathrm{B}} 2500\pi}({Z_{\mathrm{Ldown}}}^2 - 2500)\ \frac{\text{degree}}{\text{section}} \tag{8}$$

and

$$\varepsilon_{\mathrm{r,eff}} = 1 + \frac{\varepsilon_{\mathrm{r}} - 1}{2}\,. \tag{9}$$

The Bragg frequency (f_B), the frequency at which the characteristic impedance of the line goes to zero, causes the entire power to reflect back. The up-state inductance–capacitance (LC) resonant frequency of the MEMS bridges is between 300 and 600 GHz in the DMTL case, which is very high. Therefore, the operation is generally limited by the Bragg frequency of the loaded line. For linearity consideration $f_{\mathrm{B}} \geq 2.2 f_0$, where f_0 is the operating frequency [13].

Capacitance value of the switches can be determined by equations [13]

$$C_{\mathrm{Lup}} = \frac{\left({Z_0}^2 - {Z_{\mathrm{Lup}}}^2\right) Z_{\mathrm{Ld}}}{{Z_0}^2 {Z_{\mathrm{Lup}}}^2 \pi f_{\mathrm{B}}}\ [\mathrm{F}]\,, \tag{10}$$

$$C_{\mathrm{r}} = \frac{{Z_{\mathrm{Lup}}}^2}{{Z_{\mathrm{Ldown}}}^2}\ \frac{\left({Z_0}^2 - {Z_{\mathrm{Ldown}}}^2\right)}{\left({Z_0}^2 - {Z_{\mathrm{Lup}}}^2\right)}\ [\mathrm{F}]\,, \tag{11}$$

$$C_{\mathrm{s}} = C_{\mathrm{Ldown}} = C_{\mathrm{r}} C_{\mathrm{Lup}}\ [\mathrm{F}]\,, \tag{12}$$

$$C_{\mathrm{bup}} = \frac{C_{\mathrm{s}} C_{\mathrm{Lup}}}{C_{\mathrm{s}} - C_{\mathrm{Lup}}}\ [\mathrm{F}]\,. \tag{13}$$

The substrate is supposed to be quartz of $\varepsilon_{\mathrm{r}} = 3.78$, $\varepsilon_{\mathrm{r,eff}} = 2.37$. Impedance Z_0 is considered to be 94 Ω, so that the width of signal line W and spacing between line and ground is 128 and 129 micrometers. Specifications of three types of switches (5.625, 11.25 and 12.857 deg) are given in Table 1.

Table 1. The results for the three types of switches used in the proposed phase shifter

Parameter	Switch type 1	Switch type 2	Switch type 3
$\Delta\emptyset$ (degree)	5.625	11.25	12.857
f_{B} (GHz)	85	42.5	37.2
S (μm)	334	668	763
$Z_{\mathrm{L_{down}}}$ (Ω)	43	43	43
$C_{\mathrm{L_{up}}}$ (fF)	29.5	59	67.43
C_{s} (fF)	69	138	1583
C_{bup} (fF)	51.5	103	118
w×W (μm^2)	57×120	118×120	135×120

Considering data in Table 1, it is clear that the values of C_{bup} and C_{S} of the second type switch are twice as much as the values of C_{bup} and C_{S} of the first type switch. Also the C_{bup} and C_{S} values of the third type switch are 2.285 times as much as C_{bup} and C_{S} values of the first type switch. To reach the determined values, width of the bridge of the second and third type switches are taken 2 and 2.3 times longer as much as the width of the bridge of the first type switch. As is shown in Fig. 2, the air gap (g) for all bridges is considered 1.5 µm. So no extra step is added to fabrication process while the size of the DMTL phase shifter is decreased noticeably. Length of each unit cell or the distance between the switches for shift phases of 5.625 °, 11.25 ° and 12.857 ° are 334 µm, 668 µm and 763 µm. So the total structure size becomes 21 mm which is illustrated in Fig. 4.

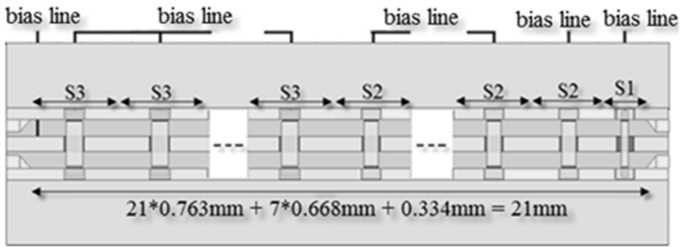

Fig. 4. Top view of the proposed six-bit DMTL phase shifter

3. Performance analysis of the phase shifter

Simulation results could be classified into two categories. First electromagnetic simulation is carried out by HFSS software. Pull-in voltages and switching times of switches are scrutinized by COMSOL software.

3.1. Analysis of electromagnetic performance

A 6-bit DMTL phase shifter is based on the 5.625 °/11.25 °/22.5 °/45 °/90 °/180 ° set of delay networks. In this paper, the 6-bit DMTL phase shifter is designed by 1×5.625 °/1×11.25 °/2×11.25 °/4×11.25 °/7×12.857 °/14×12.857 ° cells. By applying electrostatic force to the selected switches, their state is altered from OFF state to ON state and phase change is introduced to the signal. For example for a 241.875 ° phase shift, first, second, fourth and sixth bits have to be turned ON 241.875 ° ≡ 101011.

Figures 5–7 show the simulation results of the phase shift, return loss and insertion loss for the phase states of 0 °/5.625 °/11.25 °/22.5 °/45 °/90 °/180 °/270 °/354.375 °. As is shown in Fig. 5 for 000000 ≡ 0° the value of phase is 81.7228 degrees and is considered to be the reference value and the rest of the phases are compared to this reference. From Fig. 5, the phase error at 16 GHz for all phase states is smaller than 1.7 °. In Figs. 6 and 7, the return loss and insertion loss for all states are better than –11.4 dB and -1.6 dB, respectively.

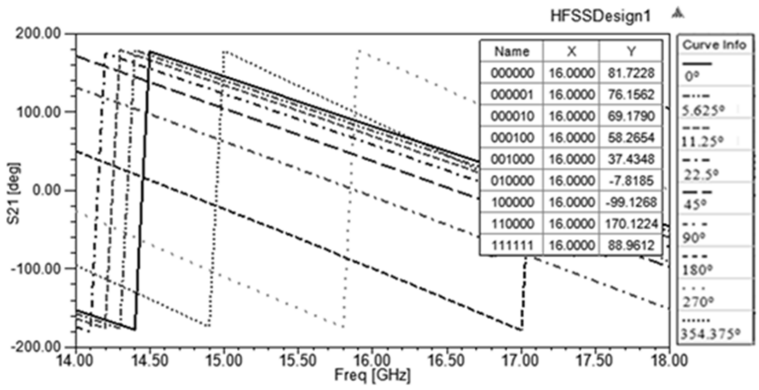

Fig. 5. Phase shift for phase states of 0 °, 5.625 °, 11.25 °, 22.5 °, 45 °, 90 °, 180 °, 270 °, 354.375 °

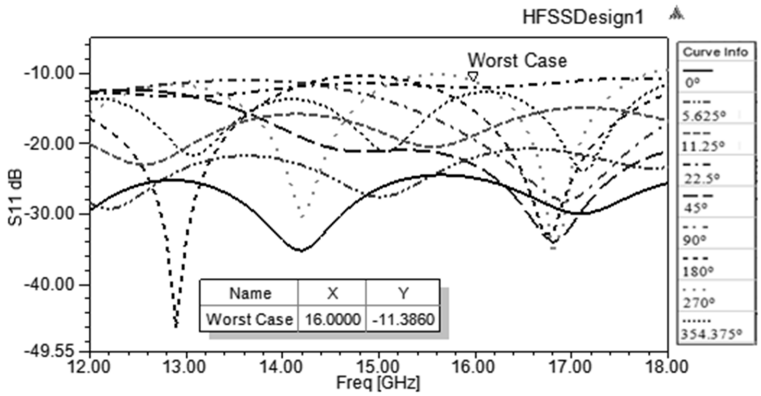

Fig. 6. Return loss for phase states of 0 °, 5.625 °, 11.25 °, 22.5 °, 45 °, 90 °, 180 °, 270 °, 354.375 °

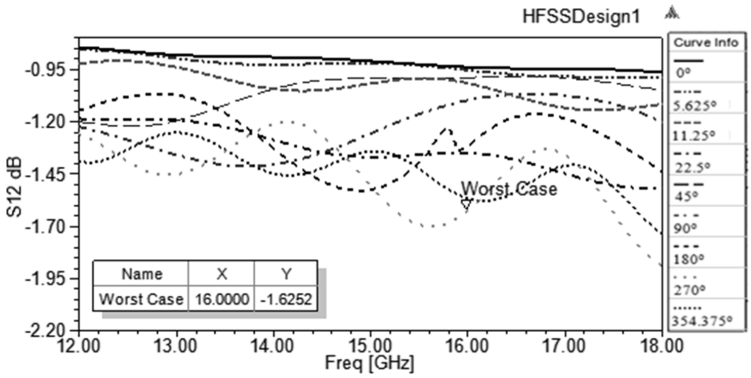

Fig. 7. Insertion loss for phase states of 0 °, 5.625 °, 11.25 °, 22.5 °, 45 °, 90 °, 180 °, 270 °, 354.375 °

3.2. Analysis of the mechanical performance

In mechanical analysis, the only difference between switches is the difference in the width of the bridges of shunt switches. Electrostatic force is applied between the bridge and the signal line to turn the switch ON. This is illustrated in Fig. 8. It is needed to consider electromechanical analysis including, pull-in voltage and switching speed analysis.

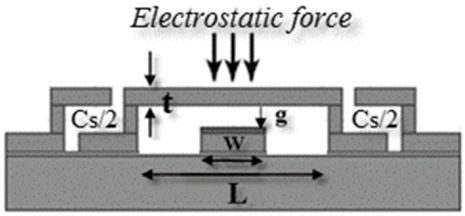

Fig. 8. Applying electrostatic force between signal line and bridge

3.2.1. Pull-in voltage analysis. ON voltage, which is usually named pull-in voltage, happens when the bridge is lowered as much as 1/3 of the air gap and can be expressed as [13, 14]

$$V_{\text{pull-in}} = \sqrt{\frac{8K}{27\varepsilon_0 wW}g^3}\,, \tag{14}$$

where W is the width of signal line, w is the membrane width, g is air gap between bridge and signal line, $\varepsilon_0 = 8.854 \times 10^{-12}\,\text{F/m}$ is the dielectric constant of air and K is spring constant of fixed-fixed beam which is formulated as [13, 14]:

$$K = 32Ew\left(\frac{t}{L}\right)3 + \frac{8\sigma\,(1-\upsilon)\,wt}{L}\,. \tag{15}$$

By substituting (15) into (14), pull-in voltage of fixed-fixed beam can be rewritten as follows

$$V_{\text{pull-in}} = \sqrt{\frac{w\left(256E\left(\frac{t}{L}\right)^3 + \frac{64\sigma(1-\upsilon)t}{L}\right)}{w(27\varepsilon_0 W)}g^3}\,, \tag{16}$$

Here, t is the membrane thickness, L is the membrane length, E is the Young modulus of the membrane material, σ is the residual tensile stress and is taken as zero and 20 MPa for pull down voltage, and ν is the Poison's ratio for the membrane material [14]. For a 1.4 µm thick electroplated Au switch ($E = 79\,\text{GPa}$, $\nu = 0.43$) with $L = 386\,\mu\text{m}$, $g = 1.5\,\mu\text{m}$, and $\sigma = 5\,\text{MPa}$, the pull-in voltage is 14.6 V.

Although the widths of the bridges of switches used in the proposed design are different, according to equation (16), pull-in voltages for all of them are identical (the effect of bridge width (w) is eliminated). Simulation results confirm this issue that has been depicted in Fig. 9.

As it is shown in Fig. 9 pull-in voltages of three switches are identical and are almost 14 V.

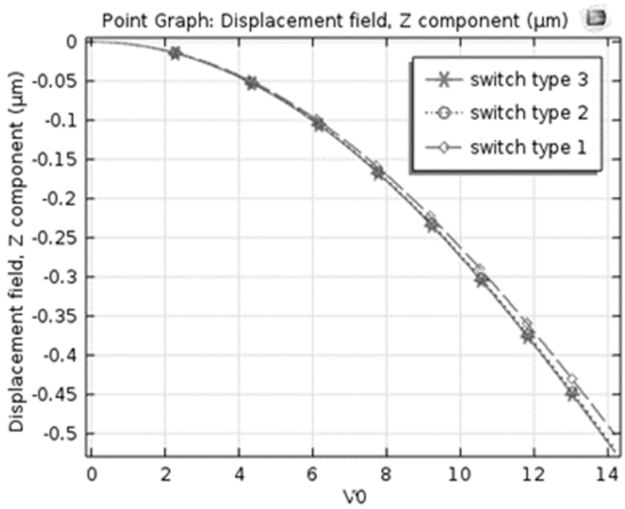

Fig. 9. Simulation results for Pull-in voltages of the switches used in the proposed phase shifter

3.2.2. Switching time analysis. When the electrostatic force is quite large for a small gap height, switching times are very similar in the case of constant damping. This time for beams with a small damping coefficient is obtained using equation (17) and is defined when $x = g$, [12, 13].

$$m_{\text{eff}} \frac{\mathrm{d}x^2}{\mathrm{d}t^2} + KX = -\frac{\varepsilon_0 A V^2}{g^2} \,. \tag{17}$$

Its solution is, [13, 14]

$$t_{\text{s}} = 3.67 \frac{V_{\text{p}}}{V_{\text{s}} \omega_0} \,, \tag{18}$$

where

$$\omega_0 = \sqrt{\frac{K}{m_{\text{eff}}}} \,. \tag{19}$$

In most cases, in a high switching speed at a reasonable voltage level, the applied voltage is 1.3–1.4 V_{p} [13]. The effective mass of the bridge is not equal to the actual mass of the bridge since only a portion of the bridge is moving. For the universal MEMS switches, when the load is applied to the center portion of the bridge, the effective mass is considered to be about the 35 % of total mass, $m_{\text{eff}} = 0.35\,\text{m}$) [12, 13]. So switching time of fixed-fixed beam can be expressed as

$$t_{\text{s}} = \frac{3.67 V_{\text{p}}}{V_{\text{s}}} \sqrt{\frac{w\, 0.35 (t L \rho_{\text{Au}}}{w \left[32 E \left(\frac{t}{L} \right)^3 + \frac{8\sigma(1-\upsilon)t}{L} \right]}} \,. \tag{20}$$

Although the widths w of the bridges of switches used in the proposed design

are different, according to equation (20), the switching times for all of them are identical and according to calculations are equal to 11 µs (the effect of bridge width is eliminated in equation (20) and $\rho_{\mathrm{Au}} = 19320\,\mathrm{kg/m^3}$). Simulation results confirm this issue that has been depicted in Fig. 10 (for $V_{\mathrm{s}} = 1.3V_{\mathrm{p}}$).

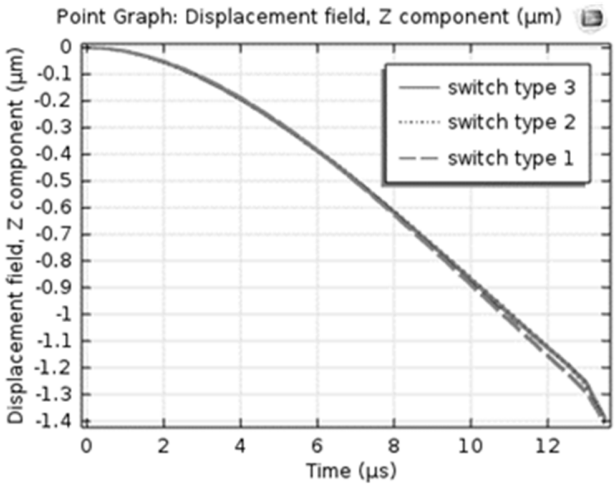

Fig. 10. Simulation results for switching times of the switches used in the proposed phase shifter

As is shown in Fig. 10, switching times of three switches are identical and are almost 13 µs. The comparison between previous works and this work is given in Table 2.

Table 2. Comparison of current state of the art DMTL phase shifters

Parameter	Hayden	Liu	Topalli	Afrang	This work
Frequency (GHz)	37.7	26	15	30	16
Bit number	2	3	3	6	6
Cell number	21	14	28	32	29
Length (mm)	8.4	11	22.4	12.8	21
Min insertion loss (dB)	–2.3	–2.6	–1.9	-	–1.62
Max return loss (dB)	–11.5	–7	–10	–11	–11.4
Max phase error	1°	8.5°	-	2.1°	1.7°
Actuation voltage (V)	20	60	16	3.4 and 6.8	14
Switching time (µs)	9	-	-	28 and 29	13

4. Proposed fabrication process

The proposed phase shifter can be fabricated through surface micromachining method taking the following steps [12]: The fabrication process starts by sputtering

Cr on glass wafer and patterning it (Fig. 11a). CPW line, lower plates of MAM capacitors and bridge anchors defined in the second step are created using liftoff process by sputtering a 1.4 µm layer of Au (Fig. 11b). Next step is silicon nitride deposition and patterning on signal line path as isolator layer (Fig. 11c). To create the gap under the bridge, it is needed to deposit and then pattern photoresist as a sacrificial layer. In fourth step in order to create the air gap, spin photoresist with thickness of 1.5 µm is applied, and then lithography is applied to open the windows which will allow to create anchors (Fig. 11d). In the fifth step, with a set of electroplating methods and then sputtering of gold as thick as 1.4 µm, anchors and electrodes are created (Fig. 11e). Finally, etch holes and spring structures are determined through masking and lithography, and then the photoresist (sacrificial layer) is removed through plasma ashing so that the final structure is reached (Fig. 11f).

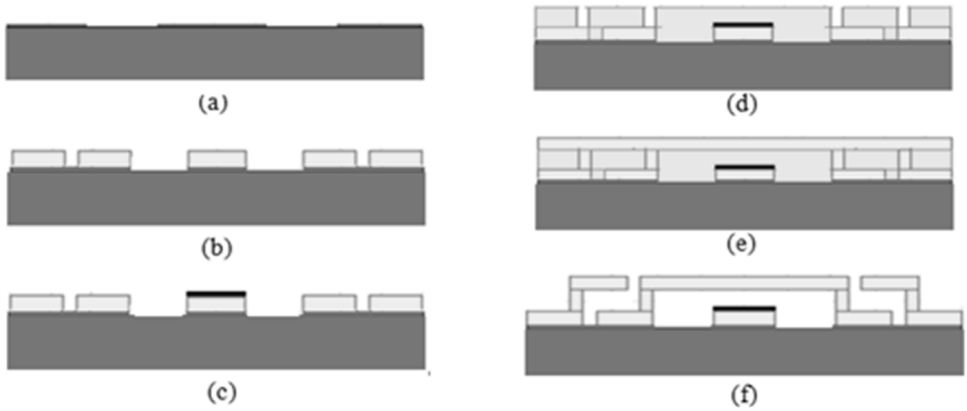

Fig. 11. Process flow used in the fabrication of the phase shifter

5. Conclusion

In this paper, a new design for a six-bit DMTL phase shifter with reduced number of switches is proposed for 16 GHz applications. Although three types of switches with phase shifts of 5.625 °, 11.25 ° and 12.857 ° are employed, impedance matching is easily achieved. Employing three types of different switches led to a total size decrement to 21 mm in comparison with ordinary 6-bit phase shifters with length of 30 mm. It is worthy to note that the size can be decreased to 10 mm at 35 GHz. In this study, electromagnetic and electromechanical analysis including phase shift, return loss, insertion loss, pull-in voltage and switching speed analyses is presented. Maximum RMS phase error, maximum return loss and minimum insertion loss are 1.7 degree, –11.4 dB and –1.6 dB, respectively. Despite having three different switches, pull-in voltages and switching times in all switches are equal to 14 V and 13 µS respectively. Calculated and simulated results of the proposed phase shifter were in a good agreement.

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