A New Structure for 6 Bit Distributed MEMS Transmission Line Phase Shifter in Ku Band

A. Gharekhani, E. Abbaspour-Sani

Department of Electrical Engineering, Urmia University, Urmia, Iran

ABSTRACT

In this paper, using only 32 MEMS switches, a new design for 6 bit DMTL phase shifter is proposed. The reduction in number of switches in ordinary 6 bit phase shifter from 63 to 32 is due to combination of one 5.625 degree for least significant bit and 11.25 degree for the rest of the switches. In new proposed method, the die size and loss of the CPW line reduced by decreasing the number of the switches. Analytical and finite element simulation with HFSS and COMSOL software, is used for considering the performance of the proposed structure. The results showed that, maximum return loss of phase shifter and mean RMS phase error are -10.5 dB and 1.4°, respectively. Although two different micro switches are used but the pull in voltages are identical. The final configuration size is 1.5 × 18.5 mm², and surface micromachining process is suggested for the phase shifter manufacturing.


1. INTRODUCTION

Phase shifters are a serious component in several RF, military industry and microwave systems. Applications include controlling the relative phase of each element in a phase array antenna in a remote communication or steerable communications link and in cancelation loops used in high linearity amplifiers[1, 2]. Depending on the application, design approach of phase shifter is classified into two groups’ viz., digital and analog [3]. According to phase shifter applications each of them has its own advantageous and disadvantageous. One of the most standard methods for implementing digital phase shifters is distributed MEMS transmission line (DMTL) [4]. The DMTL systems uses continuous number of shunt capacitive switches [5-9] and can be fabricated on micro strip [10, 11] or coplanar waveguide lines (CPW) [12-15]. Micro strip line requires via whole or radial stub which decreases quality factor and for DMTL phase shifter CPW structure is more efficient [3].

In digital approach, the DMTL phase shifters has a DC bias voltage which is applied to amount of required bits and the capacitance between line and switches variations hence the impedance of line alters, by varying the line impedance the phase of signal passing though the CPW line modifies[16]. Hayden and Rebeiz [13] 2-bit wide-band distributed coplanar-waveguide phase shifters has been offered by 21 capacitive shunt switches which 7 of distributed MEMS transmission line were devoted to first bit and rest of them to the second one. Each switch is capable of 12.857° phase shift and 90 and 180 degree is shifted by turning the first and second bit’s switches on, respectively. These results are very economical with switched transmission-line and reflection-based phase shifters.

Chen et al. [17] have developed a 4 bit phase shifter which was proposed for Ka-band operation. They have employed 15 shunt capacitive switches with 11.25 degree phase shift for each switch in this work and maximum phase shift is 168.75 degrees and bigger phase shifts are not possible. This low-loss distributed metal-air-metal MEMS phase shifter can be well functional to phased arrays.

As the number of bits of phase shifter increases, more number of switches configuration in on and off state should be studied. For example for 6 bit phase shifter, 63 conditions have to be studied but usually just few number of conditioned are studied such as 5.625°,
11.25°, 22.5°, 45°, 90°, 180° and although probing the all condition are so critical in the total performance of the system, according to the best knowledge of the author of this article, there is no literature which covers all possible condition for 6 bit phase shifter.

In order to design of 6 bit phase shifter, present structure decreasing number of switches and leads to smaller size which is very prominent issue for designers. Afrang et al. [6] have presented a new structure for 6 bit phase shifter for Ka band which contains just 32 switches instead of 63 switches for ordinary 6 bit phase shifter. They have presented a MEMS capacitive switch together with two additional electrodes near the RF line under the bridge, which is capable of altering the phase of signal for two different values (5.625° and 11.25°). Electrostatic force for phase shifts 5.625° through two additional electrodes, and for phase shifts 11.25° through the RF line were applied to the bridge. So this switch requires two different actuation voltages for each condition. Also, two additional electrodes with a different height than the other parts of cause an increase in the number of the stages of the fabrication process.

The results showed for the DMTL phase shifters with more bits and consequently with small least significant bit, the size of the phase shifter will be large. In this paper, to decrease the size of the phase shifter, a new low-loss distributed design of MEMS switch is proposed. Two different switches have been used for 5.625 and 11.25 degree phase shift. Identical actuation voltage is used for all switches which will be discussed in details in the following sections.

2. THEORY OF THE PROPOSED STRUCTURE

In Figure 1 the proposed MEMS phase shifter is composed of CPW line and 32 shunt capacitive switches which are depicted. The total structure is composed of shunt capacitive switches with predefined spacing which is called unit cell. Each switch of Figure 1, is fixed-fixed beam that is illustrated in Figure 2, in up and down position. There are two static MAM capacitors connected to the ends of the bridge (\(C_s/2\)). The equivalent capacitor of \(C_s/2\) and bridge capacitance in up and down position is called \(C_{up}\) and \(C_{down}\), respectively. It is worthy to note that in down position the bridge capacitance increases to Pico Farad range and the equivalent becomes \(C_s\), first switch is allocated for 5.625 degree phase shift and the rest of them are identical and 11.25 degree is shifted by each of 31 switches. First bit switch and one of the second bit’s switch is shown in Figure 2, in on and off conditions.

Electrical model of the switches is shown in Figure 3. In this figure, \(L_{1}\) is the per unit inductance and \(C_{0}\) is the capacitance of the unloaded line with impedance \(Z_0\).

The Switches in DMTL phase shifter in up and down conditions altered the impedance of the line which change the return loss of the CPW. Impedance mismatch in DMTL phase shifter leads to return loss. The governing equation for reflection coefficient is:

\[
\Gamma_i = 10^{\frac{R_{Lmax}}{20}}
\]

where, \(R_{Lmax}\) is maximum return loss.

Figure 1. Total structure of proposed 6 bit phase shifter with 32 switches

Figure 2. Structure of switches in up and down positions

Figure 3. Electrical model of switches

According to literature [3], in ideal conditions the overall phase shifter return loss should be smaller than -10dB. To achieve this criteria, the return loss of each
switch is considered to be -15dB. Therefore, the impedance of the switch in up and down condition can be calculated through the following equations:

\[ R_{L_{\text{max}}} = -15 \text{ dB} \rightarrow \Gamma_{\text{in}} = 10^{\frac{-15}{20}} = 0.178 \]

\[ Z_{\text{Lup}} = 50 \frac{1+\Gamma_{\text{in}}}{1-\Gamma_{\text{in}}} = 59.8 \quad (2) \]

\[ Z_{\text{Ldown}} = 50 \frac{1-\Gamma_{\text{in}}}{1+\Gamma_{\text{in}}} = 41.8 \quad (3) \]

were \( Z_{\text{Lup}} \) and \( Z_{\text{Ldown}} \) are load-line impedance in the high capacitance state and highest capacitive loading on the line, respectively. Accordingly, the line impedance in up and down states must be less than 60 and 42 ohm, respectively. Also, the computations expressed that in the proposed DMTL phase shifter, the up and down impedance is considered to be 58 and 43 ohm, respectively.

The phase shift by each switch and distance between them is formulated in Equations (4) and (5)[18].

\[ \Delta \phi = Z_{0} \frac{\tan \varepsilon_{r_{\text{eff}}}}{c} \left( \frac{1}{Z_{\text{Lup}}} - \frac{1}{Z_{\text{Ldown}}} \right) \text{degree} \quad (4) \]

\[ s = \frac{Z_{\text{Ldown}} C_{r}}{Z_{0} \eta_{\text{eff}} f_{B}} (\text{m}) \quad (5) \]

where, \( f_{B} \) is bragg frequency and \( \varepsilon_{r_{\text{eff}}} \) is effective dielectric constant of the unloaded t-line that is defined as follows:

\[ \varepsilon_{r_{\text{eff}}} = \frac{1+\varepsilon_{r}}{2} \quad (6) \]

Substituting \( Z_{\text{Lup}} \times Z_{\text{Ldown}} = 2500 \) into Equation (4), the phase shift obtained as:

\[ \Delta \phi = \frac{360 f_{B}}{2500 \eta_{\text{eff}}} (Z_{\text{Ldown}} \times 2500) \text{degree} \quad (7) \]

For each switches, the capacitance value can be determined as follows:

\[ C_{\text{Lup}} = Z_{\text{Ldown}} \frac{(Z_{0}^{2}-Z_{\text{Lup}}^{2})}{Z_{0}^{2}Z_{\text{Lup}}^{2}} \text{Farads} \quad (8) \]

\[ C_{r} = \frac{(Z_{0}^{2}-Z_{\text{Ldown}}^{2})}{Z_{0}^{2}Z_{\text{Ldown}}^{2}} (Z_{\text{Lup}}^{2} - Z_{\text{Ldown}}^{2}) \text{Farads} \quad (9) \]

\[ C_{s} = C_{\text{Ldown}} = C_{r} \times C_{\text{Lup}} \text{Farads} \quad (10) \]

\[ C_{\text{Lup}} = \frac{C_{\text{Lup}} + C_{r}}{C_{\text{Lup}} + C_{s}} \text{Farads} \quad (11) \]

For linearity consideration \( f_{B} > 2f_{0} \), where \( f_{0} \) is operating frequency [3, 5]. Since, due to loading effect of the switches the impedance of CPW line decreases, so, the characteristic impedance has to be chosen higher than 50 ohm [3, 15]. Increasing the characteristic impedance of signal line would lead to increment the phase shift which desirable and return loss that would degrade the performance of the phase shifter. Return loss is related exponentially to the characteristic impedance so there is a trade-off between the phase shift and return loss by adjusting the characteristic impedance. In DMTL phase shifters with quartz substrate (\( \varepsilon_{r} = 3.75, \varepsilon_{r_{\text{eff}}} = 2.38 \)), characteristic impedance should be between 80 and 100 ohm to achieve maximum phase shift and minimum loss. Because of the impedance of the unit cell in upstate and downstate 58.14 and 43 ohm, respectively. Therefore, using Equation (4), the Z0 is obtained as 95.2 ohm. Consequently, the width of RF line and the spacing between RF line and ground are 120 and 130 micrometer, respectively. Specifications of two type of switches (5.625 and 11.25 degree) are listed in Table 1.

The proposed DMTL phase shifter can be fabricated through surface micromachining method. According to Table 1 the capacitance of bridge for 5.625° unit cell is half of the capacitance of 11.25° unit cell, so the ratio of the width of first bit to second bit is 0.5. The air gap \( g \) for all bridges is considered to be 1.6μm. So, no extra step is added to fabrication process and the size of the DMTL phase shifter is decreased noticeably. The spacing between 11.25° switches is \( S_{0} = 586 \mu \text{m} \) and for 5.625° switch is \( S_{0} = 293 \mu \text{m} \) so the total structure size becomes 18.5mm which is illustrated in Figure 4.

### 3. VERIFICATION

Simulation result could be classified into two categories. Electromagnetic simulation is carried out by ANSYS HFSS software and pull in voltage of switches is scrutinized by COMSOL software.

<p>| TABLE 1. Specification parameters for 5.625° unit cell and 11.25° unit cell |
|---------------------------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Switch Type 1</th>
<th>Switch Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \phi ) (degree)</td>
<td>5.625</td>
<td>11.25</td>
</tr>
<tr>
<td>( f_{0} ) (GHz)</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>( Z_{0} ) (Ω)</td>
<td>95.2</td>
<td>95.2</td>
</tr>
<tr>
<td>( f_{0} ) (GHz)</td>
<td>95.4</td>
<td>47.7</td>
</tr>
<tr>
<td>( S ) (μm)</td>
<td>293</td>
<td>586</td>
</tr>
<tr>
<td>( Z_{\text{Ldown}} ) (Ω)</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>( Z_{\text{Lup}} ) (Ω)</td>
<td>58.14</td>
<td>58.14</td>
</tr>
<tr>
<td>( C_{r} )</td>
<td>2.32</td>
<td>2.32</td>
</tr>
<tr>
<td>( C_{\text{Lup}} ) (fF)</td>
<td>26.62</td>
<td>53.23</td>
</tr>
<tr>
<td>( C_{r} ) (fF)</td>
<td>61.8</td>
<td>123.5</td>
</tr>
<tr>
<td>( C_{\text{Lup}} ) (fF)</td>
<td>46.76</td>
<td>93.5</td>
</tr>
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</table>
3.1. Electromagnetic Simulation In the proposed new phase shifter, phase shift, insertion loss and return loss are simulated for all 64 conditions (0°, 5.625°, 11.25°, 16.875°, 22.5°, ..., 354.375°) by HFSS software. Applying electrostatic force to the selected switches, their condition is altered from OFF to ON conditions and introduced phase change to the signal. For example for 253.125° phase shift first, third, fourth and sixth bits have to be turned ON. The simulation results for all distinct situations are shown in Figures 5(a) and 5(b).

As it is shown in Figure 5(a) for 000000 ≡ 0° the value of phase is 91.8725 degree and is considered to be the reference value and the rest of the phases are compared with this reference. Phase error and shifts for all possible conditions are represented in Tables 2 and 3.

**Table 2. The phase shift and error for 0° to 180° conditions**

<table>
<thead>
<tr>
<th>Phase state</th>
<th>Phase shift</th>
<th>Phase error</th>
<th>Phase state</th>
<th>Phase shift</th>
<th>Phase error</th>
<th>Phase state</th>
<th>Phase shift</th>
<th>Phase error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>61.875</td>
<td>62.6085</td>
<td>0.7335</td>
<td>123.75</td>
<td>121.0884</td>
<td>-2.6616</td>
</tr>
<tr>
<td>5.625</td>
<td>6.453</td>
<td>0.828</td>
<td>67.5</td>
<td>69.2765</td>
<td>1.7765</td>
<td>129.375</td>
<td>126.602</td>
<td>-2.773</td>
</tr>
<tr>
<td>11.25</td>
<td>12.2265</td>
<td>0.9765</td>
<td>73.125</td>
<td>74.524</td>
<td>1.417</td>
<td>135</td>
<td>131.986</td>
<td>-3.014</td>
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<td>16.875</td>
<td>17.8983</td>
<td>1.0233</td>
<td>78.75</td>
<td>79.3409</td>
<td>0.5909</td>
<td>140.635</td>
<td>138.0975</td>
<td>-2.5775</td>
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<td>22.5</td>
<td>22.2352</td>
<td>-0.2648</td>
<td>84.375</td>
<td>83.9413</td>
<td>-0.4337</td>
<td>146.25</td>
<td>145.6627</td>
<td>-0.5873</td>
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<td>28.125</td>
<td>29.2352</td>
<td>1.1102</td>
<td>90</td>
<td>87.6848</td>
<td>-2.3152</td>
<td>151.875</td>
<td>150.455</td>
<td>-1.42</td>
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<td>33.75</td>
<td>32.2336</td>
<td>-1.5164</td>
<td>95.625</td>
<td>94.4969</td>
<td>-1.1281</td>
<td>157.5</td>
<td>158.5954</td>
<td>1.0954</td>
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<td>39.375</td>
<td>38.21</td>
<td>-1.165</td>
<td>101.25</td>
<td>100.9354</td>
<td>-0.3146</td>
<td>163.125</td>
<td>164.1215</td>
<td>0.9965</td>
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<tr>
<td>45</td>
<td>43.6378</td>
<td>-1.3262</td>
<td>106.875</td>
<td>106.2625</td>
<td>-0.6125</td>
<td>168.75</td>
<td>167.6052</td>
<td>-1.1448</td>
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<tr>
<td>50.635</td>
<td>49.9499</td>
<td>-0.6751</td>
<td>112.5</td>
<td>111.2605</td>
<td>-1.2395</td>
<td>174.375</td>
<td>173.2586</td>
<td>-1.1164</td>
</tr>
<tr>
<td>56.25</td>
<td>57.1382</td>
<td>0.8882</td>
<td>118.125</td>
<td>117.4572</td>
<td>-0.6678</td>
<td>180</td>
<td>177.5843</td>
<td>-2.4157</td>
</tr>
</tbody>
</table>

**Table 3. The phase shift and error for 180° to 354.375° conditions**

<table>
<thead>
<tr>
<th>Phase state</th>
<th>Phase shift</th>
<th>Phase error</th>
<th>Phase state</th>
<th>Phase shift</th>
<th>Phase error</th>
<th>Phase state</th>
<th>Phase shift</th>
<th>Phase error</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>177.5843</td>
<td>-2.4157</td>
<td>241.875</td>
<td>238.8325</td>
<td>-3.042</td>
<td>303.75</td>
<td>300.0746</td>
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<tr>
<td>185.625</td>
<td>184.083</td>
<td>-1.542</td>
<td>247.5</td>
<td>249.8504</td>
<td>2.3504</td>
<td>309.375</td>
<td>306.296</td>
<td>-3.079</td>
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<tr>
<td>191.25</td>
<td>192.133</td>
<td>0.883</td>
<td>253.125</td>
<td>255.8985</td>
<td>2.7735</td>
<td>315</td>
<td>313.1325</td>
<td>-1.867</td>
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<tr>
<td>196.875</td>
<td>197.6858</td>
<td>0.7835</td>
<td>258.75</td>
<td>258.018</td>
<td>-0.732</td>
<td>320.635</td>
<td>320.2546</td>
<td>-0.370</td>
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<tr>
<td>202.5</td>
<td>204.2172</td>
<td>1.7172</td>
<td>264.375</td>
<td>262.046</td>
<td>-2.329</td>
<td>326.25</td>
<td>326.6013</td>
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<tr>
<td>208.125</td>
<td>209.5557</td>
<td>1.4287</td>
<td>270</td>
<td>270.5891</td>
<td>0.5891</td>
<td>331.875</td>
<td>334.318</td>
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<td>213.75</td>
<td>214.4947</td>
<td>0.7447</td>
<td>275.625</td>
<td>276.9026</td>
<td>1.2776</td>
<td>337.5</td>
<td>338.0624</td>
<td>0.5624</td>
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<tr>
<td>219.375</td>
<td>219.004</td>
<td>-0.1746</td>
<td>281.25</td>
<td>281.5634</td>
<td>0.3134</td>
<td>343.125</td>
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<tr>
<td>225</td>
<td>222.4429</td>
<td>-2.5571</td>
<td>286.875</td>
<td>286.9651</td>
<td>0.0901</td>
<td>348.75</td>
<td>350.3443</td>
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<td>230.635</td>
<td>228.1601</td>
<td>-2.4649</td>
<td>292.5</td>
<td>289.6509</td>
<td>-2.849</td>
<td>354.375</td>
<td>354.6739</td>
<td>0.2989</td>
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<td>236.25</td>
<td>233.9068</td>
<td>-2.3432</td>
<td>298.125</td>
<td>297.2739</td>
<td>-0.851</td>
<td></td>
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</tbody>
</table>
Figures 6 and 7 show the $S_{11}$ and $S_{12}$ that are extracted by HFSS. $S_{11}$ and $S_{12}$ are Return loss and Insertion loss, respectively. According to [3] the overall phase shifter return loss should be smaller than -10dB and the result of this paper as it shown in Figure 8 confirmed and $S$ satisfied this issue. In 18GHz for all 64 conditions, return loss is less than -10dB and insertion loss is between -0.9dB and -1.8dB.

3.2. Mechanical Design and Simulation of Switch

As mentioned in the previous sections, the shunt capacitive switches are exploited in design of the proposed phase shifter. The only difference between first switch and the rest of them is the width of the first switch is half of the rest.

Electrostatic force is applied between the bridge and the RF line to turn the switch ON which is illustrated in Figure 8.

When the MEMS bridge is in the ON position, the corresponding voltage is usually named pull-in voltage can be obtained as follows [11, 19]:

$$V_{pl} = \frac{8K}{\sqrt{27\epsilon_0\sigma bW}}^{3/4}$$  \hspace{1cm} (12)

where, $b$ is the membrane width, $W$ is width of RF line, $g$ is air gap between bridge and RF line, $\epsilon_0$ is dielectric constant of air. The parameter $K$ is spring constant of beam with clamped-clamped boundary conditions which is expressed as follows [3, 20]:

$$K = 32EB\left(\frac{l}{t}\right)^3 \frac{1}{8\left(\frac{l}{t}\right)^2 - 20\left(\frac{l}{t}\right)^4 + 14\left(\frac{l}{t}\right)^6 - 1} + 8\sigma (1 - \theta) b \left(\frac{l}{t}\right)^2  \frac{1}{3 - 2\left(\frac{l}{t}\right)^2}$$  \hspace{1cm} (13)

The pull-in voltage of clamped-clamped micro beam can be obtained by substituting Equation (13) into Equation (12) and resultant can be expressed as follows:

$$V_{pl} = \left(\frac{8bg^3}{27\epsilon_0\sigma bW}\right)^{1/2} \times \left(32EB\left(\frac{l}{t}\right)^3 \frac{1}{8\left(\frac{l}{t}\right)^2 - 20\left(\frac{l}{t}\right)^4 + 14\left(\frac{l}{t}\right)^6 - 1} + 8\sigma (1 - \theta) b \left(\frac{l}{t}\right)^2  \frac{1}{3 - 2\left(\frac{l}{t}\right)^2}\right)^{1/2}$$  \hspace{1cm} (14)

where, $E$ is Young’s modulus, $t$ is the thickness, $L$ is the length, $\sigma$ is the residual tensile stress, and $v$ is Poisson’s ratio [8]. For an Au micro-switch electroplated with 1.2 $\mu$m thickness ($E$=79 GPa, $v$ = 0.43), $L$ = 350 $\mu$m, $g$ = 1.6 $\mu$m, $x$=250 $\mu$m, and $\sigma$ = 0 and 20 MPa, the pull-in voltage is obtained 5.2 V and 17.2 V, respectively.

While the width of the first switch is half of the switches, but according to Equation (14) pull-in voltage for all of them are identical. This issue is expected because Pull-in voltage is directly proportional to spring constant of the bridge and inversely related to the capacitance value between the bridge and bottom electrode that here is RF line. As the width of the bridge decreases (other parameters are constant) the capacitance decreases and higher pull-in voltage is expected but this issue is compensated by decreasing the spring constant of the bridge and as a result pull-in voltage remains constant. Simulation results confirm this issue that has been depicted in Figures 9(a) and 9(b).

As it is shown in Figure 9 pull-in voltage of both switches are identical and about 13 Volt. Table 4 listed the comparison results of this work and previous works. The results showed that obtained results has a good agreement with those of previous works.
4. CONCLUSION

New design for 6-bit DMTL phase shifter with compact number of switches for 18GHz were proposed. Though, the two types of micro-switches with phase shift of 5.625 and 11.25 has been presented impedance matching criteria was considered convincingly. Also identical actuation voltage is used for all switches. Employing two types of different switches led to total size decrement to 18.5mm in comparison with ordinary 6-bit phase shifter with length of 35mm. In this study all 64 possible conditions were well deliberate and simulated with HFSS software. The results indicated that, the design resulted mean RMS phase error were obtained 1.4° and for all conditions return loss is smaller than -10dB which are acceptable values for phase shifters.

5. REFERENCES


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A. Gharehkhani, E. Abbaspour-Sani

Department of Electrical Engineering, Urmia University, Urmia, Iran

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Actuation Voltage

چکیده
در مقاله حاضر، ارائه شده است کاهش تعداد سوئیچ های شیفت دهنده فاز شش بیتی از یک سوئیچ دیجیتال MEMS DMTL به کمک عملگر بازگشتی که تنها یک بازگشتی و یک سوئیچ می باشد، ارائه شده است. در تحقیق مورد نظر، میزان تلفات بازگشتی سوئیچ دیجیتال MEMS DMTL به کمک عملگر بازگشتی که تنها یک بازگشتی و یک سوئیچ می باشد تا حدود 10.5 دیجیتال MEMS DMTL به کمک عملگر بازگشتی که تنها یک بازگشتی و یک سوئیچ می باشد تا حدود 10.5 دیجیتال MEMS DMTL به کمک عملگر بازگشتی که تنها یک بازگشتی و یک سوئیچ می باشد تا حدود 10.5 دیجیتال MEMS DMTL به کمک عملگر بازگشتی که تنها یک بازگشتی و یک سوئیچ می باشد تا حدود 10.5

A new structure for 6 bit distributed MEMS transmission line phase shifter in Ku Band

A. Gharehkhani, E. Abbaspour-Sani

Department of Electrical Engineering, Urmia University, Urmia, Iran

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