An Improved Design for Ka-Band Phase Shifter Using Distributed MEMS Transmission Line Structure

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Abstract

The paper presents a model which describes the stage circuit of Distributed MEMS Transmission Line (DMTL) phase shifter at Ka band and an approach for DMTL design utilizing the saw-shaped coplanar waveguide (CPW). The result of circuit simulation and full wave analysis prove that the model is in good agreement with theoretical analysis. The model can effectively simplify the design complexity after optimization. Simulation results show that the $S_{11}$ and $S_{21}$ can achieve -20 dB and -2.5 dB, respectively, and the phase shift arrives at $-180^\circ$ at Ka band. Comparing with literature data, it has been predicted that $S_{11}$ improves about 8 dB and the phase shift can increase about 100$^\circ$ in the same condition.

Introduction

Millimeter wave phased array is widely used in radar, missile guidance, satellite communication and so on. High isolation and low loss phase shifters are required for millimeter wave applications. Microelectromechanical system (MEMS) phase shifter is very popular for its good properties, such as small size, low weight, wide frequency-band, low insertion loss, are particular easy integrated with microwave circuits, where the performance of DMTL topology and phase shifter is beyond others at Ka band applications. The idea of DMTL phase shifter is to load a t-line periodically with MEMS bridges and control bridge height with DC voltage, so the distributed capacitance on the line, phase velocity and phase shift can be varied. According to result of $S_{11}$ and $S_{21}$ were respectively achieved to -12 dB and -5 dB at 35 GHz [1]. However, the discontinuity is introduced after loading the MEMS bridges on the normal CPW transmission line for adding the shunt capacitance, so that the reflection is higher. This paper proposed a design method with saw-shaped CPW for the improvement of $S_{11}$ and $S_{21}$ and the phase shift. But the improvement is at the cost of Bragg frequency, so it narrows the bandwidth, however, the bandwidth is wide enough in the millimeter wave communication system.

Design Considerations

As shown in Fig.1, the effect of capacitance produced by MEMS bridges will be offset by the effect of discontinuity caused by saw-shaped CPW [2]. $w_1$ and $g_1$ are the width of signal trace and gap, respectively, in narrow part of saw-shaped CPW transmission line, and $w_2$ and $g_2$ are the corresponding wide part, $s$ is the periodic spacing of the bridges. For better performance, $S_{11}$ and $S_{21}$ parameters are required to be optimized. To do so, we modeled the equivalent circuit of each stage of saw-shaped CPW transmission line to establish mathematical expressions by using ABCD matrix analysis, and then $S$ matrix of the completed saw-shaped CPW transmission line topology is obtained in order to find the optimized value $w_1$. Open-circuit stubs are equivalent to shunt capacitance and short-circuit stubs are equivalent to series inductance [3]. The saw-shaped CPW DMTL phase shifter is modeled by the equivalent circuit parameters composed of inductance and capacitance, as shown in Fig. 3, where, $L_i$ and $C_i$ are the per unit length of inductance and capacitance of the unloaded transmission line, respectively.

\[ C_i = \sqrt{\varepsilon_{r,\text{eff}}}/cZ_0 \quad \text{and} \quad L_i = C_iZ_0^2 \quad (1) \]

Where the $\varepsilon_{r,\text{eff}}$ and $Z_0$ are the effective dielectric constant and characteristic impedance, respectively, of the unloaded transmission line and $c$ is the velocity of light in free space. $Z_0$ can be achieved by conformal mapping to be[4]:

\[ Z_0 = \frac{\eta_0K(k')}{4\sqrt{\varepsilon_{r,\text{eff}}K(k)}} \quad (2) \]
where $\varepsilon_{r,\text{eff}} = (\varepsilon_r + 1)/2$, $k = w/(w + 2g)$ and $k' = \sqrt{1-k^2}$. $\eta_0$ is the free space impedance and $K(k)$ is the complete elliptic integral of the first kind.

The inductance produced by the discontinuity of saw-shaped CPW transmission line, $L'$ is given by:

$$L' = (w + 2g)L_t/4$$ (3)

Accordingly, the capacitance $C'$, the capacitance produced by the discontinuity of saw-shaped CPW transmission line, can be derived as follows: The capacitance per unit length of each coplanar line is found by conformal mapping to be:

$$c(k) = \varepsilon_0\varepsilon_{\text{eff}}\left(\frac{K(k_3)}{K'(k_3)} + \frac{K(k)}{K'(k)}\right)$$ (4)

where $k_3 = \frac{\tanh(\frac{\pi(w+2g)}{4H})}{\tanh(\frac{\pi w}{4H})}$ and $\varepsilon_{\text{eff}} = 1 + (\varepsilon_r - 1)\frac{K(k_3)}{K'(k_3)} + \frac{\eta_0}{\varepsilon_0}K(k)$ with $K(k)$ is the elliptic integral ratio and $H$ is the height of the substrate. Therefore, for capacitance per unit length equivalence is:

$$\varepsilon_0x_1/g_1 = c(k_1) \quad \text{and} \quad \varepsilon_0x_2/g_2 = c(k_2)$$

For the discontinuity capacitance per unit width of a step in height $w_1$ to $w_2$ is reasonable approximation to the CPW step as in the CPW majority of the field is between the inner and outer conductors with some fringing fields, it is estimated that the fringing capacitance will take up about 25%-40% in the total capacitance, and can not be ignored. The capacitance is

$$C_u(\alpha) = \frac{\varepsilon_0}{\pi}\left[\frac{\alpha^2 + 1}{\alpha}\ln\left(\frac{1 + \alpha}{1 - \alpha}\right) - 2\ln\left(\frac{4\alpha}{1 - \alpha^2}\right)\right]$$ (5)

where $\alpha = g_2/g_1$ and $\alpha < 1$. Therefore, the actual saw-shaped CPW step capacitance is given by:

$$C' = \frac{x_1 + x_2}{2} \cdot C_u\left(\frac{g_2}{g_1}\right)$$ (6)

The function relationship of (6) is shown in Fig.3, where quartz ($\varepsilon_r = 3.8$) is chosen as the substrate and $H=500 \mu m$. Comparing with $C_b$, the loading capacitance due to the MEMS bridge [5], we find that the step
capacitance $C'(< 1 \text{fF})$ is negligible. Therefore the model shown in Fig.2 can be modified as the new model shown in Fig.4.

**Simulation and Discussions**

Fig.5 shows the reflection $S_{11}$ and the insertion loss $S_{21}$ (after neglecting the step capacitance $C'$) as functions of $w_1$, based on $C_b=20 \text{ fF}$, $h_u=1.5 \mu m$, $h_d=1.2 \mu m$, $s=100 \mu m$, $w=25 \mu m$, $f=35\text{GHz}$ and the number of sections is $n=31$, the total length is found to be $3100 \mu m$, and $C_b$ is the capacitance introduced by MEMS bridge, $h_u$ and $h_d$ are the height of up and down states of MEMS bridges, $s$ is the periodical space between MEMS bridges and $w$ is the width of MEMS bridge. We can get the optimal value, when $w_1=66 \mu m$, $S_{11}=-48$, $S_{21}=-0.000058$, theoretically. Fig.6 and Fig.7 show the results of circuit simulation with Aglient ADS and full wave analysis with Ansoft HFSS. Fig.8 shows that the relationship between the phase shift and frequency and we can arrive at $-180^\circ$ at $35\text{GHz}$, it increases about $-10^\circ$ phase shift. It has been shown that the result of circuit simulation is in good agreement with the theoretical analysis. For the result of full wave analysis, it appears that the center frequency drifts because we neglect the dielectric loss, radiation loss and the loss of MEMS bridges in the process of analysis. However, it has been predicted that all of the losses are allowed at Ka band application. From Fig.7, we can see that $S_{11}$ and $S_{21}$ achieved -20 dB and -3 dB from 35-37 GHz, and improved about 8 dB and 2 dB, respectively, comparing with previous results[1]. As for the Bragg frequency, which is given by:

$$f_{\text{Bragg}} = \frac{720}{\sqrt{(sL_4 + L)(sC_b' + C_b + C')}}$$  \hspace{1cm} (7)
We can get the conclusion easily that the $f_{Bragg}$ will be lowered, and for the $f_{Bragg}$ decides the bandwidth, so the bandwidth will be narrowed, however, from the simulation result it is wide enough in the millimeter wave system.

**Conclusion**

In this paper, modeling and design of a novel DMTL phase shifter are discussed. The inductance caused by the discontinuity of saw-shaped CPW offsets the capacitance caused by MEMS bridges so that the reflection $S_{11}$ has greatly improved about 8 dB. In addition, the fabrication technology is easy to realize. The improvement of $S_{11}$ is a active approach to better performance for the Ka band phased shifter design.

**REFERENCES**


