A Framework for Low Loss Five-bit Distributed RF MEMS DMTL Phase shifter for ku band applications

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Abstract

Phase shifters that enable the control or tuning of a signals phase angle are the need of the hour for the circuits in modern phased array antennas. The conventional phase shifter structure has limited capacitance ratio and high insertion loss. This effect is the major limitation in phase shifter designs and can cause nonlinearity and mechanically instability performance of such circuits can be improved by RF MEMS technology. MEMS varactors are a refinement of switches, and have received considerable attention in literature in recent years. Design and simulation of the proposed varactor based MEMS distributed phase shifter structure for Ku band applications is carried out using Advanced Design Systems to analyse the RF performance. The return loss of the switch is below -10dB and insertion loss is -0.36dB in down stage, in upstate the insertion loss and return loss of the structure is -0.3dB, -20dB at 17GHz. The maximum phase deviation of the single bit is smaller than 0.61º. By adopting a novel topology to diminish coupling of different bits, 5-bit varactor based Distributed MEMS Transmission Line (DMTL) phase shifter results in an average return loss of 20.98dB, an average insertion loss of 0.19dB, an average phase deviation of 2.19º.

1. Introduction

The MEMS technology has the potential of replacing many Radio Frequency (RF) components such as switches, inductors, varactors, phase shifters, Surface Acoustic Wave (SAW) devices and ceramic filters used in today's mobile, communication, satellite and radar systems and its performance is especially good for high frequency applications. MEMS technology show low insertion loss, low power consumption, and high linearity compared to the conventional techniques [1]. As a result, in the past few years RF MEMS concept has been successfully applied to develop low loss RF switching devices and variable capacitor. Although the switching speed of MEMS device may not be comparable to FET or P-I-N diode switches, the MEMS devices have better performance in terms of isolation and insertion loss at microwave frequencies. With the development of phased-array, higher performance is required for phase shifters. A Phase shifter is used as a core component in the electronically scanning phased-array antenna widely deployed in electronic warfare (EW) systems, missile tracking radar, forwarding looking radar used by airborne fighter/bomber aircraft communications systems, and space-based surveillance and reconnaissance sensors [2]. Several attempts have been made in miniaturizing FET-based phase shifters by using embedded-FET or lumped approaches for the phase-delay networks [4], [5], [6]. While such phase shifters achieve a very small size of 1–2 mm, the loss associated with the low-on-chip inductors, as well as the transistor series resistance in the embedded-FET phase-shift networks, result in phase shifters with relatively high losses (5 dB at 19 GHz for a 5-bit design [5]). Such approaches are therefore not suitable for use in the miniaturization of low-loss MEMS phase shifters. RF MEMS phase shifters are developed to enhance the performance characteristics and to reduce the cost [7]. The reported RF MEMS phase shifters are low-loss distributed phase shifters for time delay [8] compared to X-band reflection type phase shifters [9], and Ka-band switched line phase shifters [10]. MEMS varactors with analog tuning have seen limited developments mostly because of their low capacitance ratio of 1.25-1.35. A solution with separate electrodes and nonplanar membrane resulted in an analog capacitance ratio of 1.7-1.9. Among the MEMS phase shifters the DMTL phase shifter that operates on the principle of dispersion draws more and more attention because of low insertion loss, low power dissipation and broadband characteristic. In addition, the DMTL phase shifters have better performance [9] on simple coplanar waveguide (CPW) transmission line because CPW based phase shifters are uniplanar. Table1 shows the performance comparison of conventional and MEMS phase shifter. In this paper, varactor based DMTL phase shifter was designed to reduce the insertion loss. The measured loss and operation voltage the proposed phase shifters are compared with the reported MEMS phase shifters at various bands in Table I. It can be easily observed from the table that the insertion losses of the proposed phase shifters compare very well even with the lower frequency phase shifters. A DMTL phase shifter was first developed in an analog fashion by Barker and Rebeiz [11]. MEMS distributed phase shifter consists of a high impedance transmission line periodically loaded by shunt capacitive MEMS switches. By applying a control voltage to change the gap of the MEMS bridges, the loading varactors introduce different phase velocities on the transmission line and therefore provide a phase difference. The proposed configuration come with lower loss compared with conventional monolithic devices. The structure of the paper is organized as follows; section 2 describes the design of varactor based DMTL phase shifter that covers design of 5 unique phase state. Section 3 reports the simulated results and discusses the different design of DMTL phase shifters. Section 4 presents conclusions on the findings.

Table 1: Comparison of Insertion loss for Conventional and MEMS phase shifter

Type	**Reference**	**Number of bits**	**Frequency [GHz]**	**Insertion loss [dB]**	**Substrate**
Semiconductor	[12]	6	1.3	9	0.7-µm MESFET
	[13]	6	10	9	1- µm FET
	[14]	5	19	5	0.25- µm pHEMT
Ferroelectric (Analogue)	[15]	330º	21.7	6.1	BST on sapphire
	[16]	120º	2.4	1.8	BST on sapphire
RF MEMS	[17]	4	10	1.47	Series ohmic contact switches on high-resistivity GaAs
	[18]	5	10	1.54	Switches based DMTL phase shifter with on silicon
This proposed Work		5	17	0.19	Varactors based DMTL phase shifter on high resistive silicon

2. Design principle for varactor based DMTL Phase Shifter

The DMTL phase shifter consists of a high impedance (>50Ω) CPW transmission line and MEMS shunt switches that are loaded by the periodic placement of variable capacitance. The DMTL is connected to 50Ω input and output lines to match with probe pads. The proposed RF MEMS varactor based DMTL phase shifter is simulated on a CPW line with dimensions of G/W/G = 75/130/75 µm (50Ω) for dc–10-GHz on a high-resistivity silicon substrate 400µm with dielectric constant of 11.9. The bridge length is L =303.5 µm. The beam height from the thin dielectric layer and the cantilever beam is 3 µm. The height of the inserted dielectric is 0.5µm. The schematic diagram of aforementioned varactor based DMTL is shown in Fig. 1. The varactor parameters are calculated using ADS.

2.1. Loss versus impedance

For a unit cell of the MEMS phase shifter, a MEMS switch is loaded on a coplanar wave-guide (CPW). There are two states of the phase shifter, up and down. Up is the original height of the MEMS varactors while down is the state when the bridges are actuated. The loading capacitance in the switch is increased when the analog bias voltage to the center conductor pulls down the bridges closer to center conductor. In this case, the two states make the phase velocity changes, thus providing a differential phase shift. A unit of a distributed MEMS phase shifter can be approximated as a lumped circuit consisting of an inductance of transmission line (t-line) L_t in shunt with a capacitance of t-line C_t and a MEMS varactor capacitance C_v, as shown in Fig. 2.

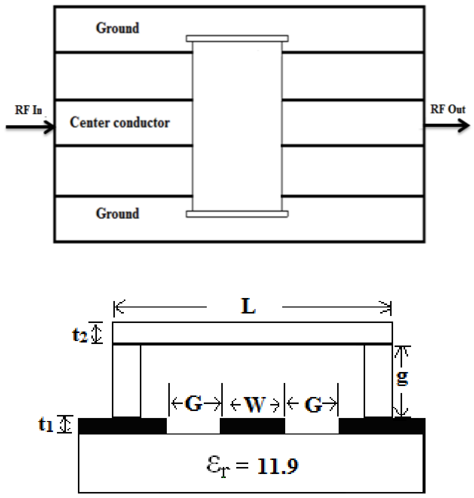

Figure 1. (a) Top view, (b) side view Schematic of the unit cell of Varactor based RF MEMS distributed phase shifter

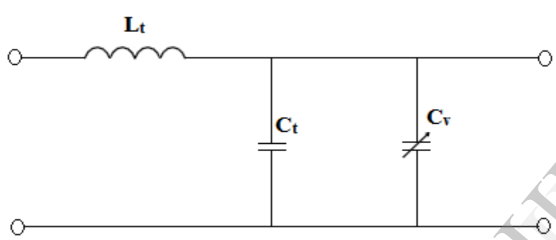

Figure 2. Equivalent circuit of the unit cell of varactor based RF MEMS distributed phase shifter

L_t, C_t and C_v can be calculated using equations (1), (2) and (3)

$$C_t = \frac{\sqrt{\varepsilon_{r,eff}}}{cZ_o} \quad \text{.... (1)}$$

$$L_t = C_t Z_o^{\ 2} \quad \text{.... (2)}$$

Where $\sqrt{\varepsilon_{r,eff}}$ is the effective dielectric constant, Z_0 the characteristics impedance of the unloaded transmission line and c is the free space velocity. The varactor capacitance is

$$C_v = s\left(\frac{L_t}{Z_{lo}^{\ 2}} - C_t\right) \quad \text{.... (3)}$$

Where Z_{lo} is Characteristic impedance of the loaded transmission line. The loaded t-line impedances Z_u (up-state position) and Z_d (down-state position) are given by

$$Z_{u,d} = \sqrt{\frac{sL}{sC + \dfrac{C_s C_v}{(C_s + C_v)}}} \quad \text{.... (4)}$$

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

The propagation velocity

$$v = \frac{1}{\sqrt{sL\left(sC + \dfrac{C_s C_v}{(C_s + C_v)}\right)}} \quad \text{.... (5)}$$

Where C_v is around 20-50 fF in the up-state position and 1-3 pF in the down-state position for a Ku-band design. 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 varactors 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 following expressions are solved to develop closed-form design equations for a phase shifter

$$f_{Bragg} = \frac{1}{\pi s\sqrt{L_t\left(C_t + \dfrac{C_v}{s}\right)}} \quad \text{.... (6)}$$

Where s is spacing between the MEMS varactors and s is represented by

$$s = \frac{Z_d C}{\pi f_B Z_o \sqrt{\varepsilon_{r,eff}}} \quad \text{.... (7)}$$

In this study, the Bragg frequency is selected to be more than 2.5 times of the design frequency at 42.5GHz. 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 $\Delta\varphi$ of this slow wave structure can be calculated by

$$\Delta\varphi = \omega\sqrt{L_t C_t}\left(\sqrt{1+\frac{C_{lu}}{sC_t}} - \sqrt{1+\frac{C_r C_{lu}}{sC_t}}\right) \quad (8)$$

By substituting the Equations (1), (2), (4) and (5) into (8), the following expression is derived as

$$\Delta\phi = \frac{s\omega Z_o\sqrt{\varepsilon_{r,eff}}}{c}\left(\frac{1}{Z_u} - \frac{1}{Z_d}\right) \quad \text{.... (9)}$$

Where Z_u and Z_d are the up and down-state characteristic impedances of loaded line. The impedance varies when the loss of the transmission line is changed due to a change in the amount of the capacitance on the transmission line.

$$C_{vu} = \frac{\left(Z_o^{\,2} - Z_u^{\,2}\right)Z_d}{Z_o^{\,2} Z_u^{\,2}\pi f_B} \quad \text{.... (10)}$$

The effective capacitance seen by the DMTL at the up-state is C_{vu}, at the down-state is C_{vd} and C_r is the capacitance ratio of the MEMS varactor ($C_r = C_{vd}/C_{vu}$).

2.2. Actuation Mechanics

It is desirable to have pull-down voltage within the range of $V_p \leq 40$ V, therefore, a wide center conductor and high un-loaded impedance is necessary [16]. For a good compromise, it is required to analyze the electrostatically deformed diaphragms. The mechanical design of the capacitance varactor involves the application of electrostatic force to deformable structures. The charges are redistributed during the bridge structure deformation, which in turn modifies the mechanical load. The pull-down force of the switching bridge due to an applied bias on the center conductor of CPW is given by

$$F = \frac{\varepsilon_o W w}{2g^2}V^2_{bias} \quad \text{.... (11)}$$

Where ε_o is the free-space permittivity and V_{bias} is applied bias voltages. In order to actuate the varactor, the center conductor of the CPW line is dc biased with respect to the ground. The resulting electrostatic forces pull the membrane toward the center conductor, with a pull-down voltage of

$$V_p = \sqrt{\frac{8Kg_o^{\,3}}{27\varepsilon_o A}} \quad \text{.... (12)}$$

Where K is the effective spring constant of the membrane, A is the contact area of the membrane and CPW center conductor, ε_o is the permittivity of free space, and g is the nominal gap height. The pull-down voltage is independent of the varactor width.

The spring constant k of the varactor is approximated by

$$k = \frac{32Et^3 w}{L^3} + \frac{8\sigma(1-\nu)tw}{L} \quad \text{.... (13)}$$

The effective spring constant k depends on the Young's modulus of the beam material, thickness t, beam length L, residual tensile stress in the beam σ, and Poison's ratio ν. Once the bias voltage is released, the mechanical stresses in the varactor overcome the stiction forces and pull the beam away from the dielectric layer, returning it to the original position. Various factors should be considered in order to analyze the electro-mechanical problems. A model that can accurately predict the dynamic behavior of the MEMS varactor structure should also integrate with several different phenomena. These phenomena include electrostatics, mechanics, residual stress, contact forces, compressible squeeze film damping and impact effects on a microscale.

2.3. Design of varactor based DMTL phase shifter

The 5-bit distributed phase shifter designed to provide 32 unique phase states from 0^o to 348.7^o at 17GHz consists of $0^o/11.25^o$bit, $0^o/22.5^o$bit, $0^o/45^o$bit, $0^o/90^o$bit and $0^o/180^o$bit.

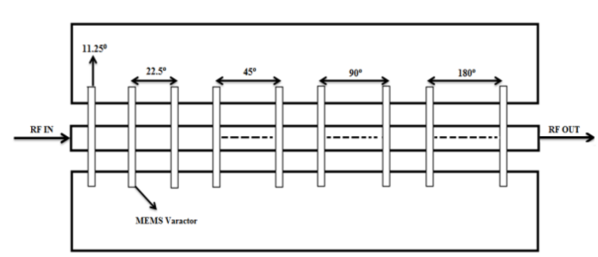

Figure 3. The topology of 5-bit distributed phase shifter

Every bit of 5-bit RF MEMS distributed phase shifter is constructed by cascading unit cells designed before and each is connected to its own bias line. The number of cascaded unit cells of $0^0/11.25^0$bit, $0^0/22.5^0$bit, $0^0/45^0$bit, $0^0/90^0$bit and $0^0/180^0$bit are 1, 2, 4, 8 and 16, respectively. The topology of 5-bit distributed phase shifter is shown in Fig. 3.

3. Results and discussion

The varactor based DMTL phase shifter measurements and characteristics were made using ADS.

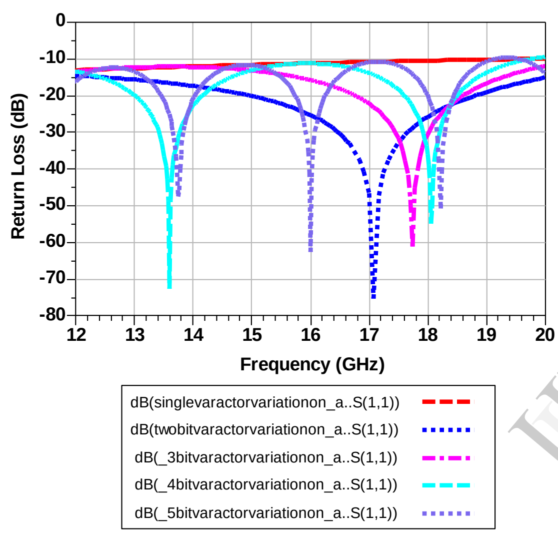

Figure 4. Return loss (S_{11}) in down state for all phase states

The RF performance of the proposed varactor based DMTL MEMS phase shifter for 11.25^0, 22.5^0, 45^0, 90^0 and 180^0 phase states is simulated and the results of each state is shown. Fig. 4 shows that Return loss is -10.94dB for 11.25^0bit, -46.80dB for 22.5^0bit, -22.25dB for 45^0bit, -13.94dB for 90^0bit and -11.01dB for 180^0bit phase states at 17GHz in down state. The phase shift obtained is linear with the frequency up to 20GHz. When the bias voltage is increased, the line impedance reduces from 70 Ω to 48Ω due to increase in capacitive loading of the line. The varactor based DMTL with capacitance ratio 4 to 8 results in larger loading on CPW transmission line and therefore a large phase shift. The simulated return loss and insertion loss in upstate and down states are shown in Fig. 4, 5, 6 and 7.

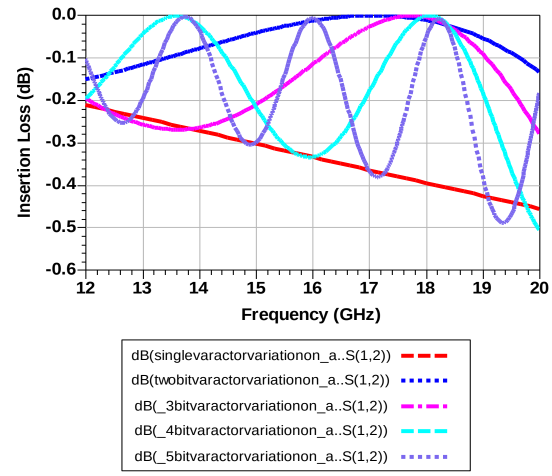

Figure 5. Insertion loss (S_{12}) in down state for all phase states

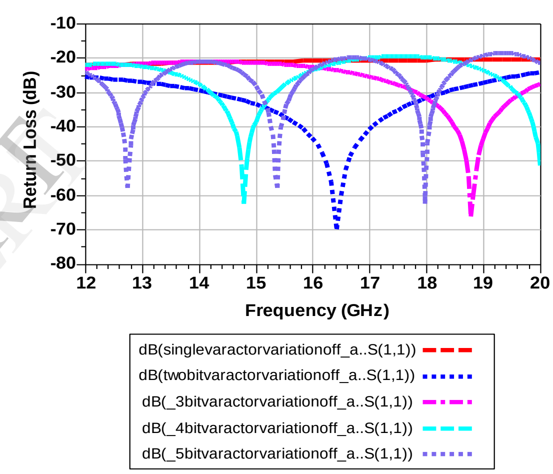

Figure 6. Return loss (S_{11}) in upstate for all phase states

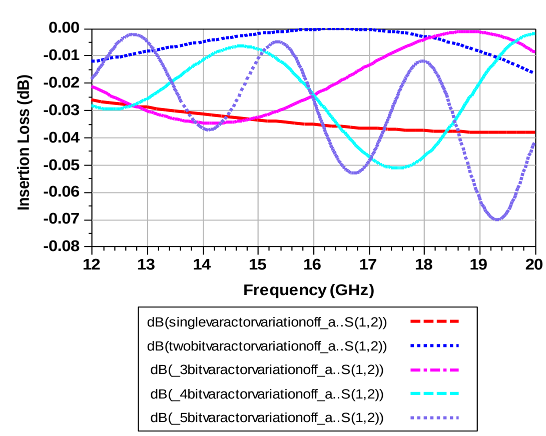

Figure 7. Insertion loss (S_{12}) in upstate for all phase states

The RF performance of the proposed varactor based DMTL MEMS phase shifter for 11.25^0 phase state is simulated and the results are shown below in Fig. 10, 11 and 12.

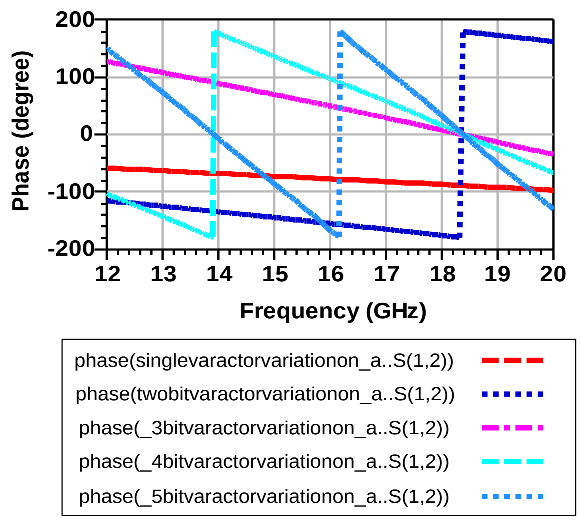

Figure 8. Phase shift (S_{12}) in down state for all phase states

32 unique phase states are obtained by combination of bits with different state. For example, in the phase states of 270^0, only MEMS varactor in the 0^0/90^0 bit and 0^0/180^{0}bit are actuated in down-state position, while the MEMS varactors in other bits remain in the up-state position.

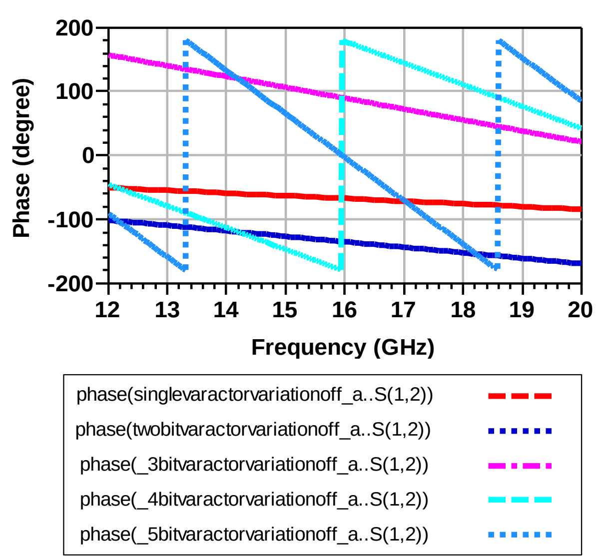

Figure 9. Phase shift (S_{12}) in upstate for all phase states

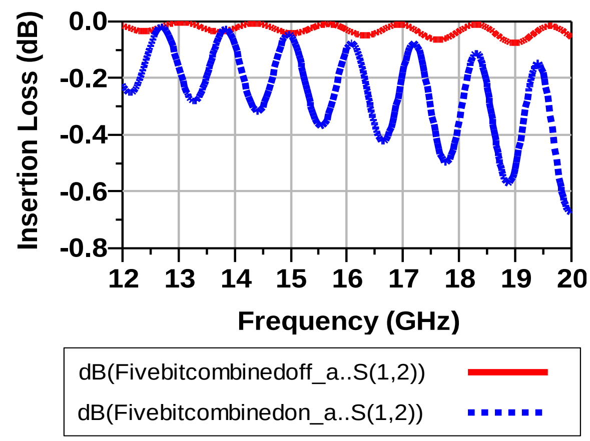

Figure 10. Insertion loss (S_{12}) in up and down state for five bit

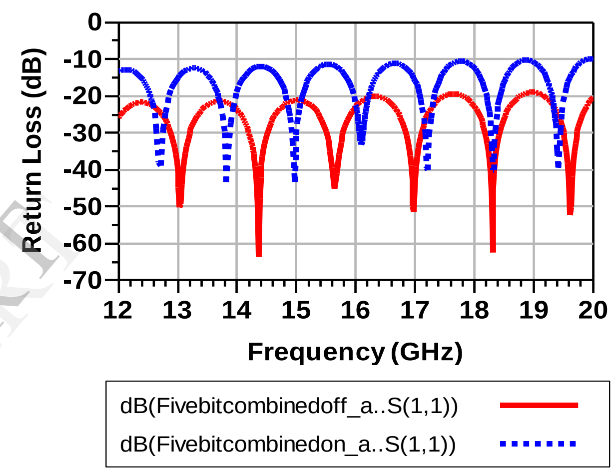

Figure 11. Return loss (S_{11}) in up and down state for five bit

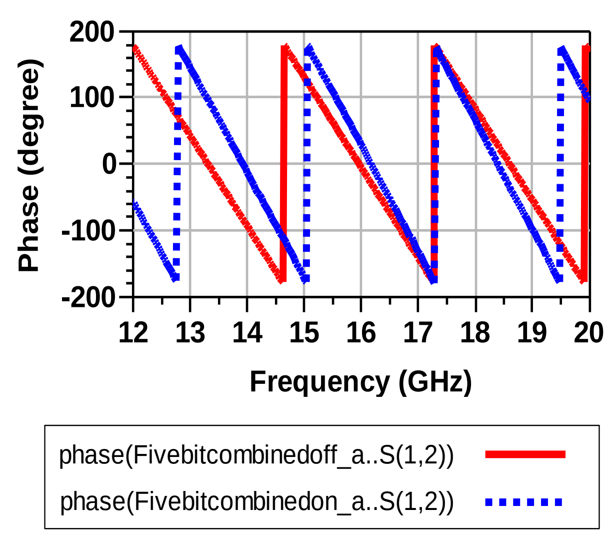

Figure 12. Phase shift (S_{21}) in up and down state for five bit

The topology of the 5-bit distributed phase shifter is not sequential arrangement conventionally from $0^0/11.25^0$bit to $0^0/180^0$bit, but is the one shown in Fig. 5. This topology is obtained by optimization to diminish coupling of different bits. Fig. 6 shows the simulated results of the 5-bit RF MEMS distributed phase shifter, which was obtained by cascading the unit cell in ADS simulator. From 12 to 20 GHz, the return loss is below than -15dB and the average insertion loss is approximately -0.024dB both when all MEMS varactors are actuated in own-state position and when all MEMS bridges are kept in up-state position.Furthermore, the averages return loss for all combinations and insertion loss are -20.98dB and -0.19dB at 17GHz, respectively.Table 2 lists the phase shifts for 5 unique phase states (excluding the phase state of 0^0) including the absolute phase errors for the designed frequency of 17GHz. The absolute value of the phase deviation from the phase shift of phase state has an average of 2.19^0 and the maximum deviation is 4.06^0 for the phase state of 180^0.

Table 2: The phase shifts, phase deviations (error) and s-parameters for 5 phase states for the designed frequency of 17 GHz (ku-band)

Phase states	**11.25^0**	**22.5^0**	**45^0**	**90^0**	**180^0**
Number of Varactors	1	2	4	8	16
Phase shift (up state) in degree	-71.86	-144.01	72.33	144.49	-70.96
Phase shift (Down state) in degree	-82.50	-165.62	29.15	58.10	113.10
Desired Phase shift in degree	11.25	22.5	45	90	180
Obtained Phase shift in degree	10.64	21.61	43.18	86.39	184.06
Phase error in degree	-0.61	-0.89	-1.82	-3.61	+4.06
Insertion loss (up state) in dB	-0.03	-0.001	-0.01	-0.04	-0.04
Return loss (up state) in dB	-20.76	-40.86	-25.47	-19.98	-20.47
Insertion loss (down state) in dB	-0.36	-0.0004	-0.02	-0.18	-0.36
Return loss (down state) in dB	-10.94	-46.80	-22.25	-13.94	-11.01

4. Conclusion

In this paper the precise equivalent-circuit model for the varactor based RF MEMS distributed phase shifter has been proposed. The unit cell is designed to achieve very small phase deviation and low insertion loss. The designed 5-bit varactor based RF MEMS distributed phase shifter has an average return loss of -20.98dB, an average insertion loss of -0.19dB and an average relative phase error of 2.19^0. Different from conventional sequential arrangement, the 5-bit RF MEMS distributed phase shifter is optimized to diminish coupling of different bits remarkably. 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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