

Miniatured Phase Shifter

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Abstract

Objective: RF MEMS has emerged as a technology with immense potential for wireless communication and defence applications. In this work, a 5 bit RF MEMS switched line phase shifter is presented using cantilever switch achieving low actuation voltage. **Methodology:** In this work 5 different phase shifters are designed to get 5 bit phase shift at a particular frequency 10 GHz. The phase shifters consist of stubs like structure designed in the ground of CPW and MEMS capacitive series switches. Solid-state phase shifters based on p-i-n diodes or Field-Effect Transistor (FET) switches are used because they provide a good planar solution at a variety of microwave frequency ranges. Micro Electro Mechanical Systems (MEMS) phase shifters are progress today are mainly have established designs because of which the solid-state switch is replaced by a MEMS switch. **Findings:** By analysing theoretically and practically the results showed that a novel RF MEMS switch was capable of liberating less than 0.1dB insertion loss and more than 19 dB isolation between input and output ports at 20 GHz. This RF MEMS switch shows a 5V actuation voltage. Switching time of RF MEMS switches is measured using a theoretical approach. The switches demonstrated maximum switching time of 0.1μs. By using this switch a 5-bit miniaturized phase shifter is designed i.e. 180° bit, 90°, 45°, 22.25° and 11.5° bits were achieved using the switched line type phase shifters at 10 GHz. A novel switched line type phase shifter loaded with multiple switch pairs was developed and was capable of liberating a multiple phase shift angles within single design.

Keywords: Actuation Voltage, Cantilever Beam, Insertion Loss, Phase Error, Phase Shift, Return Loss, Stress

1. Introduction

RF MEMS switch has vast applications in various areas like telecommunication for satellite communication. RF MEMS switches have a number of advantages over PIN diode and FET switches in basis of low insertion loss and high isolation. Because of several advantages mentioned above, RF MEMS switch is always in demand. This paper takes a RF MEMS switch¹ with a new cantilever beam² to analyse the mechanical characteristics³ of the RF MEMS switch. In this paper application of RF MEMS series⁴ is shown which is used in the phase shifter design. Phase shifters are used for several years and have a usual application in phased array antenna systems. The combination of the two technologies is the purpose for this project. Furthermore, a phase shift of 11.25, 22.5, 45, 90, and 180 is needed, which requires a 5-bit phase

shifter. The five-bit RF MEMS phase shifter consists of five different phase shifts⁵ such as 11.25, 22.5, 45, 90 and 180 kept in a similar arrangement. The phase shifters consist of stubs like structure designed in the ground of CPW and MEMS capacitive series switches Microwave and micrometer phase shifters⁶ are used in phased-array antennas for telecommunication and radar applications. Solid-state phase shifters based on p-i-n diodes or Field-Effect Transistor (FET) switches are used because they provide a good planar solution at a variety of microwave frequency ranges. Micro Electro Mechanical Systems (MEMS) phase shifters are progress today are mainly have established designs because of which the solid-state switch is replaced by a MEMS switch. MEMS-switch⁷ based phase shifters have some advantages like low-loss and wideband performance. Single-pole double throw MEMS switches have good performance are usually used

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in MEMS phase shifter applications, especially because most of them i.e. MEMS phase shifters are generally a switched-line type phase shifters⁸. In this research, the novel cantilever compact switches are being used as building blocks in the designing of MEMS phase shifter¹⁰. Below Figure 1 shows the switched line phase shifter¹² using RF MEMS series switch¹. When the transmission lines are acting as a TEM (quasi-TEM, such as CPW), this phase shift becomes a linear function of frequency, which gives a true time-delay between the input and output ports. The need for low-loss phase shifters are increasing day by day, so does the Radio Frequency (RF) MEMS as a solution to provide them. Approach is shown to in build a low loss phase shifters using RF MEMS series switches. By using a switched line¹³ 5-bit resonating phase shifter, an average insertion loss was attaining with better return loss. A novel cantilever beam is designed having low actuation voltage and better switching time to be used in the switched line phase shifter. To our acquaintance, these devices represent the lowest loss phase shifter There are different phase shifter just like switched line phase shifter¹⁶ such as DMTL it's mainly have Shunt switches but the main reason because number of shunt switches is more and complexity of the design increases and it is very difficult to get multi bit phase shift in DMTL because of which use switched line phase shifter. It's easy to design a miniature phase shifter.

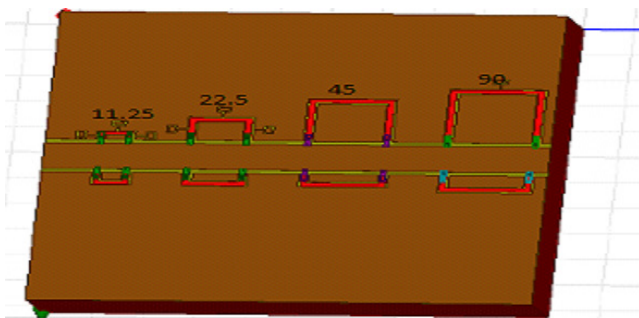


Figure 1. Switched line phase shifter.

2. Cantilever and Phase Shift

2.1 Design Description

The switch is design on CPW platform with dimension $G/S/G=60/110/60 \mu\text{m}$ for 20 GHz –dc in Figure 2. A gold material is used for making the cantilever beam, The substrate is made of silicon material. The dimple is shown is mainly. A normal CPW¹ on a dielectric substrate contain a centre strip conductor with semi-infinite

ground planes on an either side of the structure as it help quasi-TEM mode of propagation. The CPW offers many advantages over a conventional microstrip line, first it simplifies fabrication, and second it aid easy shunt as well as series surface mounting of active and passive devices. Our switch is a CPW series switch, consist of a cantilever beam⁴ having holes in it. The CPW line width should be greater than the signal width as is displayed in Figure 2. Substrate thickness plays less important role due to the fact the fields are concentrated on the slots. It generates elliptically polarised magnetic fields and all conductors are connected in the same plane.

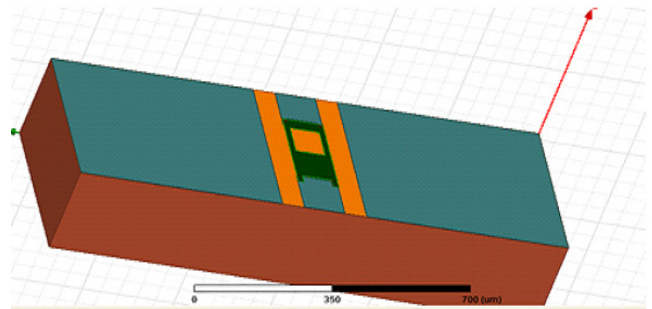


Figure 2. Side view of the switch.

2.2 DGS Structure

Defected Ground Structures (DGS)¹² are shown much potential for contrivance in different applications. They offer a sharp, electromagnetic band-gap and show slow wave factor, which help to make lesser size circuits. In these structures, well-defined shapes are made. Coplanar Waveguides (CPW) have both signal and ground on the same surface. Though they preoccupy larger area than microstrip lines, they can be considered as a good supplement for DGS. The proposed structure has the opportune of having an almost constant capacitance while the inductance varies linearly as the number of cell increases, which simplifies the design process. DGS (defected ground structure is a periodic or non-periodic etched from the ground of a planar transmission line like microstrip, coplanar and conductor backed coplanar waveguide DGS¹⁴ mainly effect the shield current distribution in the ground plane and cause the defect. This causes a disturbance in the ground plane which can rise the effective capacitance and inductance. Periodic structure in DGS is applied in a planar transmission lines and have a wide interest for their broad application in microwave circuits. Transmission lines with an annually

structures show pass filter and rejection band as low pass filters. The properties of periodic structure is slow wave effect. Periodic DGS consider the shape of the unit cell in DGS and distance between two unit cells.

2.3 Phase Shifter Description

In terms Microwave and micrometer phase shifters⁴ are used in phased-array antennas for telecommunication and radar applications. The phase shifters that are based on p-i-n diodes and Field-Effect Transistor (FET) switches are used because they provide a good planar solution at a variety of microwave frequency ranges. Maximum Microelectromechanical Systems (MEMS) phase shifters are developed today are mainly have established designs in which the solid-state switch is replaced by a MEMS switch. MEMS-switch based phase shifters⁸ have some advantages like low-loss and wideband performance. Single-pole double throw MEMS switches have good performance and are usually used in MEMS phase shifter applications, especially because most of them are switched-line type phase shifters. The above Figure 3 shows how the cantilever is designed and used as a phase shifter. Four cantilever beam⁴ is used for each phase shift. Single-pole double-throw switches is realized by differential phase shift¹⁰ of a reference transmission lines which is related to the change in length between the reference and the delay path, which is shown in the below equation. Where $\Delta\phi$ is the phase difference, λ is the wavelength and l_1 and l_2 is the line length of the reference path and the delay path.

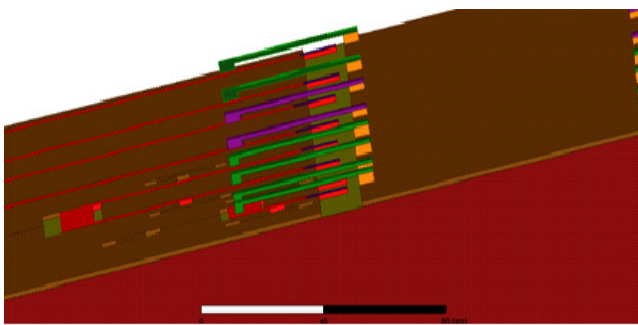


Figure 3. Cantilever phase shifter design.

$$\Delta\phi = \frac{360}{\lambda}(l_1 - l_2) \quad (1)$$

Four SP2T switches are applied to the connection of reference transmission line and delay transmission line of 180 degree phase shift, delay transmission line of 90 degree phase shift and delay transmission line of 11.25 degree phase shift. While other four SP2T switches are connected

to reference transmission line, delay transmission line of 22.5 degree phase shift, delay transmission line of 45 degree phase shift.

2.4 Formulae

2.4.1 Pull in Voltage

The actuation voltage can also be calculated by following formulas also

$$F = ma \quad (2)$$

$$F = K \Delta x \quad (3)$$

$$\Delta x = \frac{F}{K} = \frac{ma}{K} = \frac{(lwt)pa}{K} \quad (4)$$

$$V_p = V(2g_0/3) = \sqrt{\frac{8Kg_0^3}{27\epsilon Ww}} \quad (5)$$

Where F is the force applied in the beam, m is the mass of the cantilever beam, K is the spring constant value Δx is the deflection of the beam, a is the acceleration which is 9.8m/s^2 , l is the length of the beam, w is the width of the beam and t is the thickness of the beam. The mass here is calculated by multiplication of length, width and thickness of the beam. By this calculate the spring constant of the beam and this spring constant value will put in the pull in voltage and calculate the actuation voltage of the series switch. V_p is the pull in voltage of the switch

2.4.2 Stress Analysis

The stress condition is due to the different conditions that are encountered by the lower and upper layers of a uniform beam. In most of the design, it is important to reduce the stress factor⁵ because it shows the positive and negative beam curvature.

$$\Delta Z = \frac{Mi2}{2EI} = \frac{\Gamma i2}{2} \quad (6)$$

Where I is the moment of inertia of a rectangular beam ($I = wt^3/12$). The stress difference between the upper and bottom layers must be kept less than 5MPa.

2.4.3 Switching Time

The switching time depends strictly on the applied voltage since the stronger the electrostatic force and larger will be the voltage. The solution follow.

$$T_s = 3.67 \frac{vp}{v_{sw}} \quad (7)$$

The applied voltage should lie from 1.3-1.4Vp to result in a fast switching time at a sensible voltage level.

2.5 Simulation Result

2.5.1 Cantilever HFSS Result

Below Figure 4 shows the design of cantilever beam series switch. The simulation of switch for taking the RF characteristic is done in HFSS software.

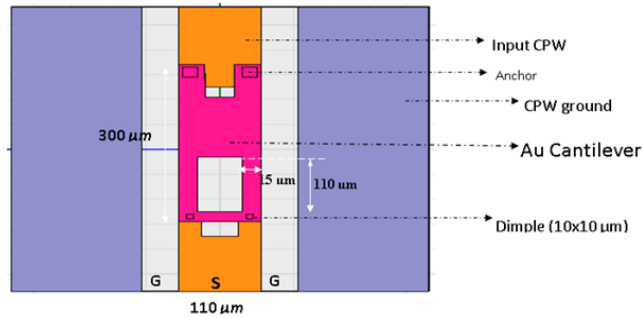


Figure 4. The cantilever switch.

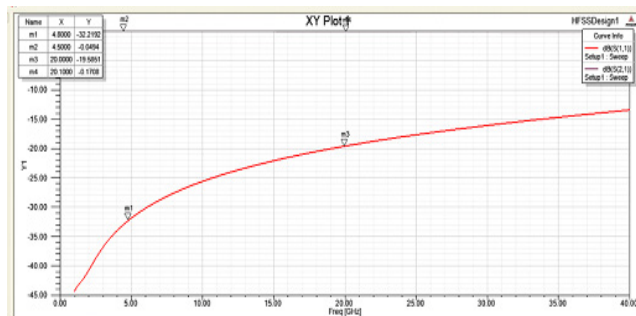


Figure 5. RF characteristics of the switch design.

The series switch must get the return loss below 10dB and the insertion loss should lie between 0.1-0.3 dB from the above Figure 5 can see that at 20GHz it is showing insertion loss as 0.1dB at 20GHz and 19dB return loss at 20GHz.

2.5.2 Cantilever INTELLISUITE Result

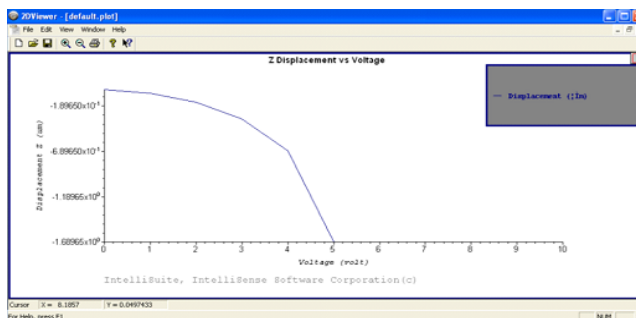


Figure 6. Actuation voltage of the switch.

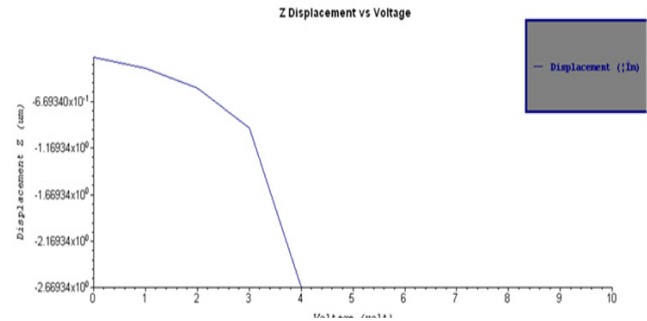


Figure 7. Pull in voltage of the switch design by holes.

The mechanical analysis of the design, of the cantilever beam is done in INTELLISUITE software. The above Figure 7 present the pull in voltage of the switch. The stress decreases because of the holes in the cantilever beam design. The actuation voltage is 5V and after giving holes in it reduce to 4v shown in Figure 7.

2.5.3 Cantilever Stress Result

Figure 8 shows the stress factor⁶ of the switch. Stress is low because of the holes in the cantilever beam design. In this design a stress factor⁷ in Figure 9 of 0.96 MPa and after giving holes the area decreases so the stress of the switch increases to 1.96 MPa. Below Figure 10 shows the stress factor when holes are given.

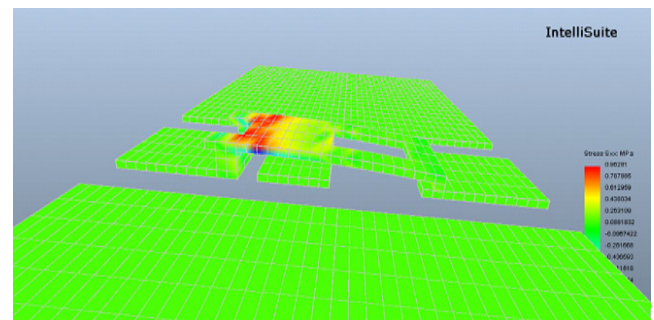


Figure 8. Stress of the switch.

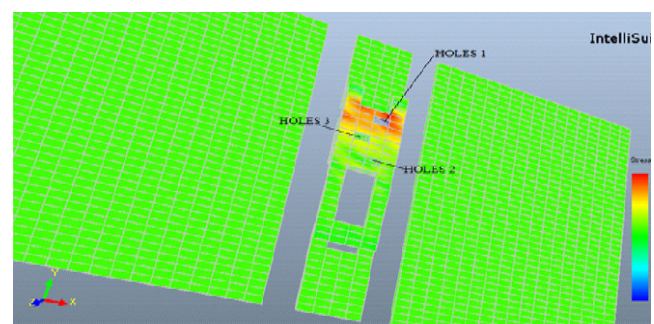


Figure 9. Hole effect in the switch design.

2.5.4 Phase Shifter Result

The switched line10 mainly used for miniaturization. It can give 5 different phase just in one design. The above Figure 1 shows the switched line phase shifter design. Here will generally discuss about the phase shift i.e. 11.25 degree, 22.5 degree, 45 degree, 90 degree and 180 degree.

Table 1. Calculation for phase shift

Phase Shift	$51 - 35.16 = 15.84$
Phase Error	$15.84 - 11.25 = 4.59$

2.5.4.1 Phase Shift 11.25

The formula discuss in previous section is used for making the stub like structure for the reference path¹¹ and the delay path. The below Figure 10 shows the first bit having the length as $124.6\mu\text{m}$ and delay path is $124.5\mu\text{m}$ so will get the phase shift of 11.25 degree are getting phase of 35.1 degree at 10GHz. Now will see the RF characteristics at 10 GHz. Getting 11dB return loss and 1.1dB insertion loss. Now will find the phase error. So will subtract the phase shift which is achieved in CPW line and the present one. From the above Table 1 are getting the phase error as 4.59 degree.

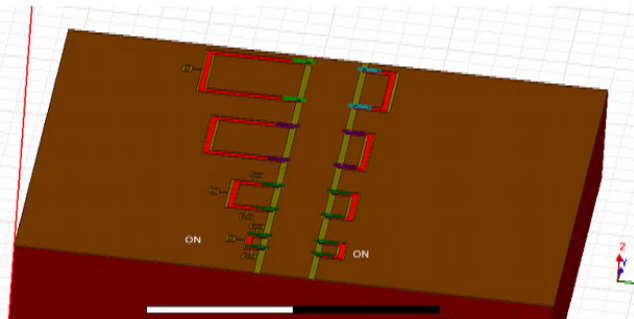


Figure 10. Phase shifter with 11.25.

2.5.4.2 Phase Shift 22.5

The below Figure 11 shows 13dB return loss and 0.8dB insertion loss. The below Figure 12 shows a phase of 27.66 degree so the total phase shift is obtained by subtracting by the normal CPW line and the phase shift obtained is shown in Table 2. The phase error is obtained by subtracting measured phase shift and the actual phase shift what to be obtained.

Table 2. Calculation for 22.5 degree phase shift

Phase Shift	$51 - 27.66 = 23.34$
Phase Error	$22.25 - 23.34 = 1.09$

To find the 22.5 degree phase the second bit reference line and the delay line is ON and the rest of switches are kept close.

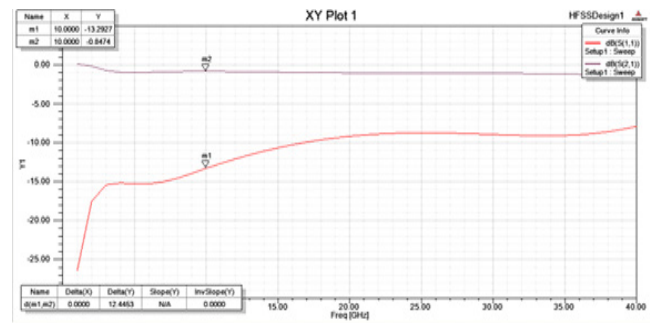


Figure 11. S parameter for 22.5 phase shift.

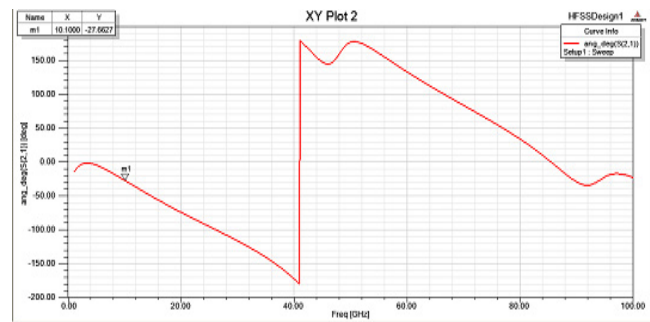


Figure 12. 22.5 phase shift.

2.5.4.3 Degree Phase Shift

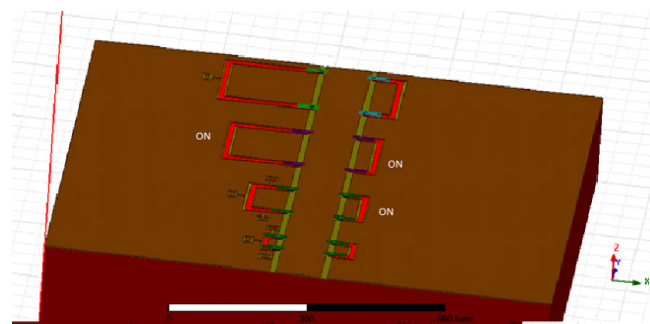


Figure 13. Phase shifter 45 degree Design.

For the 45 degree will switch on the reference path and the delay path, the below Figure 15 shows the phase shift. For 45 degree phase shift: The above Figure 13 shows the how the 45 degree shift works. The below Figure 14 and Figure 15 shows the RF characteristics and phase shift. The below Table 3 mainly shows the phase shift and the phase error. Here, are not getting any phase shift error.

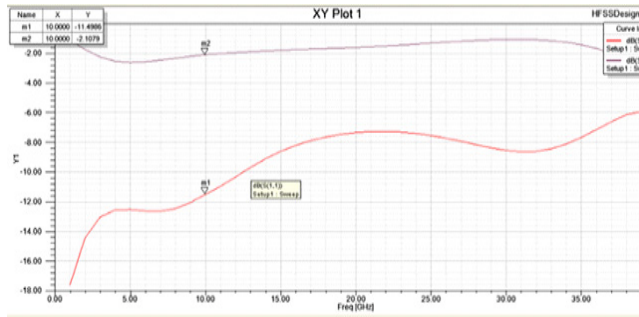


Figure 14. S parameter of 45 phase shift.

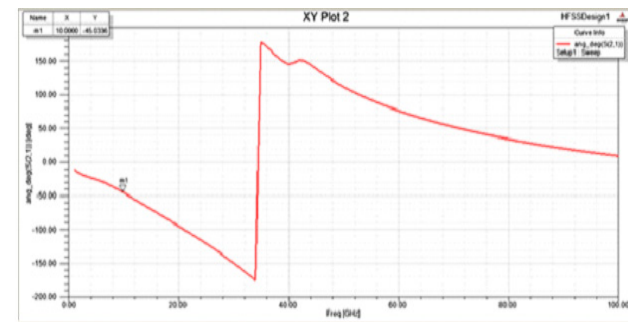


Figure 15. 45 degree phase shift.

Table 3. Calculation for 45 degree phase shift

Phase Shift	45
Phase Error	No Phase Error

2.5.4.4 90 Degree Phase Shift

For the 90 degree phase the fourth bit is switched on and making all the other switches off and this will give the phase shift For 90 degree phase shift: The above Figure 16 shows the working principle of 90 degree phase shift. The below Figure 16 shows the RF characteristics and the phase of the design also phase error of the design.

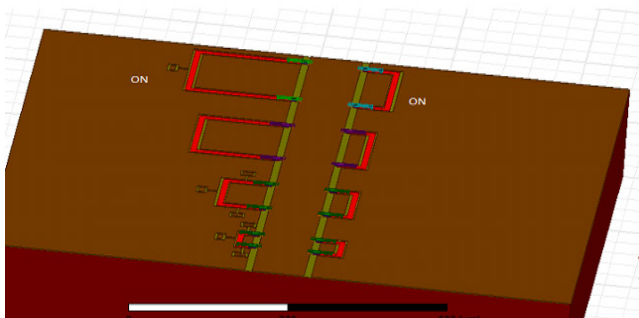


Figure 16. Phase shift with 90 degree phase shift design.

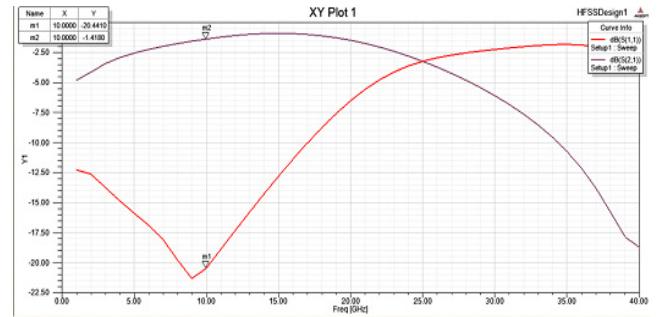


Figure 17. S parameter of 90 degree phase shift.

The above Figure 17 shows the return loss of 20dB and insertion loss of 1.4dB at 10GHz frequency. The below Figure 18 shows the phase of 39.96 degree at 10GHz frequency. This Phase is added to the CPW line and the total phase shift and the phase error is calculated that is shown in Table 4.

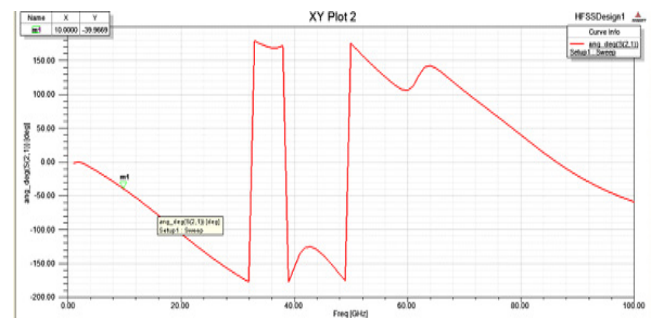


Figure 18. Phase shift of 90 degree phase shift.

Table 4. Calculation for 90 degree phase shift

Phase Shift	51+39.96=90.96
Phase Error	90.96-90=0.96

2.5.4.5 180 Degree Phase Shift

For 180 degree phase shift Figure 19 shows the RF characteristics. Phase shift and phase error are shown in Table 5. Figure 19 shows at 10GHz return loss is 16 dB and insertion loss is 0.5 db. The Table 5 also shows the error as 5.59 degree which is obtained by adding the obtained phase shift from the CPW line and the measured phase shift when the cantilever switch is ON at 180 degree.

Table 5. Calculation for 180 degree phase shift

Phase Shift	51+134.59=185.59
Phase Error	180.185.59=5.59

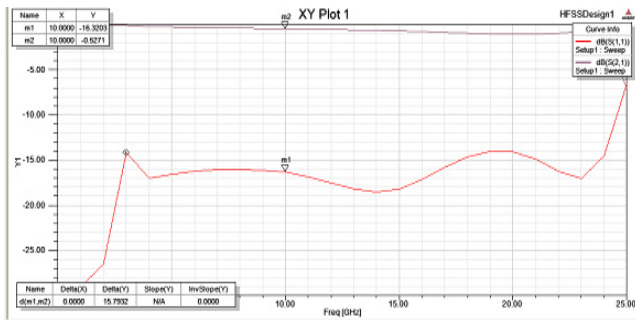


Figure 19. S parameter of 180 degree phase shift.

3. Conclusion

In this paper RF MEMS switches join the assistance of traditionally used electromechanical switches having low insertion loss and high isolation with some major advantage of solid-state switches having low power-consumption. Single-pole Single-Throw (SPST) DC-contact switches have been designed at a frequency 20GHz with a return loss of 19 db. However, previous work on compact MEMS series switches has mainly focused on cantilever based on metal to metal contact designs. In order to make the cantilever beam indifferent to stress factor, relatively thick beams are used. However, such a thick beam is very stiff and difficult to be pulled down. With a new design, this paper focused on the development of metal-to metal contact DC-contact switches using thin cantilevers to achieve high return loss and very low actuation voltage simultaneously. It has shown good results up to 40 GHz and can ultimately contribute to other application in higher frequency performance. The tip deflection is well controlled at a gap of 2.5 μ m and a single-pole-single-throw switches is designed up to 20 GHz with insertion loss 0.1 dB and isolation better than 19 dB; 3) using these switches to build switched line phase shifters up to 10 GHz. RF characteristics of phase shifters up to 10 GHz are presented. The 5 bit phase shifter (11.25°, 22.5°, 45°, 90°, 180°) shows the capability of achieve desired phase change at 20 GHz.

4. References

1. Chan KY, Daneshman M, Mansour R, Ramer R. Novel beam design for compact RF MEMS series switches. Microwave Conference; 2007 Dec 11-14; Bangkok. p. 1-4.
2. Rebeize GM. RF MEMS: theory, design and technology. John Wiley and Sons; 2003.
3. Rahman H, Chan E, Rameer R. Investigation of residual effect and modeling of spring constant for RF MEMS switches. 2009 Mediterranean Microwave Symposium (MMS); 2009 Nov 15-17; Tangiers; p. 1-4.
4. Kanthamani S, Raju S, Abhai Kumar V. Design of low actuation voltage RF MEMS cantilever switch. MICROWAVE 2008, International Conference on Recent Advances in Microwave Theory and Applications; 2008 Nov 21-24; Jaipur: IEEE; p. 584-6.
5. Romain S, Matthieu C, Pierre B, Gabriel MR. Miniature MEMS switches for RF application. Journal of Microelectronics Mechanical Systems. 2011 Dec 7; 20(6):1324-35.
6. Dutta S, Mohd I, Pal R, Jain KK, Chatterjee R. Effect of residual stress on RF MRMS switch. Microsystem Technologies. 2011 Dec; 17(12):1739-45.
7. Rebeiz GW, Muldavin JB. RF MEMS switches and switch circuits., IEEE Microwave Magazine. Dec 2001; 2(4):59-71.
8. Muldavin B, Rebeize GM. High isolation CPW MEMS Shunt Switches part 1: modeling. IEEE Transaction on Microwave Theory and Techniques. 2000 Jun; 48(6):1045-52.
9. Joseph SH, Charles LG, Rebeiz GM. 2 and 4-Bit DC-18GHz microstrip MEMS distributed phase shifters. 2001 IEEE MTT- S International Microwave Symposium Digest; 2001 May 20-24; Dig, Phoenix, AZ, USA; vol 1. p. 219-22.
10. Van Caekenberghe K. RF MEMS on the radar. IEEE Microwave Magazine. 2009 Oct; 10(6): 99-116.
11. Farinelli P, Chiappesi E, Di Maggio F, Margesin B, Colpo S, Ocera A, Russo M, Pomona I. Development of different K-band MEMS phase shifter designs for satellite COTM terminals. Proceedings of the 39th European Microwave Conference; 2009 Sep 28-29; Rome;
12. Nickolas K, Pete K, George P, John P. 14GHz MEMS 4-bit phase shifter on silicon. Silicon Monolithic Integrated Circuits in RF Systems, 2004. Digest of Papers. 2004 Topical Meeting; 2004 Sep 8-10. p. 326-28.
13. Lim J-S, Kim Ch-S, Lee Y-T et al. A new type of low pass filter with defected ground structure. European Microwave Week 2002; 2002 Sep 23-26; Milan, Italy; p. 1-4.
14. Chang I, Lee B. Design of defected ground structures for harmonic control of active microstrip antenna. IEEE AP-SIS. 2002 Jun; 2:16-21.
15. Du Y, Bao J, He Z, Jiang J. A X-band switched-line 5-bit phase shifter with RF MEMS multithrow switches. 2013 8th IEEE International Conferenceon Nano/ Micro Engineered and Molecular Systems (NEMS); 2013 Apr 7-10; Suzhou; p. 296-9.
16. Bakri-Kassem M, Mansour R.R, Safavi-Naeini S.A novel latching RF MEMS phase shifter. European Microwave Integrated Circuit Conference (EuMIC); 2014 Oct 6-9; Rome; p. 668-71.