Progress In Electromagnetics Research Letters, Vol. 5, 73–85, 2008

FRACTAL BEAM KU-BAND MEMS PHASE SHIFTER

M. Jahanbakht and M. N. Moghaddasi

Islamic Azad University, Science and Research Branch
Tehran, Iran

A. A. Lotfi Neyestanak

Islamic Azad University, Shahr_e_Rey Branch
Tehran, Iran

Abstract—A micro electromechanical phase shifter base on the fractal geometries is proposed to work at Ku frequency band with at least 23% lower actuation voltage compared with the simple rectangular membrane counterparts. In this design the membrane of the switch is chosen to be a Koch fractal and then a distributed MEMS phase shifter is set up by cascading a distinct number of these switches. This phase shifter is analyzed to obtain its parameters such as differential phase shift, group delay, and insertion and return loss. It will be shown that this phase shifter could be used as a low loss and multi bit phase shifter system because of its low insertion loss and power consumption.

1. INTRODUCTION

Micro electromechanical system (MEMS) switches were first demonstrated in 1979 as an electrostatic cantilever switch. These types of switches have the disadvantage of relatively high actuation voltage. In recent years, MEMS switches undergo a variety of material changes and geometrically improved designs to decrease the actuation voltage. These efforts were made to simultaneously decrease the spring constant of the beam, increase area of the electrostatic field and decrease the gap. But any variation in most of these parameters causes a loss on the other parameters of the micro-switch. For instance, if we decrease the gap or increase the area of the electrostatic field, it results in poor isolation [1].

Corresponding author: A. A. Lotfi Neyestanak (alotfi@iust.ac.ir).

On the other hand, phase shifter as a developed system and technology, has wide application areas, such as phased-array radars, satellite communication systems, and measurement instrumentations. By utilizing MEMS switch to replace PIN diode or FET switch of conventional loaded-line phase shifters, the insertion loss of phase shifters at high frequencies can be reduced effectively [2].

In [3] a 3-bit† phase shifter, fabricated on a glass substrate using MEMS switches and coplanar-waveguide lines, results in an average loss of 2.7 dB at 78 GHz. The associated phase error is 3° and the reflection loss is below 10 dB over all eight states. Despite the fact that the insertion loss of such a structure was practically reduced, the problem of high actuation voltage (40 V) remained for the utilizing of conventional rectangular beams.

A metal-air-metal capacitor is used in [4] to develop a 2-bit wide-band distributed coplanar-waveguide phase shifters on a 500 μm quartz substrate for X- and Ka-band operations. The designs utilize MEMS switches in a periodically loaded transmission line by MEMS switches and high Q metal-air-metal capacitors. Although they struggle to increase the insertion loss at the same time of decreasing the actuation voltage, the resulting design works on 20 V waveform which is not a dream work.

Air-gap overlay CPW couplers and low-loss series metal-to-metal contact MEMS switches were employed in [5] to reduce the loss of the reflection-type MEMS phase shifters at V-band. Phase shift is obtained by changing the lengths of the open-ended stubs using series MEMS switches. This design performs as a 2-bit reflection-type MEMS phase shifter with an average insertion loss of 4 dB. The switch elements of this paper are derived by 35–40 V which is quite large. Furthermore, the operation of such a structure would be completely frequency dependent because of the length variations of the transmission line.

In [6] and [7] a capacitive micromachined switch with low actuation voltage was proposed. In that structure both contact plates of the switch are designed as displaceable membranes. The obtained results indicate about 30% reduction in actuation voltage from the conventional single beam. The stress on the beam due to the actuation voltage is also reduced to increase the switching life time. Although the actuation voltage is reduced to 25 V under realistic conditions, the fabrication process remained as a major problem due to the fact that, two steps of metal sputtering or lithography need to be done.

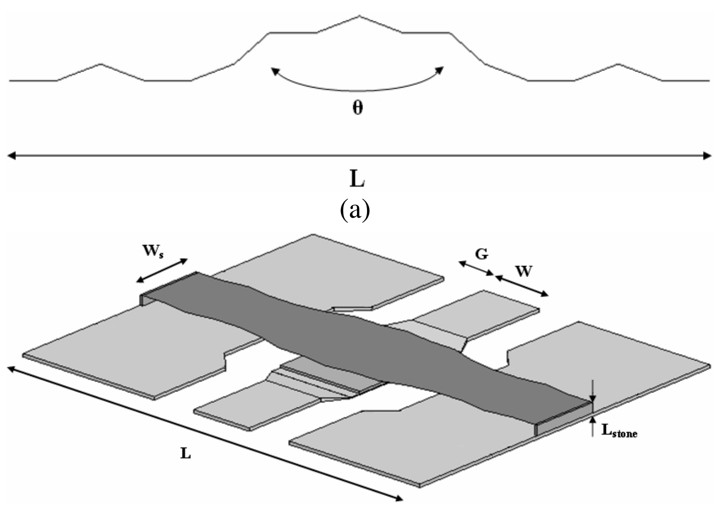
In [8] MEMS phase shifter has been developed using inductors. The design consists of a CPW line capacitively and inductively loaded by the periodic set of inductors and electrostatic force actuated MEMS

† Distributed MEMS Transmission Line (DMTL)

switches as capacitors. By applying a single bias voltage on the line, the characteristic impedance can be changed, which in turn changes the phase velocity of the line and creates a true time delay phase shift.

A novel switched beam planar fractal antenna is presented to demonstrate the capability of beam steering by controlling MEMS switches on/off [9]. The development of an original method called Scaled Changing Technique (SCT) has led to the fast analysis of planar reconfigurable phase-shifters presenting a great number of phase states. The SCT-based tool allows a fast identification of the RF-MEMS configurations that present high losses and a rapid electromagnetic analysis when the number and positions of RF-MEMS are tuned [10].

The current proposed structure utilizes a fractal beam instead of the traditional rectangular ones. According to the fractal geometry's attributes, this structure would improve the bending momentum and force/stiffness ratio of the membrane. So it shall efficiently decrease the actuation voltage of the switch element. Furthermore, in this special design other proper parameters left unchanged and a high isolation is achievable beside low insertion loss and low return loss. Moreover this phase shifter may be packed with a DSP block and antenna array to create a digitally controllable phased array antenna. This would boost its phase synthesis resolution to more than 3-bit.



(b)

Figure 1. The geometry of a 2 stage fractal Koch beam and (b) the geometry of the proposed MEMS switch element with a 2 stage fractal beam.

2. THEORY

Fractals are a part of non Euclidean geometries which obviously have influenced many branches of science and engineering because of their unique attributes. Designers and engineers have paid lots of attention to the nature of fractal geometries and it has led to many novel works in the new classes of RF applications.

The fractal Koch curves or islands have compact size, low profile, wide bandwidth and conformal shape in collation with the other fractal models. The self similarity and space filling property in Koch curves will make them like an infinite length in a certainly finite area [11]. This special trait would decrease the spring constant and increase the effective area of the bridge. So as mentioned above, the actuation voltage will decrease.

As can be seen in Figure 1(a), a Koch fractal strip has been used here as a beam of the MEMS switch. This beam has got the Koch angle of $\theta = 0.9\pi$ and its length would be choice long enough to cover the entire bridge. This beam is formed by just 2 stages repetition of the basic triangular Koch geometry. As inspected in the next section, extending this number of iterations got no influence on the results and would cause some difficulties on the micromachining process.

A coplanar waveguide with G/W/G = 35/25/35 μm dimensions is used here with a silicon nitride ($\varepsilon_r = 11.9$) substrate to mount the bridge on. This structure is shown in Figure 1(b). The dimensions of the waveguide conductors are changed to 50/30/50 μm under the bridge itself. The substrate has 0.4 mm height and the conductors are made from gold with the thickness of 2 μm which decreases to 0.5 μm under the bridge.

A 0.23 μm silicon nitride dielectric is sputtered on the central conductor of the waveguide to firstly prevent it from any possible connection to the membrane and secondary restrict the bridge deformation to the desired capacitive value of the distributed phase shifter.

The length of the beam is chosen to be 250 μm and its width is 40 μm at the narrower place next to the holder stones (cantilever) and this width is gradually increase to about 60 μm at the widest place in the middle of the bridge. This bridge is mounted 0.85 μm above the outer conductors of the waveguide. A distributed MEMS phase shifter is then yielded by cascading of 35 parts of the described MEMS switches. The spacing between the periodic MEMS switches is chosen to be 550 μm. In the phase shifter applications, the deformed bridge will not suppress the wave from passing through the bridge. Switches in this application act more like the tunable capacitors instead of real switches.

For frequencies below the Bragg frequency, with a small inevitable insertion loss, this serial switches will apply a phase shift to the signal by reducing the phase velocity of the wave [12].

3. FABRICATION PROCESS

Fabrication process of the fractal RF MEMS switch is indicated in Figure 2. At the first step, a 2 µm layer of aluminum sputters on the silicon substrate and wet etches to provide a 50 Ω coplanar waveguide (CPW). A thin layer of SiO_2 isolator lies down on the central conductor of the CPW using the well known IRE etching by 40mTorr pressure on 250 W and 0.8 selectivity adjustments versus photo-resist (PR).

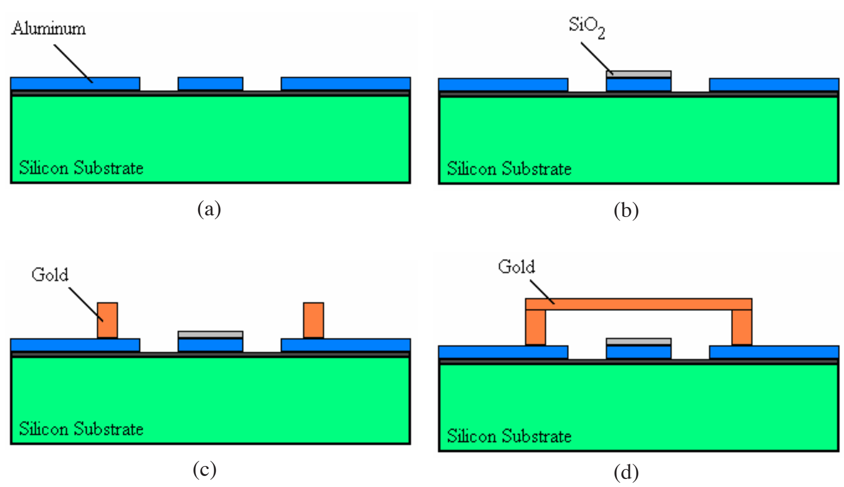


Figure 2. Fabrication process of a fractal MEMS switch.

Same process of the first step goes on to provide the major two stones of the bridge as shown in Figure 2(c). To provide the beam of the bridge, one needs to sputter a PR layer on the structure of Figure 2(c). Using the same mask as used in Figure 3(c) (to erect the stones of the bridge), all PRs on top of the stones should be removed. Then the second layer of gold sputters as the beam itself and etches using a proper mask and etchant. Finally the unwanted PR will be removed from the structure.

When one applies an electrostatic force to the bridge, it would bend along its length (L) to lay down on the sputtered silicon nitride dielectric. This height could be named as zero distance or turned on switch. It is mentioned that the optimum position of the turned on fractal bridge is where the switch acts more like a capacitor and not like a switch. Optimum position is obtained and it was investigated that when the bridge is at the 0.1 of its final position, the insertion loss is less than -0.5 dB and the return loss is more than -10 dB. So this height of the membrane is ideal for phase shifter realizations and it is 0.23 μm above the central conductor of the waveguide.

Now by gradually releasing this electrostatic force, the bridge shall get up and the switch progressively turns off. By a zero Newton electrostatic force, the bridge would stand straight upon the air and this height could be named as normalized 1 or 2.35 μm above the central conductor of the waveguide enabling the wave to cross the switch without any serious effect.

4. RESULTS

A series of results related to the MEMS phase shifter are shown and discussed in this section. A Pentium IV with a 3 GHz Intel chipset and 512 Mbytes RAM is used to calculate the results. Scattering matrix parameters of the phase shifter are all computed by means of the ANSOFT HFSS™ 10. In addition, the electrostatic and structural analyses are carried out by the ANSYS Multiphysics product of the ANSYS® release 10.

As mentioned before, the width of the fractal beam varies from 40 μm at the narrowest place to 60 μm at the widest locations. These values are used to construct four additional beams for comparison purposes. One can name these four new beams as narrow rectangle, wide rectangle, triangular, and elliptical beams.

The effect of the actuation voltage on the deformation of the bridge is investigated in the Figure 3. The required level of this electric potential is extremely depending on the shape of the bridge and its architecture. A narrow rectangular beam has a small area under electrostatic force and a wide rectangle explicates a thick cantilever so both of them are poor in operation. Elliptical beams have a wider area under electrostatic force than the triangular beams but the actuation voltage of both geometries is almost the same. Triangular, elliptical and fractal beams are all demonstrating a wide area which is coincide with narrow cantilever. The comparison in Figure 3 shows that the fractal beam is a better choice for elastic behaviors.

Regarding fractal geometries, increasing the iteration level of the Koch curves to more than two levels not only has no any salient effect on the results but also adds more difficulties to the fabrication processes. This matter is shown in the Figure 3 by comparing the

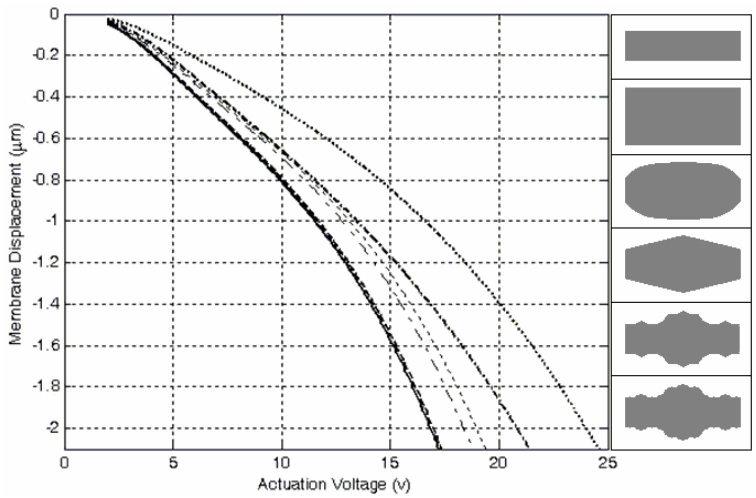


Figure 3. Displacement of the central point of the bridge vs. actuation voltage for narrow rectangular beam (●●●●), wide rectangular beam (●-●-), triangular beam (······), elliptical beam (·-·-·), Koch fractal beam with two iterations (– – –), and Koch fractal beam with three iterations (——).

actuation voltage of a Koch by 2 iterations with a Koch which is made by 3 iterations.

It is obvious from the Figure 3 that a fractal beam has an advantage of at least 23% of lower actuation voltage over the rectangular beams, even if the width of the rectangle is chosen wide enough to cover the entire fractal beam at the most wider positions. This issue has been investigated in Table 1.

Table 1. Comparison among the actuation voltages of several MEMS bridges.

Reference No.	[3]	[4]	[5]	[7]	Narrowe Rectangl (40 μm)	Wide Rectangle (60 μm)	Elliptical	Triangular	This Work (Fractal with 2 iterations)
Actuation Voltage (v)	40	20	35-40	10-30	25	22	19.5	19	17

The areas under the wide rectangular, elliptical and triangular beams are undoubtedly much more than the fractal one but their driving force are relatively high because of the better force/stiffness ratio of the fractal geometry. It is alluded that the fractal geometry treats like an infinite length in a finite area. So we encounter a mass with extremely high elasticity and high bending momentum. The insertion loss ($S21$) and return loss ($S11$) of the MEMS phase shifter are shown in Figure 4(a) when all of the 35 switch elements are turned off. On the other hand, the S parameters of the phase shifter with all the switches turned on are plotted in Figure 3(b). When the phase shifter turns off, the insertion loss remains less than -3.7 dB at 12 GHz and when it turns entirely on, this insertion loss would increase to -4.7 dB.

Figure 4 simply indicates that the upper frequency of the phase shifter would optimistically limit to 30 GHz. By the way, the return loss will always be less than -20 dB at the entire Ku frequency band and beyond. These values for insertion and return loss are compared with some other referenced papers in Table 2.

Table 2. The insertion loss, return loss, and operating frequency of several MEMS phase shifters.

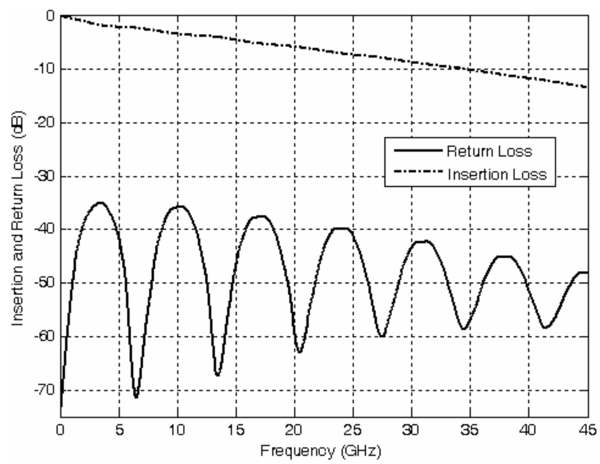
Reference No.	Number of the Bits	Frequency (GHz)	Insertion Loss (dB) at Up State (off)	Return Loss (dB) at Down State (on)
[10]	2	11.4	-0.9	-11
[11]	3	26	-1.7	-7
[12]	4	45	-2.8	-15
[13]	5	12	-4.3	-10
This Work (Fractal)	3	12	-3.7	-34

In Figure 5 it is shown that in every frequency, every one may apply a desired phase difference by turning a few or all of the switches on. So a multi bit phase shifter is obtainable by different bias circumstances implying the necessity of a DSP block. Differential phase shift means a phase difference between a certain situation and the situation in which all of the switches are off.

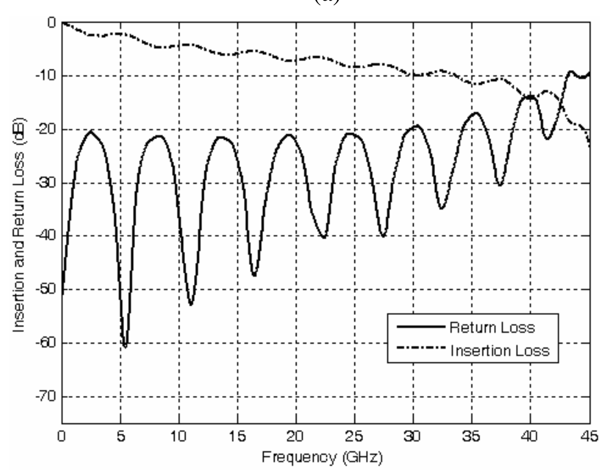
Figure 5 depicts a fairly linear behavior at the entire frequency range. So beside a microcontroller block and an antenna array, one may establish a complete phased array smart antenna.

The differential phase shift of the proposed phased shifter is shown in Figure 6 versus frequency. This plot is indicated by utilizing a microcontroller block. Despite some small non linearities, especially at the upper edges of the frequency axis, the overall digital phase shifter presents a linear behavior at the entire Ku band. According to Table 3, the Phase error would always remain negligible.

In Figure 7, the group delays of the 35 element MEMS phase shifter are shown as a function of frequency. As can be seen, this delay



(a)



(b)

Figure 4. *S* parameters of the 35 elements MEMS phase shifter vs. frequency when all of the switch elements are (a) off or up state and (b) on or down state.

remains constant (about 1.7 nano second) at the entire frequency band and this delay is not significantly affected by the status of the switch elements, whether they are partly on or off.

It is worth to mention that, once the bridge is pulled down to the silicon nitride layer, the moisture and interfacial forces would cause some sticking problems that would induce hysteresis. A suitable suggestion to get rid of these phenomena is to add some small dimples under the bridge.

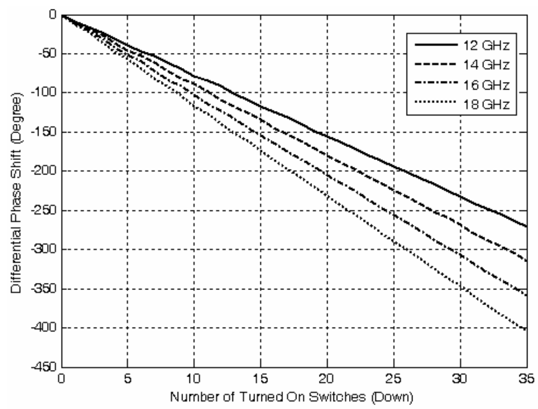


Figure 5. Differential imposed phase shift of a 35 element MEMS phase shifter vs. number of turned on switches for different frequency values while the rest of the switches are taken off.

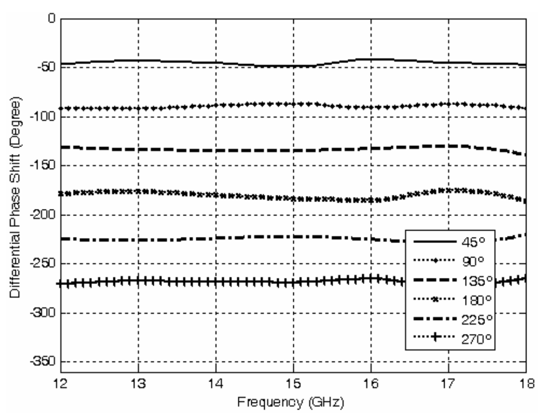


Figure 6. Differential 3-bit imposed phase shift of a 35 element MEMS phase shifter vs. frequency by introducing a 4-bit microcontroller block.

Table 3. The effect of the frequency on the phase error of the 3-bit fractal phase shifter.

Frequency (GHz)	Phase State (Degree)	Phase Error (Degree)
12	90	1.73
	180	1.5
	270	0.8
15	90	3.2
	180	3.3
	270	1.1
18	90	1.4
	180	5.6
	270	4.9

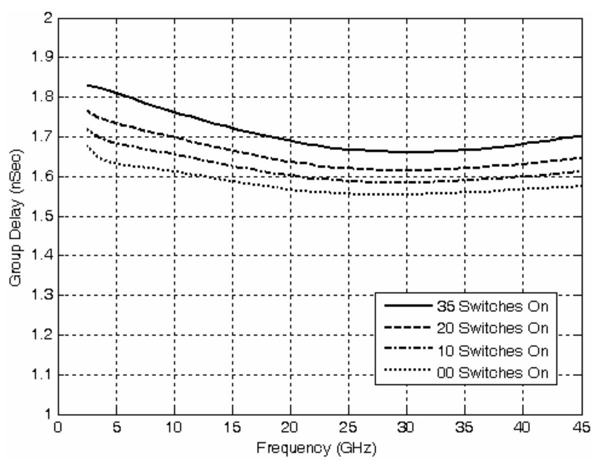


Figure 7. Group delay of the 35 element MEMS phase shifter vs. frequency for different number of switches turned on (down) while the rest of them are turned off.

5. CONCLUSION

A distributed MEMS phase shifter was developed based on the non Euclidean fractal Koch geometries. By inspecting the scattering matrix parameters of both a single switch and the phase shifter itself, it was illustrated that the operational frequency band of this structure could be around Ku band.

Furthermore, it was shown that such a fractal membrane has at least 23% lower actuation voltage from a simple rectangular beam with even wider area. By comparing this structure with triangular and elliptical geometries, it was pointed out that the fractal beam is the optimum configuration which increases the area under the electrostatic force at the same time decreases the cantilever width.

This feature extracted due to the fact that fractal curvatures of the bridge improves the bending momentum and force/stiffness ratio. This driving force was calculated to be 17 V for the proposed fractal geometry, compared with 25 V of a narrow rectangle and 19 V of triangular beam. Some progressive steps were implemented to simplify the design process. A 3-bit phase shifter with quite linear phase behavior at the entire frequency band was introduced. The group delay of such a structure was studied as well and a smooth variation over the entire frequency band was achieved.

ACKNOWLEDGMENT

The authors want to acknowledge the Iran Telecommunication Research Centre (www.itrc.ac.ir) for their kindly supports.

REFERENCES

1. Huang, J. M., K. M. Liew, C. H. Wong, S. Rajendran, M. J. Tan, and A. Q. Liu, "Mechanical design and optimization of capacitive micro-machined switches," *Sensors and Actuators A*, Vol. 93, 273–285, 2001.
2. Qing, J., Y. Shi, W. Li, Z. Lai, Z. Zhu, and P. Xin, "Ka-band distributed MEMS phase shifters on silicon using alsi suspended membrane," *Journal of Microelectromechanical Systems*, Vol. 13, No. 3, June 2004.
3. Hung, J. J., L. Dussopt, and G. M. Rebeiz, "Distributed 2- and 3-bit W-band MEMS phase shifters on glass substrates," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 52, No. 2, February 2004.
4. Hayden, J. S. and G. M. Rebeiz, "Very low-loss distributed X-band and Ka-band MEMS phase shifters using metal-air-metal capacitors," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 51, No. 1, January 2003.
5. Kim, H. T., J. H. Park, J. Yim, Y.-K. Kim, and Y. Kwon, "A compact V-band 2-bit reflection-type MEMS phase shifter," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 9, September 2002.

6. Afrang, S. and E. Abbaspour-Sani, "A low voltage MEMS structure for RF capacitive switches," *Progress In Electromagnetics Research*, PIER 65, 157–167, 2006.
7. Abbaspour-Sani, E., N. Nasirzadeh, and G. Dadashzadeh, "Two novel structures for tunable MEMS capacitor with RF applications," *Progress In Electromagnetics Research*, PIER 68, 169–183, 2007.
8. Afrang, S. and B. Y. Majlis, "Small size ka-band distributed MEMS phase shifters using inductors," *Progress In Electromagnetics Research B*, Vol. 1, 95–113, 2008.
9. Wu, W. and Y.-H. Bi, "Switched-beam planar fractal antenna," *Journal of Electromagnetic Waves and Application*, Vol. 20, No. 3, 409–415, 2006.
10. Raveu, N., E. Perret, H. Aubert, and H. Legay, "Design of MEMS controlled phased shifter using SCT," *PIERS Online*, Vol. 3, No. 2, 230–232, 2007.
11. Werner, D. H. and S. Ganguly, "An overview of fractal antenna engineering research," *IEEE Antenna and Propagation Magazine*, Vol. 45, No. 1, February 2003.
12. Rebeiz, G. M., "Phase-noise analysis of MEMS-based circuits and phase shifters," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 50, No. 5, May 2002.
13. Hayden, J. S. and G. M. Rebeiz, "2-bit MEMS distributed MEMS X-band phase shifters," *IEEE Microwave and Guided Wave Letters*, Vol. 10, No. 12, 540–542, December 2000.
14. Liu, Y., A. Borgioli, A. S. Nagra, and R. A. York, "K-band 3-bit low-loss distributed MEMS phase shifter," *IEEE Microwave and Guided Wave Letters*, Vol. 10, No. 10, 415–417, October 2000.
15. Kim, H. T., J. H. Park, S. Lee, S. Kim, J. M. Kim, Y. K. Kim, and Y. Kwon, "V-band 20-bit and 4-bit low loss and low voltage distributed MEMS digital phase shifter using metal-air-metal capacitors," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 50, No. 12, 2918–2923, December 2002.
16. Ko, Y. J., J. Y. Park, H. T. Kim, and J. U. Bu, "Integrated five-bit RF MEMS phase shifter for satellite broadcasting/communication systems," *IEEE*, 2003.