LOW ACTUATION VOLTAGE KA-BAND FRACTAL MEMS SWITCH

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Abstract—In this paper, a novel structure for Ka-band micro electromechanical switches with low actuation voltage is proposed. In this structure, the membrane of the switch is chosen to be a Koch fractal. We have analyzed these switches in order to extract their parameters such as insertion loss, return loss and deformation posture. The effect of the actuation voltage on the deformation of the bridge has been analyzed and the results are compared with simple rectangular bridges. It is shown that bias voltage of these kinds of switches is remarkably lower than that of its other counterparts. This switch may be used as a low loss and effective element for more complicated systems such as distributed phase shifters and phased arrays.

1. INTRODUCTION

Miniaturization has been the foremost technological tendency during the past decades and in this global trend; miniaturization of the Micro-Electromechanical Systems (MEMS) has become one of the most scholar research areas all over the world.

In this regard, surface micro-machining technology has been successfully used for RF applications such as switches, phase shifters, passive elements, sensors and actuators. These micro-devices are capable of getting integrated by other RF macro-elements such as

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planar and non-planar antennas, phased arrays, filters and power dividers.

In other hand, switch is a device which we are interested to shrink its size and make it more convenient to use. The main advantages of such a structure would be low power consuming, very small size, low cost, reliable, wide tuning range, low phase noise, low insertion loss and single chip packaging which are almost impossible with standard semiconductor processes. These benefits beside many others, made the MEMS switches compatible with the other integrated circuits.

MEMS switches were first demonstrated in 1979 as an electrostatic cantilever switch. These types of switches have the disadvantage of relatively high actuation voltage [1, 2]. If we overcome this problem, then this type of switches will be the best candidate for RF applications in comparison with the electromagnetic or electro-thermal switches.

In recent years, MEMS switches are undergone a variety of material changes and geometrically improved designs to decrease the actuation voltage. These efforts were put on 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 [3].

Our proposed structure is to utilize 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 and the switching rise time. Furthermore, in this special design we will not loss any other parameters. So a high isolation is achievable beside low insertion loss and low return loss.

2. THEORY

The attributes of fractal geometries have obviously influenced many branches of science and engineering. Designers 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 make them treat like an infinite length in a certainly finite area [4]. This special trait would improve the bending momentum of the bridge and increase the force/stiffness ratio of the structure. So as mentioned above, the actuation voltage will decrease.

As can be seen in Figure 1, 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 choose 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 iteration hasn't got any influence on the results and would troublesome the micromachining process.

A coplanar waveguide $(35/25/35\,\mu\text{m})$ is used here with a silicon $(\varepsilon_r = 11.9)$ substrate to mount the bridge on. This structure is shown in Figure 2. The dimensions of the waveguide conductors are changed to $50/30/50\,\mu\text{m}$ under the bridge.

The substrate has $0.4\,\text{mm}$ height and the conductors are made from gold with the thickness of $2\,\mu\text{m}$ which decreases to $0.5\,\mu\text{m}$ under the bridge. The length of the beam is chosen to be $250\,\mu\text{m}$ and its width is $40\,\mu\text{m}$ at the narrower place (next to the holder stones) and this wide is gradually boost to about $60\,\mu\text{m}$ at the wider place (at the middle of the bridge). This bridge is mounted $0.85\,\mu\text{m}$ above the outer conductors of the waveguide.
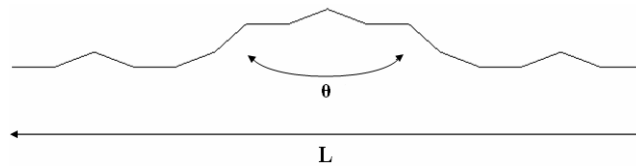

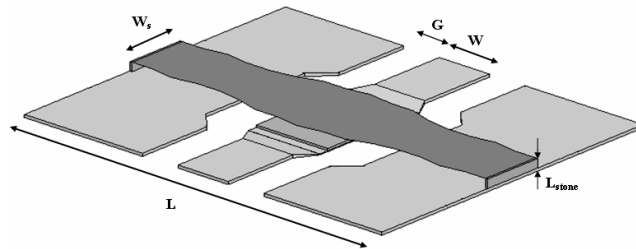**Figure 1.** The geometry of a 2 stage fractal koch beam.

Figure 2. Geometry of the proposed MEMS switch with a 2 stage fractal beam.

A $0.15\,\mu\text{m}$ silicon nitride dielectric is sputtered on the central conductor of the waveguide to avoid it from any possible connection to the bridge itself. In the distributed MEMS phase shifter applications, the deformation of the bridge under the electrostatic force will be limited by this dielectric layer to maintain an acceptable matching over a wide band. In this certain usage of MEMS switches, the

deformed bridge will not suppress the wave from passing through the transmission line [5, 6] and switches are mostly act like tunable capacitors instead of real switches.
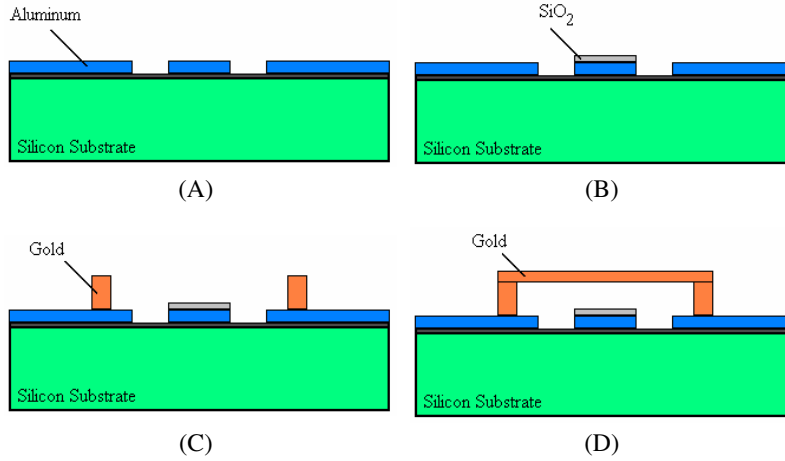

Figure 3. Fabrication process of a fractal MEMS switch.

For frequencies below the Bragg frequency, with a small inevitable insertion loss, this unique switch will apply a phase shift on the signal by reducing the phase velocity of the wave. If we attach a series of these elements together, then the desired phase shift will be achievable [7].

The fabrication process of the fractal RF MEMS switch is pointed out in Figure 3. The procedure mentioned below can be applied for fabrication process. At the first step, a $2\,\mu$m layer of aluminum sputters on the silicon substrate and wet etches to provide a $50\,\Omega$ 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 $40\,$mTorr pressure on $250\,$W and 0.8 selectivity adjustments versus photo-resist (PR).

Same process of the first step goes on to provide the major two stones of the bridge as shown in figure 3-C. To provide the beam of the bridge, one needs to sputter a PR layer on the structure of Figure 3(C). Using the same mask as used in 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 remove from the structure.

The equivalent circuit of the proposed shunt switch is shown in Figure 4. By applying a DC voltage, the bridge bents down, making an increase in the capacitance and consequently a decrease in the shunt reactance, preventing the wave from passing through [8, 9].
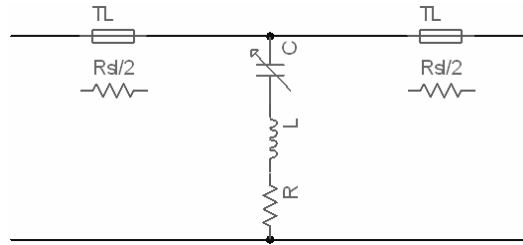
Figure 4. An equivalent circuit of the MEMS switch.

3. RESULTS

Some results related to the RF MEMS switch 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 this switch are all computed by means of the ANSOFT HFSS^{TM} 10. In addition, the Electrostatic-Structural analyses are carried out by the ANSYS Multiphysics product of the ANSYS$^{®}$ release 10.

When the switch is biased with a DC voltage, an electrostatic force applies to its membrane and the bridge is curved down and the switch turns on; suppressing all of the waves from passing through the bridge. On the other hand, by releasing this electrostatic force, the bridge will get up and the switch would say to turn off; enabling the wave to cross the switch [10, 11].

As mentioned once before, the wide of the fractal beam varies from 40 μm at the most narrower place to 60 μm at the most wider locations. These values are used to construct two ordinary rectangular beams for comparison purposes. We name these two new beams as thin and thick rectangular membranes.

The insertion loss (S_{21}) and return loss (S_{11}) of a fractal and rectangular MEMS switches are shown in Figures 3 and 4 for both of the possible switch positions (up and down). When the switch is off, the return loss remains less than -15 dB from UHF band to millimeter wave and when it turns on, the lower operational frequency of the switch will constrain to Ku band and the upper frequency would be still the millimeter wave. So the effective bandwidth of this type of switch would be around the Ka band [12].

The beam shape has a minor effect on the insertion and return loss [12]. S_{12} increases at lower frequencies of Figure 6 which means, the 0.15 μm silicon nitride dielectric could help unwanted waves to pass the bridge at lower frequencies, so the behavior of this Ka band switch
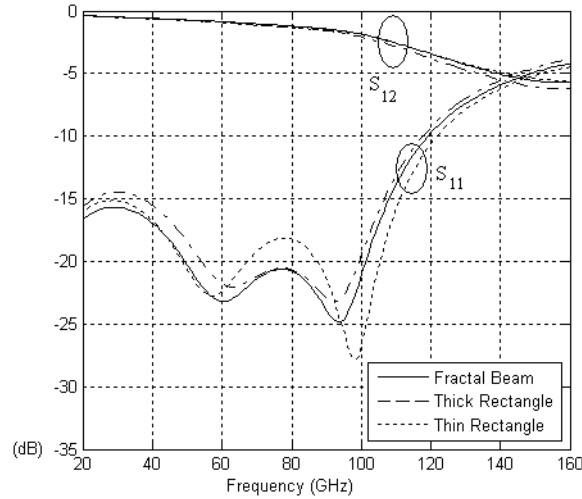
Figure 5. S parameters of the fractal and rectangular MEMS switches vs. frequency for the off [up] state of the bridge.

needs not to be considered at lower frequencies.

In another point of view, the insertion loss for an off switch is about -1 to $-2\,dB$ and when the switch turns on this insertion loss rises to less than $-10\,dB$ which means isolation to us.

As can be seen from Figures 5 and 6, according to the field and wave theory, there is no such a serious difference between a rectangular and a fractal beam. Actually the fractal beam could pass or reject signal from passing through the bridge as effective as a wide rectangular membrane.

Figure 7 represents the insertion and return losses of the MEMS switch as a function of normalized membrane curvature at $50\,GHz$. When we apply an electrostatic force to the bridge, it would bend along its length (L) to lay down on the sputtered silicon nitride dielectric. We name this height as zero distance. 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 we name this height as normalized 1 (or $2.35\,\mu m$ above the central conductor of the waveguide).

Figure 7 helps us to understand the optimum position of the membrane for the phase shifter applications. It is mentioned once above that the optimum position of the bridge is where the switch acts more like a capacitor not a switch. As can be seen in Figure 7, when the bridge is at the 0.3 of its final position, the insertion loss is more
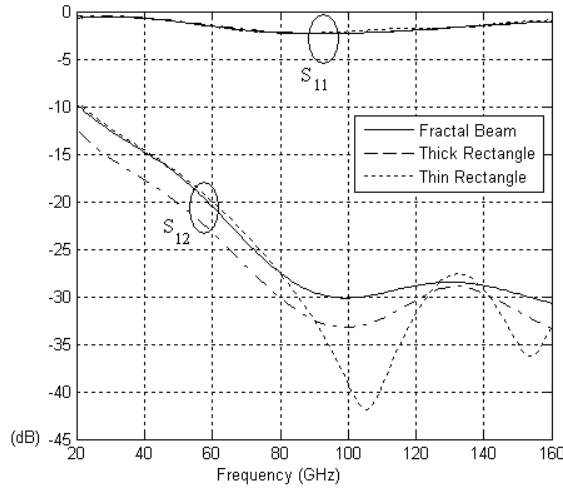
Figure 6. S parameters of the fractal and rectangular MEMS switches vs. frequency or the on [down] state of the bridge.
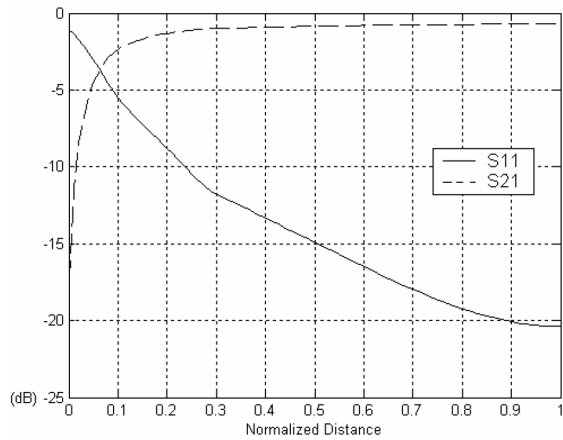

Figure 7. S parameters of the MEMS switch vs. bridge deformation at $50\,\text{GHz}$.

than $-2\,\text{dB}$ and the return loss is less than $-10\,\text{dB}$. So this height of the membrane is ideal for phase shifter realizations and it is $0.81\,\mu\text{m}$ above the central conductor of the waveguide.

The effect of the actuation voltage on the deformation of the bridge is investigated in the Figure 6. When a DC voltage applies to the membrane, it would bend under the pressure of the electrostatic force.

In the MEMS switch applications, it is very important to tilt the bridge as long as it lies down on the separating silicon nitride layer to guaranty the wave from not passing through.

The required level of the electric potential is extremely depending on the shape of the bridge and its architecture but when we talk about fractal geometries, increasing the iteration level of the Koch curves to more than two levels, not only haven't got any salient effect on the results but also adds more difficulties to the fabrication processes. This matter is shown in the Figure 6 by comparing the actuation voltage of a Koch by 2 iterations with a Koch which is made by 3 iterations.
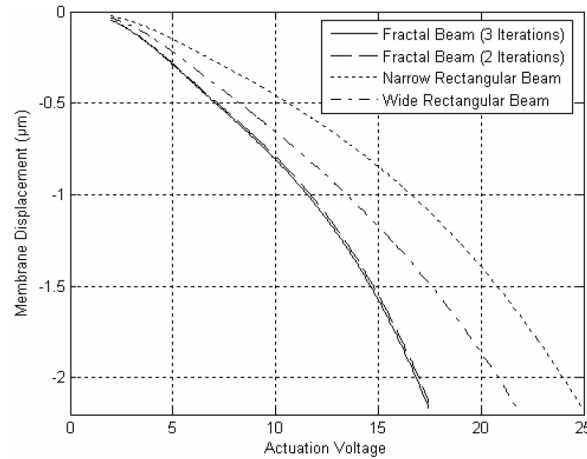

Figure 8. Displacement of the central point of the bridge vs. actuation voltage for fractal, thin rectangular and thick rectangular membrane.

It is obvious from the Figure 8 that a fractal beam has an advantage of lower actuation voltage over the rectangular beams; even if the wide of the rectangle is chosen wide enough to cover the fractal beam at the most wider positions. The area under the thick rectangular beam is undoubtedly much more than the fractal one but its driving force is relatively high and it's because of the better force/stiffness ratio of the fractal geometry. It 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.

By choosing the fractal geometry, it can be seen from the Table 1 that a 17.5 V actuation voltage is simply achievable. If we utilize a simple 40 μm wide rectangular beam, 25 V is necessary to tilt the beam and by a 60 μm rectangle, this voltage will improve to about 22 V which is still 4.5 V more than the proposed fractal beam.

Table 1. Comparison between the different types of the beams at the frequency of 50 GHz.

Beam Type	$S^{\dagger}_{11Up}$	S_{12Up}	S_{11Down}	S_{12Down}	Actuation Voltage
Fractal Beam (2 Iterations)	0.0985 < 168.9143	0.9204 < −130.6823	0.8808 < 64.8023	0.1361 < 150.9863	17.5 V
Rectangular Beam (0.4 μm)	0.0906 < 169.1861	0.9159 < −130.3502	0.8779 < 62.9680	0.1393 < 150.3061	25 V
Rectangular Beam (0.6 μm)	0.1179 < 157.5670	0.9171 < −130.5335	0.8881 < 65.0221	0.0971 < 151.0600	22 V

$^{\dagger}S$ parameters were represented in (Abs < Degree) form

At the end, it is worthy 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 this phenomenon is to add small dimples under the bridge.

4. CONCLUSION

A fractal based Koch structure is designed and analyzed to utilize as a MEMS switch. By inspecting the scattering matrix parameters of this switch, it was illustrated that the operational frequency band of this structure could be from near the end of the Ku band to the millimeter wave.

In addition to the switching usage of this construction, the possible phase shifter applications of this switch were studied as well and some useful hints were issued to simplify the design process. Furthermore, it was shown that such a fractal membrane has a lower actuation voltage from a simple rectangular beam with even wider area and it is all because of its improved bending momentum and force/stiffness ratio. This driving force was calculated to be 17.5 V for the proposed fractal geometry; compared to 25 V of a narrow rectangle and 22 V of a wide rectangle.

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