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Shunt Micro-Electro-Mechanical Systems (MEMS) Switch With Holes And Integrated Complementary Split Ring Resonator (CSRR) Meta-Materials For RF Applications

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Abstract

Complementary Split Ring Resonator (CSRR) structures form a negative refractive index meta-material giving negative permeability. MEMS Switches are advantages in terms of very low insertion loss, high linearity, high return loss, low power consumption and high isolation. Integrating both would yield very good results as the proper use of meta-materials can reduce the size of the structure by many manifolds .In this paper a MEMS switch using silicon substrate on a co-planar wave guide technology is integrated with CSRR meta-material and its electrical and mechanical characteristics are shown. The electrical characteristics show a low insertion loss of 0.4dB, return loss of 20dB in the up-state and isolation of 35dB in the down state in the range of 14 to 16GHz using An soft HFSS which are very well suited in the Ku-band for satellite communications applications. The mechanical response also yields an actuation voltage of 15V with a Von Mises stress gradient of 11MPa using Intellisuite v8.7 software.

Keywords: Radio Frequency, MEMS, Intellisuite, Ansoft HFSS, metamaterial

Introduction

Radio Frequency Micro-Electro-Mechanical Systems (MEMS) technology offers small size, low cost, low insertion loss, high return loss, high linearity, low power consumption ,high power handling capabilities[1], low contact force and high isolation[2][3][4] thereby offering very good RF performance when compared to the existing CMOS/Semiconductor technologies like the PIN diode and MOSFETs [5]. One of the most widely used MEMS device is the MEMS switch in communications field. MEMS switch has various applications in the communications viz. phase shifters, phased array antennas, varactors, voltage controlled oscillator and so on .Lifetime of RF MEMS switches is one of the main concern for use in repair free applications in remote places [6].A few issues to be encountered are high actuation voltage of around 10-30V (semiconductor devices operate below 5V), slow switching speeds in the order of µs, reliability issues and packaging constrains. Reliability issues have been given in the literature [7] [8] [9]. The most widely used actuation method is the electrostatic actuation due to its low contact force, very low power consumption and linearity. MEMS switches are categorized into two viz. series and shunt switch based on the configuration of the beam position and the operation of the membrane. As MEMS technology is derived from CMOS technology its fabrication processes remain similar. The use of serpentine suspensions with higher meander sections have been used to achieve lower actuation voltage, which often compromise with space limitation and design complexity[10]. A non-uniform serpentine flexure suspension has been proposed [11].

Meta-materials have grown tremendous interest in the electromagnetic domain not only because of their reversed electromagnetic properties viz. permittivity and permittivity [12] but due to their tremendous applications in the microwave and optical domain. The first left hand metamaterial property proved by Smith [13] constructed by a combination of wire array and magnetic resonator array to obtain a negative refractive index has been researched by many groups to enhance their models like tunable filters and antennas[14]. The wire array provide negative permittivity and magnetic resonator array usually split ring resonators constitute to form the metamaterial structure. Metamaterial inclusion brings in a change of frequency as the equivalent structure is composed of an inductor and a capacitor thereby a tuning circuit [15].

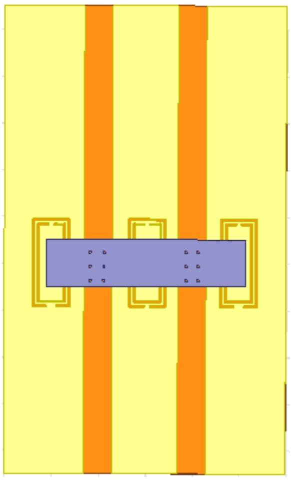
In this paper a MEMS switch is proposed which incorporates holes in the membrane with a complimentary split ring resonator (CSRR) etched the signal portion of the co-planar wave guide. The CSRR embedded in the signal enhances the capacitance ratio of the MEMS switch which further enhances the RF performance of the switch. Various models of the MEMS switch with metamaterials have been analyzed to get the parametric analysis. Holes are incorporated in the membrane of the shunt switch to make the surface micromachining process simpler and also reduce the effective spring constant of the switch thereby reducing the pull-in voltage and stress of the switch [16].

Switch Description

The proposed switch was built on a silicon substrate with 50Ω impedance. A fine layer of silicon dioxide is present between the gold co-planar wave guide transmission line and the silicon substrate in order to reduce the oxidation rate of silicon substrate. The gold co-planar waveguide (CPW) transmission line has G/S/G of 60/140/60µm with a thickness of 4µm.The MEMS switch made of gold [17] stands on two anchors made of gold of 3µm height. This height is a very important parameter as it is one of the determining factors of a low actuation voltage. A metamaterial layer mask is created and etched out from the center conductor of the CPW. The switch is deposited onto the anchors with a photo-resist (PR) layer beneath the membrane. After the deposition it is removed during surface micromachining process. Holes are etched in the shunt membrane in order to facilitate easy fabrication process and to lower spring constant. The values for the switch are given in Table.1.

Table 1: Parametric values of the CPW

Parameter	Value(µm)
G/S/G	60/140/60
Thickness(t)	4
Length(l)	1000



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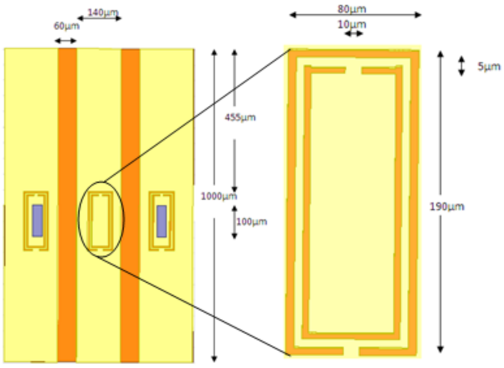

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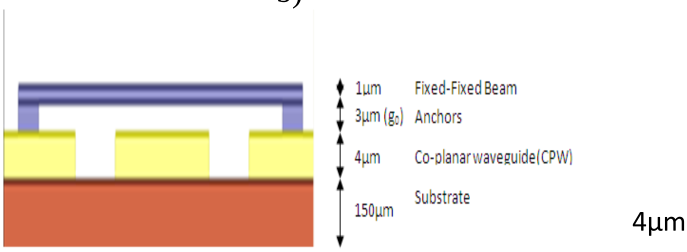

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Figure 1: a) MEMS Switch with Cantilever, b) MEMS Switch (hiding cantilever) and expanding the Complimentary Split Ring Resonator (CSRR), c) MEMS Switch with Cantilever (Enlarged)

Theory and Design

The CPW transmission line's impedance is matched to 50Ω.

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{eff}}} \frac{K(k_0')}{K(k_0)} \tag{1}$$

Where Z0 is the impedance of the CPW

.ε_{eff} is the effective permittivity of the CPW

$$k = \frac{\sinh(\pi S/4h)}{\sinh\{[\pi(S+2W)]/4h\}} \tag{2}$$

$$k' = \sqrt{1-k^2} \tag{3}$$

CPW transmission line is selected for the MEMS switch as it provides us the facility to utilize the two grounds for two anchors in case of a fixed-fixed beam MEMS switch and losses are less as compared to a microstrip line transmission line [18].Various parametric analysis have been performed and optimized value of the CPW is given in table.1.

Shunt MEMS switches can be reduced to an equivalent circuit as given in Fig.2.

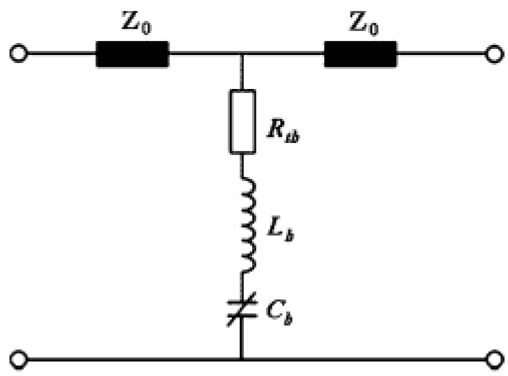


Figure 2: Equivalent Circuit model of RF MEMS Switch [19]

From the equivalent circuit it is evident that the inductance and capacitance provide the resonance of a shunt switch. The length of the beam acts as an inductance and the gap acts as a capacitance and the internal resistance of the material as the switch resistance.

Hence the resonant frequency is given by the formula (4)

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

C in the equation pertains to two different states of the switch viz. C_d is the down state capacitance and C_u is up-state capacitance of the switch.

The optimized values for the MEMS switch is given in table 2

Table 2: Optimized Values of The Switch

Parameter	Value(μm)
Length	425
Width	100
Thickness	4
.g_0	2

Split Ring Resonator (SRR) is a metamaterial structure as shown in Fig.1b (right side enlarged image)

The SRR etched onto a material yields Complementary Split Ring Resonator (CSRR). The split present provides the capacitance and the whole length of CSRR provides the inductance. Self-inductance per unit length is given by (5) [20]

$$L_c = \frac{\mu_0(2w+b)}{\sqrt{\pi}}\left[\log\left(\frac{64w+32b}{w\sqrt{\pi}}\right) - 2\right] \text{-} \quad (5)$$

Capacitance is hard to determine as multiple capacitances like between membrane and dielectric capacitance and CPW gap capacitance interfere with the total capacitance. Hence a roughly estimated capacitance is given.

When the MEMS switch is in down state [21]

$$C_0 = \frac{A_0 \varepsilon w t}{g} \quad (6)$$

-A_0 is loss factor due to various other capacitances

-ε is permittivity

-w is width

-t is thickness

-g is gap

When the MEMS switch is in up state

$$C_1 = \frac{A_1 \varepsilon w t}{g_1} \quad (7)$$

-A1 is loss factor due to various other capacitances

-ε is permittivity

-w is width

-t is thickness

-g is gap

Finally the magnetic resonant frequency is given by

$$\omega = \frac{1}{\sqrt{LC}} \quad (8)$$

From (8) it is evident that the magnetic resonant frequency depends on the gap of the MEMS switch. Therefore we can tune the frequency of the switch in this manner which in turn has many applications like electronically steerable antennas, tunable filter, etc.

MEMS shunt switches with CSRR equivalent circuit is given by Fig.3

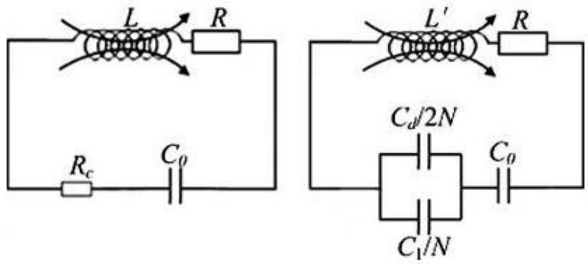


Figure 3: MEMS Switch Equivalent Diagram With CSRR [21]

The fixed-fixed beam is etched with holes on the lines of the gaps of the co-planar waveguide for two reasons:

1. When the holes are etched in the middle of the beam, the beam becomes vulnerable to breakage due to the lowering of material stiffness.
2. When the holes are etched near to the anchors, then the whole purpose of drilling holes is easier fabrication is not satisfied.

Etching of holes on the beam facilitates easier fabrication during surface micromachining on the removal of photo-resist. A switch without holes, with holes and with CSRR and holes is compared in table.3

Table 3: A Comparison of Switch With And Without Metamaterials

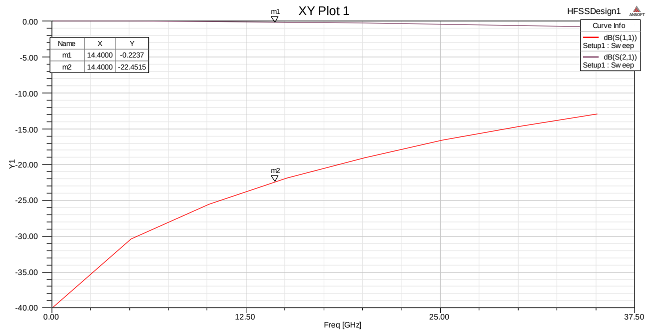
Parameter	Simple Switch	Switch with holes	Switch with holes and CSRR
Frequency(GHz)	51.10	45.30	14.40
Insertion Loss(dB)	-0.26	-0.32	-0.22
Return Loss(dB)	-21.50	-18.57	-22.45
Isolation(dB)	-47.63	-41.3	-33.20

From Table. 3 it can be analyzed that the simple switch which has been designed works at 51.1GHz and the insertion loss is -0.26dB, return loss is -21.5dB and isolation is -47.63dB. It can also be observed that switch with holes has an advantage over fabrication process with a trade-off in return loss of 3dB and a trade-off of 6dB in isolation. When CSRR is incorporated in the switch it can be deduced that the return loss improves by 4dB but again there has been a trade-off of isolation by nearly 14dB. But the interesting point to be noted is the frequency shift brought out by the CSRR which is very important feature to design the switch with same dimensions.

Electrical Analysis

The MEMS switch is a fixed-fixed beam type membrane situated on two anchors which are placed on the ground of the CPW. A silicon nitride is placed between the membrane and signal line of CPW to prevent the switch from stiction problems and dielectric charging. When a voltage is given to the signal line an electrostatic force is developed on the membrane and this attracts it downwards to define two states of the switch viz. ON state and OFF state. When the membrane is up-wards it is ON state and when the membrane shorts with the ground it is in OFF state. This analysis helps us in using the switch in digital operations. In the ON state C_u is important and in down state C_d is important in determining the frequencies of operation. The ratio of C_d to C_u gives the figure of merit or efficiency of the switch [16].

Electrical analysis is presented using Scattering parameters(S-parameters). The ON state (up state) and OFF state (down state) values are given in Fig. 4



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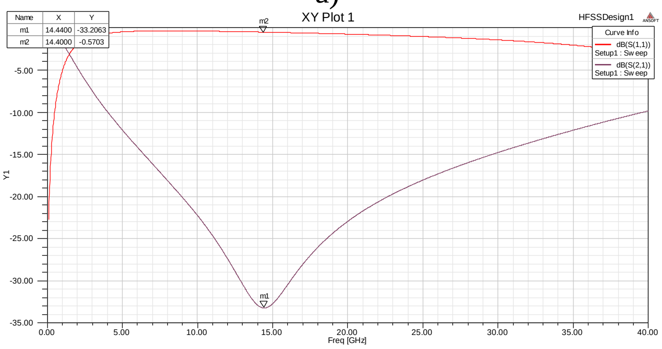

b)

Figure 4: a) Up state of switch, b) Down state analysis of RF MEMS Switch

Mechanical Analysis

When a membrane is subject to electrostatic actuation the fixed-fixed beam bends downwards thereby creating stress in the membrane. In order to overcome the stiffness of the beam an additional voltage has to be applied named pull-in voltage. During the actuation there is a possibility of creation of stiction which is overcome by the restoring spring force which in turn increases the switching time.

The pull-in voltage and switching time are given by the formula (9) (10)

$$V_P = \sqrt{\frac{8k_s g_0^3}{27\varepsilon_0 A}} \tag{9}$$

$$t_s = 3.67\frac{V_p}{V_s \omega_0} \tag{10}$$

V_p- Pull in voltage
k_s- Spring constant
g_0- Gap between the membrane and CPW

ε_0- Permittivity of free space
A- Actuation area
t_s - Switching time
Vs- Threshold voltage
ω_0- Frequency of operation
The structure designed in Intellisuite is given in Fig.5

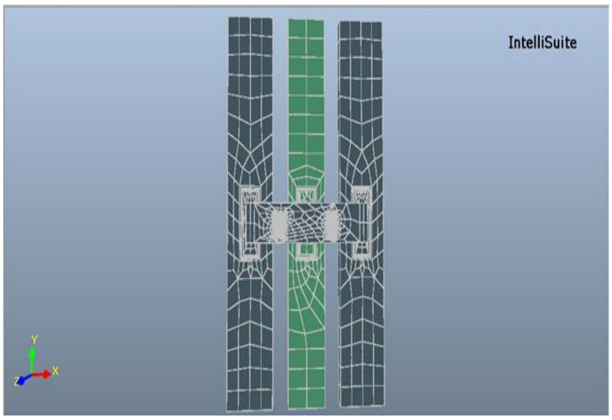

Figure 5: Structure of The RF MEMS Switch

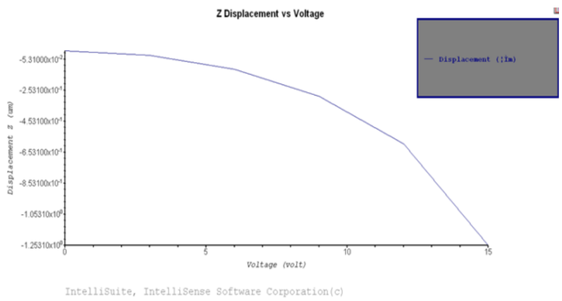

Figure 6: Pull-in Voltage graph of RF MEMS Switch

The pull-in voltage is 15V because the displacement for $1/3^{rd}$ of g_0 is observed at this voltage from Fig.6. The displacement analysis, Von Mises Stress analysis is also presented in Fig.7 and Fig. 8 respectively.

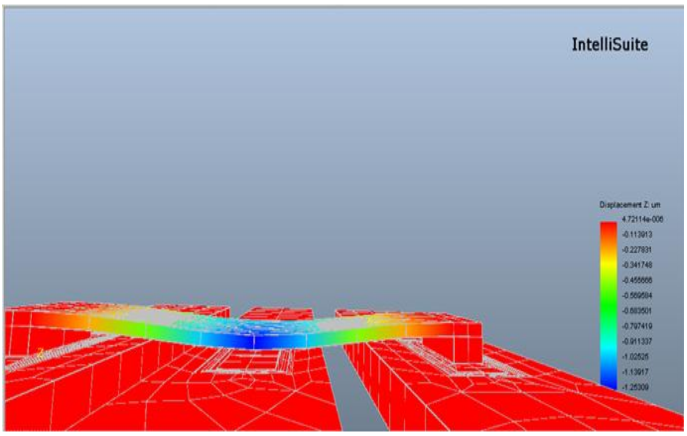

Figure 7: Displacement Analysis of an RF MEMS Switch

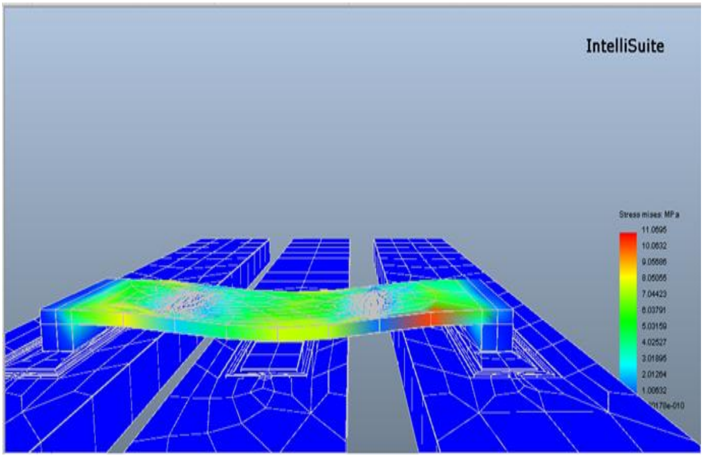

Figure 8: Von Mises Stress Analysis of an RF MEMS Switch

Conclusion

The electrical and mechanical analysis with holes and CSRR have been performed and very low insertion loss of -0.22dB, good return loss of -22.45dB and high isolation of -33.20dB have been observed. Mechanical analysis yields a Von Mises stress gradient of 11MPa and a pull-voltage of 15V. The frequency being in the Ku band can be used for various applications like RADAR, satellite and many more RF applications.

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