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Design and Analysis of CPW based Shunt Capacitive RF MEMS Switch

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Abstract— This paper is about, the design and analysis of shunt capacitive RF MEMS switch with less actuation voltage, low insertion losses and high isolation losses. The switch design is incorporated the Electrostatics MEMS actuation technique with vertically deforming bridge. In terms of actuation voltage the switch performance is improved by choosing step type actuation structure with holes. The switch Radio Frequency(RF) performance is analysed over the frequency range 0.6GHz to 40GHz. The major achievements in this work are actuation voltage is reduced to 4.2V for 0.9µm displacement, the return loss is below -16dB, the insertion loss is below -0.44dB, and the isolation loss is -20dB. The dielectric material used between the membrane and the CPW line is Aluminum Nitride (AlN) with dielectric constant 9.5. The substrate material used for the CPW transmission line is quartz with dielectric constant 3.9. The bridge is designed with meanders, step structure by using gold material with thickness 0.5µm. The switch upstate capacitance is capacitance ratio of the shunt capacitive switch is 65.22.

Index Terms— **RF MEMS Switch, CPW Transmission Line, Pull-in Voltage, Up Capacitance, Down Capacitance, MEMS Actuation Mechanisms, Electrostatic MEMS Actuation, Insertion Losses, Isolation Losses.**

I. INTRODUCTION

The RF MEMS switches have a predominant role in the design of present day advanced communication applications. To design reconfigurable microwave antennas and filters RF MEMS switches are preferable than solid state devices like FET and PiN diode [1]. MEMS technology has scope for miniaturization when compared to CMOS and GaAs technologies. The major advantages in MEMS technology based RF MEMS switch are better linearity, high isolation, low noise, low power consumption, and high operating frequency [5]. The RF MEMS switch performance depends on return losses, isolation losses, insertion losses, switching time and actuation voltage. The materials used in the design also decides the performance, stiction of the cantilever depends on the contact material used in the switch [4]. MEMS technology offers different actuation mechanisms like electrostatic, magneto static, piezoelectric and thermal. In this electrostatic actuation technique is preferable because other techniques re quire more dc voltage to actuate the structure [5]. The RF MEMS switches are electrically classified as series type and shunt type. Based on contact type the switches are classified as capacitive and resistive. Capacitive switches are preferable for high frequency and resistive switches are preferable for low frequency applications. In capacitive switches the isolation losses mainly depends on the dielectric material used between the electrodes, generally silicon nitride, silicon dioxide and Aluminum Nitride are used. The MEMS structure may be bride type (or) cantilever type (or) diaphragm type. The bridge structure with supporting meanders and step type will help to minimize the actuation voltage [1] [2].

II. THEORETICAL ANALYSIS

In this paper an electrostatically actuated shunt type capacitive RF MEMS Switch is designed by adopting new techniques in the shape of structure like meanders, step, and holes to the structure as shown in figure 4.

A. CPW Transmission Line

CPW and Microstrip transmission lines are used to design RF MEMS switches. The return losses, operating frequency depends on the dimensions of the transmission line. In this paper co-planar wave (CPW) transmission line is used to design the shunt capacitive RF MEMS switch. In CPW transmission line both the conductors are in same plane as shown in the Fig. 1.

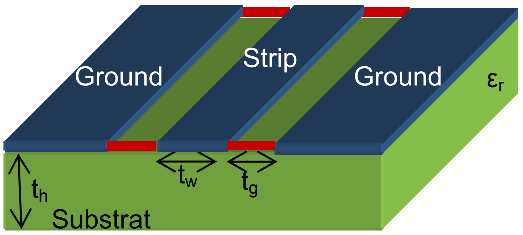


Fig. 1. CPW Transmission Line

Here t_h is the height of the substrate, t_w is the width of the CWP line and t_g is the gap between the CPW planes. ε_r is the substrate dielectric constant generally in between 3.3 to 4.7. The switches are designed for radio frequency applications so the CPW line metal thickness is considered as 0.0001µm≈0µm.

B. Beam Structure

To design an RF MEMS switch different structures like cantilever, diaphragm, and beam or bridge are preferable. The shape and dimensions of the beam decides the magnitude of actuation voltage and isolation losses. In this paper an RF MEMS switches is design using beam structure with meanders, step and holes as shown in Fig.2.

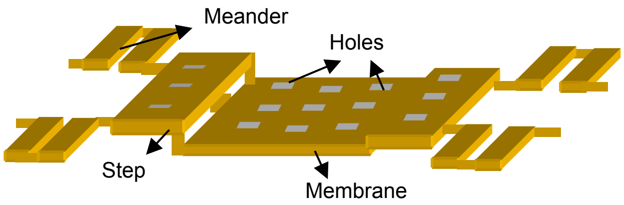


Fig. 2. MEMS Actuation Structure (Beam)

The mass of the structure is associated with the mass of the meanders (m_d), mass of the steps (m_s) and mass of the membrane (m_m). The total effective mass (m_t) can be calculated by subtracting holes mass (m_h) from overall mass.

$$m_t=m_d+m_s+m_m-m_h \qquad (1)$$

The switch is an electrostatically actuated switch, which require a actuation voltage (V_p) to deform the structure can be expressed as

$$V_p = \sqrt{\frac{8k_{eff}}{27A\,\varepsilon_0}\left(g_1+\frac{t_d}{\varepsilon_r}\right)^3} \qquad (2)$$

Where k_{eff} is the effective spring constant of the beam i.e. it is the overall spring constant of the meanders, step and membrane.

The spring constant will decide the required actuation voltage i.e. more spring constant means more actuation voltage is required. The deforming structure spring constant generally expressed as

$$k = \frac{EWt^3}{l^3} \qquad (3)$$

Where E is the young's modules, w is the width, t is the thickness, *l* is the length of the beam.

The meander structure used in this paper is associated with different beams as shown in Fig.3. Each beam is associated with own spring constant i.e. k_1, k_2, k_3, k_4, k_5. The mean spring constant (k_m) can be expressed as

$$\frac{1}{k_m} = \frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}+\frac{1}{k_4}+\frac{1}{k_5} \qquad (4)$$

The overall effective spring constant(k_{eff}) associated with actuation structure can be expressed as

$$k_{eff} = 4k_m \quad (5)$$

Here the mean spring constant is multiplied by 4 because the structure is associated with for meanders on four sides as shown in Fig. 2.

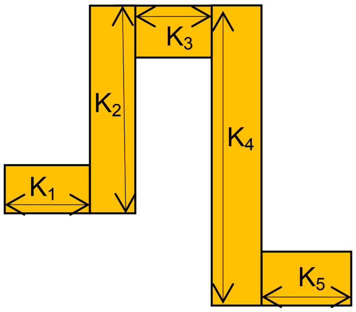


Fig. 3. Meander with Non-Uniform Spring Constants

The capacitive RF MEMS switch performance can be improve by decreasing the upstate capacitance and increasing the downstate capacitance. The capacitance variation mainly depends on the dielectric material used between the bottom electrode and membrane, generally silicon nitride or silicon dioxide or Aluminum nitride is used as dielectric material. The dielectric constant of these materials is in between 3.3 to 9.5. The upstate capacitance (C_u) can be expressed as

$$C_u = \frac{\varepsilon_0 A}{g_1 + \frac{t_d}{\varepsilon_r}} + C_f \quad (6)$$

Where A = W * w is effective area between membrane and bottom electrode as shown in Fig. 5., W is the width of the membrane, w is width of the bottom electrode, g_1 is the gap between the bottom electrode and membrane, t_d is the thickness of the dielectric used between the membrane and bottom electrode, ε_r is the dielectric constant, C_f is the fringing field capacitance.

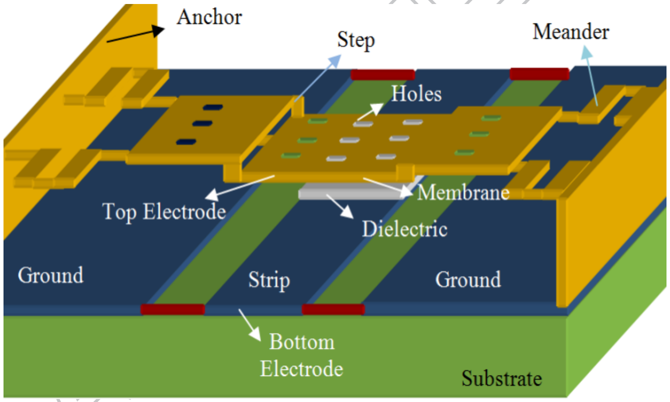


Fig. 4. Shunt Capacitive RF MEMS Switch Top View

When an actuation voltage is applied the membrane associated with the structure start deforming and come to down state. Under this condition the downstate capacitance (C_d) can be expressed as

$$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d} \quad (7)$$

Generally the capacitance ratio is defined as the ratio of down state capacitance to upstate capacitance i.e. C_d/C_u.

The switch speed is decided by the switching time of the switch, the switching time depend on the actuation voltage (V_p), supply voltage

(V_s), and the resonant frequency ($\boldsymbol{\omega}_0$). The actuation structure resonant frequency is given as

$$\boldsymbol{\omega_0} = \sqrt{\frac{\boldsymbol{k_{eff}}}{\boldsymbol{m}}} \qquad (8)$$

Where k_{eff} is effective spring constant, m is the total mass associated with the deforming structure.
Generally the RF MEMS switches switching time is in milliseconds. The switching time of the switch is expressed as

$$\boldsymbol{t_s} = \mathbf{3.67}\frac{\boldsymbol{V_p}}{\boldsymbol{V_s\omega_0}} \qquad (9)$$

The RF MEMS switch designed in this paper is shown in Fig.4. and Fig. 5. in top view and side view respectively.

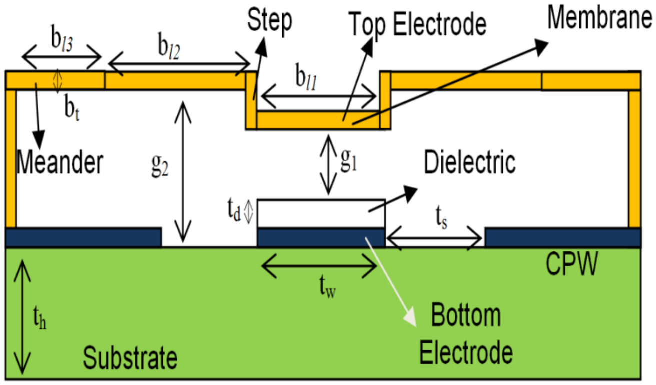


Fig. 5. Capacitive Shunt RF MEMS Switch Side View

III. DESIGN AND SIMULATION

A micro level RF MEMS switch can be design and simulate using Finite Element Method (FEM) or Finite Element Analysis(FEA) tool's. The capacitive shunt RF MEMS switch designed in this paper is using COMSOL FEM tool. The designed switch performance is analysed over the frequency raange 0.6GHz to 40 GHz. The overall switch is designed on a quartz die with dimentions 220µm length, 220µm width, 30µm height. The switch dementions are shown in Table 1.

Table 1. Switch Dimensions

Parameter	Value (µm)
CPW substrate height(t_h)	30
CPW substrate dielectric constant(ε_r)	3.9
Gap between strip and ground(t_s)	15
Width of the strip(t_w)	60
Length of CPW lines	200
Membrane width (W)	80
Bottom electrode width (w)	60
Gap between membrane and bottom electrode(g_1)	0.9
Overlap Area (A=W*w)	80x60
Dielectric thickness (t_d)	0.1
Dielectric constant (ε_r)	9.5
Gap between transmission line and membrane (g_2)	2.5
Bridge thickness (b_t)	0.5

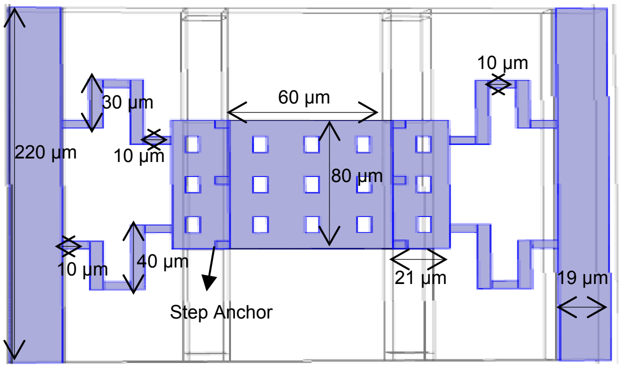


Fig. 6. Dimensions of RF MEMS Switch

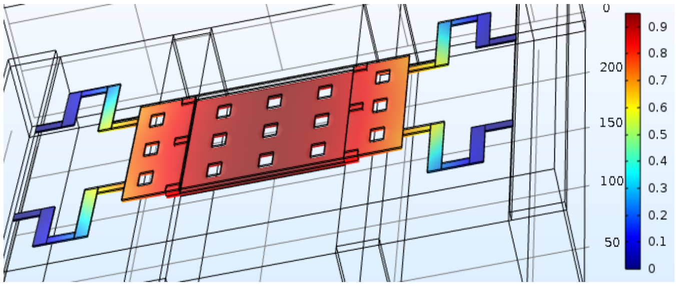
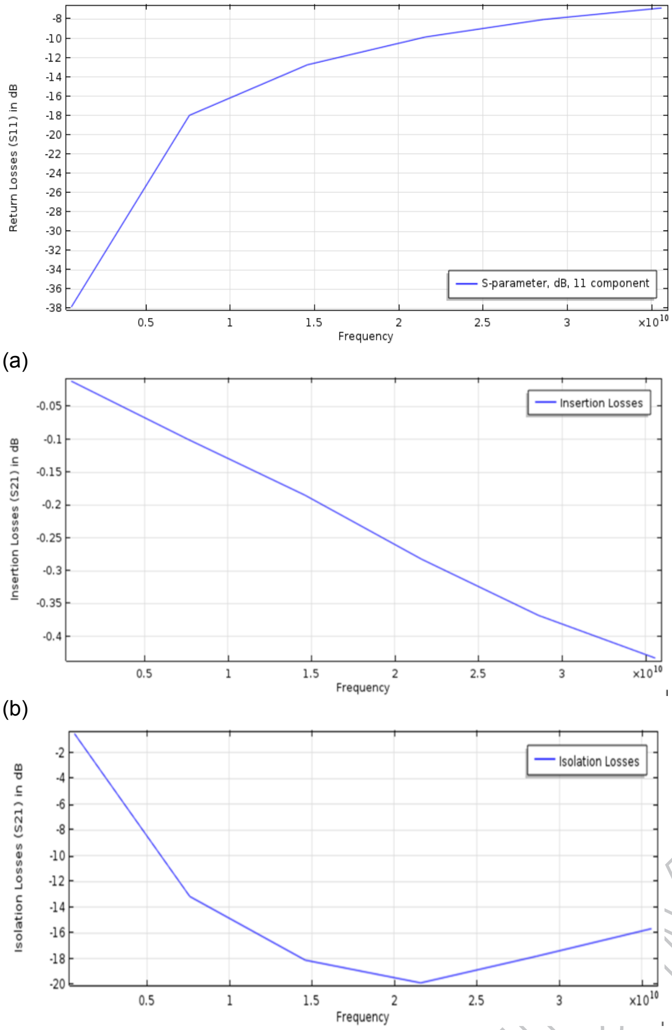


Fig. 7. A Displacement of 0.9µm for 4.2V Actuation Voltage

The switch designed in this paper, works depending on electrostatic actuated, i.e. if the actuation voltage is not applied the actuation structure is in upstate and the capacitance offered by the shunt switch is very low in the order of femto farad under this condition the input Radio frequency input signal will go to the output ($RF_{out} = RF_{in}$). if an actuation voltage is applied to the switch electrodes then the actuation structure will come to downstate and the switch offer a capacitance in the order of pico farad under this condition the input Radio frequency input signal will not go to the output ($RF_{out} \approx 0$).



(a)

(b)

(c)

Fig. 8. Losses in Switch (a) Return Loss (S_{11}) in dB (b) Insertion Loss (S_{21}) in dB (c) Isolation Loss (S_{21}) in dB

The RF MEMS switch designed in this paper, is designed with a membrane structure associated with the non uniform meander's which is helped to reduce the actuation voltage. Here we achived a displacemnt of 0.9µm for actuation voltage of 4.2 V is as shown in Fig.7. The switch actuation structure is a step type structure because of this also the actuation voltage is reduced significantly. The switch Radio Frequency (RF) properties are analyzed over 0.6GHz-40GHz frequncy range, and we onserved that the switch is offering a return losses in the range -42dB to -16dB as shown in Fig.8(a), insertion losses in the range -0.01dB to 0.45dB as shown in Fig. 8(b), isolation losses of -20dB at 21GHz is shown in Fig. 8(c).

Table 2. Meander with Non-Uniform Spring Constants Dimensions

Name	Length (µm)	Width (µm)	Thickness (µm)
K1	10	5	0.5
K2	30	5	0.5
K3	10	5	0.5
K4	40	5	0.5
K5	10	5	0.5

Uniform rectangular holes are formed in the beam structure to minimize the mass of the beam, each hole dimension is 5µm width and 10µm length. A step is taken in the structure, the dimentions of the anchors used in this is 2µm height, 5µm length and 5µm width.
The overall mass of the actuation structure is 57514x10^{-15} kg, the mass removed by the rectangular holes is 7237x10^{-15} kg, so final mass of the structure is 50276x10^{-15} kg, because of the holes in the structure 12.58% of the mass is removed from the overall mass.

Table 3. Switch Materials and Properties

Name	Material	ε_r	Young's Modules (E)	Electrical Conductivity ($\boldsymbol{\sigma}$)
Substrate	Quartz	3.9	-	-
Bridge	Gold	-	70GPa	-
CPW Lines	Gold	-	-	45.6e6[S/m]
Dielectric Material	AlN	9.5	-	-

Table 4. Switch Up State and Down State Capacitance

Parameter	Equation	Theoretical Value (in F)	Practical Value (in F)
Up State Capacitance (C_u)	$C_u = \frac{\varepsilon_0 A}{g_1 + \frac{t_d}{\varepsilon_r}} + C$	46 x 10^{-15}	57.08 x 10^{-15}
Down State Capacitance (C_d)	$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d}$	3.78 x 10^{-12}	3.74 x 10^{-12}
Capacitance Ratio(C_r)	$C_r = \frac{C_{max}}{C_{min}} = \frac{C_d}{C_u}$	82	65.22

If the beam is in upstate the gap (g_1) between the membrane and the bottom electrode is 1μm and a parallel plate capacitance of 0.05708 pF is achieved. When an actuation voltage of 4.2V is applied the beam deforms and come to down state therefore the resultant gap (g_1) is 0.1μm, and the resultant capacitance is 3.74pF. So, the capacitance ratio (C_d/C_u) for the proposed switch is 65.22.

Table 5. Different Capacitive Shunt RF MEMS Switches Comparison

Switches @ 40GHz	Ref. [9] 2003	Ref. [10] 2004	Ref. [11] 2005	Ref. [12] 2009	Proposed
Suspender Material	0.9 μm Ti/Au	0.35/7.5 μm Ti-Au/Au	0.5 μm Al	0.9 μm Au/Ni/Au	0.5 μm Au
Dielectric	150nm Si_3N_4 ε_r=7.6	Dielectric Less	400nm PZT ε_r=190	300nm AIN ε_r=9.8	100nm AIN ε_r=9.5
Air Gap	1.5μm	0.3 μm	2.5-3μm	2-2.5μm	0.9μm
Upstate Capacitance (C_u)	70 fF	224fF	---	40fF	57.05fF
Downstate Capacitance (C_d)	2.7pf	2.2pF	---	1.55pF	3.74pF
Capacitance Ratio (C_d/C_u)	38	10	400	38	65.22
Insertion Losses	0.1dB	1.5dB	0.1dB	0.2dB	0.1-0.4dB
Isolation Losses	35dB	20dB	38dB@ 10GHz	38.5dB	20dB

Actuation Voltage	25V-30V	30V	35V-40V	12V	4.2V

IV. CONCLUSION

In this paper a capacitive shunt RF MEMS Switch is designed and analysed over the frequency range 0.6GHz to 40GHz using FEM Tool. The actuation structure used in the design is anchored with the meanders, having step and holes to the membrane these all things helped to reduce the actuation voltage to 4.2V. The beam and the CPW lines are designed using Gold (Au) material. The dielectric used between the electrodes is an Aluminum nitride (AlN) which is helped to improve the quick change capacitance. The structure is in upstate the capacitance is 0.05708pF, and structure is in downstate the capacitance is 3.74pF. The capacitance ratio for the proposed switch is 65.22. The RF MEMS switch designed in this paper is achived a displacemnt of 0.9 µm for actuation voltage of 4.2 V. Return losses in the range -42dB to -16 dB, insertion losses in the range -0.01dB to -0.45dB, isolation losses of -20dB. Based on the switch performance the switch can be used in X, Ku band applications.

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Ethics approval and consent to participate

Authors are agreed the Ethics of the paper and ready to participate for discussions

Consent for publication
This work is novel work for possible Publication

Availability of data and material
This work is solely done by the authors

Competing interests
The authors declare that they have no competing interests

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Authors' contributions

All the authors contributed in the design and analysis of RF MEMS capacitive shunt Switch for the current study by COMSOL and HFSS. T.Lakshmi Narayana and K.Girija Sravani performed the coding in MATLAB and drafted the manuscript. K.Srinivasa Rao supervised the study and advised on the draft and the corrections in the manuscript. All authors read and approved the final manuscript.

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Public Interest Statement

RF MEMS Switches are mainly used to design the reconfigurable communication modules like antennas and filters. There are different types of RF MEMS switches i.e. series and shunt switches. Shunt switches has more operating frequency and offer high isolation. In this work we designed a shunt capacitive Radio Frequency(RF) operated MEMS Switch which offers more isolation, good insertion and requiring low actuation voltage. The switch is having good capacitance ratio. Here, the working of the proposed switch, if the membrane or beam is in upstate the switch is act like open circuit and RF_{in} is equal to RF_{out}, the the membrane is down state switch is acts like closed circuit and RF_{out} is equal to zero.