International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 15 (2018) pp. 11830-11838
© Research India Publications. http://www.ripublication.com

RF MEMS Capacitive Shunt Switch: A study based practical overview

Surendra K. Waghmare
Faculty E&TC Engineering, G.H.Raisoni College of Engineering & Management, Pune
Savitribai Phule Pune University
Pune-412207, Maharashtra, India

Dr. D. D. Shah
JSPM's Imperial College of Engineering, Wagholi, Pune
Savitribai Phule Pune University
Pune-412207, Maharashtra, India

Abstract
This paper gives a study based practical overview of Electrostatically Actuated Radio Frequency Micro-Electro-Mechanical-Systems (RF MEMS) Capacitive shunt switches. Switch configurations and their working principles are discussed. Attention is given towards design and modeling considerations of RF MEMS switches i.e. mechanical design, electromechanical design and radio frequency design aspects. Advantages and performance comparisons of RF MEMS switches against semiconductor switches and application areas are highlighted. A study of fixed-fixed gold bridge structure CPW based shunt capacitive switch with dual actuation electrodes is done for analysis and simulation of mechanical and electromagnetic characteristics. Pull-in voltage findings are 7 Volts for perforated gold bridge structure with k= 0.9276 N/m and dual actuation electrode area of 200 × 110 um^2. Small capacitance switch with capacitance area of 150X70 μm^2 and large capacitance switch with capacitance area of 150X150 μm^2 are optimized for RF performances: return loss ≤ 0.1 dB, insertion loss ≤ 0.15 dB and better isolation ≥ 20 dB for k to k_a band applications (18-33 GHz).

Keywords: RF MEMS, capacitive shunt switch, electrostatic actuation, pull-in voltage, isolation loss, insertion Loss, return loss, CPW.

INTRODUCTION
Tremendous advancement in MEMS technology gave an amazing growth of RF MEMS devices in Commercial, Communication and defence applications due to their potential futures and replaced PIN and FET based devices. High frequency MEMS switches finds their applications as a crucial component operating in microwave regime e.g. cellular phones and wireless LAN and into the mm-wave regime e.g. defence and satellite communication. [1][2][4] RF MEMS Switches are a device that employs mechanical moving structures to *make and break* an electric circuit in the RF transmission line. RF MEMS switches finds their applications (i) in RF communication systems for routing RF signal through right antenna by switching between transmitter and receiver, routing signal to different blocks in multiband systems, (ii) in phase shifters of radar and satellite systems, etc. [3][4]

RF MEMS CONFIGURATIONS AND WORKING PRINCIPLE

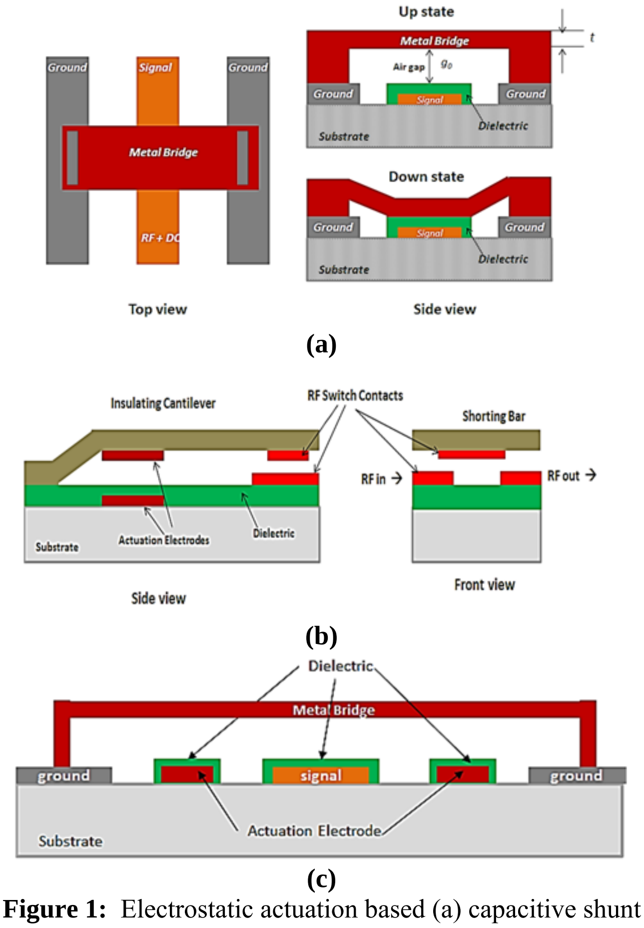


Figure 1: Electrostatic actuation based (a) capacitive shunt fixed-fixed beam type switch (b) ohmic series cantilever beam type switch (c) Dual actuation electrode capacitive shunt switch

Switching action of ON and OFF states is achieved via a mechanical movement of freely movable structure or bridge. Actuation i.e. mechanical movement can be done through electrostatic, magnetostatic, electrothermal or piezoelectric mechanisms. Electrostatic Actuation mechanism is widely preferred in almost most of the RF MEMS Capacitive Switches. Advantages of electrostatic kind of actuation are: zero current in device and hence very low (almost zero) power consumption (only during switching power is consumed), easy

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 15 (2018) pp. 11830-11838
© Research India Publications. http://www.ripublication.com

to fabricate and compatible with IC processes, simple integration with coplanar and micro-strip transmission lines. However, difficulties with electrostatics actuation are high actuation voltage.

Fixed-Fixed RF MEMS capacitive shunt switch uses a thin metallic bridge structure (made up of Al, Au, Cu, Poly Si, Ni) anchored at both the ends and electrically coupled to the ground conductor of CPW. A thin dielectric layer (SiO_2, AlN, HfO_2, Si_3N_4) is used underneath bridge on overlap area of central signal line of CPW. Bridge is suspended at certain height above the dielectric layer on signal line. This separates DC voltage of the switch from CPW conductor and thus forming a capacitor between metal bridge and signal line. With no actuation DC voltage, capacitance formed is very small (10–100fF), which do not affect impedance of signal line and thus switch simply acts here as an ON state causing RF signal to pass through transmission line from one end to other end. When a DC actuation voltage along with RF signal, is applied between signal transmission line and ground via bridge, an electrostatic force develops across oppositely charged plates of capacitor, causing metal bridge to collapse on dielectric layer over a signal line conductor which in turn increases capacitance of switch by 30-100 folds which affects impedance of signal line which couple RF signal to ground. Switch is termed here as an OFF state. When actuation voltage is removed, switch returns back to its original state due to restoring mechanical stiffness of the bridge. High down-state capacitance (C_d) and Low up-state capacitance (C_{up}) is desired for better RF characteristics of switch i.e. high isolation during OFF and low insertion loss during ON state respectively [1][2][4]. Dual electrode capacitive shunt switch contains two pull-down electrodes on either side and near to the central signal line of the switch.

Table 1: Performance comparison between semiconductor and RF MEMS Electrostatic switches [1]

Parameter	**RF MEMS**	**PIN Diode**	**FET**
Voltage (V)	20-80	± 3-5	3-5
Current (mA)	0	3-20	0
Power Consumption (mW)	0.05-0.1	5-100	0.05-0.1
Switching Time	1-300 µs	1-100 ns	1-100 ns
Capacitance Ratio	40-500#	10	N/A
Cut-off frequency (THz)	20-80	1-4	0.5-2
Isolation (1-10 GHz)	Very High	High	Medium
Isolation (10-40 GHz)	Very High	Medium	Low
Isolation (60-100 GHz)	High	Medium	None
Insertion Loss (1-100 GHz) dB	0.05-0.2	0.3-1.2	0.4-2.5
Power handling (W)	< 1	< 10	< 10

Only for Capacitive type switch

Advantages of RF MEMS switches over semiconductor switches

No current consumption leads to very low power dissipation. High Isolation and low Insertion losses at microwave frequencies. Low fabrication cost due to surface micromachining techniques. High Cut-off frequency. Low intermodulation product and 30 dB better performance.

RF MEMS CAPACITIVE SHUNT SWITCH DESIGN AND MODELING CONSIDERATIONS

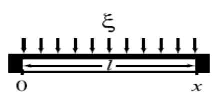
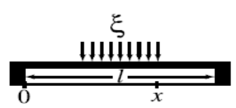
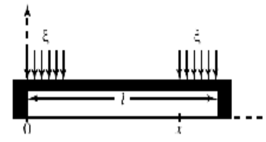
A) Mechanical Design and Modeling

As most of the capacitive switches uses fixed-fixed metallic bridge structure for mechanical movement in equilateral direction. Hence to understand mechanical behavior of the switch, spring constant *k (N/m)* needs to derive. Deflection Δg *(m)* of fixed-fixed bridge structure for an applied external force *F (N)* is obtained using $F=k\Delta g$. Here total spring constant $k = k' + k''$ where k' is stiffness of the bridge due to material properties such as Young's modulus E (*GPa),* moment of inertia I (m^4), Poisson's ratio v, and k'' is part of spring constant due to biaxial residual stress σ (Pa) within the structure.

Thus, looking to spring constant equations for various force loading conditions of fixed-fixed bridge structure given in Table 2, it is important that k is directly depending on Young's Modulus E(Gpa) of the material used, thickness of bridge (t), Length of Bridge (L), width of the bridge at anchor location (w). From Hook's Law, Spring constant $k=F/\Delta g$ N/m i.e. force applied on bridge to deform bridge by displacement Δg.

Young's modulus $E = \frac{Stress}{Strian}$, where stress is directly related to force and strain is related to displacement. Hence spring constant k is directly related to Yong's modulus of metallic bridge used. Figure 2 shows the spring constant variation with beam t / L ratio for Gold (Au) beam with Young's modulus of 80 GPa, for three different cases of load distribution as described above.

Table 2: Spring constant of fixed-fixed bridge with various force distribution loading techniques.

Force Loading Techniques [1][4]	**Spring-constant Equation [1][4]**
1.1 Uniformly ***loaded bridge***	
	$k_a' = \frac{-F}{y_{max}} = 32Ew(\frac{t}{L})^3$
1.2 ***Force evenly distributed about center of bridge***	
	$k_c' = \frac{-F}{y_{max}} = 32Ew\left(\frac{t}{L}\right)^3 \frac{1}{\left[8\left(\frac{x}{L}\right)^3 - 20\left(\frac{x}{L}\right)^2 + 14\left(\frac{x}{L}\right) - 1\right]}$
1.3 ***Force distributed over areas near the anchor (end sides)***	
	$k_e' = \frac{-F}{y_{max}} = 4Ew\left(\frac{t}{L}\right)^3 \frac{1}{\left[\frac{x}{L}\left(1 - \frac{x}{L}\right)^2\right]}$

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 15 (2018) pp. 11830-11838
© Research India Publications. http://www.ripublication.com

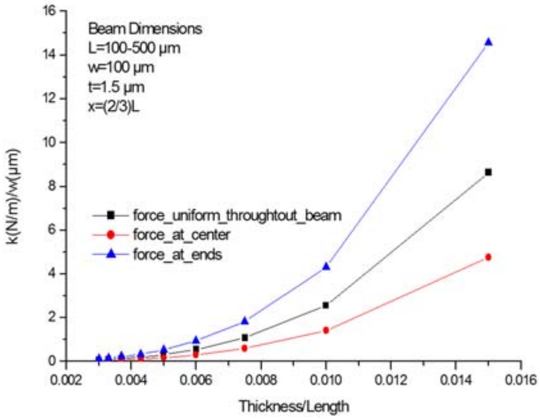


Figure 2: Variation of normalized spring constant (k / w) versus (t/L) of Gold beam

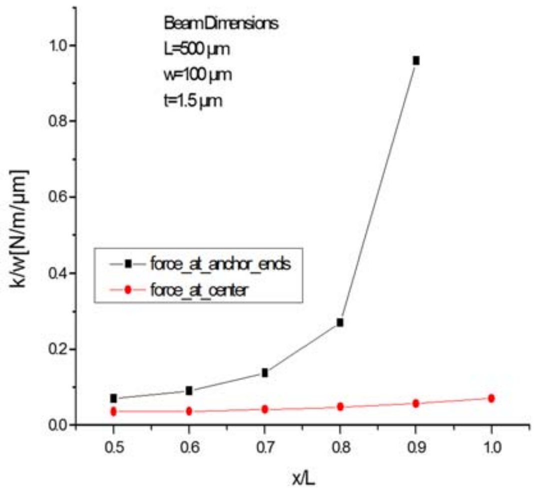


Figure 3: Variation of normalized spring constant (k / w) versus (x /L) of Gold beam

It is found that from Figure 2 and Figure 3, bridges with central loads are more flexible and spring constant increases as load moves towards an anchor location. Gold material Bridge geometry with L=500 µm, w=100 µm and thickness t=1.5 µm is used for results in Figure 3.

Critical stress of fixed-fixed bridge structures

Stiffness of beam and geometrical dimensions of bridge causes some sort of compressive stress, that bridge can withstood before buckling called critical stress given by [1]

$$\sigma_{cr} = \frac{\pi^2 E t^2}{3L^2\left(1-\nu\right)} \tag{1}$$

Results in Figure 4 shows a compressive stress of 1-10 MPa (Gold) and 0.8-8 MPa for Al can be tolerated before buckling occurs. Hence Gold material is more preferred over Aluminum.

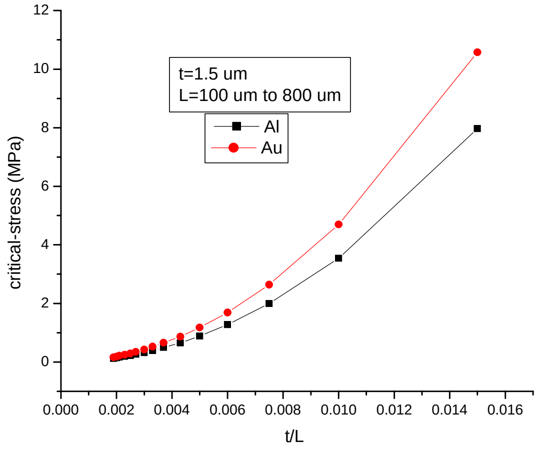


Figure 4: Critical stress of Au and Al beam

B) Electromechanical Modeling: Electrostatic Actuation and pull-in voltage

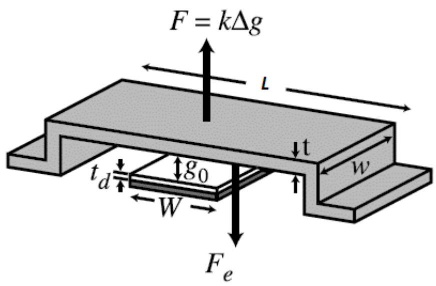


Figure 5: MEMS fixed-fixed bridge switch with electrostatic actuator [1]

When an external dc potential is applied between two conductive plates of actuator, an electrostatic force F_e cause upper fixed-fixed bridge to collapse on lower electrode separated by dielectric by overcoming mechanical restoring force (F_s) as per Hook's Law at 2/3 of gap g_0.

Table 3: Geometrical and material parameters descriptions for Electrostatic Actuator based capacitive switch

Length of Beam	L
Width of Beam	w
Thickness of beam	t
Width of Lower Electrode (Signal Conductor)	W
Thickness of Dielectric	t_d
Overlap or Contact Area of Actuator	$A = W \times w$
Height of Beam above Dielectric	g_0
Dielectric Constant or relative permittivity of dielectric material	ε_r
Permittivity of vacuum or free space	ε_0

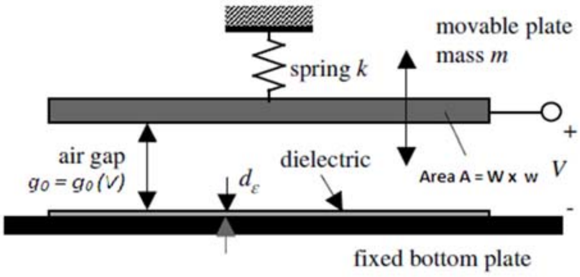


Figure 6: spring-mass and capacitor model of switch [2]

Pull-in or pull-down voltage of the electrostatic actuator is given by [1][4]

$$V_{pull-down} = V(2/3g_0) = \sqrt{\frac{8k}{27\varepsilon_0 A} g_0^{\,3}} \qquad (2)$$

Here ε_0 is permittivity of vacuum.

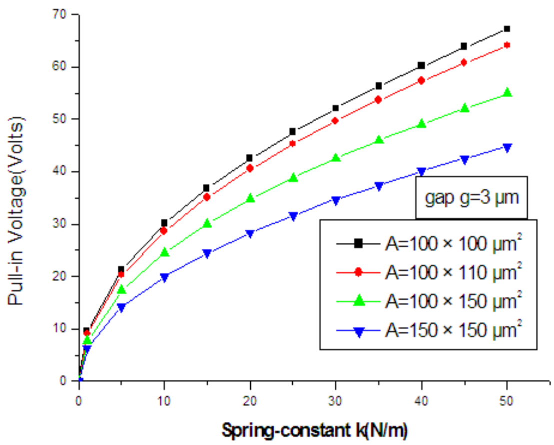


Figure 7: Pull-in voltage dependency on actuation area and spring constant

From equation (2) it is realizing that pull-in voltage can be optimized for lower values by means of:

i) Reducing gap (g_0) between beam and dielectric layer.
ii) Increasing the actuation contact or overlap area *A*,
iii) Lowering the spring constant *k* of bridge used.

However, reduction of height of beam above dielectric layer affects insertion loss (high frequency OFF state performance). Increasing actuation contact area of actuation electrodes affects increase in switch dimensions.

Spring constant *k* gives more flexibility for low pull-in voltage. From Table (1), spring constant is directly related to Young's modulus (*E*), therefore pull-in voltage is also directly relating to Young's modulus (*E*).

With presence of dielectric layer in between actuation electrodes, pull-in voltage is given by [1][4]

$$V_{pull-down} = V\left(\frac{2}{3}g_0 + \frac{1}{3}\frac{t_d}{\varepsilon}\right) = \sqrt{\frac{8k}{27\varepsilon_0 A}\left(g_0 + \frac{t_d}{\varepsilon_r}\right)^3} \qquad (3)$$

Once switch is pulled down by actuation voltage, it is essential to hold down the bridge in same state (OFF) to ensure electrostatic force to be larger than mechanical restoring force. This is achieved by hold-down given by [1][4]

$$V_{hold-down} = \sqrt{\frac{2k_e}{\varepsilon\varepsilon_0 A}(g_0 - g)\left(g + \left(\frac{t_d}{\varepsilon_r}\right)\right)^2} \qquad (4)$$

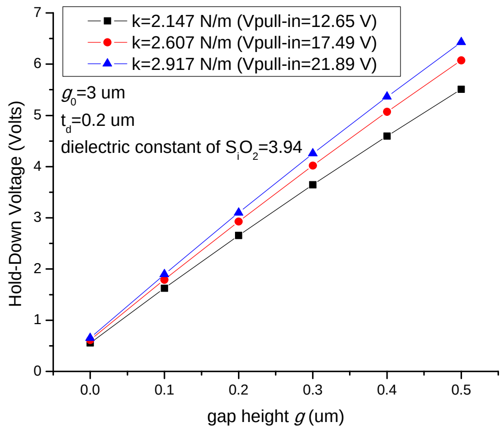


Figure 8: Hold-down voltage versus gap height for different spring constant designs

Fig. 9 shows that capacitive switches require 4-10 volts less hold-down voltage than the pull-in voltage. When switch is actuated then lowering the value of hold-down voltage reduces possibilities of injection of charges into the thin dielectric layer. It reduces adhesion of beam with dielectric due to repulsive forces and improves switch reliability. To ensure this reliability, high resistivity dielectric material can be used [4]. Equations (8) and (9) shows that pull-in voltage and hold-down voltage of capacitive switch are directly dependent on thickness of dielectric and inversely proportional to dielectric constant or relative permittivity of dielectric material. Hence dielectric layer with higher dielectric constants are preferred for lower pull-in and hold-down voltages.

C) Resonant Frequency or Speed of actuation

In electrostatic actuation fixed-fixed bride undergoes deformation during ON and OFF state of actuator. Resonant frequency of mechanical movement is the natural frequency of vibration of bridge structure given by [1][4]

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (5)$$

Where *k* is spring constant and *m* is mass of the structure. This implies that actuating frequency is directly proportional to $\sqrt{k}$.

Equation for switching time of mechanical membrane is given by [1][4]

$$t_s \approx 3.67\frac{V_p}{V_s\omega_0} = 3.67\frac{V_p}{V_s\sqrt{\frac{k}{m}}} \qquad (6)$$

Where V_s is the applied voltage generally higher than pull-in voltage. This indicates that depending on particular application high speed switch needs higher pull-in voltage while lower switching time devices needs low pull-in voltage.

D) Electromagnetic Modeling and Design

To know the electrical behavior, capacitive shunt switch is represented by its circuit model as shown in Figure 9.

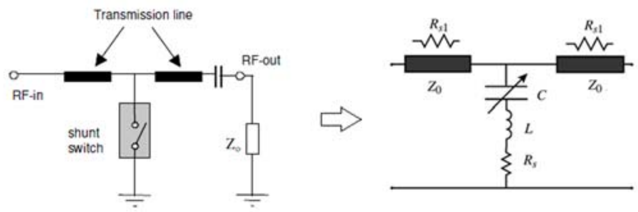


Figure 9: Equivalent circuit model [1][2]

Switch model shows two half sections of transmission line representing impedance and lumped *C-L-R* model of bridge with up and down state capacitance value. Down state capacitance (C_d) is due to bridge-dielectric-transmission line active overlap contacts. In up-state air gap results in small capacitance (C_{up}). R is finite resistance of bridge while L is finite inductance of bridge portion over active area

Switch impedance in shunt configuration is given by [1]

$$Z_s = R_s + j\omega L + \frac{1}{j\omega C} \quad (7)$$

The series resonant frequency is

$$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{LC}} \quad (8)$$

Depending on application frequency range the switch impedance can be approximated as [1]

$$Z_s = \begin{cases} \frac{1}{j\omega C} \\ R_s \\ j\omega L \end{cases} \quad (9)$$

For $f << f_0$ model behaves as a capacitor, for $f >> f_0$ it behaves an inductor and at resonance $f = f_0$ model reduces to bridge resistance.

In up-state switch is modeled as a shunt capacitance to ground and no role of inductance for $f < 100$ *GHz* [1]. Cut-off frequency (f_c) is defined at which the ratio of up-state and down-state impedances tends to unity.

$$f_c = \frac{1}{2\pi C_u R_s} \quad (10)$$

Majority capacitive switches are designed and implemented on standard 50 Ω coplanar waveguide structure.

Two-port Electrical model characterize the RF performance by deciding R, L and C values which are extracted from S-parameters by simulation or measurements [1][4].

In unactuated state (ON-state/up state) the scattering parameters, $\boldsymbol{S_{11}}$ and $\boldsymbol{S_{21}}$ are the return and insertion loss. In down sate $\boldsymbol{S_{21}}$ is the isolation loss of the switch [1][4].

***Insertion Loss* ($\boldsymbol{S_{21}}$)**

It is the measure of switch efficiency when RF signal is in transmission i.e. switch is in ON state. It is transmission coefficient between input and output port of a switch expressed in dB. Major reasons of losses are resistive losses at low frequencies and skin depth effects of signal line at higher frequencies.

***Isolation* ($\boldsymbol{S_{21}}$)**

It is transmission coefficient between input and output port of a switch expressed in dB during OFF-State. Larger (dB) value indicates very poor coupling between input and output port. Leakage current may degrade isolation due to coupling between movable beam and stationary signal line.

***Return Loss* ($\boldsymbol{S_{11}}$)**

It is the reflection coefficient determining reflection of signal through transmission line.

Reflection and transmission coefficients with switch impedance (Z_s) and CPW characteristics impedance (Z_0) are given by [4]

$$S_{11} = -20\log\left|\frac{-Z_0}{2Z_s + Z_0}\right| \quad (11)$$

$$S_{21} = -20\log\left|\frac{2Z_s}{2Z_s + Z_0}\right| \quad (12)$$

Up-state capacitance (C_{up})

Return-loss and insertion-loss during ON state is depending on C_{up}. It is due to air capacitance and insulator capacitance in series given by

$$C_{up} = \frac{A\varepsilon_0}{g_0 + \frac{t_d}{\varepsilon_r}} \quad (13)$$

For $f << f_0$, switch acts as a capacitor, the reflection coefficient (S_{11}) or return loss is given by [1]

$$S_{11}\Big|_{f<<f_0} = -20\log\left|\frac{-j\omega C_{up}Z_0}{2 + j\omega C_{up}Z_0}\right| \quad (14)$$

For $S_{11} \le -10dB$ or $\omega C_{up}Z_0 \le 2$ reflection coefficient becomes [1]

$$|S_{11}|^2 \simeq \frac{\omega^2 C_{up}^2 Z_0^2}{4} \quad (15)$$

Equation (13) do not includes fringing field capacitance hence simulated or measured reflection coefficient plots are used to extract accurate up-state capacitance of the switch.

To ensure low insertion loss and zero return loss, $\boldsymbol{C_{up}}$ should be very small. Equation (13) shows to have small value of $\boldsymbol{C_{up}}$**,** actuation area A need to be small. Generally, width of beam over active actuation area is kept small. Shunt switches operating in microwave and milli-meter regime have typical value of up-state capacitance between 35-160fF.

Down-state capacitance (C_d)

When switch is in actuated state, bridge metal-dielectric– signal line conductor forms down-state capacitance (C_d) which shorts signal line to ground given by [1]

$$C_d = \frac{\varepsilon_0\varepsilon_r A}{t_d} \quad (16)$$

As thickness of dielectric layer is too small (0.08 – 0.1 μm), fringing capacitance do not affect down-state capacitance.
At operational frequencies below resonance frequency $f << f_0$, switch isolation is given by [1][4]

$$S_{21}\Big|_{f<<f_0} = -20\log\left|\frac{2}{2+j\omega C_d Z_0}\right| \qquad (17)$$

In actuated state, down state capacitance (C_d) is expected to very high as possible to have high isolation. To optimize this needs larger actuation area.

Operating frequency region and Capacitance ratio

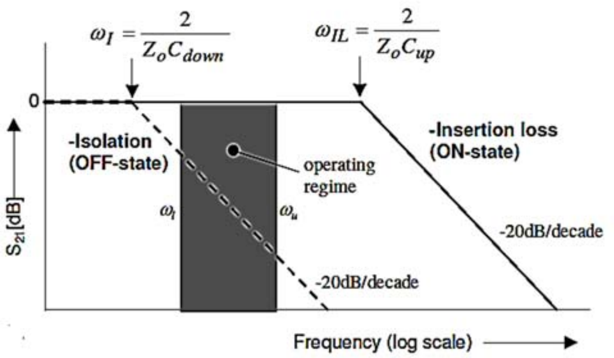


Figure 10: Asymptotic transfer characteristics S_{21}[dB] [2]

RF MEMS shunt switch acts like a low-pass filter with corner frequency $f_{-3dB} = 1/\pi C Z_0$. While switching between OFF and ON states f_I changes to f_{IL} i.e. from region of isolation to region of insertion loss. Thus, operating region is bounded by f_H (f_{IL}) and f_L(f_I)and characterizes low-insertion loss and high isolation as shown in Figure 10 [2]. This shows for wide band operating regime high ratio of corner frequencies and subsequently high ratio of capacitances in ON and OFF state is required given by equation

$$\frac{\omega_{IL}}{\omega_I}\Big|_{shunt} = \frac{C_{down}}{C_{up}} = \frac{\varepsilon_r g_0}{t_d} \qquad (18)$$

Equation (18) shows that to have higher capacitance ratio it needs to optimize gap (g_0), dielectric constant (ε_r) and thickness (t_d) of insulator material used. Gap (g_0) cannot be increased as it increases pull-in voltage. Dielectric layers with too thinner thickness cannot withstand electric field due to pull-in voltage and causes dielectric breakdown. Hence alternative is to use high-*k* thin dielectric materials like strontium–titanate–oxide (STO) or barium–strontium–titanate
(BST) [1][2].

Switch Resistance

In capacitive MEMS switch, current conducts through bridge to ground during actuation of switch. Total resistance of switch (R_s) is given by [4] $R_s = R_b + R_{cpw}$.
where R_b is bridge resistance and R_{cpw} is CPW line resistance
Bridge resistance is given by [1]

$$R_b = \frac{1}{2}\frac{\sigma_b (L/2)}{A_{cr}} \qquad (19)$$

Where σ_b is electrical resistivity of bridge material, L is length of bridge and A_{cr} is area of the bridge. Equation (19) shows that in order have low RF power loss during actuation state in captative MEMS switches, bridge material with low resistivity are preferred.
CPW line resistance is given by [1]

$$R_{CPW} = 2\alpha Z_0 L \qquad (20)$$

Here *α* is signal line loss (ohmic and dielectric).
Skin depth or depth of penetration is given by [1]

$$\delta = \frac{1}{\sqrt{f\pi\mu_0\sigma}} \qquad (21)$$

Where μ_0 is free space permeability, σ is conductivity of metal used. If bridge thickness $t << 2\delta$ then switch resistance remains constant with frequency and for bridge with thickness $t >> 2\delta$ switch resistance varies with frequency as $1/\sqrt{f}$ due to skin depth effect [1]

Case Study: Fixed-Fixed RF MEMS Capacitive Shunt Switch with dual actuation electrodes

Mechanical modelling- Analytical Model

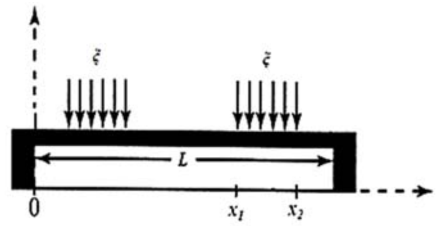


Figure 11: Fixed-Fixed Bridge structure with force loading at ends more near to central signal line

Spring constant for this case is found from deflection versus load position given by

$$k_e' = \frac{-F}{y_{max}} = 4Ew\left(\frac{t}{L}\right)^3 \frac{1}{\left[(A-1)^3+(B-1)^3+AB(A+B-3)+1\right]} \qquad (22)$$

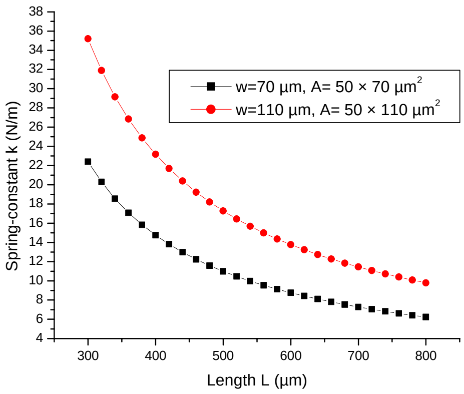
Where $A = \frac{x_1}{L}$ and $B = \frac{x_2}{L}$

Actuation electrodes are considered to be 50 μm away from anchor post.
For varying structure length and various geometric means, analytical spring constant *k* is shown in Figure 13.

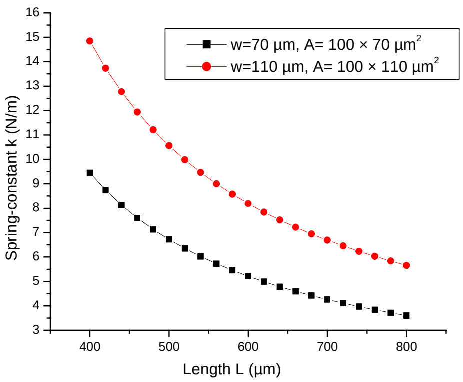
Table 4: Structure geometry with various dimensions

Parameter	Case-I	Case-II
Width (w)	70 μm and 110 μm	
Thickness (t)	1.5 μm	
X_2	(L-50) μm	
X_1	(L-100) μm	(L-150) μm
Length of Actuation Electrode (X_2 - X_1)	50 μm	100 μm
Actuation electrode area (A)	(50 × 70) μm^2 And (50 × 110) μm^2	(100 × 70) μm^2 And (100 × 110) μm^2

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 15 (2018) pp. 11830-11838
© Research India Publications. http://www.ripublication.com



(a)



(b)

Figure 12: Spring-constant for varying structure lengths (a) Electrode length 50 µm, (b) Electrode length 100 µm

Figure 12 results points that with longer length and higher actuation electrode area, stiffness of lower values and hence low actuation voltage are obtained for structures under consideration. The structures with width dimensions 70 µm gives lower stiffness values as compared to 110 µm width structures. From above conclusion a structure is designed with longer length (L=790 µm) having large actuation electrode area and electrodes located at 120 µm away from anchor post. The width of the structure is not uniform throughout the length. The width of the structure at anchor location is kept 70 µm, at actuation force area the width is kept as 110 µm and at central contact area where the switch makes capacitive contact with transmission line, the width of the bridge is 150 µm. Actuation electrode length is varied from 50 µm to 200 µm for which stiffness is found from static structural analysis.

Static structural simulation

For this switch structure, by varying actuation electrode length, stiffness is found analytically and from FEM ANSYS® Simulations, which validate analytical results within 3-8 % values. Static structural simulation is done for this case with various electrode lengths by applying an equivalent structural pressure to deflect the bridge 3 µm downwards. For this perforated structure, as simulation results indicates that structure stiffness is reducing when actuation electrode area is increasing. The stiffness is minimum (k= 0.9276 N/m and $V_{pull\text{-}in}$= 7 Volts) for actuation electrode length 200 µm i.e. when actuation electrostatic force area is 200 × 110 um². For this case resonant frequency obtained is 3.54 KHz.

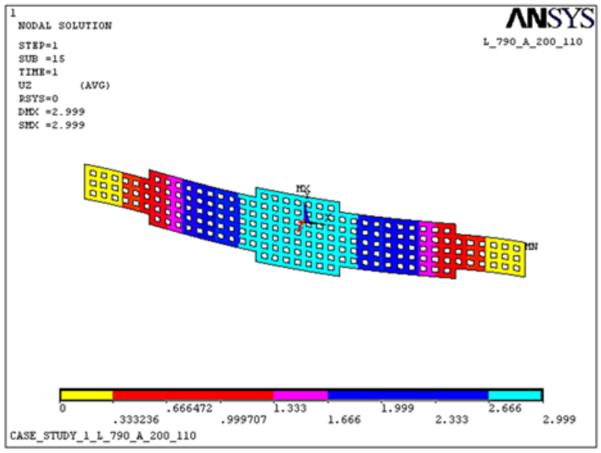
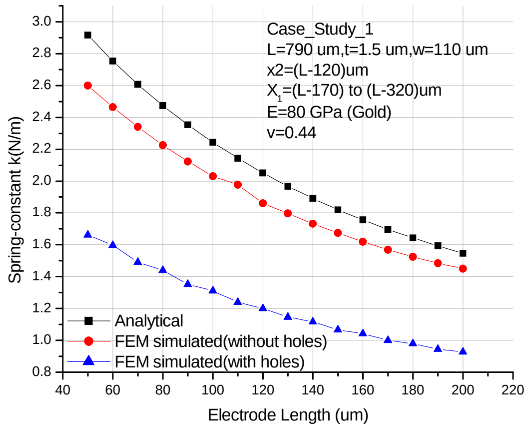


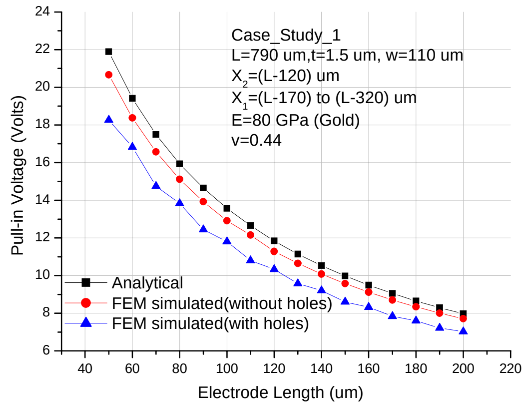
Figure 13: Structural simulation of fixed-fixed gold bridge for displacement of 3 µm

Table 5: Dimensions and Material Properties of structure for Case Study

Material for structure	Gold
Young's modulus (GPa)	80
Poisson's ratio	0.44
Density (g/cm³)	19.3
Length L (µm)	790
X_2 (µm)	L-120
X_1 (µm)	(L-170) to (L-320)
Thickness (µm)	1.5
Width at load location (µm)	110
Actuation electrode Length (µm)	50 to 200
Actuation Electrode Area (µm²)	(50 × 110) to (200 × 110)
Central Contact Area (µm²)	150 × 150
Width at anchor location (µm)	70



(a)



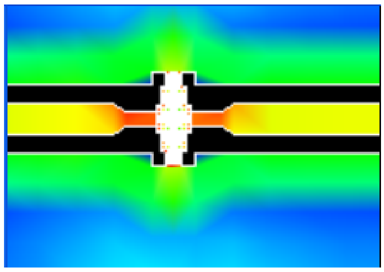
(b)

Figure 14: Simulation results for Case Study:
(a) Spring-constants for varying electrode lengths
(b) Pull-in voltage for varying electrode lengths

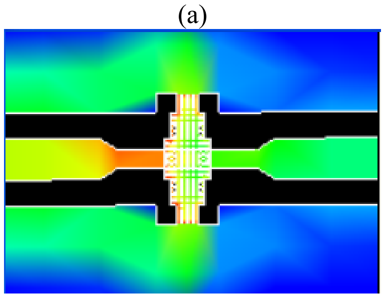
RF SIMULATION

The RF simulation of capacitive shunt switch is done in 50 Ω standard CPW transmission line configuration with S_iO_2 as an insulator with thickness of 0.1 µm, between the moving membrane and transmission line center conductor. The RF response is simulated by varying the active capacitance area with fixed length and simply varying transmission line width dimensions using Mentor Graphics IE3D®
C_{up} and C_d are calculated using Equation 13 and Equation 16 respectively. Various losses in switch i.e. return loss (S_{11}) in dB, insertion loss (S_{21}) in dB and isolation loss (S_{21}) in dB are shown in Figure 17. The smaller value of up-capacitance results in less insertion loss at frequencies above 10 GHz while larger capacitance switches are useful for low frequency range only. Switches with larger capacitance have a higher reflection coefficient at higher frequencies [4] It points out that higher capacitance switch is suitable for lower frequency range only because of small reflection coefficient. But smaller capacitance switch is suitable for higher frequency range because of low insertion loss and smaller reflection coefficient. The reflected power thus can be reduced in two ways- with smaller overlap area or with large gap height.

From results of isolation loss in down state with varying overlap area and varying capacitance it is observed that for higher frequencies better isolation s found. For larger capacitance values i.e. for large overlap area isolation is better (≥ 20 dB) at lower frequencies i.e. at 22 GHz for C_d=7.84 pF while isolation is better (≥ 20 dB) for small capacitance at high frequency i.e. at 29.5 GHz for C_d=3.66 pF



(a)



(b)

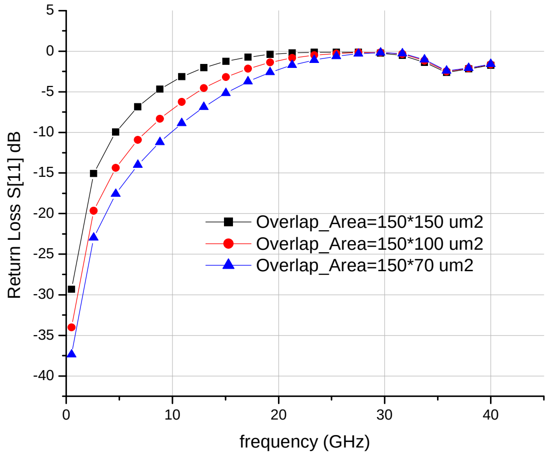
Figure 15: Current distribution on fixed-fixed bridge in (a) ON State (b) OFF-State using

Table 6: Calculated ON- state capacitance for three different capacitive switches.

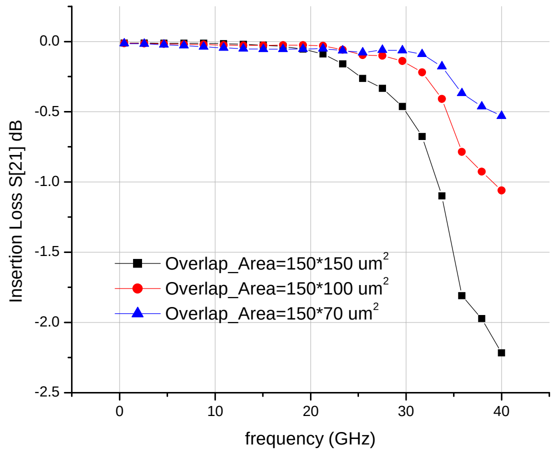
Capacitive Area (µm²)	Air gap (µm)	Dielectric Thickness (µm)	Dielectric Constant (S_iO_2)	Calculated C_{up} (*fF*)
150X150	3	0.1	3.94	65.84
150X100				43.89
150X70				30.72

Table 7: Calculated OFF- state capacitance for three different capacitive switches.

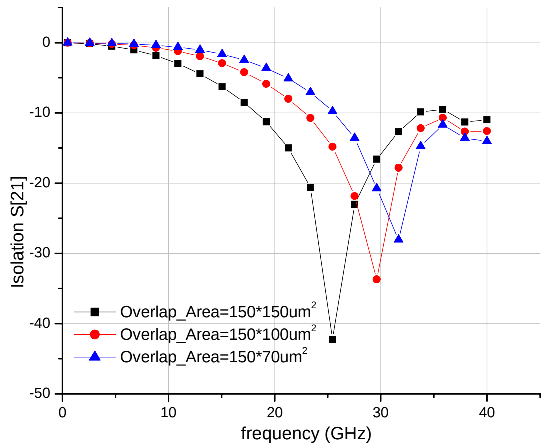
Capacitive Area (µm²)	Air gap (µm)	Dielectric Thickness (µm)	Dielectric Constant (S_iO_2)	Calculated C_d (*pF*)
150X150	0	0.1	3.94	7.84
150X100				5.23
150X70				3.66



(a)



(b)



(c)

Figure 16: Switch Losses (a) Return Loss S_{11} in dB b) Insertion Loss S_{21} in dB (c) Isolation S_{21} in dB

DISCUSSION AND CONCLUSION

Design considerations of RF MEMS capacitive shunt configured switches are discussed. In mechanical design and modeling aspects, spring-constants analysis for fixed-fixed gold bridge structures for geometric variations like thickness, length and with various force loading techniques are done. Central force loaded beams are more flexible with low spring constants. Gold metal beams can tolerate more critical stress than aluminum metal beams. Spring constant *k* gives more flexibility for low pull-in voltage. Spring constant is straightforward related to Young's modulus (*E*) of the metal used for beam, therefore pull-in voltage is also directly relating to Young's modulus (*E*). Hence in switch design, metal beams with low Young's modulus are preferred. Fixed-Fixed perforated gold bridge structure with force loading at ends more near to central signal line are investigated using FEM simulator ANSYS® to find out pull-in voltage of 7 Volts with k= 0.9276 N/m and actuation electrode area of 200 × 110 um^2. RF design aspects of capacitive MEMS switch are discussed. RF performance parameter are simulated in a standard 50 Ω CPW transmission line using 3D electromagnetic simulator Mentor Graphics IE3D®. RF results shows that switch can be applicable for k band to k_a band applications. Simulated RF parameters optimized are: return loss ≤ 0.1 dB, insertion loss ≤ 0.15 dB and better isolation ≥ 20 dB between frequency range 18 GHz to 33 GHz.

REFERENCES

[1] Gabriel M. Rebeiz, *"RF MEMS Theory, Design and Technology",* 1st Edition, John Wiley-Interscience, 2003.

[2] Harrie A. C. Tilmans, *"MEMS components for wireless communications" (invited paper)* The 16th European Conference on Solid-State Transducers | September 15-18, 2002, Prague, Czech Republic

[3] Vijay K.Varadan, K.J.Vinoy, K.A.Jose, "*RF MEMS and their Applications"* John Wiley & Sons, Ltd., 2003.

[4] Kamaljit Rangra, *"Electrostatic Low Actuation Voltage RF-MEMS Switches for Telecommunications, Ph.D Thesis".* University of Trento, Italy, FEB- 2005.