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TECHNICAL PAPER

Design and performance analysis of uniform meander structured RF MEMS capacitive shunt switch along with perforations

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Abstract This paper presents design and simulation of uniform structured RF MEMS capacitive shunt switch using FEM tool and HFSS software. The switches with different shaped meanders and perforations which result in less spring constant, less pull-in voltage, high isolation loss, high switching speed and low insertion loss have been designed. From the simulated results it is observed that the rectangular perforations gives the better results, when compared with square and cylindrical shaped perforations. Comparative study is done for zigzag, plus and three square shaped meander along with rectangular perforations on each structure. When the gap between the dielectric and the movable beam is 0.8 µm, the up state capacitance for HfO_2 is 4.06fF and for Si_3N_4 is 3.80fF. The downstate capacitance for HfO_2, Si_3N_4 is 49fF, 26.9fF respectively. The capacitance ratio is 120.6. Poly-tetra-fluoro-ethylene material is given for the movable beam whose young's modulus is 0.4 GPa and the spring constant is calculated theoretically for each structure; by using this the pull in voltage and the settling time are calculated. Step switch with three square Meander has switching time 10.25 µs, pull in voltage as 2.45 V. By using HFSS 3-D electromagnetic model we observed the return loss (S_{11}) is less than −60 dB, the insertion loss is less than −0.07 dB in the range of 1–40 GHz frequency and switch isolation (S_{21}) is −61 dB at 28 GHz frequency.

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1 Introduction

Radio Frequency Micro Electro Mechanical Systems is an innovative and the recently emerging technology especially in the design of switching devices (Rebeiz et al. 2003). The name itself indicates that it has an interdisciplinary nature. The size of the device varies between 1 and 100 micrometres. MEMS devices combine the advantages and overcome the disadvantages of electro-mechanical switches like coaxial, waveguide switches and semiconductor switches such as PIN diodes, FETs (Molaei and Ganji 2016). As the component size is in the order of the microns, it facilitates many advantages like less consumption of power, low cost, linearity, low operating voltage, high isolation, high reliability, less insertion loss and moreover it provides an opportunity to fabricate in large arrays (He et al. 2011). As it has fabulous characteristics, it could be used in many applications like Smart Mobile device, Antennas, Space systems, Bluetooth, T/R modules, Communication. Mainly RF MEMS switches are designed for microwave applications like cell phone, short range communications like Bluetooth and WLAN, automotive industries. These devices were employed in RF, i.e., from 30 KHz to 300 GHz with different and WLAN, automotive industries. These devices were employed in RF, i.e., from 30 KHz to 300 GHz with different geometrical structures and characteristics like low insertion loss and high isolation (Angira et al. 2014).

In a short time ago many RF MEMS capacitive shunt switches have been designed and fabricated by introducing different technologies; in this paper we are presenting the design and simulations of the capacitive shunt switch which is a fixed-fixed structure in FEM Tool. In order to increase the performance of switching of the fixed-fixed structure some modifications are done to the structure; the modifications include the addition of meander, perforations to the existing structure, and also by building the step down structure to the movable beam. All the proposed structures have fixed and movable beam as parallel whereas for step-down structure fixed beam and movable beam are separated by gap which resembles a bridge structure. Stepdown structure with 3 square meander has very low actuation voltage when compared to uniform 3 square meander structure; this is due to dielectric layer as Hfo2 is used. For uniform structures both stepdown and switch has 3 square meander, but the overall performance is better for uniform step structure with 3 square meander when compared to switch with uniform 3 square Meander. Stepdown structure with 3 square meander has very low actuation voltage up to 2.45V and high isolation upto -61dB at a frequency of 40GHz. This uniform structure with 3 square meander along with perforations has very low actuation voltage of 2.5 V, low insertion loss up to -0.07dB at a frequency of 40GHz and high isolation of -43dB at a frequency of 28GHz.

2 The structural model of MEMS shunt capacitive switch

Fixed-fixed capacitive shunt switch is the most commonly preferred switch in RF MEMS. The schematic of the proposed structure is shown in the below figure. The structure consists of a movable beam, dielectric, two fixed blocks and two anchors (Guha et al. 2016) (Figs. 1, 2).

As poly-tetra-fluoro-ethylene (PTFE) has very less weight and cost effective, it is used for movable beam, anchors, fixed blocks. Silicon nitrate (Si3N4) or hafnium oxide (HfO2) is used as dielectric (Bachman et al. 2012). Silicon dioxide that has high resistivity is used as substrate (Table 1).

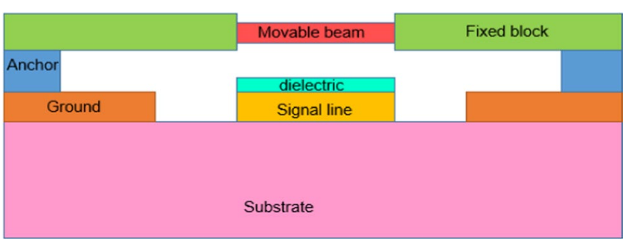

Fig. 1 Schematic of RF MEMS switch

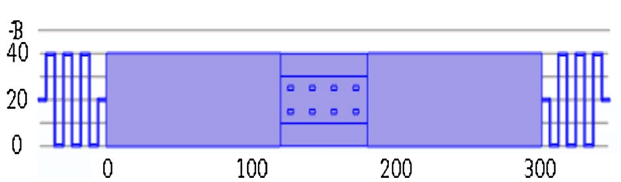

Fig. 2 Schematic of rectangle perforation on Fixed–fixed switch with three square meander

Table 1 Dimensions of the blocks

	Length (L)	Width (W)	Height (H)
Fixed block 1 (μm)	60	40	1
Dielectric (μm)	60	20	1
Movable beam (μm)	60	20	1

2.1 Perforations

Here we observed the results by introducing the different shaped perforations in the movable beam. The perforations facilitate the switch to perform at low actuation voltages (Sharma et al. 2015). The shapes for the perforations are rectangle, square and cylindrical. Addition of these perforations decreases the mass of the beam, resulting in more deflection. Flexibility of the switch is more efficient when it is provided with rectangular-shaped perforations (Table 2).

2.2 Meander

Meander technique helps to decrease the value of pull-in voltage and increase the speed of switching of the device (Manfaineiad et al. 2013). A comparative study is done for different shaped menders with rectangular shaped perforations on each structure. The shape of meander used are plus shape, zigzag shape, three square shape (Figs. 3, 4, 5; Tables 3, 4, 5).

3 Theoretical analysis

In shunt capacitive fixed–fixed switch, RF response depends on the capacitance ratio (Shekhar et al. 2014). Up state capacitance (C_{on}) of the switch is calculated by using the formulae

$$C_{On} = \frac{\varepsilon oxy}{g_o + \frac{t_d}{\varepsilon_r}}$$

Table 2 Dimensions of the perforations

Perforation	Rectangular (μm)	Square (μm)	Cylindrical (μm)
Dimension	L = 4 W = 2 H = 1	L = 2 W = 2 H = 1	R = 2 H = 1

where C_{ON} is up state capacitance,x is Width of the actuation electrode, y is width of the actuation electrode, t_d is dielectric thickness, g_o is gap between beam and dielectric, ε_r is relative permittivity of dielectric material, εo is relative permittivity of free space. The up state capacitance varies for different materials based on their relative permittivity (Angira et al 2013). The relative permittivity of HfO_2 is 14 and for Si_3N_4 is 7.6 (Table 6).

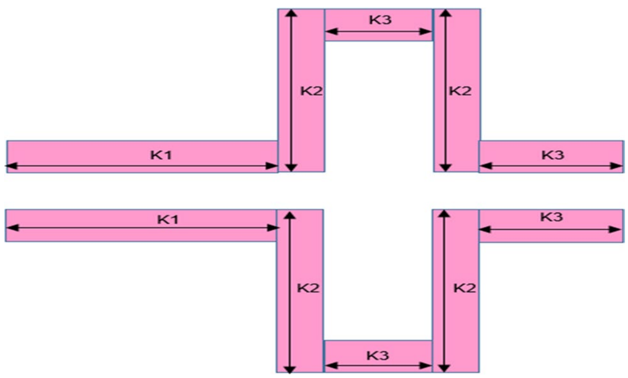

Fig. 3 Schematic of plus meander

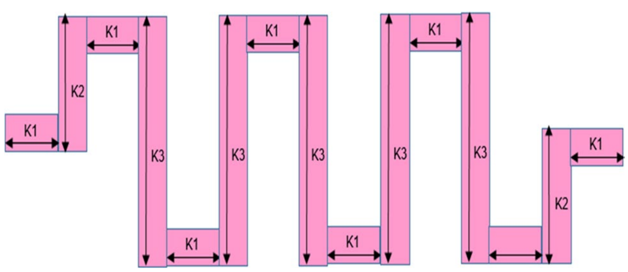

Fig. 4 Schematic of three square meander

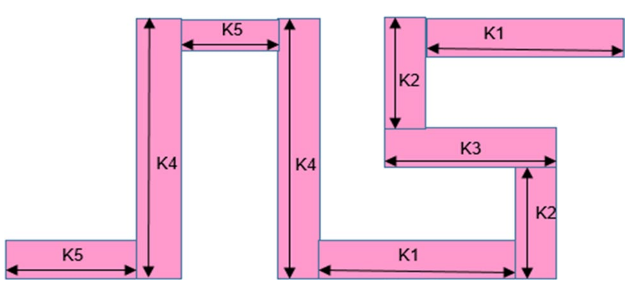

Fig. 5 Schematic of three square meander

Table 3 Dimensions of each block in a Plus shaped meander

Spring constant	Length (L)	Width (W)	Height (H)
K1 (μm)	29	1	1
K2 (μm)	1	15	1
K3 (μm)	10	1	1

From the table it can be clearly observed that the capacitance value decreases as the gap between the dielectric and the movable beam increases.

C_{off} is the Down state capacitance and is calculated by using the formulae

$$C_{off} = \frac{\varepsilon_o \varepsilon_r xy}{t_d}$$

where C_{Off} is down state capacitance, $\varepsilon_o = 8.85 \times 10^{-12}$ F m^{-1} which is called electric constant or permittivity of free space.

Down state capacitance is independent of the gap. The down state capacitance for HfO_2, Si_3N_4 is 49fF, 26.9fF respectively.

The capacitive ratio can be calculated by ratio of up state capacitance to the downstate capacitance (Balaraman et al. 2012).

$$C_{ratio} = \left(\frac{C_{down}}{C_{up}}\right) = \frac{\frac{\varepsilon_o \varepsilon_r xy}{t_d}}{\frac{\varepsilon_o xy}{g_o + \frac{t_d}{\varepsilon_r}}}$$

C_{ratio} is also known as figure of merit (Fedder et al. 1994), ε_r is relative dielectric constant. Dielectric constant for HfO_2 and Si_3N_4 is 14 and 7.6 respectively.

4 Results and discussions

The FEM abbreviated as Finite Element Method is used to analyze the electrical and mechanical characteristics of the RF MEMS switch using electro-mechanics study in COMSOL Multi-Physics software. The electro-mechanics force is responsible for the deflections in the movable beam which enable the functioning of the switch (Ramli et al. 2012). Hence to obtain the better deflections in the switch the gap between the dielectric, movable beam is preferred as 0.8 μm and material used is HfO_2 for dielectric. Figures 6 and 7 presents the basic structure of uniform switch with, without meander and the displacement is 8.27×10^{-3}, 0.01 in negative direction of z-component at 2.5 V as pull in voltage respectively.

Figures 8 and 9 shows the step-down movable beam structure of uniform switch with, without meander and the displacement is 9.2×10^{-3}, 7.46×10^{-7} in negative direction of z-component at 2.5 V as pull in voltage respectively.

4.1 Electro mechanical analysis

Structure of a switch is an efficient part in overall performance of the switch (Verma et al. 2013). Hence structural analysis is done by plotting the graphs for source voltage

Table 4 Dimensions of each block in a three square meander

Spring constant	Length (L)	Width (W)	Height (H)
K1 (μm)	5	1	1
K2 (μm)	1	20.5	1
K3 (μm)	1	40	1

Table 5 Dimensions of each block in a zigzag meander

Spring Constant	Width (W)	Depth (D)	Height (H)
K1 (μm)	24	1	1
K2 (μm)	1	7	1
K3 (μm)	18	1	1
K4 (μm)	1	15	1
K5 (μm)	10	1	1

Table 6 Up state capacitance for different gaps

	C_{ON} for HfO_2	C_{ON} for Si_3N_4
g = 0.8 μm	4.06fF	3.802fF
g = 1 μm	3.304fF	3.12fF
g = 1.5 μm	2.25fF	22.17fF
g = 2 μm	1.708fF	1.66fF
g = 2.5 μm	1.37fF	1.345fF
g = 3 μm	1.15fF	1.130fF

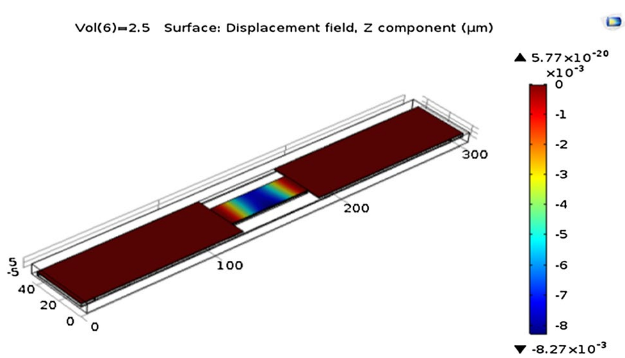

Fig. 6 Z component displacement of switch without meander

and beam deflection by varying the gap between movable beam and dielectric for switch with and without meanders and step down switch along with rectangular perforations (Figs. 10, 11, 12, 13, 14, 15, 16).

4.2 Switching analysis

RF MEMS Switch for transmit/receive switching applications parameters like low return loss and high isolation

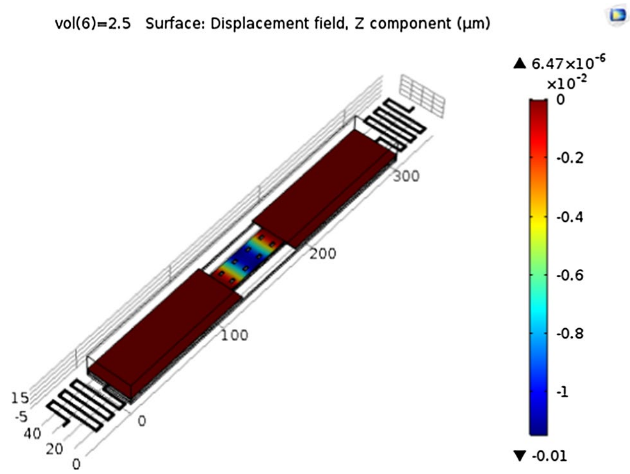

Fig. 7 Z component displacement of switch without meander

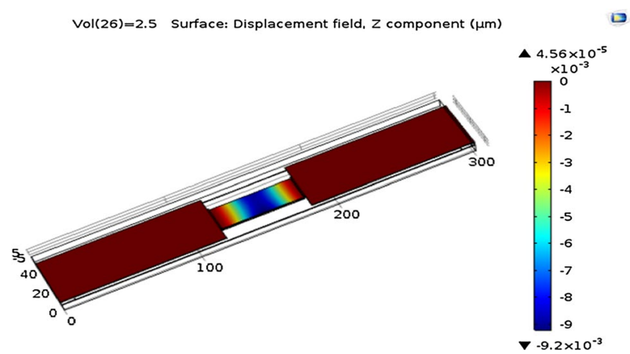

Fig. 8 Z component displacement of switch with step-down movable beam and without meander

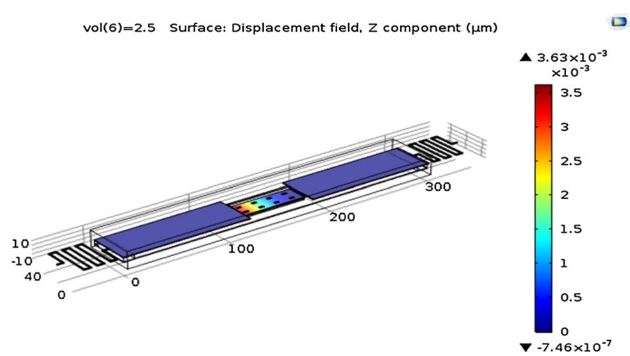

Fig. 9 Z component displacement of switch with step-down movable beam and without meander

loss a very important (Lee et al. 2004). Along with these parameters switching speed is also a major factor that influence the working of switching for transmit/receive applications.

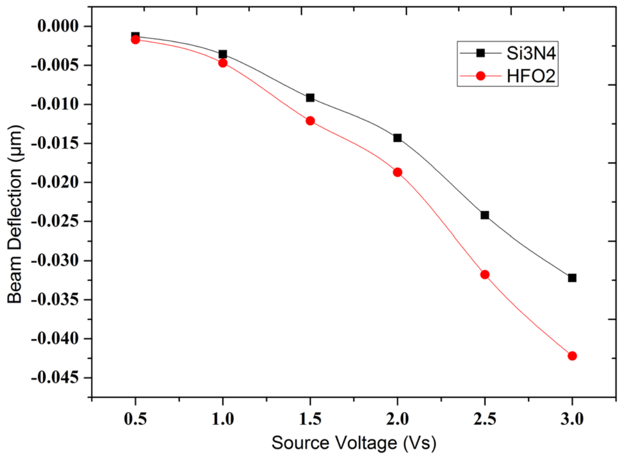

Fig. 10 Plot of displacement versus voltage for switch without meander when the gap between the dielectric and the movable beam

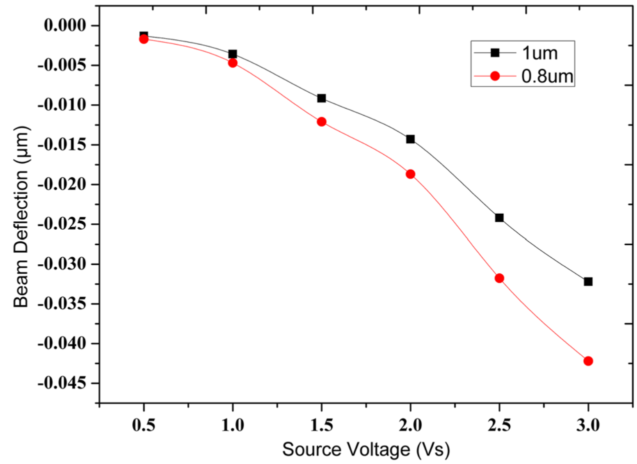

Fig. 12 Plot of displacement versus voltage for switch with plus shaped meander when the gap between the dielectric and the movable beam is 0.8 μm and material for dielectric is HfO_2

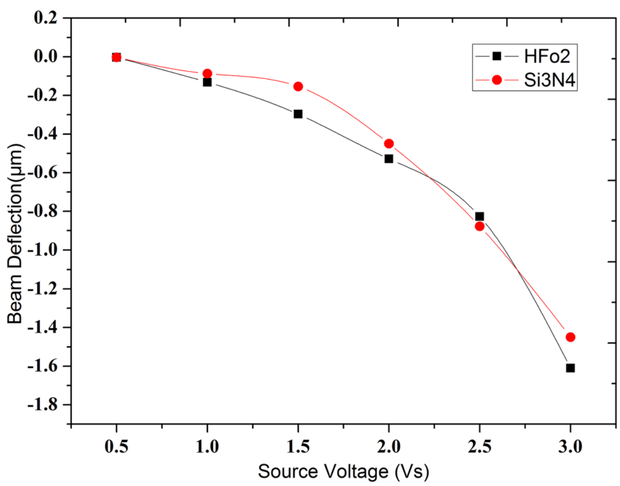

Fig. 11 Plot of displacement versus voltage for switch without meander when the gap between the dielectric and the movable beam is 1 μm

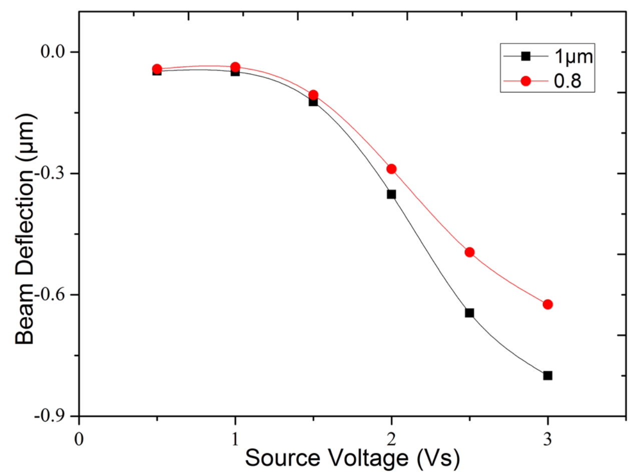

Fig. 13 Plot of displacement versus voltage for Switch with three square meander when the gap between the dielectric and the movable beam is 0.8 μm and material for dielectric is HfO_2

The time required for the switch to toggle from active state to inactive state and vice versa is called switching time. The switching time performance is the key parameter that to be considered for studying the switch functioning.

The switching time (t_s) is calculated by using the formulae

$$t_s = 3.67\frac{V_{pi}}{w_o V_s}$$

where V_{pi} is the pull in voltage, V_s is source voltage, w_o resonant frequency.

For the efficient performance of the switch we need the less actuation voltage and huge isolation. A low voltage MEMS switch makes it more convenient for a switch to be embedded into real applications. By using the spring constant (K_z) the pull in voltage (V_{pi}) can be calculated by using the below formulae

$$V_{pi} = \sqrt{\frac{8K_z g_0^3}{27A\varepsilon_0}}$$

Pull-in-voltage should be as less as possible so to reduce it, the spring constant (K_z), air gap (g_0) should be less. The reduction in gap may result in migration of the charges and breakdown of dielectric. The area of the switch cannot be increased as it results in increase of the size of the device. So, the probability is to lessen the value of the spring constant

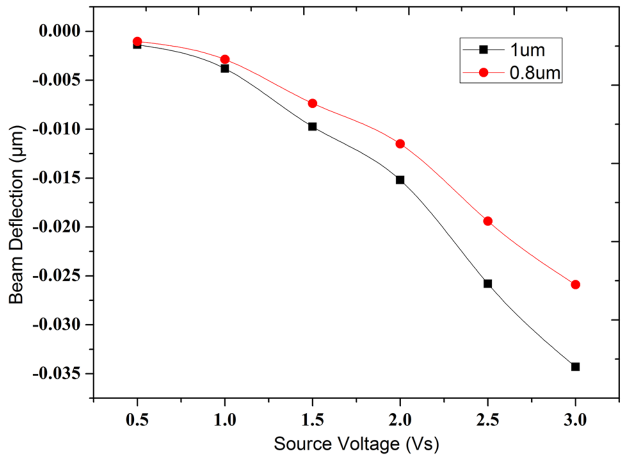

Fig. 14 Plot of displacement versus voltage for switch with zigzag meander when the gap between the dielectric and the movable beam is 0.8 μm and material for dielectric is HfO_2

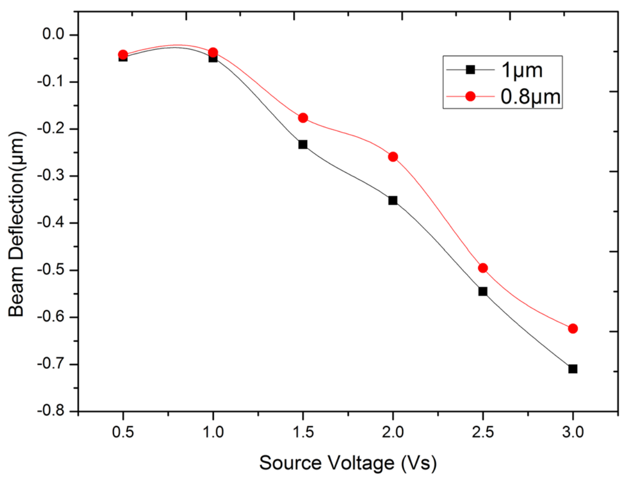

Fig. 15 Plot of displacement versus voltage for switch with step down structure when the gap between the dielectric and the movable beam is 0.8 μm and material for dielectric is HfO_2

The spring constant of each block is calculated by using the formulae

$$K = \frac{YWt^3}{l^3}$$

where Y is Young's modulus of the material of movable beam (young's modulus of PTFE is 0.4 GPa) W, l and t are width, length and thickness of the block. Thus the spring constant of the device mainly rely on the choice of the material used for the movable beam, dielectric and their dimensions (Verma et al. 2013).

Resonant frequency (w_o) of the device explains about the physical variation of the device when it is put to

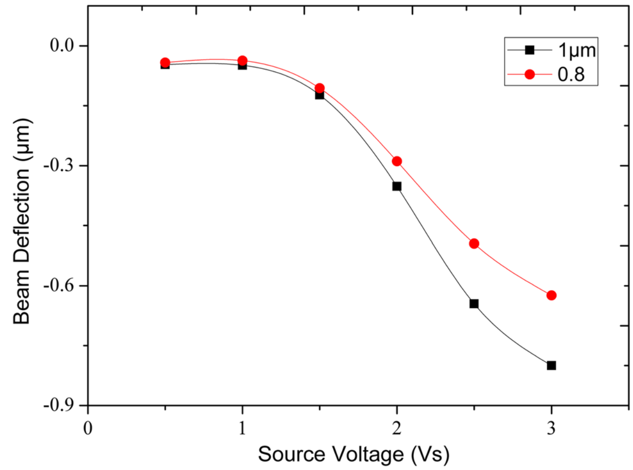

Fig. 16 Plot of displacement versus voltage for switch with step down structure with three square meander. When the gap between the dielectric and the movable beam is 0.8 μm and material for dielectric is HfO_2

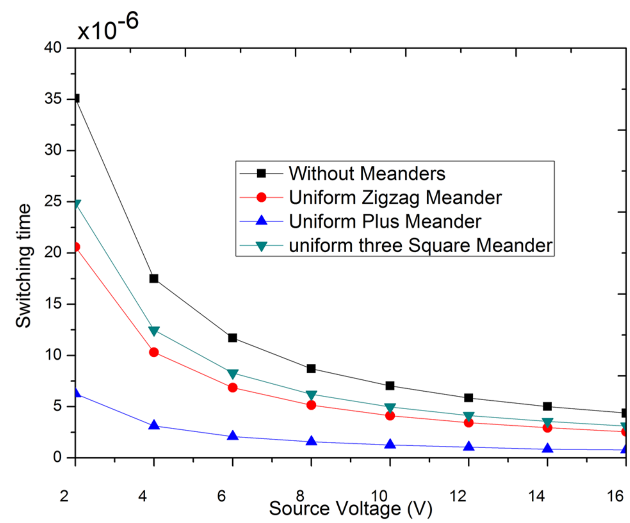

Fig. 17 Plot of switching time analysis for the switches with different meander

stress. It is also one of the important parameter in switch performance evaluation.

$$f = 1.03\sqrt{\frac{Y}{d}\frac{h}{l^2}}$$

where f is resonant frequency, d is density, h is beam height.

Thus the switching time for Switch without Meander is 35 μs, Switch with three square Meander is 25 μs, step switch without meander is 62 μs and step switch with three square meander is 10. 25 μs at $V_s = 2$ V (Figs. 17, 18).

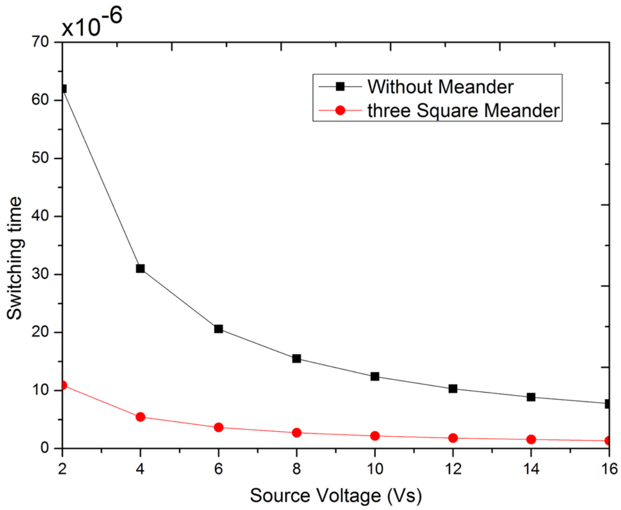

Fig. 18 Plot of switching time analysis for step down structure without and with three square meander

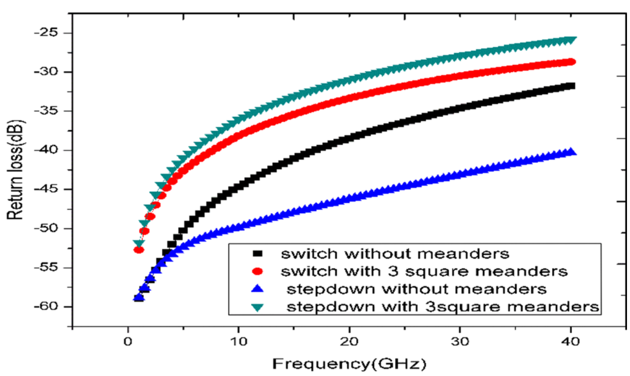

Fig. 19 Return loss (S_{11} parameter) analysis

4.3 Performance analysis

The movable beam is supplied with positive dc voltage and the dielectric acts as ground, these two conductors separated by distance acts as a capacitor and capacitance is developed between them. The switch can be demonstrated as a capacitor between the movable beam and the dielectric. Proposed microwave characteristics are considered using HFSS software.

Return loss S_{11} is defined as the measure of efficient impedance matching of the devices. It is usually represented as negative number. It is measured in dB.

Insertion loss and isolation are represented by S_{21} parameter.

When the switch is in OFF and ON state respectively (Patil et al. 2013).

High isolation loss in the on state of the switch and the less insertion loss in the off state of the switch are

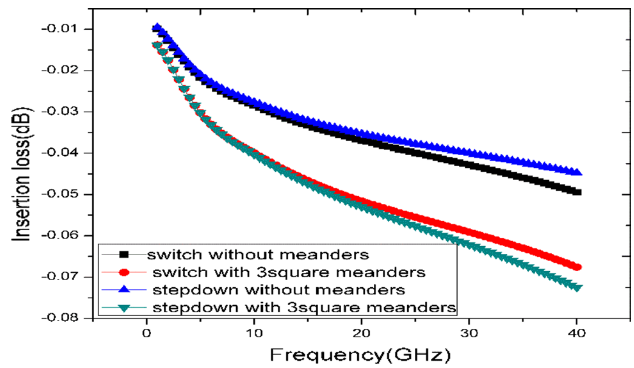

Fig. 20 Insertion loss (S_{21} parameter) analysis

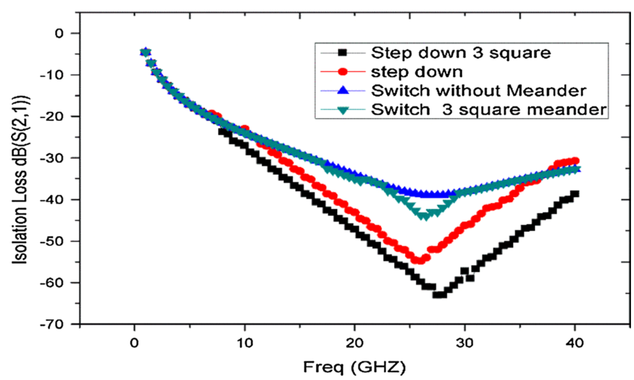

Fig. 21 Isolation loss (S_{21} parameter) analysis

obtained when the down state capacitance is high and the up state capacitance is low (Molaei and Ganji 2016) (Figs. 19, 20, 21; Table 7).

5 Conclusion

In this paper, Comparative analysis for Fixed–Fixed RF MEMS Capacitive Shunt switch with, without meanders and also step down structure of the movable beam is done to obtain less pull in voltage, low insertion, return losses and high isolation and is investigated under 1–40 GHz for k-band applications at different applied voltages. From the simulated results it is observed that the rectangular perforations gives the better results, when compared with square and cylindrical shaped perforations. So the structures with zigzag, plus and three square shaped meander are provided with rectangular perforations on the movable beam of each structure. Step switch with three square Meander has switching time 10.25 µs, pull in voltage as 2.45 V. The material dependency is a major contribution for switching time and Structural Analysis of Shunt Capacitive switch. The Dielectric material is used

Table 7 Simulation analysis for the different meander structures

Parameters	Switch without meander	Switch with three square meander	Step switch without meander	Step switch with three square meander
Beam thickness (μm)	0.8	0.8	0.8	0.8
Beam height (μm)	1	1	1	1
Pull down voltage (V)	2.9	2.5	2.83	2.45
Capacitance ratio	120.6	120.6	120.6	120.6
At frequency (GHz)	27	27	27	27
Switching time (μs)	35	25	62	10.25
Return Loss (dB)	−38	−33	−47	−30
Insertion Loss (dB)	−0.04	−0.05	−0.03	−0.06
Isolation Loss (dB)	−38	−42	−55	−61

as Si_3N_4 and HfO_2, HfO_2 obtained better results, as its dielectric constant is high. Further the Performance analysis depends on S-parameters and the observed results are the return loss (S_{11}) is less than −60 dB, the insertion loss is less than −0.07 dB in the range of 1–40 GHz frequency and switch isolation (S_{21}) is −61 dB at 28 GHz frequency.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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