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TECHNICAL PAPER

Analysis of RF MEMS shunt capacitive switch with uniform and non-uniform meanders

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Abstract This paper reports on electromechanical, switching time and performance analysis of capacitive shunt RF MEMS switch with uniform and non-uniform meanders. The MEMS switch is a freely moving membrane over coplanar wave guide. Electromechanical analysis is done for movable beam with gold as material and dielectric as Si_3N_4 and HfO_2. For these dielectric materials pull in voltage is 2.3 and 2 V respectively with beam thickness of 0.8 µm by using COMSOL FEM Tool. Si_3N_4 with dielectric constant of 7.6 gives C_{ratio} of 8.69 and 11.13 for 0.8 and 0.6 µm of beam thickness respectively. RF performance analysis is done by using HFSS software and the simulation results states that non uniform single meander has return loss as −60 dB, insertion loss −0.2 dB and isolation loss −14 dB at 20 GHz frequency and uniform 3 meander switch has return loss as −55 dB. Switching time analysis is done by using MATLAB. For uniform three meander it is 0.12 ms and for non-uniform one meander beam it is 0.7 ms. Whereas use of HfO_2 with dielectric constant of 14 as dielectric gives C_{ratio} of 14.93 and 19.66 for 0.8 and 0.6 µm of beam thickness respectively with gap between the electrode beam and dielectric as 0.8 µm.

1 Introduction

Innovation of MEMS technology lead to the development of low power and low cost RF components which are used at high frequency applications. Increasing demand for low cost, high performance and miniaturized wireless communication systems has considerably increased the development of novel devices for radio frequency applications. Conventional semiconductor devices exhibit low performance when compared to RF MEMS switches such as zero power consumption, good isolation, high power handling capability, low return loss, high capacitance ratio along with insubstantial size (Kawakyu et al. 1996; Palmour et al. 2001). Compared with FET, PIN diodes RF MEMS switches shows brilliant performance at microwave to millimeter wave frequencies (Muldavin and Rebeiz 2000).

RF MEMS switches can be broadly divided as shunt or series or ohmic contact type. Cantilever beam comes under series Switches whereas fixed–fixed beam type beam comes under shunt switches. There are different actuation mechanisms which are unable to avoid the structural complexities and low switching speed as well as increased power consumption. By using electrostatic actuation mechanism, we can achieve low actuation voltage and also zero power consumption (Aghaei and Abbaspour-Sani 2010; Goldsmith et al. 1998). There are many ways to decrease pull-in-voltage of RF MEMS switches such as changing the dimensions of the beam, air gap between beam and dielectric (Balaraman et al. 2002; Mafinejad et al. 2012; Ramli and Sidek 2012; Rizk et al. 2000; Taye et al. 2013, Verma and Singh 2013). Capacitive type of shunt switch is proposed for millimeter wave application. 'metal-to-dielectric' contact had high reliability when compared to that of 'metal-to-metal' ohmic contact switches.

In this paper, a RF MEMS switch with capacitive technique is designed and proposed. To trim pull in voltage of switch, we have designed bridge type structure to trim the air gap between dielectric layer and membrane. To get high isolation, we have selected material with high dielectric constant. Also, a kind of meander have to design in order to increase the inductance of the switch.

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2 The structure of MEMS shunt capacitive switch

Among all the configurations of RF MEMS switch fixed–fixed beam capacitive shunt switch is most common design. Micro strip and coplanar waveguide (CPW) are the most popular transmission lines for RF MEMS devices. Micro strip lines has less monolithic integration with RF MEMS devices whereas CPW transmission line shows integration capability of lumped component in series and shunt configurations (Fedder 1994; Sharma and Gupta 2012). Figure 1 shows the fixed–fixed beam structured MEMS switch with CPW transmission line.

The switch is electrostatically actuated by applying DC voltage between the MEMS Bridge and the CPW which leads to an electrostatic force causes the beam to collapse on the dielectric layer and there will be increase in switch beam capacitance (Hijazi et al. 2003). When the switch is pulled down, the perforations which were defined on the beam are used to squeeze the air to reduce the damping and increase the switching speed.

Various switch structures have been proposed mainly with more number of meanders in order to reduce pull in voltage by reducing the spring constant of the beam because pull in voltage is directly proportional to the square root of spring constant. Hence by reducing the spring constant we can reduce the pull in voltage by square root times. Crab-leg flexures, folded flexures and serpentine flexures are some of the common beam designs used to reduce the spring constant of beam thus reducing the pull in voltage (Sharma and Gupta 2014). From all these structures, it is clear that by increasing number of meanders that will reduce pull in voltage but it will increase area and make the switch structure complex. We have done the comparison of the performance of uniform three meander design with non-uniform single meander, double meander, triple meander design by using Si_3N4 and HfO_2 as dielectric.

The proposed non uniform single meander based design of RF MEMS shunt switch helped in reducing pull in voltage by reducing the spring constant at the same time saving precious switch area and reducing complexity of switch for fabrication (Sharma and Gupta 2013; Rayit 1997) (Fig. 2).

Design specifications of Shunt RF MEMS switch is included in Table 1, for both uniform three meander design and non-uniform single meander, double meander, triple meander designs.

Amongst the different uniform meander structure the three meander structured switch is preferable due to high beam deflection which is shown in the Fig. 3.

The material having low young's modulus and low density will be chosen as the good material for the beam. Hence according to the Fig. 4, gold is used as beam material because it has smaller Young's modulus than other conductors so that it can reduce the excitation voltage. By having the lower Young's modulus an result in reduction of stiffness of the beam which in turn reduces the spring constant and helps to get lower excitation voltage (Singh 2013). The fringing field due to perforations can be neglected (Rebeiz 2003).

3 Description of MEMS switch

RF MEM switch is designed on a coplanar waveguide (CPW) with dimensions (G/W/G) of 60/100/60 (all in µm) and characteristic impedance (Z0) of 50 Ω and (Rebeiz 2003). Silicon substrate is used and separate anchors are used to fix the gold beam at both ends. Gold is preferred choice because resistivity has direct impact on RF performance. In this design, gold is chosen for both beam and CPW transmission line. The dielectric material is chosen such that relative permittivity (ε_r) should be high for low pull in voltage and resistive should be low to achieve low AC losses (Fig. 5).

The switch is designed and simulated with the silicon nitride Si_3N_4 and HfO_2 as a dielectric layer in order achieve high performance of the switch.

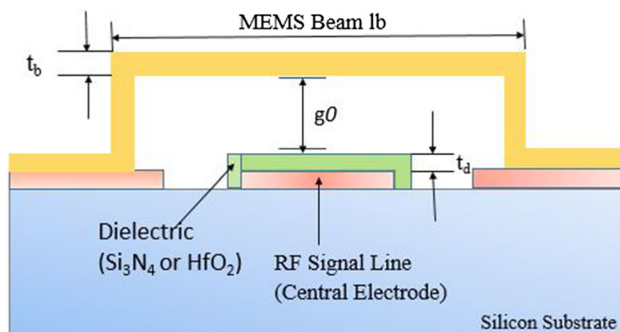

Fig. 1 Schematic of RF MEMS switch with Si_3N_4/HfO_2 as dielectric

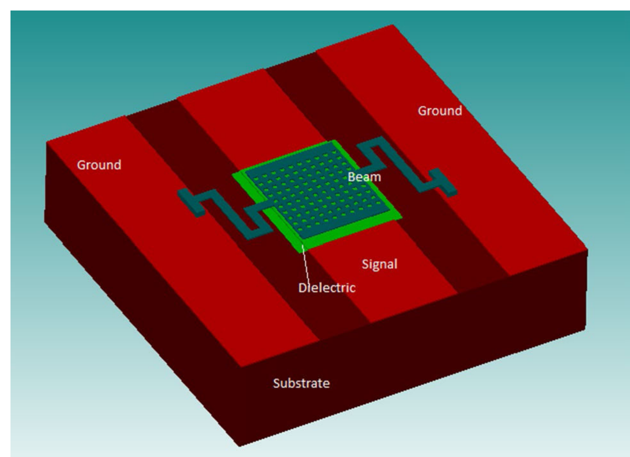

Fig. 2 3D model of non uniform one meander RF MEMS switch

Table 1 Design specification of uniform three and non-uniform one, two, three meanders perforated switch with Si_3N_4 and HfO_2 as dielectric

Parameters	Symbols	Uniform with meander			Non uniform with meander		
		1	2	3	1	2	3
Beam width (μm)	w	120			120		
Electrode width (μm)	W	100			100		
Beam thickness (μm)	tb	0.8			0.8		
Beam height (μm)	g0	1.0			1.0		
Beam length (μm)	*lb*	350			260		
Dielectric constant	ε_r	7.6 (Si_3N_4)			7.6 (Si_3N_4)		
Dielectric constant	ε_r	14 (HfO_2)			14(HfO_2)		
Young modulus (GPa)	E	79 (gold)			79 (gold)		
Mechanical resonant frequency (kHz)	f0	64.28			24.3		

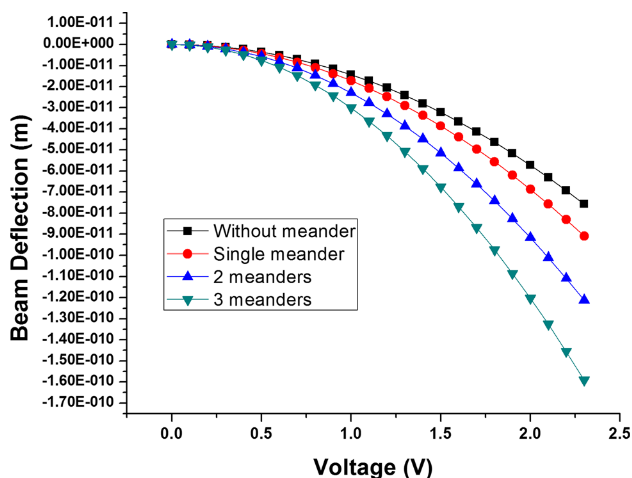

Fig. 3 Comparative of beam deflection for different uniform meander

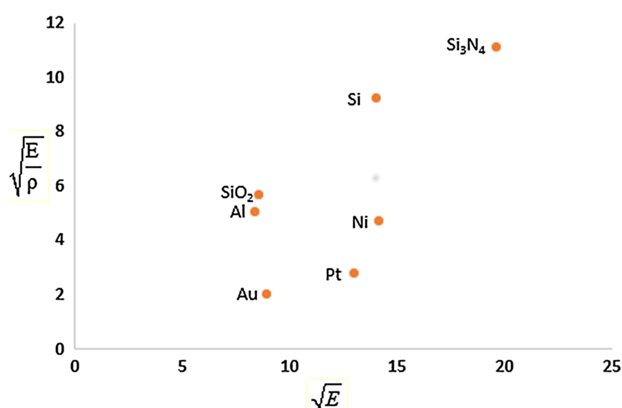

Fig. 4 Material selection of the beam

3.1 Operation of the switch

Actuation techniques for RF MEMS switch are piezo-electric, thermal and electrostatic. Because of complexity in fabrication thermal and piezoelectric actuation techniques are less preferred over electrostatic actuation

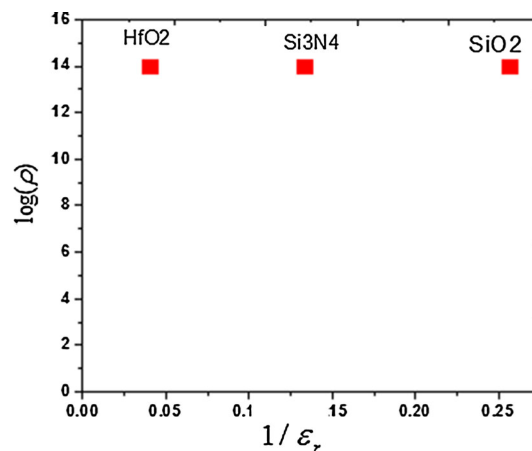

Fig. 5 Material selection for the dielectric layer

technique even though they requires less pull in voltage to deflect a beam. But in electrostatic actuation technique we have to face the challenges of getting high pull in voltage and low switching speed. Membrane is pulled towards the CPW center conductor by the electrostatic actuation by overcoming the spring force which results in the capacitive loading of the transmission line pull-in voltage is given by Muldavin and Rebeiz (2000)

$$V_p = \sqrt{\frac{8Kg^3}{27\varepsilon_o Ww}} \tag{1}$$

3.2 Theoretical analysis

3.2.1 ON and OFF capacitance

The RF switch performance is determined by up and down state capacitance. Up state capacitance (C_{ON}) of the switch is calculated by using the formula

$$C_{ON} = \frac{\varepsilon_o Ww}{g + \frac{t}{\varepsilon_r}} + C_f \tag{2}$$

where C_f is fringing field capacitance, t is thickness of dielectric, g is gap between beam and dielectric, ε_r is relative permittivity of dielectric material, ε_o is the permittivity of free space, W is width of movable beam and w is the width of dielectric. The up state capacitance varies for different materials based on their relative permittivity.

Down state capacitance (C_{off}) of the switch is calculated by using the formula

$$C_{off} = \frac{\varepsilon_0 \varepsilon_T W w}{t} \tag{3}$$

The capacitive ratio $C_{ratio} = \left(\frac{C_{down}}{C_{up}}\right) = \frac{\frac{\varepsilon_0 \varepsilon_r W w}{C_d}}{go + \frac{C_d}{C_f} + C_f}$ (4)

Insertion loss and return loss are dependent on the up state capacitance whereas isolation is based on down state capacitance. Efficiency of RFMEMS switch is based upon the capacitance ratio. Use of high-K dielectric material improves the capacitance ratio of the switch which gives the better performance of the switch by improving the S-parameter. Si_3N_4 with dielectric constant of 7.6 gives C ratio of 8.69 and 11.13 for 0.8 and 0.6 µm of beam thickness respectively whereas use of HfO_2 with dielectric constant of 14 as dielectric gives C_{ratio} of 14.93 and 19.66 for 0.8 and 0.6 µm of beam thickness respectively with gap between the electrode beam and dielectric as 0.8 µm.

4 Results and discussions

4.1 Electromechanical analysis

The Pull in voltage is directly proportional to root over spring constant, which is a material as well as structure dependent (Jaspreet et al. 2014). Non uniform one meander design has 2.3 and 2 V for Si_3N_4 and HfO_2 dielectrics respectively whereas for same design specification uniform three meander switch has pull in voltage Vpi of 2.5 V. Deflection of beam with applied voltage shown in Figs. 6 and 7 shows the beam bending corresponding to increase in applied voltage for non uniform 1 meander and uniform 3 meander structure switches respectively.

4.2 Switching time analysis

RF MEMS switch for transmit/receive switching applications requires high switching speed capabilities along with parameters like low return loss and high isolation loss. 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.

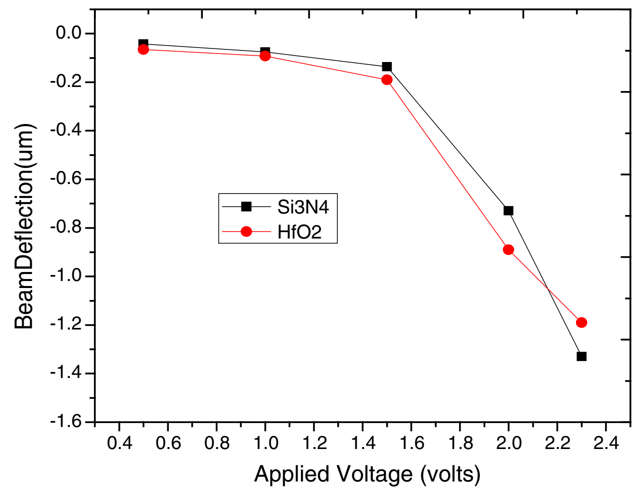

Fig. 6 Pull in voltage for Si_3N_4 and HfO_2 at 1 µm gap height non-uniform 1 meander

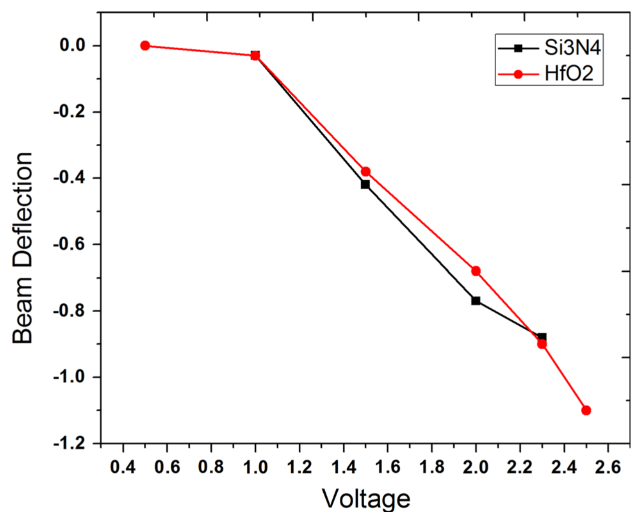

Fig. 7 Pull in voltage for Si_3N_4 and HfO_2 at 1 µm gap height for uniform 3 meander

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

$$t_s = 3.67 \frac{V_p}{V_s \omega_o} \tag{5}$$

V_p is the pull in voltage can be calculated by using Eq. 1, V_s is source voltage, w_o resonant frequency. In order to calculate pull in voltage we require spring constant and it can be calculated by using formula:

$$\mathrm{K} = \frac{EWt^3}{i^3} \tag{6}$$

where E is Young's modulus of the material of movable beam (Young's modulus of gold is 79 GPa). Thus the

material chosen and the dimensions of the blocks mainly effects the spring constant. Resonant frequency (w_o) of the device explains about the physical variation of the device when it is put to stress. It is also one of the important parameter in switch performance evaluation.

$$f = 1.03\sqrt{\frac{Y}{d}\frac{h}{l^2}} \quad (7)$$

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

Mechanical resonant frequency of the uniform three meander and non-uniform single meander, double meander, triple meander design is calculated by MATLAB of the shunt switch model as 64.28 and 24.3 kHz respectively (Table 1). Stiffness of the beam can be reduced by increasing the number of meander (Bedier and Abdel Rassoul 2013). Also from relation (5) switching time is directly proportional to Vp, thus we see the switching time of switch ts, at Vs = 2 V, is 0.12 ms for uniform three meander and for non-uniform one meander beam it is 0.7 ms (Fig. 8).

4.3 S-parameter performance analysis

Efficiency in the switch performance can be directly indicated with scattering parameters. The RF performance of MEMS switch is done in up and down states. RF MEMS switch can be carved as two port network with shunt contact. RF MEMS switch S-parameter can be given as (Fedder 1994)

$$S_{11} = -20\log\left|\frac{-Z_b}{2Z_b + Z_0}\right| \quad (8)$$

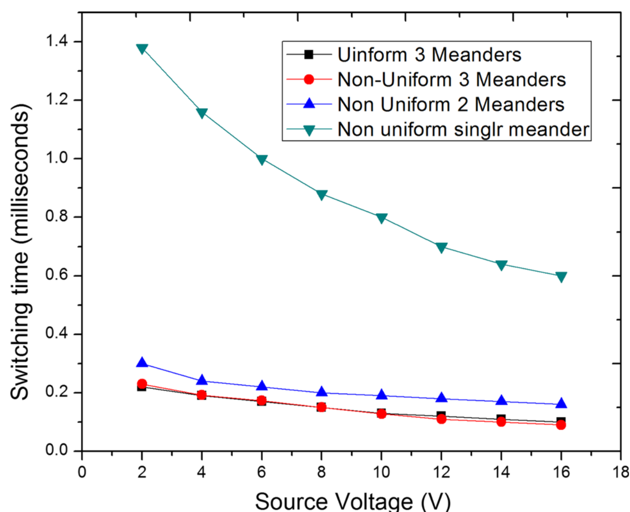

Fig. 8 Switching time comparison of uniform and non-uniform structure meander beams

$$S_{21} = -20\log\left|\frac{2Z_b}{2Z_b + Z_0}\right| \quad (9)$$

where Z_0 is the characteristic impedance of CPW and Z_b is beam impedance. S-parameters S_{11} represents return loss in upstate as well as in down state and S_{22} represents insertion loss in upstate whereas in down state it gives isolation of RF MEMS switch. The insertion and isolation across the range of frequencies can be resolved by total capacitance of RF-MEMS switch in both actuated and unactuated state (Rayit 1997). In order to get high isolation and low insertion loss. RF MEMS switch should maintain high capacitance ratio. All these scattering parameters are calculated with CPW transmission line impedance (Z0) as 50 Ω, bridge resistance as 0.5 Ω and bridge inductance as 7 pH in both states.

With the help of Eq. (6), we can calculate the parameter of RF MEMS switch such as return loss, insertion loss and isolation loss given the capacitance of the switch. Uniform three meander switch with Si_3N_4 as dielectric has un-actuated capacitance of 64.32 fF and actuated capacitance of 5.5 pF. For non-uniform one meander beam structure un-actuated and actuated capacitance details for Si_3N_4 and HfO_2 as dielectric is tabulated in Table 2.

At higher frequencies we can achieve higher isolation by getting high downstate capacitance by using higher bridge width. At higher frequencies return loss will reaches to 0 dB in actuated state and it can be further improved by varying the width. Using HFSS software S parameters are simulated for uniform single, double, triple meanders and non-uniform single meander structures by varying the material for dielectric as HfO_2 and Si_3N_4. Graphs are plotted for return loss and insertion loss for all switch structures using HfO_2 as dielectric material (Figs. 9, 10).

5 Conclusion

In this paper, capacitive shunt MEMS switch with different number of meanders were designed and simulated. Generally RF MEMS switches are used widely in communications and so far many switches are design with various structures mainly concentrating on pull in voltage. But this paper reports on electromechanical, switching time and performance analysis of capacitive Shunt RF MEMS switch with uniform and non-uniform meanders. The MEMS switch is a freely moving membrane over coplanar wave guide. Electromechanical analysis is done for movable beam with gold as material and dielectric as Si_3N_4 and HfO_2. For these dielectric materials pull in voltage is 2.3 and 2 V respectively with beam thickness of 0.8 μm by using COMSOL FEM tool. Si_3N_4 with dielectric constant of 7.6 gives C_{ratio} of 8.69 and 11.13 for 0.8 and 0.6 μm of

Table 2 Capacitance ratio for Si_3N_4 and HfO_2 dielectric materials by changing the gap between beam and dielectric

Dielectric layer	Si_3N_4						HfO_2					
Parameters												
Beam thickness (μm)	0.8						0.8					
Beam height (μm)	0.8	1	1.5	2	2.5	3	0.8	1	1.5	2	2.5	3
Up capacitance (fF)	117.31	96.08	66.15	50.44	40.76	34.2	123.9	100.4	68.2	51.6	41.5	34.7
Down capacitance (pF)	1.02						1.85					
Capacitance ratio	8.69	10.61	15.43	20.23	25.06	29.8	14.93	18.4	27.12	35.85	44.57	53.3
Dielectric layer	Si_3N_4						HfO_2					
Parameters												
Beam thickness (μm)	0.6						0.6					
Beam height (μm)	0.8	1	1.5	2	2.5	3	0.8	1	1.5	2	2.5	3
Up-capacitance (fF)	120.8	98.4	67.2	51.08	41.18	34.4	126	101.8	68.8	51.9	41.7	34.9
Down capacitance (pF)	1.345						2.478					
Capacitance ratio	11.13	13.66	20.01	26.33	32.66	39.09	19.66	24.34	36.01	47.74	59.42	71

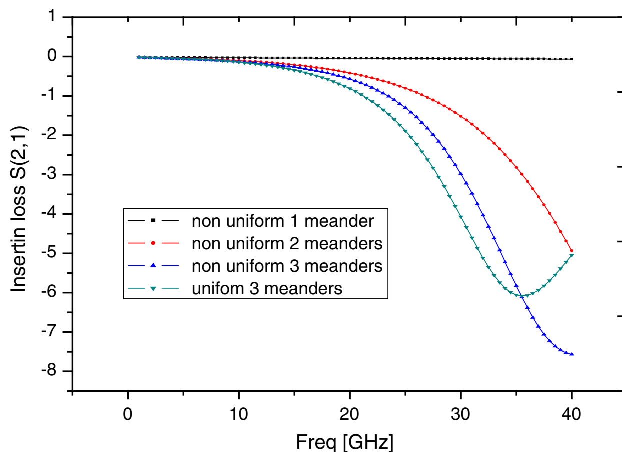

Fig. 9 Insertion loss of RF MEMs switch in upstate

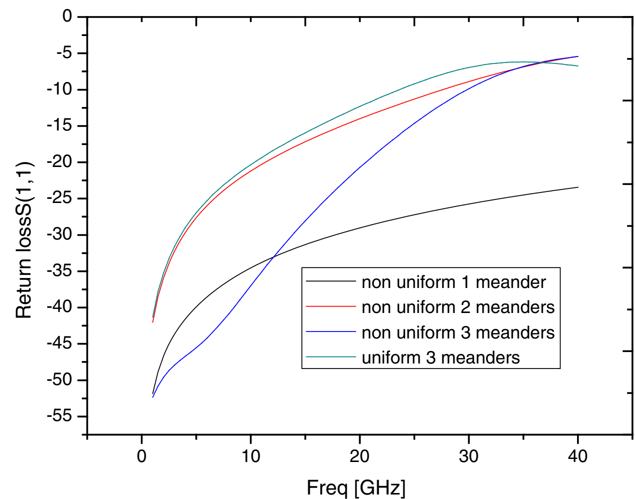

Fig. 10 Return loss of RF MEMS switch in upstate

beam thickness respectively. Whereas use of HfO_2 with dielectric constant of 14 as dielectric gives C_{ratio} of 14.93 and 19.66 for 0.8 and 0.6 μm of beam thickness respectively with gap between the electrode beam and dielectric as 0.8 μm. RF performance analysis is done by using HFSS software and the simulation results states that non uniform single meander has return loss as −60 dB, insertion loss −0.2 dB and isolation loss −14 dB at 20 GHz frequency. Coming to uniform 3 meander switch has return loss as −55 dB. Switching time analysis is done by using MATLAB. For uniform three meander it is 0.12 ms and for non-uniform one meander beam it is 0.7 ms.

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