



On characterization of symmetric type capacitive RF MEMS switches

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Abstract

This paper presents the design, fabrication and characterization of capacitive type MEMS switch for space and terrestrial communication applications. The deviation in measured actuation voltage and RF response of the switches are discussed in terms of the process variation which occurred unintentionally during the fabrication of devices. For example the measured actuation voltage is 15 V, about 20% higher than the designed voltage of 12.25 V. The deviation corresponds to the increase in thickness of the membrane while electroplating. The impact of process parameters on mechanical resonance frequency of the switches, and on/off time is also discussed. Measured S-parameters shows isolation of > -20 dB for 7–16 GHz and an insertion loss better than -0.6 dB up to 20 GHz. The capacitance ratio of the fabricated switch is 77, which is 15% lower than the designed capacitance ratio. The switch has been tested for 1 million 65 thousand cycles without switching failure. The deviation of simulated and measured results is discussed in the following sections.

1 Introduction

RF MEMS switches have gained ample recognition in the recent years and impressive progression has been made in its research and development.

The switches are widely adapted in wireless communication systems such as switching networks, phase shifters, receivers and transmitters (Rebeiz et al. 2003). The drive for RF MEMS applications in communication has been mainly due to the highly linear characteristics of the switches over a wide range of frequencies. The MEMS devices offer better isolation (> 30 dB) and low insertion loss (< 0.15 dB) as compared to contemporary solid state devices. With high levels of integration, negligible current, low power consumption and improved overall performance, RF switches are preferred for space, air borne and

hand held communication applications. However, switching speed, low RF power handling capability and reliability are some issues which need to be addressed more efficaciously. Reliability against self biasing, external shocks and vibrations and the power handling capability of RF switches are important issues which need to be considered along with electro-mechanical properties of the devices.

MEMS switches closely follow the electro-mechanical relays except the dimensional scale, superior performance and negligible power consumption. Resembling other switches they too have two stable states: ‘on’ and ‘off’. Switching between these two states is achieved through the displacement of a suspended membrane actuated by electrostatic, piezoelectric, electro-thermal or electromagnetic actuation mechanism. Majority of MEMS switches bank upon electrostatic actuation which offers extremely low power consumption, simple fabrication technology and high degrees of compatibility with standard IC processing (Tilmans 2002). Switch resistance to external vibrations and self-biasing can be improved by fabricating a second bridge over the movable membrane which will work as an electrode to clamp the bridge in its on-state. This not only undermines the reliability but also affect the on-state characteristics of the switches. Fabricating two bridges at different levels is a complex process. Self-actuation and sensitivity to external vibrations can be improved by using symmetric toggle switch (STS) configuration (Rangra 2005). STS is a capacitive type RF MEMS switch, based on push-pull mechanism to obviate the problem of self-

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biasing and external vibrations and shocks. Figure 1a shows a SEM micrograph fabricated device.

STS is based on the 50 Ω CPW configuration and consists of two pairs of actuation electrodes, placed symmetrically along the transmission line. Figure 1b shows the working principle of STS. As shown, STS is a combination of two micro-torsion actuators which are connected to each other by connecting levers and an overlap area. Beneath the torsion actuators, there are 4 actuation electrodes; inner two are used for pull-in and outer two are used for pull-out. When voltage is applied at inner pair of actuation electrodes, switch comes in contact with the dielectric, thus increasing the capacitance and turning the switch into off-state. On the other hand, when the voltage is applied at the outer pair of electrodes, switch clamps in the up-state, thus decreasing the capacitance and turning the switch to on-state.

2 Fabrication process

Figure 2 shows the optical micrographs of the fabrication steps for STS (Maninder 2013). The surface micro-machined devices have been fabricated on high resistivity silicon substrate (5 k Ω). Initial thermal oxidation is followed by the LPCVD growth of polysilicon which is further patterned through RIE to obtain actuation electrodes (Fig. 2a). After this PECVD oxide is deposited throughout the wafer and is patterned using RIE to open the contact

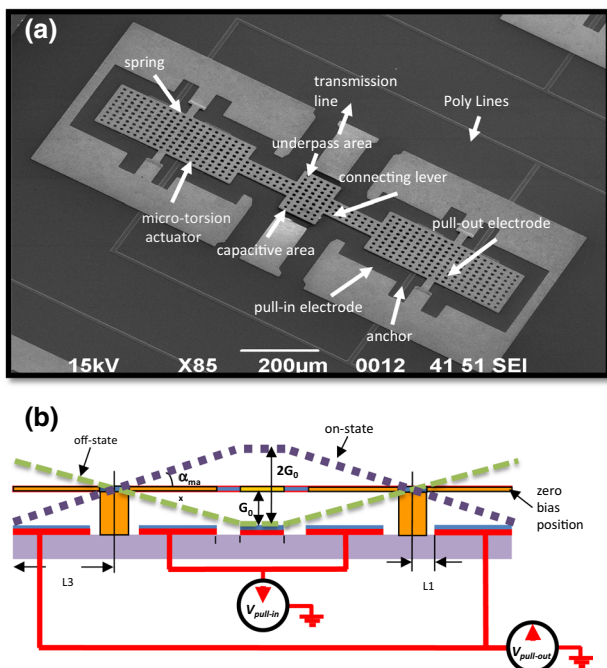


Fig. 1 a SEM micrograph of fabricated device (STS), b working principle of STS

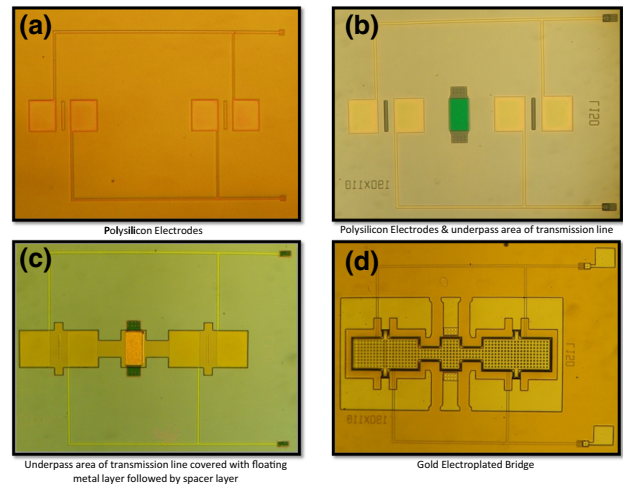


Fig. 2 Optical micrographs of different process levels

holes. Afterwards, the underpass area (or overlap area of transmission line) for signal transmission, which is a multilayer stack composed of sputtered Ti/TiN/Al:Si/Ti/TiN thin layers is deposited (Fig. 2b). Again PECVD oxide layer is deposited on the above stack and via holes are patterned through it for making external contacts in further steps. This oxide layer works as a dielectric for the capacitive type switch and also prevents the short circuit conditions between the underpass area and the movable bridge.

Above is followed by the deposition of thin metal layer, which acts as a floating metal layer to obtain the optimum capacitance (Fig. 2c) (Maninder 2013).

Movable structure is realized through electroplating process over a 3 μm thick photoresist which is used as a sacrificial layer. Over this sacrificial layer, a thin seed layer of Cr/Au for electroplating is sputter deposited. Further, gold electroplating for 1.5 μm thick movable bridge (Fig. 2d) has been done. For release process, thin seed layers were etched followed by release through modified plasma ashing process to avoid stiction problem (SEM of released device is shown in Fig. 1a).

3 Characterization

3.1 Capacitance ratio results

The primary measure of electrical performance for a RF switch is capacitance ratio, which can be calculated using the Eqs. 1, 2, 3, 4 (Rebeiz et al. 2003; Tilmans 2002).

$$C_{ratio} = \frac{C_d}{C_{up}}, \quad (1)$$

$$C_{up} = \frac{\epsilon_0 A}{g + \frac{t_d}{\epsilon_r}} + C_f, \quad (2)$$

where $C_f = 0.3-0.4 C_{pp}$.

$$C_{pp} = \frac{\epsilon_0 A}{g + \frac{L}{\epsilon_r}} \tag{3}$$

$$C_d = \frac{\epsilon_0 \epsilon_r A}{t_d} \tag{4}$$

where, C_d , C_{up} , ϵ_0 , A , g , t_d , ϵ_r and C_f are down state capacitance, up state capacitance, permittivity of free space, overlap area, gap between the two plates, dielectric thickness, permittivity of the dielectric material and fringing capacitance. Capacitance ratio is the ratio of the down-state capacitance to the up-state capacitance. The capacitive switches ‘mechanically’ control the RF signal by using the on to off state impedance ratio. A high capacitance in down state creates a low impedance path between the signal line and the ground and thus blocks the RF signal from passing through to the other side of the signal line. Hence, a high capacitance ratio (C_{off}/C_{on}) is required for the optimum performance and a wide

operating regime of a capacitive switch. The capacitance ratio measurements were performed with ‘Keithley 4200-SCS’ characterization system using KITE software. The switch shown in Fig. 1a has a designed capacitance ratio of 90.77. C-V plot of the switch is shown in Fig. 3. The measured capacitance ratio of the switch is 77.4 (3.87 pF/50 fF). Decrease in capacitance ratio indicates either decrease of down state capacitance or an increase of up-state capacitance. Optical micrographs shown in Fig. 4a, b shows the distorted floating metal layer which corresponds to decrease in down state capacitance thus reflecting decrease in capacitance ratio. Table 1 shows the comparison chart for calculated, simulated and experimental/measured capacitance values.

Simulated actuation voltage for the same switch is 12.25 V (using Coventor Ware) (Coventor Ware 2008) and the calculated is 11.25 V (Eq. 5) (Maninder et al. 2009). As it can be seen from the plot of Fig. 3, the measured actuation voltage is 15 V. The increase in actuation voltage corresponds to the higher thickness of the suspended bridge after fabrication. The bridge was designed for thickness of 1.5 μm ; however the measured thickness of bridge after electroplating and seed layer etching is 1.9 μm . This corresponds to an increase in stiffness of the bridge thus increasing the actuation voltage. For a bridge thickness of 1.9 μm , calculated actuation voltage is 14.22 V and simulated actuation voltage is 15.75 V. For presented topology pull in voltage is given by:

$$V = \sqrt{\frac{E}{2.3914\epsilon_0 W} \left(\frac{g}{L}\right)^3 \left(\frac{k_1}{(1+\nu)} \frac{b_s h_s^3}{l_s} + \frac{L b h^3}{l^2 \cdot 6}\right)} \tag{5}$$

where, E is young’s modulus, ϵ_0 is permittivity, g is gap between transmission line and movable bridge, W & L are width and length of actuation electrodes, b_s , h_s & l_s are width, thickness and length of springs and b , h and l are width, thickness and length of connecting levers (Bao 2005).

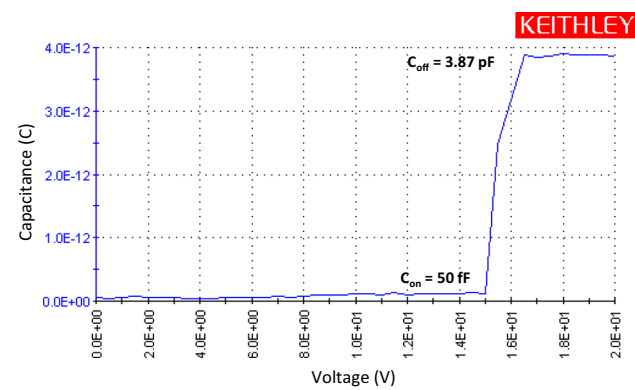


Fig. 3 Measured C-V response of the fabricated device

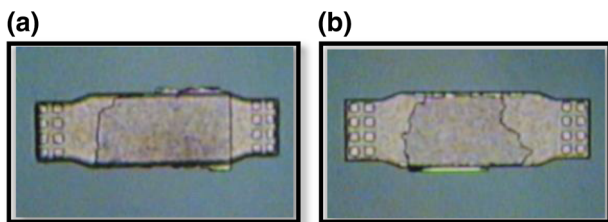


Fig. 4 Optical micrographs of distorted floating metal layer

Table 1 Calculated, simulated and measured comparison of up state and down state capacitance of capacitive switch

S. no	Method	C_{up} (fF)	C_{down} (pF)	C_d/C_{up}
1	Calculated (C_{pp} effect included)	62.764	5.697	90.77
2	Calculated (without C_{pp} effect)	48.28	5.697	118
3	Simulated (MEM-electro)	54.95	3.290	59.87
4	Simulated (actuation state)	54.95	1.060	19.2
5	Experimental (with FLOMET)	50	3.870	77.4

4 RF measurements

The electrical characteristics or RF response of the switch is characterized by measuring the S-parameters. The scattering parameters are measured in on and off states indicating insertion loss (S21) and return loss (S11) in on—

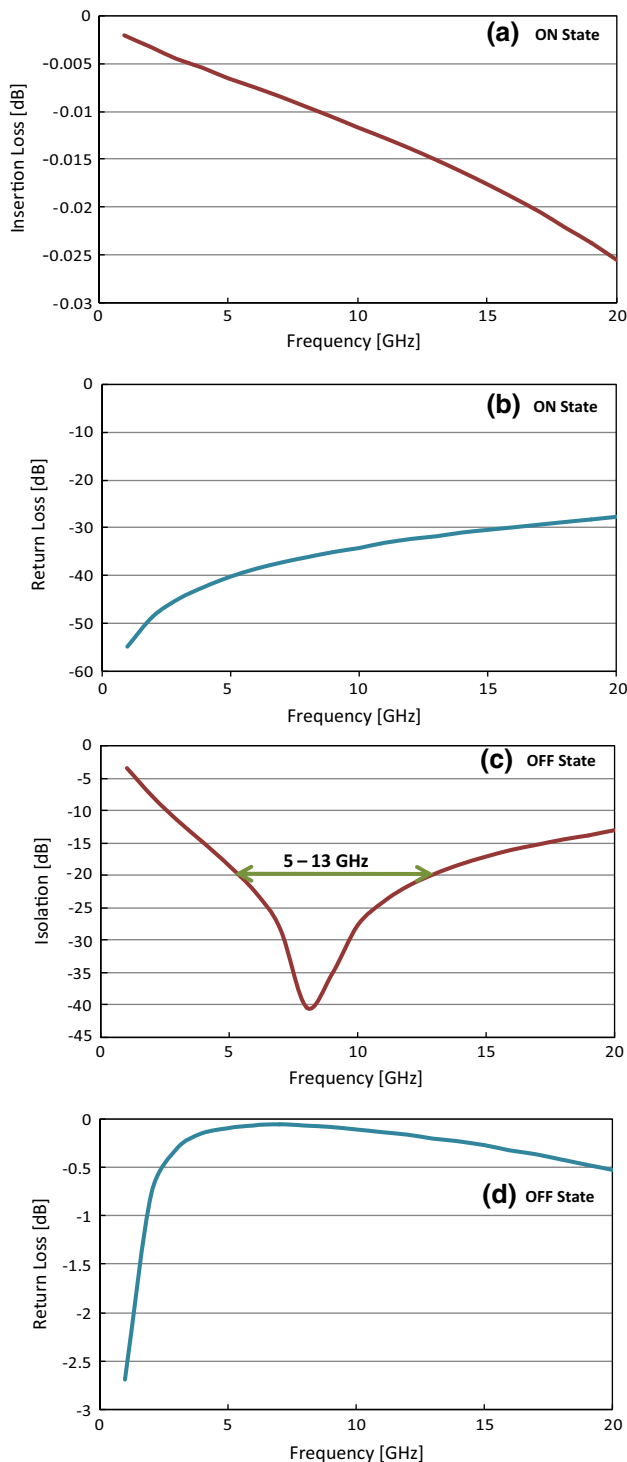


Fig. 5 Simulated RF response of the switch **a, b** in on state, **c, d** in off state

state and isolation (S12) in off state. Figures 5 and 6 show the respective simulated and measured results. As can be compared from off-state responses of Figs. 5 and 6, isolation is better than -20 dB in X-band in simulated as well as measured results. A -20 dB loss indicates a

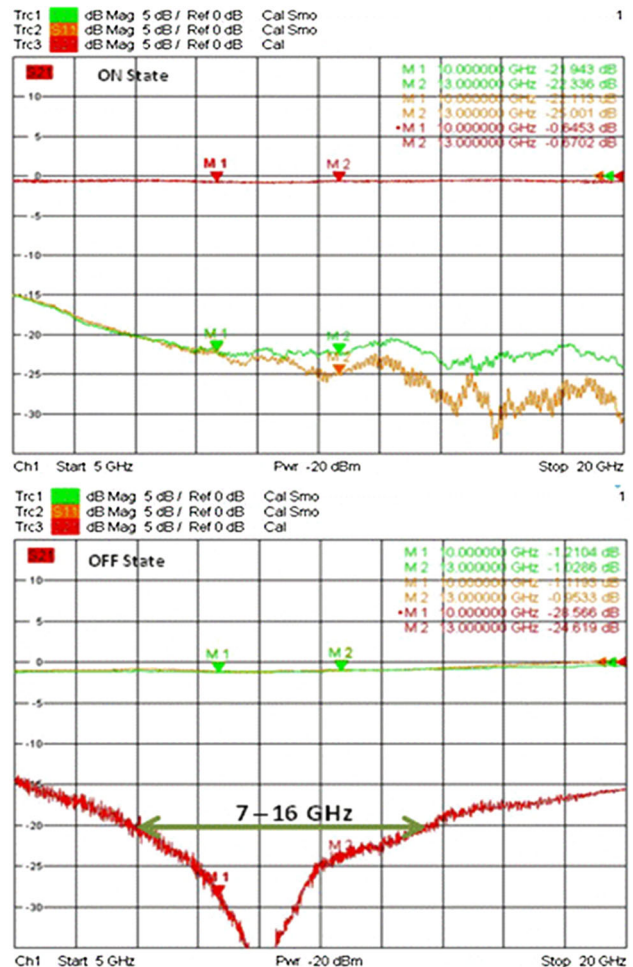


Fig. 6 Measured RF response of the device

decrease in 99% of applied RF power and -30 dB loss indicates a decrease in 99.9% of applied RF power. Measured results show a loss more than -30 dB from 11–12 GHz, showing high level of isolation in off-state. The shift in resonance frequency from 8 GHz in simulated results to 11.5 GHz in measured results corresponds to decrease in down state capacitance. This is due to the change in overlap area, which is because of the distortion of floating metal layer during lift off process as discussed in reference to Fig. 4.

In on-state, return loss is better than -20 dB for X and Ku band as shown by simulated and measured results. In on-state, simulated insertion loss is less than -0.025 dB in X and Ku bands (Fig. 5a); whereas, measured value of insertion loss is less than -0.7 dB (Fig. 6a). The return loss is better than -20 dB above 7 GHz and up-to 20 GHz.

A return loss better than -20 dB means a VSWR of 1.20 or less indicating a power transfer of 99.18% or more. The difference in simulated and measured insertion loss results is due to the difference in measurement conditions.

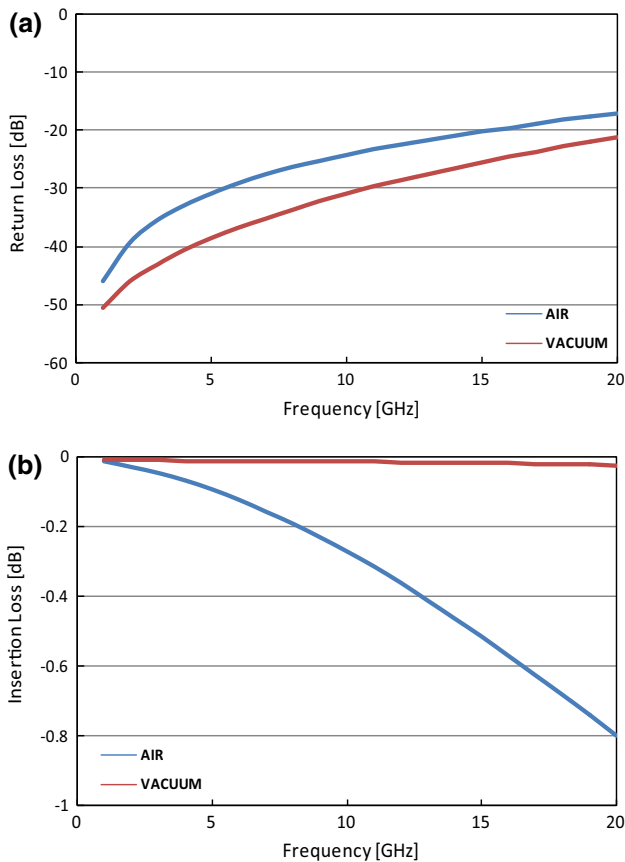


Fig. 7 Simulated RF response of the switch in on-state in air boundary conditions **a** return loss, **b** insertion loss

For simulations, vacuum boundary conditions are considered whereas; final measurements were carried under a laminar flow bench in an open environment. As the devices are unpackaged, the ambient conditions (temperature and humidity) affect the measured results (Rebeiz et al. 2003). This can be verified from the comparison of simulated on-state response of STS shown in Fig. 7. As shown, when the switch is subjected to air boundary conditions, the insertion loss of the switch deteriorates to -0.8 dB from -0.025 dB @ 20 GHz. For RF measurements the switch has been given an actuation pulse of $+20-0$ V to $-20-0$ V and was actuated for 7 h 30 min, with 60 cycles per min. In 7 h 30 min, 27,000 switching cycles (on-off cycles) have been completed by the switch.

In Fig. 8, performance of the switch after 27,000 cycles shows that the return loss is better than -20 dB and insertion loss is less than -0.7 dB in X and Ku bands. In off-state, isolation is better than -20 dB in X and Ku band even after 27,000 actuations. Thus, the performance of the switch is not much deteriorated after 27,000 cycles indicating the stable switch performance for satellite applications. The switch has been tested for 1 million 65 thousand switching cycles without switching failure.

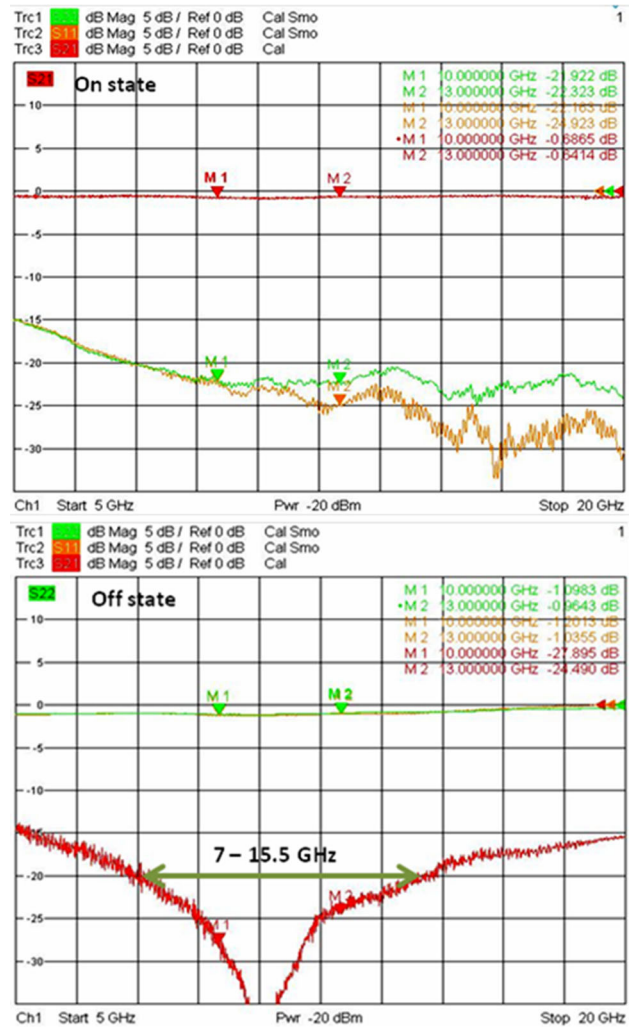


Fig. 8 Measured RF response of the switch after 27,000 actuations. Insertion loss is less than -0.7 dB in X and Ku Band, return loss better than -20 dB above 6 GHz in on state, and isolation better than -20 dB from 7–15.5 GHz in off state

5 LDV measurement

Laser Doppler Vibrometry is used to measure the mechanical resonance frequency of the structural membrane. Resonance frequency is used to calculate the switching time (on-off time) of the switch. As discussed above, on state of the switch is the relaxed state without any bias. In off state, voltage is applied to pull the beam down. On removal of actuation bias, the beam regains its original position either by mechanical restoration or by applying voltage to the outer electrodes.

The restoration time of a device depends on its natural resonance frequency. The time taken by the beam from up state to down state and back is referred to as on-off time. For STS, off time (beam up state to down state) depends on the voltage applied.

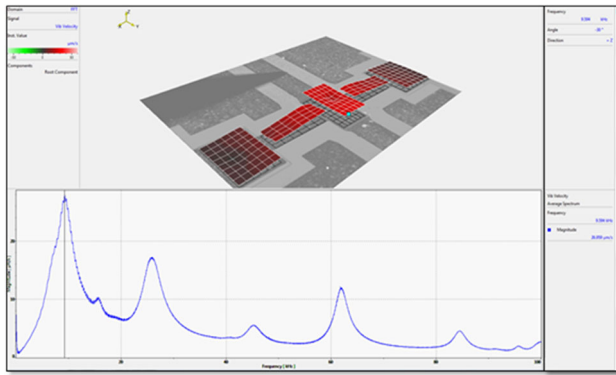


Fig. 9 First resonance mode of the fabricated device is @ 9.59 kHz, measured using LDV

The on time can be calculated from the mechanical resonance frequency or by pull-out voltage dependency. Simulated resonance frequency for first out of plane mode is 9.76 kHz and the measured is 9.59 kHz. Figure 9 shows the measured LDV response of the device. On and off time can be calculated using the Eqs. 6, 7, 8.

$$t_d = 3.67 \frac{V_{PI}}{2\pi V_{app} f_0} \quad (6)$$

$$t_{up} = \frac{1}{f_0} (Restoration) \quad (7)$$

$$t_{up} = 3.67 \frac{V_{PI}}{2\pi V_{app} f_0} \quad (8)$$

As mentioned in previous section, measured pull-in voltage (V_{PI}) for the switch is 15 V and the voltage applied for the actuation is in cycle + 20–0 V to – 20–0 V. The down state and up state time of the switch are calculated as 45.70 and 104.27 μ sec respectively.

6 Conclusion

Design, fabrication and electro-mechanical characterization of a RF MEMS capacitive type switch has been presented. The simulated and measured results show

considerable match. The minor deviations are discussed with reference to the process variations. The designed RF response is well matched with the fabricated device with optimum performance up-to a million switching cycles. The measured on state insertion loss is high when compared to the designed device due to the measurements in open setup. Isolation bandwidth is 8–9 GHz, which makes this device suitable for satellite and communication applications. The RF characteristics show no significant deviation over a million on–off cycles.

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