



Design and simulation of RF MEMS shunt capacitive switch with non-uniform meanders for C-band applications

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Abstract

This paper presents, the design and simulation of RF MEMS shunt capacitive switch. The electromechanical and electromagnetic analysis of the switch has been done using COMSOL(FEM) and HFSS tools. The proposed switch has the design with non-uniform meanders and dielectric material Silicon Nitrate (Si_3N_4). Different beam materials such as Gold, Aluminum, and Platinum are used to design the switch and analyze it. In the electro mechanical analysis of the switch, the pull-in voltage obtained for the beam material Platinum is 10.56 V for a gap (between the beam and signal-line dielectric) of 2.5 μm which is effective in comparison to the other materials like Gold and Aluminum. As far as the RF performance analysis is concerned, the isolation, insertion loss and return loss have been calculated. The isolation, return loss and insertion loss are – 25 dB, – 14.3 dB and – 0.33 dB respectively. On performing the stress analysis of the switch, a stress value of 0.05 N/m^2 has been obtained for the applied pull-in voltage. The proposed switch is used for C band applications.

1 Introduction

MEMS technology provides miniaturized devices through micromachining process in our day to day life (Girija Sravani and Srinivasa Rao 2018). These can be made using materials like ferroelectric, magnetic, ceramic and semiconductor materials. The components of MEMS range from millionth of a meter (μm) (Puli et al. 2018) to a thousandth of meter(mm). It is the growing technology used in biomedical applications (Girija Sravani and Srinivasa Rao 2018), wireless and optical communications (Girija Sravani and Srinivasa Rao 2019a, b), automobile industries (Prasad and Srinivasa Rao 2018) where new technologies and innovations are being emerged every day (Mafinejad et al. 2013).

One of the prominent technology in MEMS is RF MEMS, which provides the Radio-Frequency functionality to the MEMS devices. Different components of RF MEMS include resonators, self-sustained capacitors, switches and

varactors. The basic functionality of the switch is to make or break the connection in a circuit. Switches which operate at the frequencies ranging from 0.1 to 100 GHz are termed as RF MEMS Switches. The properties of the miniaturized devices and radio-frequency functionalities like less weight, low power, low insertion loss, good reliability, affordability altogether made the switch an advantageous one (Girija Sravani and Srinivasa Rao 2017). These switches use a radio-frequency transmission line to attain open or short circuit. Based on the electromagnetic and electrostatic forces switches are differentiated as series and shunt switches. Series switch, initially is disconnected and gets connected when the necessary voltage is applied, where as in shunt switches which are meant for capacitive coupling, initially is connected and when the required voltage is applied it gets disconnected (Reddy and Shanmuganatham 2014).

Several studies have been conducted on RF MEMS switches in order to optimize the parameters like pull-in voltage, insertion loss etc. For a K-band shunt capacitive switch, return loss is better than 10 dB at lower frequency and insertion loss is less than 0.3 dB (Verma and Singh 2013). A comparative analysis of dielectric materials AlN and Si_3N_4 has been done. For a dielectric thickness of 300 nm and air gap of 2.3 μm the AlN switches showed an improvement in the isolation and a better insertion loss

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compared to Si_3N_4 . But the leakage current for AlN devices is 10 times larger than that of Si_3N_4 (Fernandez-Bolanos Badia et al. 2012). Researches show that switch with non-uniform 3 meanders (Tulasi and Prasad 2017) has a return loss at -55 dB where as the switch with one uniform meander has a return loss of -60 dB. This makes a mark that the switches with uniform meanders exhibit less return loss (Girija Sravani and Srinivasa Rao 2017).

A bridge is a thin metal membrane suspended over the center conductor of the coplanar wave guide (Kumar et al. 2018). The frequency range and the characteristic impedance of the proposed switch is about 0.1–10 GHz and 50Ω respectively (Rao and Bhavitha 2017). The applications of switches are widespread in different electronic devices such as Phase Shifters, Tunable Filters and Matching Networks and Reconfigurable circuits (Muldivin and Rebeiz 2001). Switches connecting high-pass or low-pass filter networks used as phase shifting units for which binary phase shifters are used (Ganesh and Srinivasa Rao 2017). In order to achieve low-loss and potential integration of optimized MEMS, the development of MEMS-based phase shifters took place. The tunable filters and the tunable matching networks are being extensively used in the laboratories. These make the microwave systems adaptable to fast-changing signal conditions by pacifying signal interference. Reconfigurable circuits provide the multifunctional capability (Newman 2002). The RF MEMS switches ranging from the frequency range 0.1–100 GHz are used in circuits called Switch Matrices which are adopted in Automotive radar and antennas.

In this paper, the switch design is carried out using fixed–fixed beam. The electromechanical analysis of the switch has been done practically to observe the pull-in voltage and respective displacement of the device. The solid mechanics has been used to evaluate the stress on the device, and the isolation, insertion and return losses of the device has been done in the electromagnetic analysis of the switch. These analyzing patterns have been performed for different dielectric materials Gold, Aluminium and Platinum. The design, mechanism and results of the analysis is discussed below.

2 Theory

2.1 Proposed design

The proposed RF MEMS switch designed on $200 \mu\text{m}$ thickness of silicon substrate which acts like base of the switch, and the dielectric is of $0.5 \mu\text{m}$ thickness placed above the substrate and coplanar wave guide (CPW) is used to transmit the signal from the I/O ports, ground and signal line is of $1 \mu\text{m}$ thickness. The signal dielectric of

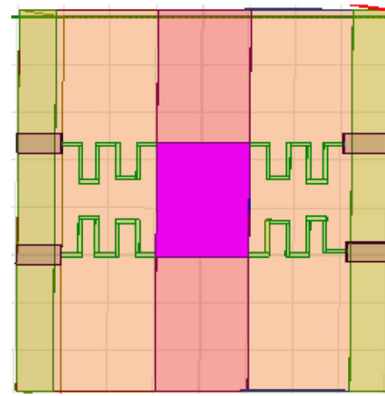


Fig. 1 The Schematic view of the proposed device

$0.1 \mu\text{m}$ thickness is placed above the signal line of CPW. A beam was placed above the signal dielectric of $0.5 \mu\text{m}$ thickness which was fixed to the four fixed constraints placed on either side of ground, with the gap of $2.5 \mu\text{m}$. The principle operation of this device is shunt type fixed–fixed beam RF MEMS switch as shown in the Fig. 1.

In this design we have implemented non-uniform meanders, because in analysis we have observed advantages over non-uniform meander RF MEMS switch as it reduces the pull in voltage and also helps in reducing area of the switch.

2.2 Dimensions

Platinum material is used in the proposed design (ground, signal line, meanders), on the analysis we got the low pull in voltage for platinum compare to gold and aluminum. And for substrate, silicon material is used. Holes are introduced on the area of the membrane in aspect of reducing the pull in voltage. Thickness of the holes are $2 \mu\text{m}$ inserted on the membrane, with the array of 6×5 . The gap between the ground and signal line(G/S/G) is $110 \mu\text{m}$ (Table 1).

2.3 Working principle

The RF MEMS shunt switch with fixed–fixed beam design can be operated in UP and DOWN states. The switch is ON in UP-state whereas the switch is OFF in DOWN-state. The

Table 1 Dimensions of various parameters in the switch

S. no	Parameters	Width	Depth	Height (μm)
1	Dielectric	$400 \mu\text{m}$	$400 \mu\text{m}$	0.5
2	Signalline dielectric	$100 \mu\text{m}$	$120 \mu\text{m}$	0.1
3	Beam	$100 \mu\text{m}$	$120 \mu\text{m}$	0.5
4	Meander1 (m1)	$22 \mu\text{m}$	$4 \mu\text{m}$	0.5
5	Meander2 (m2)	4 m	35 m	0.5

applied RF signal at the signal line is transmitted to the output port when the bridge is above the transmission line which is UP-state. The switch is operated by the applied pull-in-voltage between the signal line and bridge. This applies an electrostatic force between signal line and bridge which leads to bend down of bridge and contact the dielectric layer on the signal line is DOWN-state.

3 Results and discussions

Forces act on the solid object that cause the object to move or deform. Interactions arise between the electromagnetic fields and solids, elastic structures or rigid bodies. The analysis of these interactions are grouped as electromechanical, electromagnetic analysis. The stress analysis provides an indication of device structural reliability.

3.1 Theoretical analysis

Under the electromechanical analysis, spring constant, pull in voltage and switching time has been analyzed. Switching time is the time required for the switch to toggle from active state to inactive state or the time inactive state to active state. In order to transmit or receive in applications, high switching speed is necessary. It is calculated by using the equation (Chan et al. 2003)

$$t_s = 3.67 \frac{V_p}{V_s \omega_0} \tag{1}$$

V_p is the pull-in voltage, V_s is the source voltage and ω_0 is the resonant frequency. The term pull-in voltage is associated with the electromagnetic relays. It is the voltage at which the relay turns to its rest position. The pull-in voltage is applied across the switch, causing it to collapse onto the dielectric layer. Pull- in voltage is given by (Lakshmi Narayana et al. 2017)

$$V_p = \sqrt{\frac{8Kg^3}{27\epsilon_0 A}} \tag{2}$$

g is the gap between the beam and signal-line dielectric, ϵ_0 is the permittivity of free space, K is the spring constant and A is the area of actuators.

The pull-in voltage is directly proportional to the root over the spring constant, the spring constant is given by (Jaafar et al. 2014)

$$K = \frac{EWt^3}{l^3} \tag{3}$$

E is the Young’s modulus of the dielectric material, W is the width, t is the thickness and l is the length of beam. The

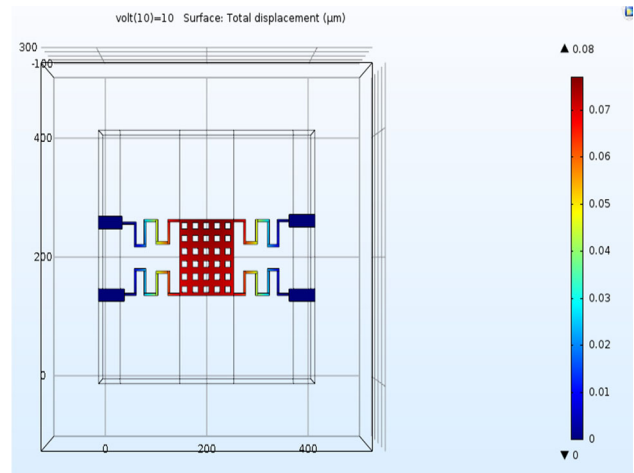


Fig. 2 Displacement of beam at pull-in-voltage

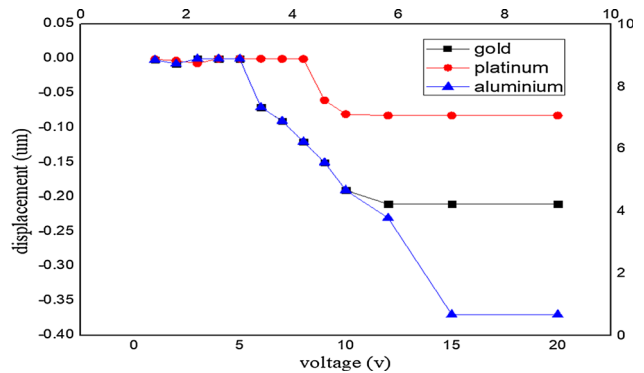


Fig. 3 Pull-in-voltage for different types of materials with gap 2.5

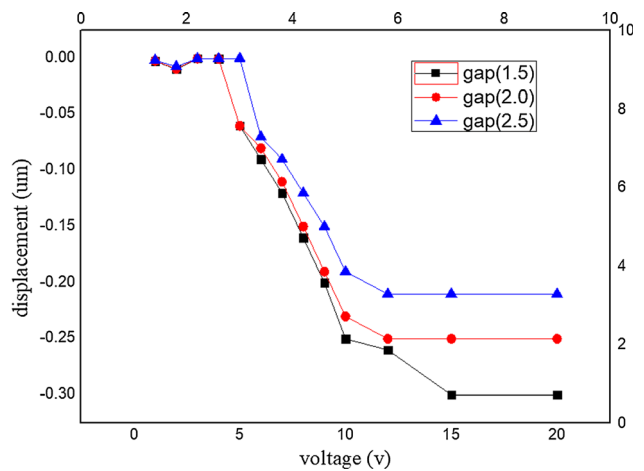


Fig. 4 Pull-in-voltage for material platinum with different gaps

pull-in voltage and spring constant values for Platinum with the beam thickness of 0.5 μm and the gap of 2.5 μm are 10.56 V and 11.86432 respectively.

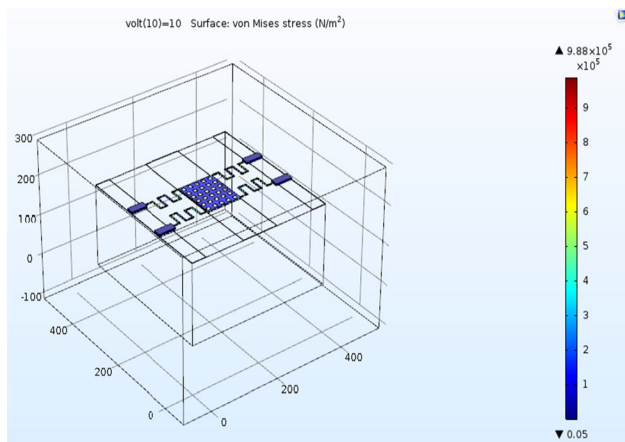


Fig. 5 Stress at pull-in voltage 10 V

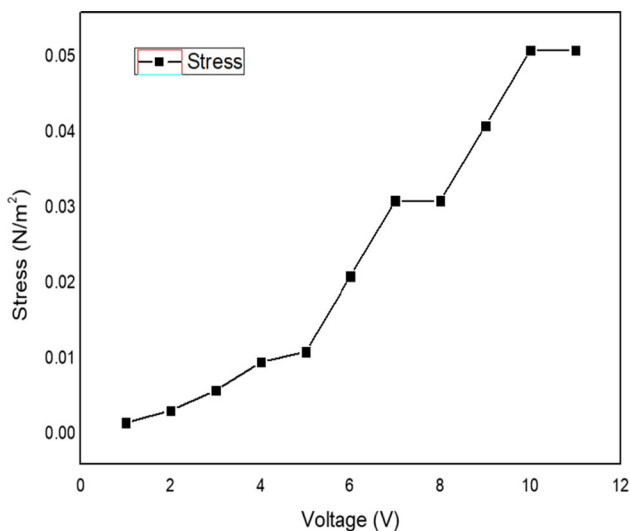


Fig. 6 Voltage versus stress graph

3.2 Electromechanical analysis

Pull in voltage is directly proportional to the square root of spring constant and also depends on the material and dimensions used in design, proposed switch is designed with two non-uniform meanders and holes has 10Vp for Si₃N₄ dielectrics with gap 2.5 between the beam and signal line dielectric. The nature of beam change according to the increase in pull in voltage applied for meanders (Sundaram 2014) (Figs. 2, 3, 4 and 5, Table 2).

3.3 Stress analysis

The proposed structure is modeled using finite element modeler to compute beam effective stress. Since meshing plays a major role in computation time reduction, it is needed before computing the model in finite element modeler. We can achieve realistic solution in smaller mesh. Von Mises stress effects in the beam are analyzed at the particular spring constant for a necessary force acting on the beam. Figure 6 illustrates the platinum beam displays an stress of 90Mpa approximately, which is suitable for platinum and is smaller than material ultimate tensile strength. It simply denotes the meanders reliability in the beam. So it does not affect lot more switching cycles (Singh 2013).

3.4 RF performance analysis

The s-parameters indicate the performance and behavior of the electric switch. The s-parameters are expressed as return loss, insertion loss and isolation. In general, return loss is defined as the ratio of reflected power to the incident power when a signal is transmitted through a transmission line. Calculation and analysis of return loss is done to

Table 2 Voltage and displacement values of different types of materials with gap 2.5

Material Voltage (V)	Gold Displacement (μm)	Platinum Displacement (μm)	Aluminium Displacement (μm)
1	– 1.85e–3	– 7.69e–4	– 1.86e–3
2	– 7.41e–3	– 3.08e–3	– 7.44e–3
3	– 0.02e–2	– 6.92e–3	– 0.02e–2
4	– 0.03e–2	– 0.01e–2	– 0.03e–2
5	– 0.05e–2	– 0.02e–2	– 0.05e–2
6	– 0.07	– 0.03e–2	0.07
7	– 0.09	– 0.04e–2	0.09
8	– 0.12	– 0.05e–2	0.12
9	– 0.15	– 0.06	0.15
10	– 0.19	– 0.08	0.19
12	– 0.21	– 0.082	0.23
14	– 0.21	– 0.082	0.37
15	– 0.21	– 0.082	0.42

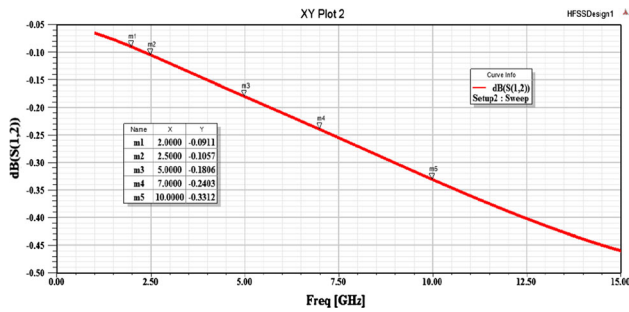


Fig. 7 Simulated S(1,2) parameter

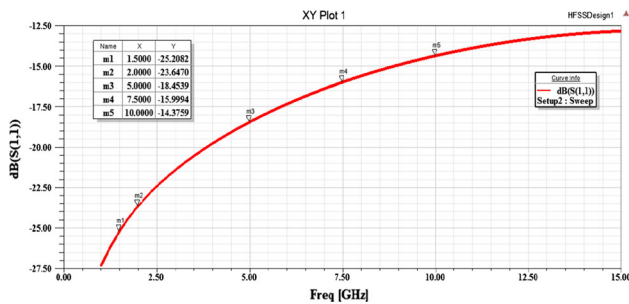


Fig. 8 Simulated S(1,1) parameter

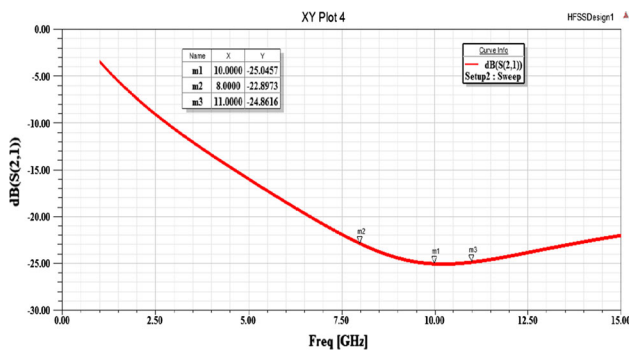


Fig. 9 Simulated S(2,1) parameter

assess the input characteristics of RF components. The return loss is calculated by (Angira and Rangra 2014). Simulated S(1,2), S(1,1), S(2,1) are shown in Figs. 7, 8 and 9 respectively.

$$s_{11} = -20 \log \left| \frac{-Z_b}{2Z_b + Z_0} \right| \tag{4}$$

Z_b is the beam impedance and Z_0 is the characteristic impedance.

The ratio of the power transmitted to the load before to the power received by the load is characterized as the Insertion Loss. When a radio frequency signal is

Table 3 Comparison of the proposed design results with previous literature results

Parameters	Mafinejad and Kouzani (2017)	Mafinejad and Kouzani (2009)	Proposed design
Frequency	164 kHz	50 GHz	10 GHz
Isolation	18 dB	14.79 dB	25 dB
Return loss	24 dB		14.3 dB
Insertion loss	0.9 dB	1.94 dB	0.33 dB
Pull in voltage	20 V	32 V	10.56 V

transmitted through the transmission line, insertion loss gives information about how much input signal is being reached at the output. The isolation is determined using the follow equation (Newman 2002) (Table 3).

$$S_{21} = -20 \log \left| \frac{2Z_b}{2Z_b + Z_0} \right| \tag{5}$$

4 Conclusions

In this paper, we have proposed a RF MEMS shunt capacitive switch with different parameters like pull in voltage, S parameters, spring constant, capacitance all these were verified both theoretically and practically by adding different materials like gold, aluminium, platinum.

Finally, we conclude that with the pull in voltage 10.56 V by adding holes to the beam with platinum material and the gap between signal line dielectric and beam is 2.5 μm . The isolation obtained is -25 dB, return loss and insertion loss are -14.3 dB and -0.33 dB respectively. A stress of 0.05 N/m² has been recorded. The switch shows good RF characteristics below 10 GHz. So, it is applicable for SP6T LTE Transmit/Receive Switch.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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