



# Analytical model and analysis of RF MEMS switch for Ka-band applications

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## Abstract

This paper aims to develop an RF MEMS shunt switch with low actuation voltage and improved RF performance at high-frequency applications. Here we have developed two beam structures for the analysis of electromechanical and electromagnetic parameters using COMSOL and HFSS software. The pull-in voltage of each beam is calculated as 5.8 V for beam-1 and 3.6 V for beam-2, the simulated results are compared with the theoretical results with the analytical model equations. The capacitance analysis of the proposed switch is 11.09 fF, 4.61 pF and the switching time is 6.2  $\mu$ s. Capacitance is a key parameter to obtain good RF performance, the return and insertion loss of the proposed beam structures are  $-35.29$  dB,  $-42.95$  dB,  $-0.76$  dB,  $-0.87$  dB, and the isolation is obtained as  $-21.02$  dB,  $-22.34$  dB at 20 GHz and 41.21 GHz. The switch can be utilized in high-frequency communication systems such as point-to-point microwave links, satellite communication systems, and 5G wireless networks to improve signal routing and frequency tuning.

## 1 Introduction

Micro-Electro-Mechanical Systems, or MEMS, is a technology that merges miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using microfabrication techniques. The critical physical dimensions of MEMS devices can range from

several micrometers to millimetres (Rebeiz and Muldavin 2001; Zheng et al. 2005; Caekenberghe and Koen, and Kamal Sarabandi. 2008). These devices generally consist of components like microsensors, microactuators, microstructures, and microelectronics, all integrated onto the same silicon chip. MEMS technology has a wide range of applications across various industries. In the automotive industry, for example, MEMS sensors are used for airbag systems and tire pressure monitoring. In healthcare, MEMS devices are used in medical imaging, diagnostics, and therapeutics (Goldsmith and Yao 1998; Papaioannou et al. 2010; Bansal et al. 2014). In consumer electronics, they're found in smartphones, tablets, and gaming consoles, where they're used for functions like navigation, motion sensing, and more. MEMS technology presents an exciting opportunity. The key is to effectively communicate the benefits of MEMS technology to our target audience. This includes its small size, low power consumption, high performance, and cost-effectiveness. We can leverage these benefits in our marketing campaigns, using them to highlight how MEMS technology can meet the needs of consumers and businesses alike. Moreover, it's crucial to stay abreast of the latest trends and advancements in MEMS technology. The electronics are fabricated using integrated circuit (IC) process sequences, while the micromechanical components are fabricated using compatible "micromachining"

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processes. MEMS promises to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, making it possible to produce systems-on-a-chip (Ansari and Khosroabadi 2019; Zolfaghari et al. 2018; Han et al. 2018; Hsu et al. 2011; Mafinejad et al. 2017; Demirel et al. 2015). MEMS technology has diverse applications across various sectors, including automotive, healthcare, consumer electronics. For instance, in the automotive industry, MEMS are used in systems like airbag deployment and tire pressure monitoring. In healthcare, they're used in devices for diagnostics, therapeutics and medical imaging (Patel and Rebeiz 2012).

RF MEMS switches, on the other hand, are type of MEMS that operate in the radio frequency range. They are used to manage and control the flow of signals in various RF applications. These switches are known for their superior performance characteristics, including low insertion loss, high isolation and low power consumption (Mafinejad et al. 2020; Sharma et al. 2020). They are used wide range of applications, from telecommunications to defense systems. From a marketing perspective, the key selling points of RF MEMS switches are their efficiency, reliability, and versatility. They can be used in a wide range of applications, from telecommunications to defense systems, making them a valuable asset for many different industries. To market RF MEMS switches effectively, we need to highlight these benefits in our marketing materials (Mafinejad et al. 2020; Swarnkar et al. 2019). For instance, we could create case studies that demonstrate how RF MEMS switches have improved the performance of certain devices or systems. We could also develop content that explains the technology behind RF MEMS switches in a way that's easy for our target audience to understand.

The motivation behind RF MEMS shunt switches lies in their potential to address the challenges associated with high-frequency RF signal control and manipulation in various industries, including wireless communication, radar systems, test and measurement, and scientific research. These switches aim to offer improved RF performance, fast switching times, and enhanced signal integrity, making them valuable components for advanced RF systems and devices.

RF MEMS shunt switches are micro-electromechanical systems that operate in the radio frequency spectrum. They are designed to provide superior performance in terms of low insertion loss, high isolation, and low power consumption, making them ideal for a variety of applications in the telecommunications industry.

One of the key advantages of RF MEMS shunt switches is their ability to operate at high frequencies with minimal signal loss. This makes them particularly useful in applications such as wireless communication systems, radar

systems, and electronic warfare systems. The optimal condition of an RF MEMS shunt switch is achieved when the parameters such as fast switching time, high linearity, reliability and good RF performance are carefully balanced and optimized to meet the specific requirements of the intended application or industry. The study likely investigates these parameters to determine the optimal operating conditions for the RF MEMS shunt switch, considering factors such as material properties, design considerations, and fabrication techniques. Designed a shunt type switch with decreased air gap, and they have proposed dielectric materials are  $\text{SiO}_2$  and  $\text{Si}_3\text{N}_4$  rather than  $\text{AlN}$  material for enhance the isolation (Molaei and Ganji 2017). The pull-in voltage of perforated and non-perforated type t switches are 10.5 V and 6.80 V. The return loss and insertions are  $-43$  dB,  $-0.05$  dB, and the isolation is obtained as  $-12$  dB at 62 GHz (Kurmendra et al. 2019). The actuation voltage of fixed fixed meander type switch is 9.2 V, and the S-parameters of insertion and isolation are measured as  $-0.5$  dB and  $-25$  dB for Ka-band frequency range (Molaei et al. 2017; Bhatia et al. 2021).

This paper is classified as, in Sect. 2 structure of shunt switch, working principle and it's analytical modelling analysis. In Sect. 3, results and discussions and the Section-4 is conclusion of the proposed work.

## 2 Structure of RF-MEMS shunt switch and description

The structure of an RF MEMS shunt switch typically includes a movable membrane, control electrodes, and a transmission line. The movable membrane is usually made of a conductive material and is suspended over the transmission line. The control electrodes are used to apply a voltage that can move the membrane, thereby opening or closing the switch. When the switch is in the 'OFF' state, the membrane is pulled down towards the transmission line by the electrostatic force generated by the control electrodes. This effectively shorts the transmission line, preventing any signal from passing through. When the switch is in the 'ON' state, the voltage is removed, and the membrane returns to its original position, allowing the signal to pass through.

The CPW (Coplanar Waveguide) configuration refers to the specific layout of the transmission line used in the switch. It consists of a center conductor flanked by two ground planes as shown in Fig. 1, which helps in achieving low loss and high isolation characteristics. The switch is having a suspended thin metal membrane or beam which allows or blocks the electronic transmission through the mechanical movement of the membrane above the electrode. Due to the near zero power consumption and

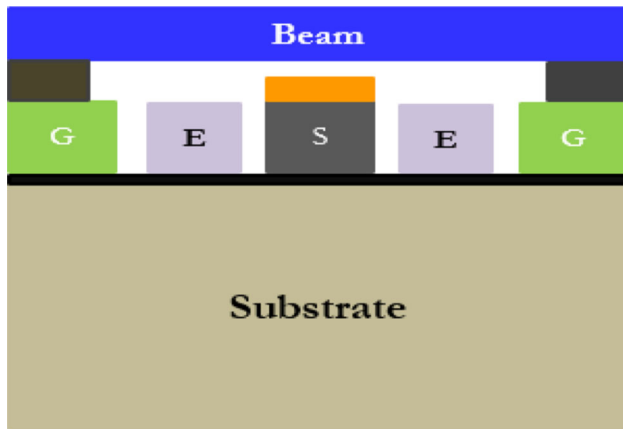


Fig. 1 Schematic of RF-MEMS shunt switch

linearity, electrostatic actuation is the most widely used, in which electrostatic force is generated between the fixed electrode and movable membrane for switching operation.

The switch is designed on a substrate having a length of 600  $\mu\text{m}$ , which can be made of silicon, the beam and CPW which considering as ground (G), signal line (S) having gold material. The choice of substrate depends on factors like cost, compatibility with the fabrication process and desired performance. The switch consists of two contact pads (E) that come into contact or separate when the switch is actuated. These contact pads are typically made of as gold, here we have taken beam-1 and beam-2 which as with and without perforations and meanders as shown in Fig. 2. The design of the contact structure aims to minimize contact resistance and ensure reliable electrical connections.

A dielectric layer is placed between the contact pads to provide electrical when the switch is in the open state. This layer prevents electrical leakage and ensures proper isolation between the switch’s contacts. The switch is controlled by external circuitry that provides the necessary voltage or signal to actuate the switch. This control circuitry can be integrated on the same substrate or connected externally.

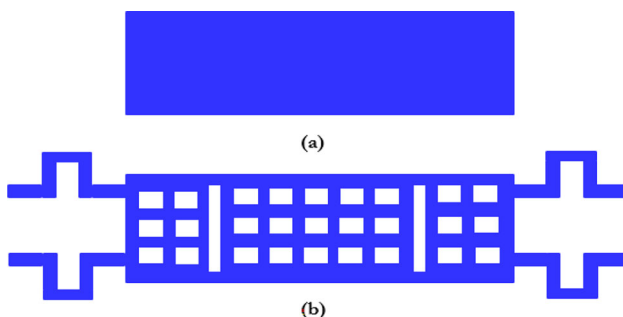


Fig. 2 Various beam structures (a), normal beam (b) meander type beam with perforations

Perforations and meanders are two key design elements used in RF MEMS shunt switches. These design features play crucial role in the performance and functionality of these switches.

These holes are strategically placed to enhance the switch’s electrical and mechanical properties. Perforations help in reducing the overall capacitance and inductance of the switch, which is important for achieving high-frequency operation. By reducing these parasitic elements, the switch can maintain good RF performance and minimize signal loss. Meanders, on the other hand, are zigzag patterns incorporated into the switch’s structure. These patterns are designed to increase the switch’s surface area without significantly increasing its overall size. By increasing the surface area, meanders help in improving the switch’s power handling capability and reducing the contact resistance. The performance of the switch with two moving plates was analyzed by demonstrating the standard equation for both plates.

The device is operating the electrostatic actuated by employing a DC voltage between the beam and CPW, and causes the membrane to fall onto the dielectric layer due to the generated electrostatic force the schematic is shown in Fig. 3. RF MEMS shunt switches utilize an actuation mechanism to control the switch’s state Electrostatic actuation is commonly used, where applying a voltage creates an electrostatic force that moves the switch’s contact.

The shunt switch operates by using a MEMS capacitor that can be electrically controlled to change its capacitance. When the capacitor is in its low capacitance state, it effectively shorts the RF signal to ground, diverting it away from the main transmission path. Conversely, when the capacitor is in its high capacitance state, it allows the RF signal to pass through the switch. The proposed model

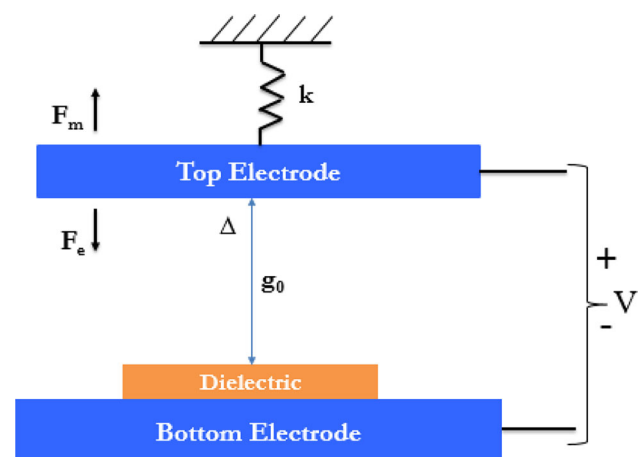


Fig. 3 Schematic equivalent model of mechanical RF MEMS shunt switch

allows the use of capacitance–voltage characteristic’s derivative, which slope is directly related to the device mechanical characteristics (Koutsourelis et al. 2016),

The DC voltage is applied between the two plates, the moving plate is displaced by  $\Delta_d$ ,

$$\Delta_d = \frac{A_r}{2k_i \epsilon_0} \left[ (V\mu_a - \mu_b)^2 + V^2 \sigma_a^2 + \sigma_b^2 - 2Vcrn_{(a,b)} \right] \quad (1)$$

The capacitance for unit area is calculated by,

$$a(x_i, y_i, \Delta_d) = \frac{\epsilon_0}{dis(x_i, y_i) + \frac{d\epsilon}{\epsilon_r}} \left[ 1 + \frac{\Delta_d}{dis(x_i, y_i) + \frac{d\epsilon}{\epsilon_r}} \right] \quad (2)$$

From the Eq. 1 substituting the ‘ $\Delta$ ’,

$$C = A_r \mu_a + \frac{A_r^2}{2k\epsilon_0^2} (\mu_a^2 - \mu_b^2) \times \left[ (V\mu_a - \mu_b)^2 + V^2 \sigma_a^2 - 2Vcrn_{(a,b)} + \sigma_b^2 \right] \quad (3)$$

The variant capacitance of the area is ‘ $\mu_a$ ’ ‘ $\mu_b$ ’ and ‘ $crn_{(a,b)}$ ’ is the relation between the two random variables,  $(x_i, y_i)$  are the moving electrodes.

The final capacitance of the switch is,

$$\frac{dcap(V)}{dV} = \frac{A_r^2}{k\epsilon_0^2} \left[ (\mu_a^2 + \sigma_a^2) \times V - \mu_a \mu_b - crn_{(a,b)} \right] \quad (4)$$

The proposed switch dimensions are given in the Table 1.

## 3 Results and discussions

### 3.1 Pull-in voltage

The pull-in voltage of an RF MEMS shunt switch is a critical parameter that determines the voltage at which the switch transitions from the ‘OFF’ state to the ‘ON’ state. This is the voltage at which the electrostatic force overcomes the mechanical restoring force, causing the movable membrane to be pulled down towards the transmission line, thereby closing the switch.

The exact pull-in voltage can vary depending on several factors, including the design of the switch, the materials

used, and the dimensions of the components. However, it’s typically in the range of a few volts to tens of volts.

The pull-in voltage is calculated by using formula is (Gopi et al. 2022),

$$V = \sqrt{\frac{8Kg_0^3}{27\epsilon_0 A}} \quad (5)$$

where, ‘ $A$ ’—actuated area, ‘ $K$ ’- spring constant, ‘ $g_0$ ’—the gap between, ‘ $\epsilon_0$ ’ is the permittivity. The spring constant ‘ $K$ ’ is calculated by,

$$K = \frac{EWt^3}{L^3} \quad (6)$$

where ‘ $E$ ’ is the young’s modulus, ‘ $w$ ’, ‘ $t$ ’ are the width and thickness, ‘ $L$ ’ is the length.

The various beam structures are designed with gold materials for calculating pull-in voltages are 5.8 and 3.6 V for beam-1 and beam-2 with airgap of 1.8  $\mu\text{m}$ . The simulation results and graphical representation of both switches are shown in Figs. 4, 5 and 6. From the Figs we have observed that non-uniform meanders with perforations-type beam obtained low pull-in voltage.

### 3.2 Capacitance analysis

In the ‘OFF’ state, when the movable membrane is not in contact with the transmission line, the switch behaves like a parallel plate capacitor. The capacitance in this state, often referred to as the OFF-state capacitance, is determined by the area of the plates (the beam and the transmission line), the distance between them, and the permittivity of the material in between.

When the switch is in the ‘ON’ state the membrane makes contact with the transmission line, effectively shorting it. The capacitance in this state, known as the on-state capacitance, is typically much higher than the ‘OFF’ state capacitance. The up state capacitance is calculated as (Sravani et al. 2019),

**Table 1** Dimensions of the proposed design

Sl. no	Structural component	Length ( $\mu\text{m}$ )	Breadth ( $\mu\text{m}$ )	Height ( $\mu\text{m}$ )	Material
1	Substrate	600	200	180	Silicon
2	Oxide layer	620	200	2	Silicon dioxide
3	Ground	300	300	1	Gold
4	Signal line	80	200	1.5	Gold
5	Beam	220	70	1	Gold
6	Meanders	30	10	1	Gold
7	Perforation	10	10	1	–

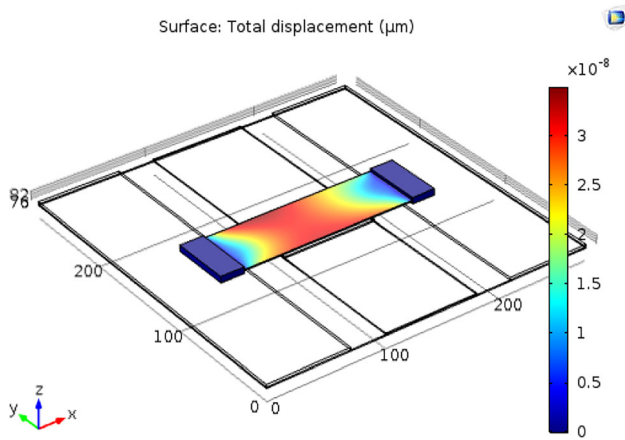


Fig. 4 Voltage versus displacement of the beam-1

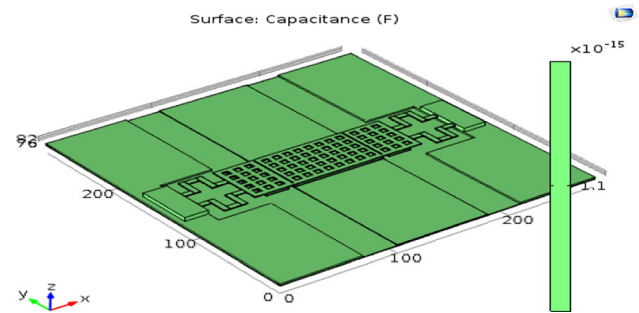


Fig. 7 Capacitance analysis of proposed beam-2

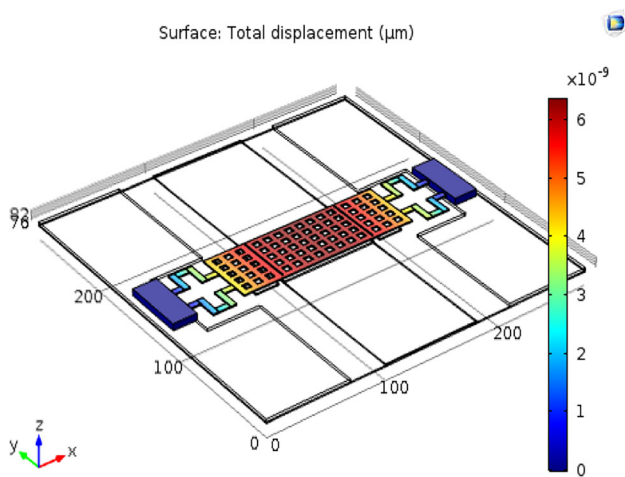


Fig. 5 Voltage versus displacement of the beam-2

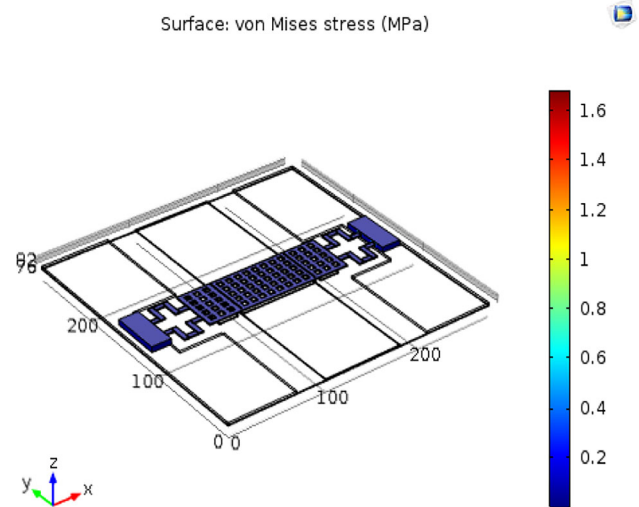


Fig. 8 Stress analysis simulation of beam-2

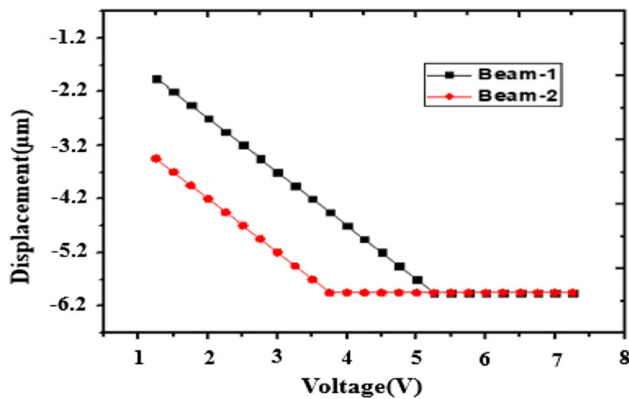


Fig. 6 Voltage versus displacement of beam-1 and beam-2

$$C_u = \frac{\epsilon_0 A}{g_0 + \frac{t_d}{\epsilon_r}} \tag{7}$$

where ‘A’- area, ‘ $t_d$ ’- thickness, ‘ $\epsilon_r$ ’- relative permittivity of

dielectric layer. The simulation of proposed beam-2 is shown in Fig. 7.

$$C_d = \frac{\epsilon_0 \epsilon_r A}{t_d} \tag{8}$$

The up and down state capacitance proposed beam-2 is obtained as 11.09 fF, 4.61 pF. The calculated capacitance values are crucial for achieving good RF performance in RF devices as they directly influence signal loss, signal integrity, switching speed, frequency response, power consumption, and impedance matching, all of which are essential for high-performance RF applications.

### 3.3 Stress analysis

The stress analysis of an RF MEMS shunt switch is a crucial aspect of its design and performance evaluation. This involves understanding how mechanical stress can affect the switch’s operation and longevity.

The movable membrane in the switch, which is typically made of a thin layer of metal or semiconductor material, is

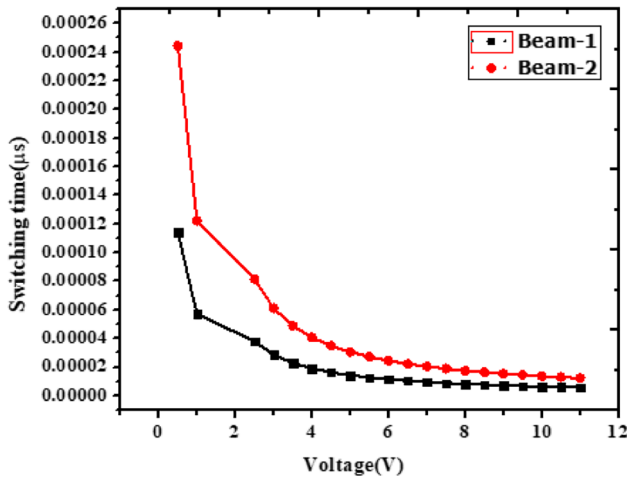


Fig. 9 Switching time of beam-1 and beam-2

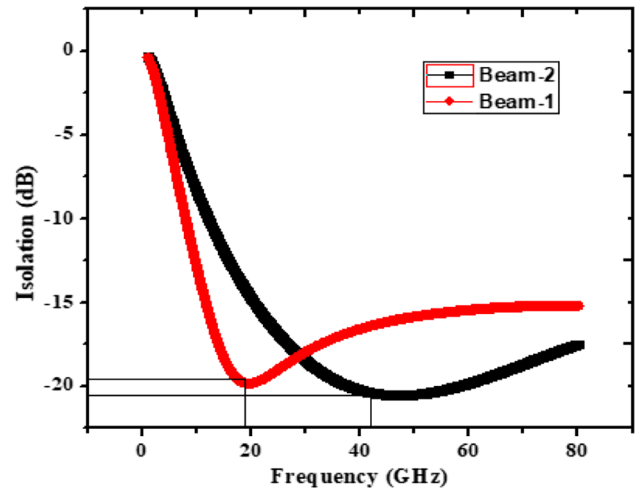


Fig. 12 Measured isolation of both beam structures

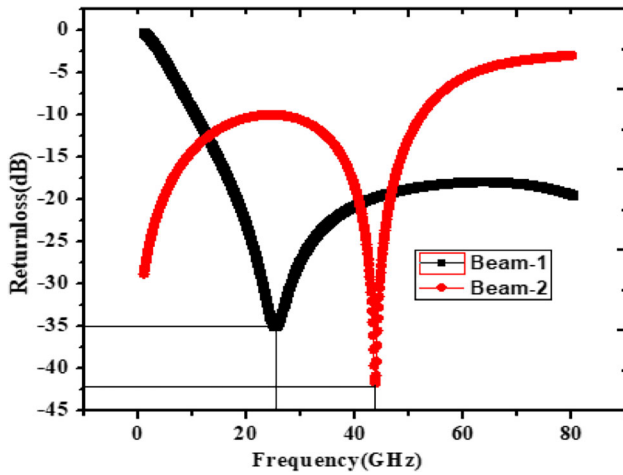


Fig. 10 Return loss of proposed beam-1 and beam-2

subject to various stresses. These include tensile stress when the switch is in the ‘OFF’ state and the membrane is

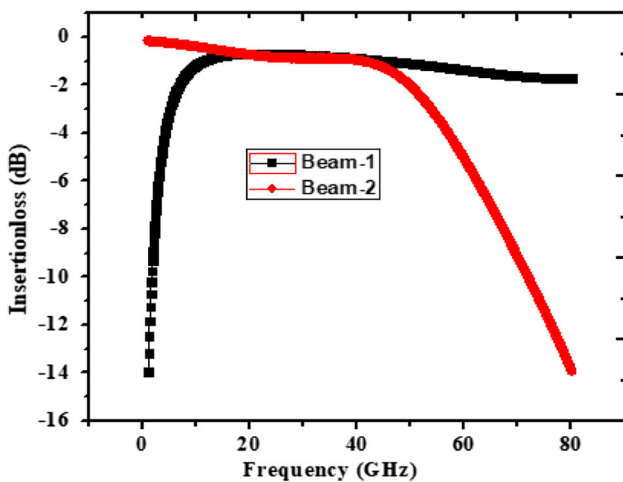


Fig. 11 Insertion loss of two beams

Table 2 S-parameters of proposed models

S-Parameters	Beam-1 (dB)	Beam-2 (dB)
Return loss	− 35.29	− 42.95
Insertion loss	− 0.76	− 0.87
Isolation	− 21.02	− 22.34

suspended above the transmission line, and compressive stress when the switch is in the ‘ON’ state and the membrane is pulled down towards the transmission line, the stress analysis is calculated and simulated by using (Gopi et al. 2021) Eq. 9, it is having 1.6 MPa Poisson’s ratio ( $\nu$ ) as shown in Fig. 8.

$$\sigma_{cr} = \frac{\pi^2 E t^2}{3l^2(1 - \nu)} \tag{9}$$

where, ‘ $t$ ’, ‘ $l$ ’ are thickness and length, ‘ $E$ ’- the material Young’s modulus, ‘ $\nu$ ’ is the Poisson’s ratio.

### 3.4 Switching time analysis

The mechanical properties of the membrane, such as its stiffness and damping, play a significant role in determining the switching time. A stiffer membrane will generally have a faster switching time, while a higher damping factor can slow down the switching process. The actuation mechanism, which applies the voltage to move the membrane, also affects the switching time. The design and efficiency of the actuation mechanism can impact the speed at which the membrane moves, thus influencing the overall switching time.

The switching time of an RF MEMS shunt switch can have a significant impact on its RF performance. The fast

**Table 3** Comparison analysis of proposed switch with previous works

Switch parameters	Reference (Mafinejad et al. 2017)	Reference (Demirel et al. 2015)	Beam-1	Beam-2
Pull-in Voltage	18 V	22 V– 25 V	5.8 V	3.6 V
Up-capacitance	0.13fF	–	–	11.09 fF
Down capacitance	2.2 pF	–	–	4.61 pF
Stress analysis	15–25 MPa	5 MPa	–	1.6 MPa
Switching time	3 μs	–	2.5 μs	6. 2 μs
Return loss	– 20 dB at 6– 24 GHz	–	– 35.29 dB at 20 GHz	– 42.95 dB at 41.21 GHz
Insertion loss	– 0.9 dB at 6–24 GHz	–	– 0.76 dB at 20 GHz	– 0.87 dB at 41.21 GHz
Isolation	– 18 dB at 6–24 GHz	– 20 at dB 28 GHz	– 21.02 dB at 20 GHz	– 22.34 dB at 41.21 GHz

switching time of RF MEMS switches makes them suitable for high-frequency RF applications where rapid switching is required. However, it’s important to note that the actual switching time can vary based on the specific implementation and operating parameters of the RF MEMS switch.

The various voltages of switching time graph as shown in below Fig. 9, It is obtained as 6. 2 μs

$$T_s = \frac{3.67V_p}{V_s\omega_0} \tag{10}$$

‘ $V_p$ ’ pull-in voltage, ‘ $V_s$ ’ is supply voltage, ‘ $\omega_0$ ’ is resonance frequency.

A fast switching time is generally desirable as it allows for faster reconfiguration of the RF circuitry, which can be crucial in applications such as adaptive RF systems, and RF front-end modules.

### 3.5 Electromagnetic analysis

RF performance analysis of an RF MEMS shunt switch involves evaluating its performance characteristics in the radio frequency (RF) domain. This analysis helps determine how well the switch operates within the desired frequency range and meets the requirements of specific RF applications.

Capacitance is a key parameter for achieving good RF performance in RF MEMS switches and other RF devices due to its influence on the device’s electrical characteristics. The capacitance of the switch affects its ability to maintain signal integrity at high frequencies (Ahmadpour et al. 2023a, 2023b, 2023c). Lower capacitance leads to reduced signal loss and distortion, which is essential for maintaining the quality of RF signals in high-frequency applications. The insertion loss refers to the amount of signal power loss when the switch is in the ‘ON’ state. Lower insertion loss ( $S_{12}$ ) is desirable as it indicates better signal efficiency. Return loss ( $S_{11}$ ) quantifies the amount of reflected power at the switch’s input or output ports. A lower return loss indicates better impedance matching and

reduced signal reflections. Isolation ( $S_{21}$ ) measures the ability of the switch to prevent signal leakage when it is in the ‘OFF’ state. Higher isolation ensures minimal interference between different RF paths. The S-parameters are obtained by using (Pramanik et al. 2023; Liu et al. 2017; Zhu et al. 2022, 2023; Jiang et al. 2023) the below Eqs. 11 and 12,

$$S_{11} = -20 \log \left| \frac{-j\omega C_u Z_0}{2 + j\omega C_u Z_0} \right| \tag{11}$$

$$S_{21} = -20 \log \left| \frac{2}{2 + j\omega C_d Z_0} \right| \tag{12}$$

where, ‘ $C_u$ ’- up-state capacitance, ‘ $C_d$ ’- down-state capacitance  $\omega$  is the resonance frequency, ‘ $Z_0$ ’- characteristics impedance.

When the switch is in ON state the return and insertion losses of beam-1 and beam-2 are measured as – 35.29 dB, – 42.95 dB, – 0.76 dB, – 0.87 dB at 20 GHz and 41.21 GHz as represented in Fig. 10, 11. The isolation is measured as – 21.02 dB, – 22.34 dB at 20 GHz and 41.21 GHz as shown in Fig. 12. From the Figs. 10,11,12 we have observed that by comparing both beam structures, the beam-2 is having good RF-performance also changing the frequency shifting from 20 to 41.21 GHz range, because of we have incorporated the uniform meander and perforations, these techniques is enhance the performance and frequency shifting. The S-parameters of the proposed models are represented in Table 2.

The proposed beam-1 and beam-2 are compared with existing works as shown in Table 3.

## 4 Conclusions

In this paper, an RF MEMS shunt type switch is designed for multi-frequency applications. For selection of beam is the crucial part for getting good performance, here two beam structures are designed and simulated. Various techniques are used to obtain low actuation voltages and improve RF performance. Here we have adopted uniform

meanders and perforations (beam-2) for low actuation voltage of 3.6 V, normal beam (beam-1) is obtained as 5.8 V compared to analytical and simulated. The switching time is obtained as 6.2  $\mu$ s. The capacitance of the proposed switch is 11.09 fF, 4.61 pF. The measured S-parameters of return and insertion loss are  $-35.29$  dB,  $-42.95$  dB,  $-0.76$  dB,  $-0.87$  dB, and the isolation is obtained as  $-21.02$  dB,  $-22.34$  dB at 20 GHz and 41.21 GHz, the improved RF performance offered by the RF MEMS shunt switch can find applications in Ka band and various high-frequency systems and devices that require fast and reliable RF signal switching and control.

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**Data availability** The authors will be provided the data upon reasonable request.

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