Design and performance analysis of a low-pull-in-voltage RF MEMS shunt switch for millimeter-wave therapy, IoT, and 5G applications

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Abstract
Recent advancements in wireless communication systems utilize miniaturized devices based on microelectromechanical system technology for present and future 5G wireless applications. Nowadays, RF devices are utilizing frequencies up to 30 GHz with substantial signal propagation that leads to a slow data rate. On the other hand, there is a huge spectrum available in the millimeter-wave frequency range of 30–300 GHz. The millimeter-wave spectrum is attractive for the development of smart systems based on 5G technology. In this paper, a low-pull-in-voltage capacitive type RF MEMS switch is proposed to operate at frequencies above 30 GHz. The switch is proposed with a new iterative meandering technique where the span length of each section in the meanders differs relative to the first section. A low pull-in voltage of 1.8 V is achieved with a large capacitance ratio of 63. The switch exhibits low insertion loss of −0.24 dB at 41 GHz and possesses high isolation of −46.7 dB at 38 GHz. The design is validated by comparing the theoretical and simulated results, and the switch can be efficiently utilized for millimeter-wave applications.

Keywords Iterative meander · Millimeter wave · 5G applications · High isolation · Low insertion loss · Low pull-in voltage

1 Introduction
Over the past decade, the evolution of microelectromechanical (MEMS) technology has contributed significantly to the development of modern-day devices, especially in the fields of wireless communication systems, sensors, and biomedical applications [1]. Nowadays, MEMS devices operating in the radio-frequency (RF) range have shown superiority over contemporary semiconductor devices and paved the way for the development of a wide variety of reconfigurable devices [2], which can change their characteristics based upon the application. Passive components such as reconfigurable antennas, reconfigurable filters, variable inductors, and phase shifters are major devices in communication systems [3] which utilize RF MEMS switches as their primary component for their reconfigurable functionality. Traditionally, semiconductor switches such as PIN diodes and field effect transistors (FETs) have been used in these architectures to develop reconfigurable functionality, but they suffer from serious RF losses when operating at high frequencies (above 3 GHz). Therefore, in high-frequency applications, RF MEMS switches have evolved as a best alternative for semiconductor switches. They possess negligible leakage current, high isolation, and low insertion losses during signal transmission and have large tuning ratios and low power consumption [4].

RF MEMS switches are mainly classified into series and shunt types based on the configuration. The series type switches can be easily realized with metal-to-metal contact, whereas the shunt configuration utilizes a capacitance model which does not establish any physical contact to change its state [5]. Series switches are developed using a cantilever beam structure and require less voltage to actuate, whereas capacitive shunt switches are bridge type models connected
at both ends and require high voltage for beam deformation. In spite of high actuation voltage, capacitive shunt switches offer higher isolation and lower insertion losses during signal transmission than cantilever type switches at both microwave and millimeter wave frequencies (above 10 GHz) [6].

Over the past two decades, extensive research has been carried out to lower the actuation voltage. Manivannan et al. in 2011 focused on reducing the switch pull-in voltage by proposing a suspended spring in the form of a cantilever beam with varying sections. In the analysis, it was found that the total number of sections could not be reduced by a value of 10 because of low stiffness of the beam. Hence, the meander could not hold the beam lying above the contact area and was not appreciable. The proposed switch showed a low pull-in voltage of 5.22 V at \( n = 10 \) and beam thickness \( = 1 \mu m \) [7, 8]. Shekhar et al. in 2014 presented a low pull-in-voltage RF MEMS switch with L-shaped supports as meanders to suspend the beam. The switch was optimized with a beam thickness of 0.5 µm and obtained low pull-in voltage of 4.8 V. Besides low pull-in voltage, the fabricated switch showed high reliability of 10 million cycles without degradation of RF performance [9]. Attaran and Rashidzadeh proposed a helix-structured restoring spring to achieve low pull-in voltage. Perforations were introduced in the beam to reduce the damping effect and increase the actuation mechanism. The switch was designed and optimized using the CoventorWare tool, and measurement results indicated a pull-in voltage of 0.5 V, making the switch ideal for integration with available low-voltage complementary metal–oxide–semiconductor (CMOS) technology, but the switch suffered from low RF performance characteristics [10]. Molaei and Ganji et al. proposed a novel beam with a step structure to lower the pull-in voltage by reducing the gap between the beam and electrodes. Uniform serpentine single meanders were used to suspend the step-structured beam with an air gap of 2 µm over the electrodes and 0.7 µm above the transmission line. The pull-in voltage obtained with this proposed step-structured beam was 2.9 V, with high isolation in RF performance characteristics [11]. In 2017, Narayana et al. developed a nonuniform meander switch with aluminum nitride as a dielectric layer. The nonuniform meander offered low spring stiffness to produce low pull-in-voltage of 4.2 V with a high capacitance ratio of 65.22. However, the proposed switch did not show satisfactory results in terms of isolation, which was 20 dB at around 2 GHz for X-band applications [12]. During the period 2015–2018, Guha et al. proposed different uniform and nonuniform meanders to reduce pull-in voltage. They proved that a nonuniform single meander offered low pull-in voltage to 4.9 V [13]. In 2018, Shekar et al. proposed an electrostatically actuated RF MEMS switch for millimeter-wave applications designed and fabricated with L-shaped beams as a spring and achieved a low pull-in voltage of 4.8 V. The switch also displayed good RF performance of \(-27.5 \) dB at 40 GHz and good reliability, with a quality factor of 1.2 and fast switching time of 33 µs [14].

In this paper, a novel uniform meander is proposed that utilizes two sections formed by a series connection of beams. The span length of the second section is double that of the first section, where to further reduce the spring constant the section has to be increased by increasing the span length in an iterative manner. Hence, the meander is often referred to as an iterative meander type, which is presented by having two sections. The meander offers a low spring constant to reduce pull-in voltage. When the voltage is removed, the first section offers strong restoring forces which restore the suspended membrane to its original position. The proposed meander reduces the pull-in voltage of the switch and provides good electrostatic actuation in transmission of RF signals through a coplanar waveguide (CPW). The switch was designed with optimized dimensions to transmit RF signals at 41 GHz. The performance parameters of the proposed switch are then analyzed using a finite element method (FEM) tool.

The remainder of the paper is organized as follows: Section 2 describes the parametric modeling of the switch. Section 3 explains the proposed structure and fabrication process. In Sect. 4 the performance parameters are analyzed. The work is summarized in the conclusion section, followed by references.

## 2 Structure and design methodology

### 2.1 Structure and dimensions of proposed switch

The two-dimensional (2D) model of the proposed switch, which is presented in Fig. 1, is composed of silicon substrate that acts as a platform for the transmission line. A CPW was chosen as the transmission line to propagate the RF signal. Between the transmission line and substrate, a thick layer of insulator is taken to avoid substrate leakage effects during signal transmission. A membrane is suspended over the CPW transmission line to regulate the passage of RF signal

![Fig. 1 Two-dimensional schematic of the proposed switch](image)
through the CPW, which is achieved by the capacitance effect formed between the suspended beam and CPW. To enhance the capacitance, a thin dielectric layer is placed over the signal line of the CPW (Fig. 2). During signal transmission mode, the suspended beam is not pulled down, offering a very negligible impedance path. To turn OFF the switch, the suspended membrane is actuated vertically downwards with the help of biasing pads placed adjacent to the signal line. These biasing pads are supplied with voltage to attract the suspended beam towards them and cause the breakdown of the suspended beam over the dielectric layer. This increases the total impedance of the switch, and the switch moves into an OFF condition without propagating the RF signal. Perforations are introduced into the membrane to reduce the air damping effect on it during actuation. The typical dimensions of the switch presented in the three-dimensional (3D) structure in Fig. 3 are optimized to propagate the RF signal at 41 GHz and are given in Table 1.

2.2 Proposed fabrication process

A four-mask process was utilized to fabricate the proposed RF MEMS switch with optimized dimensions prescribed for it. Initially, a silicon wafer, as shown in Fig. 3a, was chosen as a substrate due to high resistivity (> 10 K Ω cm) and also the possibility for monolithic integration. The first step in the process was the development of a 1-μm oxide layer as shown in Fig. 3b over the silicon surface by a thermal oxidation process carried out at 975 °C. A lift-off resist (LOR) and positive photore sist (PPR) material (AZ5214) was deposited over the insulating layer as shown in Fig. 3c. Photolithography was carried out using mask-1 (defined for the CPW and biasing pads), and the exposed region of the LOR and PPR was etched off to form trenches for the CPW and biasing pads, as shown in Fig. 3d. A Cr/Au/Cr stack with thickness of 50 nm/400 nm/50 nm was deposited over the patterned surface by a DC sputtering technique, as shown in Fig. 3e. Later, the LOR and PPR was lifted off such that the Cr/Au/Cr stack present over it was also lifted off, thus forming the desired CPW and biasing pad structures, as shown in Fig. 3f. Mask-2 (defined for the dielectric layer) was used in photolithography to define the region for the dielectric layer, as shown in Fig. 3g–h. Later, a thin layer of silicon nitride having a thickness of 0.1 μm was deposited using the plasma-enhanced chemical vapor deposition (PECVD) method over the top of the switch surface, as shown in Fig. 3i. The region where the dielectric layer should be present was taken as a dark field in the mask-2, and the other region was exposed to UV rays by photolithography. The exposed region was then etched off to form the required thin dielectric layer over the signal line of the CPW. A sacrificial layer made of
positive photoresist was grown to a height of 2 µm, as shown in Fig. 3j, which is useful for forming the suspended structure of the membrane. Photolithography was carried out using mask-3 (anchors), and the trenches were formed for anchors. Gold metal was then deposited with a thickness of 0.5 µm using a DC sputtering technique at room temperature, as shown in Fig. 3k. Again, photolithography was carried out using mask-4 (defined for the meanders and membrane), and an undefined region for anchor meanders and the perforated membrane was etched off using a wet etching process (KI:I₂:H₂O). Later, the membrane was released, as shown in Fig. 3l, by washing away the sacrificial layer with isopropyl alcohol (IPA), distilled water, and H₂SO₄ solutions. The released switch was then placed in a critical-point dryer to remove the moisture on the surface of the switch to avoid stiction problems.

### 3 Parametric modeling of the switch

The proposed structure of the RF MEMS switch was realized by using a movable beam, where one end was fixed to the anchor through a spring and the other was movable, as shown in Fig. 4. Here, the suspended membrane acts as a movable beam, and the iterative meanders acts as a spring. The gap between the lower electrode and suspended membrane was reduced by electrostatic actuation.

During electrostatic actuation of the switch, the suspended membrane experiences two forces: mechanical force ($F_m$) offered by the stiffness of the spring (meanders) and electrostatic force due to existence of potential difference between the lower electrode and suspended membrane. The mechanical restoration force is equal to the rate of change in potential energy w.r.t. displacement ($I_{g_0} - g = \delta$) [15].

$$F_m = \frac{dE_p}{d(g_0 - g)} = k(g_0 - g) = K\delta$$  \hspace{1cm} (1)

where

$$E_p = \frac{1}{2}K(g_0 - g)^2$$  \hspace{1cm} (2)

When a potential difference is created between parallel plates, an electrostatic force is induced between them and is given by

$$F_e = \frac{1}{2}V^2dC(g) = -\frac{\epsilon_0AV^2}{2g^2}$$  \hspace{1cm} (3)

At equilibrium state, the mechanical and electrostatic force are equal in opposite directions.

$$F_e = F_m$$  \hspace{1cm} (4)

Equating the two forces, we express the supply voltage as

$$\frac{1}{2}\frac{\epsilon_0AV^2}{g^2} = K(g_0 - g)$$  \hspace{1cm} (5)

Supply voltage

$$V = \sqrt{\frac{2K}{\epsilon_0A}}g^2(g_0 - g)$$  \hspace{1cm} (6)

The supply voltage is a function of the spring constant, overlapping area, and gap between the parallel plates. The instability of the switch occurs after the suspended membrane is deflected to a certain extent, and the gap can be evaluated by the derivation in supply voltage with respect to $g$.

$$\frac{dV}{dg} = 0$$  \hspace{1cm} (7)

$$\frac{2K}{\epsilon_0A}g_0 = \frac{2K}{\epsilon_0A}3\epsilon^2 = 0$$  \hspace{1cm} (8)

### Table 1 Switch specifications

| Switch component | Length (µm) | Breadth (µm) | Thickness (µm) | Assigned material |
|------------------|-------------|--------------|----------------|------------------|
| Substrate        | 820         | 620          | 450            | Silicon          |
| Membrane         | 320         | 90           | 0.5            | Gold             |
| Biasing pads     | 100         | 90           | 1              | Gold             |
| Signal line      | 620         | 100          | 1              | Gold             |
| Dielectric layer | 100         | 100          | 0.1            | Si₃N₄            |
| Insulating layer | 820         | 620          | 1              | SiO₂             |
| Anchor × 4       | 10          | 5            | 2.5            | Gold             |

µm = micrometers
Hence, the instability of the switch occurs at two thirds of the air gap between the parallel plates. Therefore, the pull-in voltage of the switch is obtained by substituting the $g$ value in the supply voltage (Eq. 6)

$$V_{\text{pull-in}} = V\big|_{g = \frac{2g_0}{3}} = \sqrt{\frac{8K}{27\varepsilon_0 Ag_0}}$$

where $K$ is the spring constant of the meanders, and $A$ is the overlapping area between the suspended membrane and biasing pads along the signal line.

The spring constant of the switch is provided by the proposed iterative meanders as shown in Fig. 5. The span length of the first iteration is taken as 40 µm, whereas the second iteration is 80 µm. Hence, the overall spring constant can be calculated by evaluating the stiffness of each iteration section. Each iteration section of the beam is connected end-on-end such that the stiffness of each beam can be calculated by the equation

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

As the switch membrane is suspended by four single iterative meanders, the total spring constant of the switch is four times the effective spring constant.

Initially, when the switch is not actuated with any supply voltage, a small RF voltage (1 mV) is applied to the signal line, which creates a potential difference between the suspended beam and signal and develops the upstate capacitance given by

$$C_{\text{up}} = \frac{\varepsilon_0 W_s w_b}{g_s + \frac{A}{\varepsilon_s}}$$

where $W_s$ is the width of the signal line and $w_b$ is the width of the suspended membrane, $g_s$ is the air gap between the parallel plates, and $t_d$ is the thickness of the dielectric layer. During this up state, the RF signal is transmitted through the CPW with low reflection losses developed by upstate capacitance which is given by [16]

$$S_{11} = \frac{-j\omega C_{\text{up}}Z_0}{2 + j\omega C_{\text{up}}Z_0}$$

The insertion losses ($S_{21}$) occur during this state due to material properties of the transmission [17] and are calculated as

$$|S_{21}|^2 = \frac{1}{|S_{11}|^2} \left( \frac{C_{\text{up}}}{C_{\text{down}}} \right)^2$$

where $W_{bp}$ is the width of the biasing pads. The developed capacitance at this state is very high in terms of picofarads and changes the state of the switch to OFF condition. Isolation is the RF parameter which shows the effectiveness of the switch operation to isolate input and output ports during the OFF state [18]. It is given as

$$|S_{21}|^2 = \begin{cases} \frac{4}{\omega^2 C_{\text{down}}^2 Z_0^2} & \text{for } f \ll f_0 \\ \frac{4R_s^2}{\omega^2 L_s^2} & \text{for } f \approx f_0 \\ \frac{4}{\omega^2 L_s^2 Z_0^2} & \text{for } f \gg f_0 \end{cases}$$

4 Results and discussion

4.1 Electromechanical analysis

Simulations of the switch were carried out using an FEM tool (COMSOL Multiphysics software) designed in the electromechanical interface physics environment. The suspended membrane along with the meanders, which is movable during actuation, was considered as linear elastic material.
meanders were fixed to the anchors by assigning a fixed constraint to the anchors. A contact force equal to the electrostatic force was applied to the suspended membrane and was supplied with a ground terminal. A supply voltage terminal was assigned to the biasing pads to develop capacitance during switch actuation. The total spring constant of the switch was obtained as 0.68 N/m and supplied the necessary mechanical force opposite the electrostatic force over the membrane. The pull-in voltage of the switch was identified by observing the membrane displacement equal to one third of the air gap, which was 0.8 µm, as shown in Fig. 6. Theoretically, by using Eq. (6), it was obtained as 1.7 V.

The calibration of the membrane displacement w.r.t to supply voltage was analyzed, and the pull-in voltage of the switch was observed to be 1.8 V, as shown in Fig. 7. Initially, when the switch was not actuated with supply voltage, a small capacitance evolved due to a potential difference existing between the signal line and suspended membrane. From Eq. (13), theoretically, the upstate capacitance was obtained as 37 fF, which is very close to the simulation result of 36.4 fF, as shown in Fig. 8.

When the switch was actuated to the down state, the increase in capacitance was theoretically observed as 2.24 pF and was also very close to the simulated result of 2.31 pF, as shown in Fig. 9. The calibration of the increase in the capacitance of the switch at various supply voltages is presented in Fig. 10. A sudden increase in the capacitance occurred at the pull-in voltage of the switch, which showed the transition of the switch from the ON to OFF state.

4.2 Electromagnetic analysis

The electromagnetic characteristics of the switches were examined using Ansys HFSS software. Insertion loss is the transmission loss that occurs during the ON state, and isolation occurs during the non-transmission mode, which is the OFF state. During transmission modes, insertion loss should be minimum for better transmission of the signal fed through the CPW structure, and isolation should be high. The proposed switch was simulated to analyze the electromagnetic characteristics over the frequency range of 0–65 GHz, as presented in Fig. 11. The switch was optimized to transmit
the signal with the upper cutoff frequency of 41 GHz. Without optimization, the switch design can allow a wide range of frequencies, but it degrades the signal power during transmission. The optimized design shows very low return loss of $-49.2$ dB at 41 GHz and good insertion loss of $-0.24$ dB (less than $-1$ dB) and can be efficiently utilized for millimeter-wave applications. The proposed optimized switch design showed resonance at the desired frequency of 41 GHz. High isolation of $-46.7$ dB was seen at 38 GHz. The proposed design was compared with state-of-the-art switches for validation (Table 2).

### 5 Conclusion

In this paper, the design and performance analysis of a shunt type capacitive RF MEMS switch is proposed using an iterative meandering technique for low pull-in voltage actuation. A low spring constant meander (0.68 N/m) was developed to reduce the pull-in voltage, achieving 1.8 V during actuation. Capacitance variation during switch actuation was observed with a capacitance ratio of 63. The proposed switch showed good insertion loss of $-0.26$ dB at 41 GHz and exhibited high isolation of $-46.7$ dB at 38 GHz. The switch showed good performance over the millimeter-wave frequencies (22–71 GHz) and can be efficiently employed in devices used for high-frequency 5G mobile applications (38–41.5 GHz and 60 GHz) [19], millimeter-wave therapy (30–45 GHz) [20], and Internet of Things (IoT) small cell technology (22–86 GHz) [21].

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### Table 2 Comparison of the proposed design with state-of-the-art RF MEMS switches

| Parameter                      | Lin et al. [22] | Angira and Rangra [23] | Li et al. [24] | Shekhar et al. [14] | Pertin et al. [25] | This work |
|--------------------------------|-----------------|------------------------|----------------|---------------------|-------------------|----------|
| Membrane thickness (μm)        | 1               | 2                      | 1              | 0.5                 | 1                 | 0.5      |
| Air gap (μm)                   | 3               | 2                      | 3              | 2–3                 | 0.6               | 2        |
| Dielectric layer thickness (μm)| –               | 0.1                    | 0.3            | 0.15                | 0.4               | 0.1      |
| Pull-in voltage (V)            | 12              | 12.75                  | 18.3           | 4.8–6.3             | 19.2              | 1.8      |
| Capacitance ratio              | –               | –                      | –              | –                   | –                 | 63       |
| Switching speed (μs)           | –               | –                      | –              | 40                  | –                 | 11.2     |
| Insertion loss (dB)            | 0.8 dB @ 36 GHz | <1 dB up to 25 GHz    | 0.29 dB @ 35 GHz | 0.7 dB @ 50 GHz    | 0.05 dB @ 61.5 GHz | 0.24 dB @ 41 GHz |
| Return loss (dB)               | –               | 7.67 dB @ 25 GHz      | –              | –                   | –                 | 49.2 dB @ 41 GHz |
| Isolation (dB)                 | 19 dB @ 36 GHz  | 44.5 dB @ 10 GHz      | 20.5 dB @ 35 GHz | 30 dB @ 40 GHz     | 12 dB @ 61.5 GHz  | 46.7 dB @ 38 GHz |
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Data availability  Enquiries about data availability should be directed to the authors.

Declarations

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

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