Optimized vertical RF-MEMS switch design with a small actuation voltage

Kusum Dalal[1] · Tejbir Singh[1] · Pawan Kumar Singh[1]

Abstract

A vertical RF-MEMS (Radio Frequency Micro ElectroMechanical Switch) switch design is proposed in this work that features a shunt capacitive configuration and can operate at a very low actuation voltage. Besides operating on a low switching voltage, the switch behold a small value of insertion loss in Up (ON) state and offers a towering isolation factor in Down (OFF) state. A horizontal structure of bridge membrane is used in the proposed design and the switch function (with ON and OFF operating states) is provided by the vertical movement of this membrane structure that is controlled by the electrostatic actuation technique. The actuation pad is centrally fed by a Coplanar Waveguide structure. The switch performance has been analysed over a wide frequency range from 1 to 40 GHz. For obtaining a 1.5 μm vertical displacement of the bridge membrane, a sheer 3.0 Volts of pull-in voltage (V_{PI}) is required. CoventorWare and HFSSv13 tools are used in this work for designing and analysing the proposed switch. The use of fixed-fixed flexure beam configuration is chosen for switch design. Simulation results showcase excellent RF characteristics with isolation factor of −47 dB (at 32.5 GHz) and insertion loss in range of −0.01 to −1.10 dB (for 1−40 GHz frequency).

1 Introduction

RF-MEMS switches have attracted special attention, especially in the last decade, as a contender of switching devices in reconfigurable antennas designs due to their low profile and low losses advantages offered at high frequencies. It offers number of advantages over other switching circuits such as PIN diodes and FETs (Field Effect Transistors) while designing reconfigurable antennas and filters [1]. The RF-MEMS switch operates with minimum power consumption and shows high isolation factor with low insertion loss besides offering good linearity characteristics [2–8]. These features make it very useful or nearly ideal for switching purpose in wireless equipment's which works at ground as well as in space such as mobile cell phones and satellite systems. However, low switching

speeds, low shelf life and packaging issues are some of the major issues with RF-MEMS switches. Another major concern related with RF-MEMS switches is of the high voltage (around 15–60 Volts) that is needed for generating the required amount of electrostatic force which is responsible for switching action, high voltage of such magnitude creates compatibility issues of RF-MEMS switches with related control circuits [9]. Such high actuation voltage or pull-in voltage (V_{PI}) is much higher as compared to voltages associated with CMOS switches (which are around 5 Volts) and thus reducing this actuation voltage in RF-MEMS switches acts as a big challenge to the researchers.

On the basis of movement of beam/actuating structure, the RF-MEMS switches can be categorized as lateral and vertical. Surface contact and out-wafer plane displacement can be achieved using lateral switches; while, sidewall contact and in-wafer plane displacement can be obtained by using vertical switches. The vertical type switches are fabricated by using surface micromaching technique in which metal is used as structure material. On the contrary,

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bulk microfabrication technique is utilized for fabricating lateral switches wherein Polysilicon acts as structure material. Vertical type switches are more frequently used as they offer several advantages such as a low profile attribute, uncomplicated actuating structure, excellent RF performance and easy vertical movement, but vertical switches can realize only one dimensional movement (upward and downward). For achieving multi dimensional movement, lateral switches can be used but for this they need structures that have large depth to width ratios; making them incompatible with associated feedline structure [10].

A number of papers have been reported on the RF behaviour of the lateral and vertical RF-MEMS switches at higher frequencies. A comparative analysis for some RF-MEMS switches and proposed design is reflected in Table 1. Furthermore, competency of proposed design in terms of various performance parameters is illustrated in Table 1.

In this paper Sect. 1 presents introduction and related literature work. Section 2 describes the switch structure for proposed RF-MEMS switch and also its design procedure. Section 3 reflects the simulated design and performance analysis for designed switch and paper is concluded in Sect. 4.

2 Structure and design procedure for proposed RF-MEMS switch

2.1 Proposed RF-MEMS switch structure

The actuator designed in this work is arranged in shunt capacitive mode as depicted in Fig. 1, where a bridge

Table 1 Comparative analysis of various RF-MEMS switches with proposed RF-MEMS switch design

| Reference no.	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	Proposed design
Type of switch	L	L	L & V	L	L	L	V	V	V
Actuation mechanism	Electro-static	Thermal	Electrostatic	Magnetic + Electro-static	Electro-static	Electro-static	Electro-static	Electro-static	Electro-static
Structure material	Nickel	Poly-Si	Single-crystalline silicon with SOI wafers (L),Silicon dioxide and metals (V)	Silicon	Sputtered aluminium	Alumina	Silicon	Silicon	Silicon
Operating Frequency	f_o=5, 40 kHz	DC to 40 GHz	> 5 kHz	f_o=750 Hz, 4.5 kHz	1–5 GHz	1–30 GHz	Upto 140 GHz	26.5–60 GHz	1–40 GHz
Isolation (dB)	–	20	–	–	> 30	31	13.4(at 50 GHz)	45 (at 30 GHz)	47 dB (at 32.5 GHz)
Insertion Loss (dB)	–	0.1	–	–	< 0.3	< 0.67	0.33(at 50 GHz)	0.9 (upto 65 GHz)	0.01–1.10 dB (for 1–40 GHz)
Actuation voltage(V)	35–150	2.5–3.5	50–260 (L), 20–100(V)	10	9.0	90	2.5-3.0	12	3
Contact resistance (Ω)	5–20	0.1–0.3	1000 (L),3(V)	2–8	–	1.89-6	–	–	0.15–0.3
Switching speed (μs)	–	300	30 (L), 5(V)	100 (close) 20 (open)	5.0	38	–	–	-
Size	–	0.8 × 0.34 mm²	1.2 × 0.6 mm²	2 × 2 mm²	550 × 50 μm²	0.33 × 0.19 mm²	–	-	120 × 40 μm²

L Lateral, V Vertical
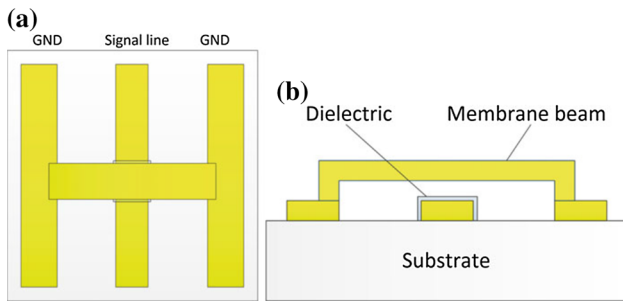
Fig. 1 Shunt capacitive configuration for RF MEMS switch. **a** Top view, **b** Side view [10]

membrane is connected with two ground strips of Coplanar Waveguide (CPW) structure and the signal strip coated with dielectric material lies underneath membrane [10].

In order to achieve actuation (vertical movement of bridge membrane) in this configuration, a switching voltage is needed at which the membrane collapses on the dielectric coated signal strip of CPW. This pull-in voltage (V_{PI}) or actuation voltage is given by standard Eq. (1):

$$V_{PI} = \sqrt{\frac{8 K_{eff} g_0^3}{27 A \epsilon_0}} \tag{1}$$

where K_{eff} is the effective spring constant of the bridge, g_0 is the in-between gap of membrane and actuation pad and A is actuation pad area.

As per Eq. (1), V_{PI} can be decreased by adopting any of the below mentioned approach:
1. By contracting the air gap g_o.
2. By increasing the actuation area A.
3. By limiting the spring constant $Keff$.

The aforesaid methods to trim down the switching voltage and boost the isolation have some consequences, like, when the air gap will be reduced, the isolation at high frequency will be decreased or insertion loss will be increased. Therefore, the method using reduction in air gap makes the switch well-suited for the low frequency applications only. On the other hand, increasing the area of actuation pad leads to bulkier switch design, while compactness is of the major goal while designing a switch. Another crucial parameter in reducing the actuation voltage is the spring constant. The lesser is the spring constant, the lesser is the actuation voltage but, the spring constant cannot be reduced beyond a certain limit, due to the fact that beam mass cannot be reduced beyond one- third of the total mass of the beam.

In this work structural aspect is utilized for reducing the pull-in voltage. Different structural designs are available for fabrication of a RF-MEMS switch such as, cantilever structure, diaphragm structure or beam/bridge structure. The fixed-fixed beam structure is used in this work to

design the MEMS switch to accomplish the lower actuation voltage. A Coplanar Waveguide (CPW) is used as the feeding structure in this paper as it shows less dispersion characteristics, offers wide impedance bandwidth and is compatible with active devices. The CPW structure is developed over the silicon substrate and have profile dimensions set as: S/W=84/120 and H=600 μm (50 ohm). The proposed actuator design is depicted in Fig. 2.

2.2 Design procedure

The steps taken in designing the desired optimized RF-MEMS switch are mentioned as under:
1. A buffer layer of silicon dioxide (SiO_2) of 1 μm thickness is planted over the silicon (Si) substrate.
2. A gold (Au) layer with a depth of 4 μm is deposited over SiO_2 buffer layer and patterned for designing the Coplanar Waveguide feedline structure.
3. Silicon Nitride (Si_3N_4) layer with 0.15 μm thickness is deposited over Au layer using Chemical Vapor Deposition process and patterned to act as a dielectric layer in-between bridge membrane and CPW feedline structure.
4. For attaining a flat membrane a fill-in layer is spun coated in the CPW feedline slots using photoresist layer of 4 μm thickness.
5. For providing support in framing a stable and smooth bridge membrane a photoresist sacrificial layer of 1.5 μm thickness is deposited and patterned.
6. A bridge membrane of thin gold (Au) film of 0.6 μm thickness is formed by evaporation and wet etching process.
7. In order to liberate the metal membrane, the fill-in layer and sacrificial layer made up of photoresist material are etched out using oxygen plasma etching process.

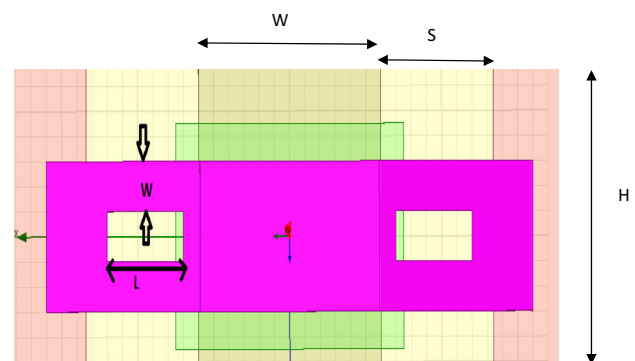The profile details for proposed switch are tabulated in Table 2.

Fig. 2 Fixed-fixed flexures beam structure over CPW

Table 2 Profile details for proposed RF-MEMS switch

A (μm^2)	w (μm)	l (μm)	t (μm)	g_o (μm)	L (μm)
120 × 40	10	184	0.6	1.5	508

2.3 Proposed RF-MEMS switch design

CoventorWare simulation tool is used for designing the proposed switch. The 3-D model of designed switch is depicted in Fig. 3.

The bridge membrane and Coplanar Waveguide feedline will behave as a parallel plate capacitor with silicon nitride (Si_3N_4) as the dielectric layer in-between. In absence of applied voltage between these electrodes, the two electrodes lie far apart and a very small capacitance (up-state capacitance C_u) exist between them, which allows input signal to reach output port successfully. In this arrangement the switch lies in its ON state as shown in Fig. 4 (b). On application of required pull-in voltage, the bridge membrane collapses on the dielectric coated signal line of CPW due to electrostatic force and this leads to the development of a relatively large capacitance (down-state capacitance C_d) which results in reflection of input signal at certain frequencies. In this arrangement the switch lies in its OFF state as shown in Fig. 4 (a).

3 Simulation results and analysis

The investigation of micro level RF-MEMS switch can be conducted using FEM (Finite Element Method)/ FEA (Finite Element Analysis). CoventorWare and HFSS v13 simulation tools are used in this work for designing the switch and carrying out the performance analysis of the

designed shunt capacitive switch. The performance of designed switch is analyzed over an extensive range of frequency varying from 1 to 40 GHz.

3.1 Electrostatic performance

The proposed switch shows excellent electrostatic performance resulting in actuation of switch at a small actuation voltage of 3 Volts. The displacement versus pull-in voltage curve is depicted in Fig. 5, which shows the required actuation voltage to be 3 Volts. The electrostatic force distribution over the metal bridge membrane structure (fixed-fixed flexure beam structure) of the designed switch is depicted in Fig. 6.

3.2 RF performance

The insertion loss (S_{12}) and isolation factor (S_{21}) are the two valuable parameters that characterize the RF performance of a RF-MEMS switch as they aid in calculating the C_u and C_d respectively. The relationships of both have been shown in standard Eqs. (2) and (3) respectively:

$$|S_{12}|^2 \approx \frac{\omega^2 C_u^2 Z_0^2}{4} \tag{2}$$

$$|S_{21}|^2 \approx \frac{4}{\omega^2 C_d^2 Z_0^2} \tag{3}$$

HFSSv13 simulation tool is used in this work for getting the desired simulation results for insertion loss (S_{12}) and isolation factor (S_{21}) and the characteristic plots of both S_{12} (for ON state) and S_{21} (for OFF state) are presented in Figs. 7 and 8 respectively.

It is observed from Fig.7 that the insertion loss extends in the range of –0.01 to –1.10 dB for 1–40 GHz frequency. A maximum isolation factor of –47 dB is monitored at 32.5 GHz as shown in the Fig. 8 . The frequency at which maximum isolation is obtained can be varied by adjusting

Fig. 3 Three-Dimensional model of proposed switch **a** Side view **b** Top view
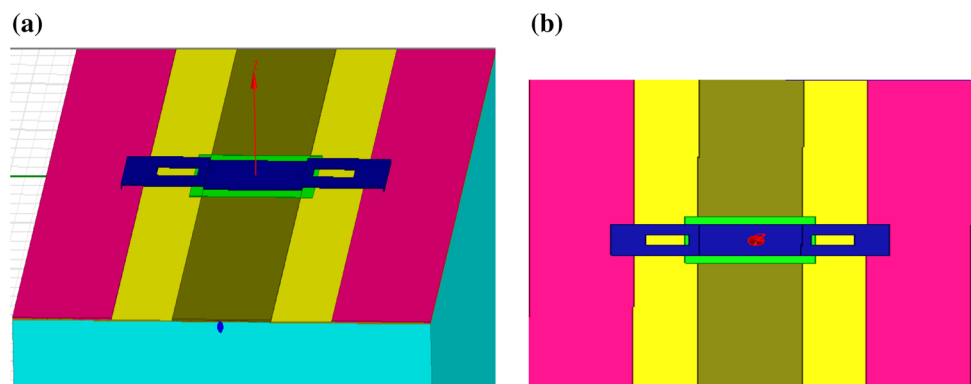
(a)

(b)

Fig. 4 Switch states **a** Side view down (OFF) state, **b** Side view up (ON) state.

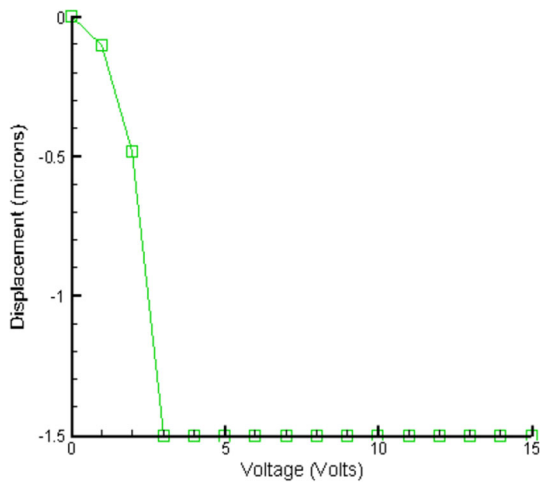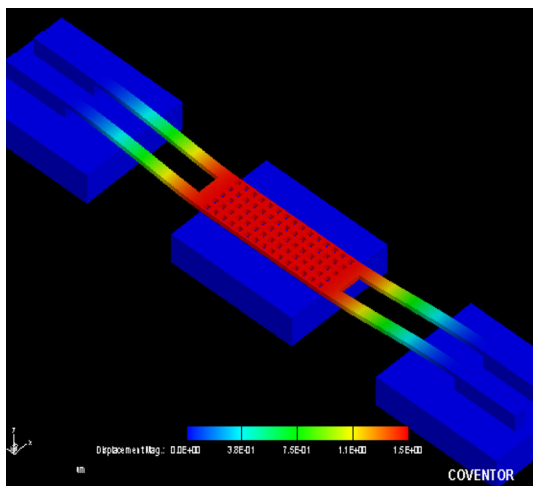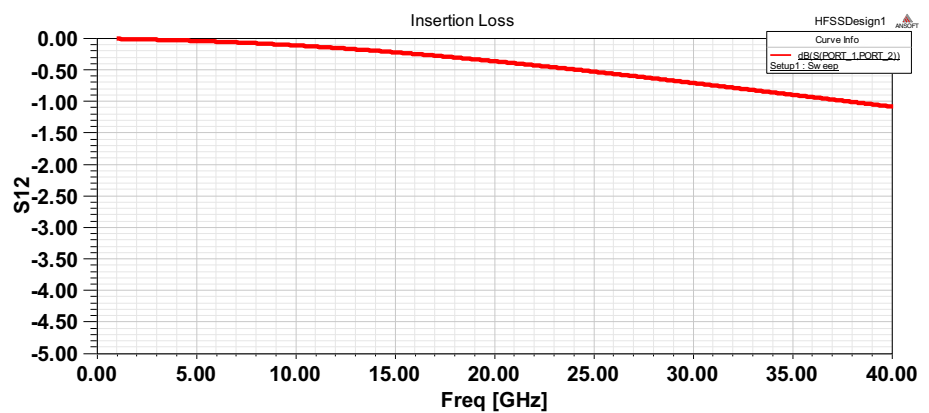**Fig. 5** Displacement versus V_{PI} characteristics

Fig. 6 Electrostatic force distribution on bridge membrane (OFF state)

the OFF state capacitance C_d. This property makes such switches well suited for high frequency applications.

In Fig. 9 (a) and (b), the return loss is illustrated for the proposed switch design for both ON and OFF switching states. In OFF state (Down state) almost a 100 % reflection of input signal has been observed as seen from Fig. 9 (a). While, in ON state (Up state), the maximum power transfer from input to output has been visualized from the Fig. 9 (b).

4 Conclusions

This paper presents an optimized vertical shunt capacitive RF-MEMS switch design that actuates at a very low pull-in voltage. The performance of the proposed design has been analyzed over an extensive range of frequency varying from 1 to 40 GHz using FEM/FEA method. CoventorWare and HFSSv13 simulation tools are used in this work for designing and analyzing the proposed switch. The fixed-fixed flexure beam structure has been used for designing the proposed switch, which helps to minimize the actuation voltage upto the satisfactory level of 3.0 Volts. The simulation results portray an excellent RF performance for the designed switch over the entire selected frequency band. A small insertion loss in the range of –0.01 to –1.10 dB for 1–40 GHz frequency and an elevated isolation factor of the order of –47dB (32 GHz) has been witnessed from the simulation results. Such RF characteristics make such switch suitable for high frequency applications. The return loss results also verify the promising switching capabilities of the designed switch.
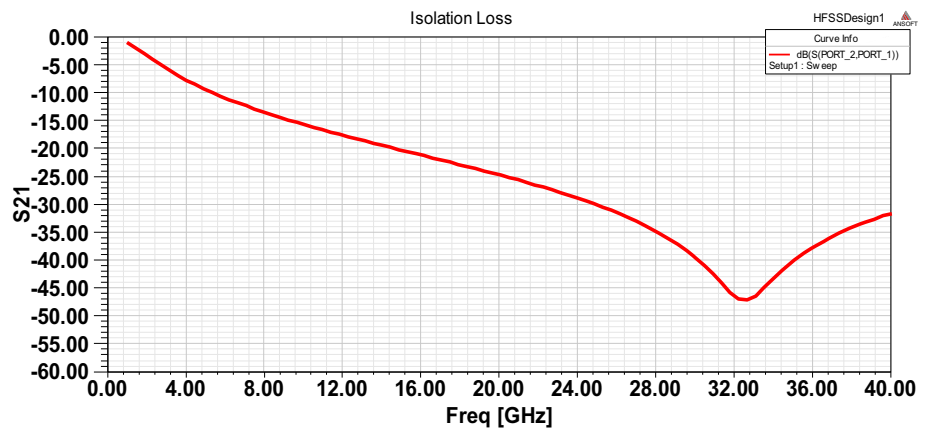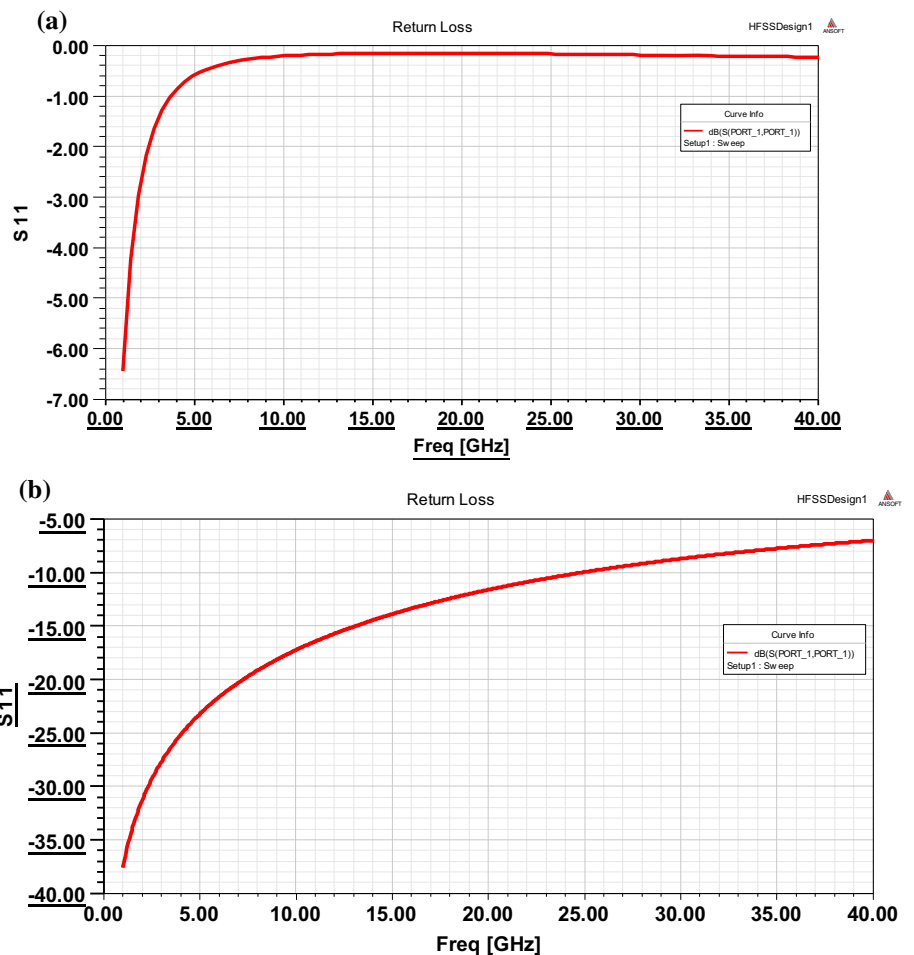
Fig. 7 Insertion Loss for Up (ON) State

Fig. 8 Isolation Factor for Down (OFF) State

Fig. 9 The Return Loss curves **a** Down State (OFF) and **b** Up (ON) State

Declarations

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

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