Design, Simulation and Performance Analysis of Novel Cantilever Rf-Mems Switch Using Serpentine Meanders

N. Siddaiah, Vamsi Aravind Swamy Tentu, MD. Z Rehman

Abstract: In this paper, we have designed a novel RF MEMS cantilever structure and optimised its dimensions through parametric analysis to minimize the actuation voltage and to enhance the performance of the RF MEMS series switch at Ka-Band frequency. The selection of appropriate materials for the device is also done through the electromechanical parametric analysis. We minimised the dimensions of the switch and increased the performance. To enhance the performance and characteristics of the proposed device electromechanical and solid mechanical analysis such as pull in voltage ,capacitance, switching time, stress analysis, RF performance analysis have been done. The pull in voltage is reduced to 5.5V and the switching time taken by the switch is 0.10msec, Up capacitance formed between the electrodes in ON state is 29.3Ff and Down capacitance is 3.05Pf which are obtained through the Finite element model tools i.e., Comsole 5.0.The RF performance of the switch is done by using the Ansys HFSS simulator ,the switching is having less than 1dB insertion loss and isolation of -28.0dB at 30GHz. the proposed device structure can be used at high frequencies in wireless applications and satellite applications.

Index Terms: Cantilever beam, RF-MEMS switch, serpentine meander, spring constant.

I. INTRODUCTION

The RF-MEMS switches are an alternative to mechanical switches and semiconductor switches which are being used at present in the electronic and satellite communication sectors. As we know the mechanical switches are capable of providing very less losses but are slower in performance and bulk in size. On the contrary, the semiconductor switches have faster switching time and smaller in size but obtain high insertion loss. [1] To rectify this problem the RF-MEMS switches come into the picture. RF-MEMS switches are miniaturized in size as well as offer less isolation losses and obtain faster switching time [2]. The RF-MEMS switches are of categorized into two categories: a) Cantilever type b) Air-bridge type based upon their clamp configuration. Among these the cantilever type RF-MEMS switch has been considered because this switch has less actuation voltage when compared to the Air-bridge type RF-MEMS switch [3].

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The radio frequency (RF) technology has been transformed tremendously since the early 1990's over a series of events. The need for distributed systems has been increased over the existing centralized systems which lead to the preference of short range systems with moderate RF power over the long range systems with large RF transmit power[4]. On the other hand, the conventional switches such as the P-I-N diodes and FETs are comparatively larger in size and cannot be used for the re-configurability of the devices [5]. High linearity, minute losses, wide band range and near zero power consumption are a few characteristics of ohmic contact type RF-MEMS switches when compared to the conventional switches. These kind of switches are highly apt for the communication and radar applications such as reconfigurable antennas and tunable filters [2]-[6].These switches are mainly used in reconfigurable antennas to activating and deactivating the antenna elements and alter its electrical length and frequency characteristics. Based on the mechanical movement of the beam in switches can be used for high frequency applications. First MEMS device switch is fabricated in 1979 by Petersen and the actuation of MEMS switches has investigated by many researches. The eminent research work is going on it leads to a rapid development in RF MEMS .The RF MEMS switches can be used at frequency of (27GHz - 40GHz) for 5G, Satellite communications and military air craft applications [8]. The characterization to modulate for 50 GHz frequency of RF MEMS 2-state normal state attenuator is proposed by Ianncci. Inorder to implement more number of complex RF signaling functions, the basic state module can be exploited to be a building block [20]. In the present scenario, 5G mobile communication and IOT had huge demand in the mobile communication field as stated by Ianncci. Out of the available devices, the RF MEMS switches deliver efficient results upto range of 110GHz which are being fabricated by surface micromachining technique [21]. Whereas this simple cantilever switch has been designed into a novel structure which has been restructured using the scaling laws so that the basic dimensions of the switch are kept intact while the factors effecting the spring constant are taken into consideration to reduce the actuation voltage. This makes the switch more suitable for mobile and satellite communication applications [7]. We discuss about the various parameters on which a simple cantilever type RF-MEMS switch is depended upon and perform various theoretical and simulation analysis on a cantilever type RF-MEMS switch with dimensions fixed through Ashby's method of determining the materials and dimensions for a structure.

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Now considering the switch structure the various parameters such as the spring constant, actuation voltage, insertion loss, switching time, etc are theoretically analysed and the simulation analysis is performed. The novel cantilever type RF MEMS switch has reflected various effective results which enhance the switching time, insertion loss and other parameters required for the switching operation. Here we presented a novel cantilever type RF-MEMS switch such that it reduce the limitations of the existing MEMS switch and will be a replacement to the presently using P-I-N diodes and FETs in the mobile and satellite communication. We reduced the size and pull in voltage and increased the performance of the switch which can be used at high frequency. The paper is organised as follows, section 2 explains novel structure design and its specifications, section 3 discuss about the parametric analysis of the design and simulation analysis and their discussions and section finally concludes the work done in this paper.

II. SWITCH DESIGN AND SPECIFICATION

2.1 Proposed RF MEMS switch

The RF-MEMS switch is the vital component used in the designing of reconfigurable antennas. A simple cantilever type RF-MEMS switch consists of a beam which is hanging above the RF-out terminal with a gap of 3 µm. The beam acts as a barrier between the input signal line and the output signal line. Gold is used as the beam material as it performs efficient switching when compared to other materials. A di-electric layer is deposited upon the RF output signal line such that it reduces the stiction problem during the time of contact of the cantilever beam with the Output signal line. An electrode is placed in between the RF-input signal line and the RF-output signal line such that it can be used as a pull down electrode for the cantilever beam to work as a switch. The area overlapped by the beam on the pull down electrode is known as the actuation area as it leads to the amount of voltage required for the switch to perform switching operation.

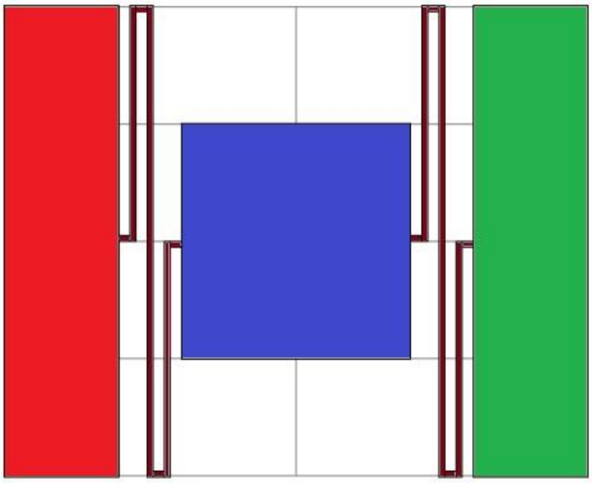

Fig.1. Design of Novel structured cantilever type RF-MEMS switch.

The novel structured RF-MEMS switch is an updated model for the existing simple cantilever type RF-MEMS switch. This structure has been introduced in order to eliminate the drawbacks and improve the efficiency of the switch. Various factors are taken into consideration such as actuation voltage, switching time, insertion loss, etc. and the work has been done in such a manner so that a novel kind of switch with better parameters has been designed. In this structure the overall area of the beam has been reduced such that the spring constant of the switch can be more reduced. By this phenomenon the actuation voltage for the switch is minimized. The contact area of the beam to the RF output signal line is also reduced by introducing a tip at the end of the beam so that stiction problem can be reduced.

Table 1. Device Dimensions

Components	Length(µm)	Width(µm)	Thickness(µm)
Beam support	250	50	1
Actuation region	100	100	1
Beam tip	50	50	1
Substrate	500	100	30
RF-input signal	75	100	1
RF-output signal	75	100	1
RF-output Dielectric	75	100	0.2
Actuation electrode	100	100	1
Pull down Dielectric	100	100	0.2

1.2 Material selection

The materials used in the designing of the switch also plays an important role in analysis of the switch. These materials have to be determined based upon various parameters such as the relative permittivity, young's modulus, density, etc. so that the switch is working in a better condition. The working principle of the switch is the process of the beam moving towards the RF-output signal line such that when the beam comes in contact with the RF-out, there is a transfer of the RF signal thus the transmission of the data takes place. But for the cantilever beam to have movement, we need to use a pull down electrode such that on applying some external voltage in between the beam and the electrode, due to the capacitance generated between the beam and the electrode the beam moves towards the RF-out signal line. This voltage applied in between the cantilever beam and the pull down electrode is known as actuation voltage.

Table 2. Materials used for the components.

Structure	Material
Beam	Gold(Au)
Substrate	Gallium arsenide(Ga As)
Di-electric layer	Silicon Nitride(Si_3N_4)
Actuation Electrode	Aluminium(Al)
Input and Output signal lines	Aluminium(Al)

III. RESULTS AND DISCUSSIONS

3.1 Parametric Analysis for Proposed Switch

The device structure has to be analysed in such a way that it should be capable of performing in various conditions.

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Thus the device has to be designed with dimensions and materials that are best suited for the application in which the RF-MEMS cantilever switch is being used.

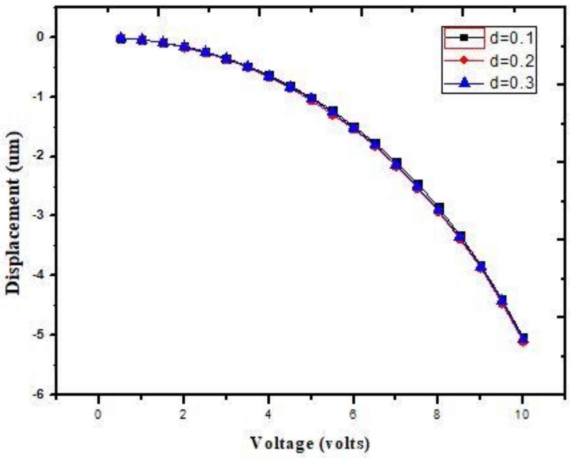

Fig. 2. Voltage vs displacement for various di-electric thickness

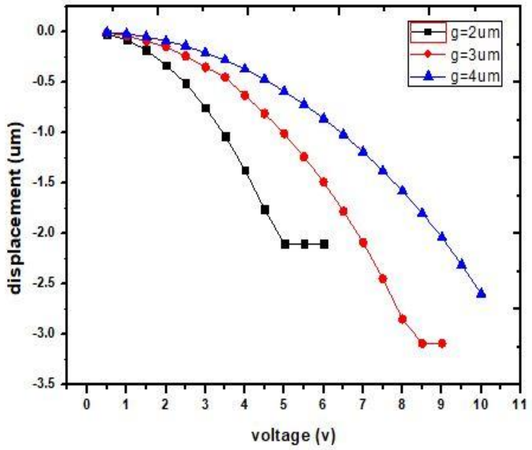

Fig. 3. Voltage vs displacement for various gaps.

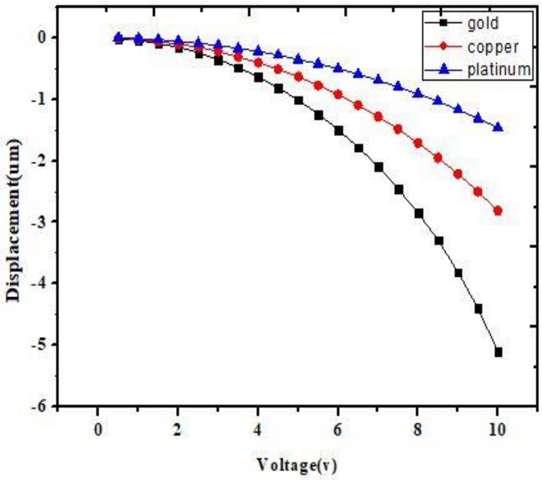

Fig. 4. Voltage vs displacement for various materials.

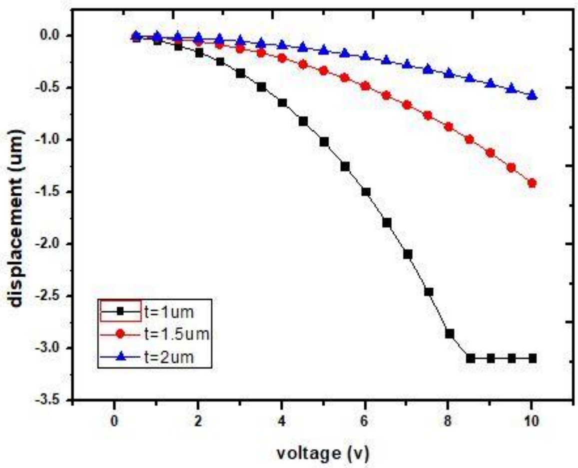

Fig. 5. Voltage vs displacement for various beam thickness.

The above information is obtained by optimizing the device structures in such a way such that the materials and the dimensions of the structure are fixed which are capable of deriving efficient outputs. Through the above analysis we had obtained that gold(Au) is a better material for the beam when compared to other elements as it has the best characteristics in terms of young's modulus, sensitivity, conductivity, etc., with respect to the remaining elements. The dimensional analysis of the switch is also performed and the switch physical characteristics such as the thickness of the beam, di-electric and gap between the actuation electrode and ground are fixed where reliable results can be obtained.

3.2 Electromechanical analysis of the device

3.2.1 Pull-in Voltage

The pull – in voltage or the actuation voltage (V_p) of the series type RF MEMS cantilever beam type switch is calculated by the equation as follows:

$$V_p = \sqrt{\frac{8kg_0^3}{27\varepsilon_0 A}} \qquad (1)$$

Where, k is the spring constant of the beam, $\varepsilon_0 = 8.85\times10^{-12}$ F/m is the permittivity of the free space, g is the gap between the actuation electrode and the ground electrode and A is the overlapping area of actuation electrode and ground electrode.

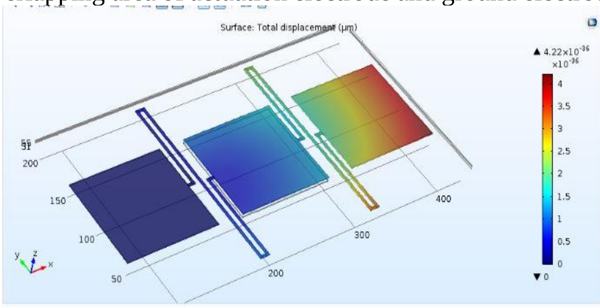

Fig. 6. Displacement of cantilever beam on applying voltage.

The actuation voltage of the proposed switch basically depends on three key factors of the beam structure. The spring constant of the beam which denotes the stiffness(K) of the structure, the actuation region of the device between the actuation electrode and the ground and the gap between the both the electrodes.

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Though the actuation voltage can be minimized by decreasing the gap between the electrodes and increasing the actuation area, is would lead to the permanent break down of the switch due to the trade off formed between the actuation voltage and total surface area of the device[9]. Moreover, the increase of actuation area leads to the increase of size of the device. Hence, minimizing the spring constant is an efficient process for decreasing the actuation voltage. In order to reduce the spring constant, the beam is designed by using an anchor to the actuation electrode and a tip structure at the end. The spring constant of the cantilever beam is given as

$$K = \frac{Ewt^3}{4l^3} \quad (2)$$

Where E is the young's modulus of the material of the beam, w is the width of the beam structure, t is the thickness of the beam and *l* is the length of the cantilever beam. From the equation above, the obtained spring constant of the cantilever beam is 0.2528 N/m.

Therefore, by substituting the obtained spring constant (K) in the equation 1, the theoretical value of the pull-in voltage is derived to be 4.78V.

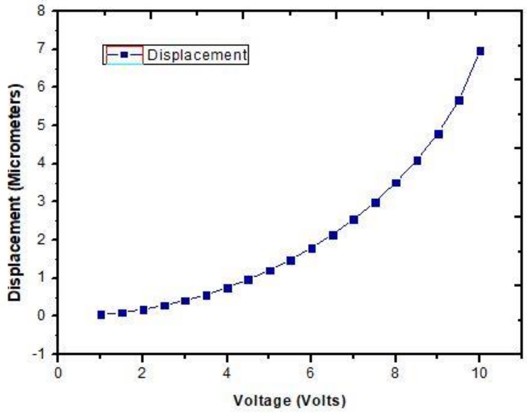

Fig. 7. Voltage vs Displacement of the cantilever beam

The RF MEMS device is simulated using COMSOL 5.2 FEM tool to obtain the required behavioural analysis results. By applying a particular voltage in between the beam and the pull down electrodes, the switch gets actuated. Thus an electrostatic force is builded in between the electrodes thus making the beam to cause displacement. The ohmic contact is displaced to 3µm at an actuation voltage of 5.5 V.

3.2.2 Switching Time Analysis

The switching time is one of the key factor in determining the performance of the switch. Pull-in voltage controls the switching time as the electrostatic forces acting on the beam are strengthened by increasing the actuation voltage [10]. The equation for obtaining the switching time is derived by equalling the initial applied force and considering the electrostatic force to be constant, we get following equation as:

$$T_s = \frac{3.67V_p}{V_s\omega_0} \quad (3)$$

Where V_p is the actuation voltage, V_s is the source voltage (V_s=1.4V_p) and ω_0 is the angular resonant frequency.

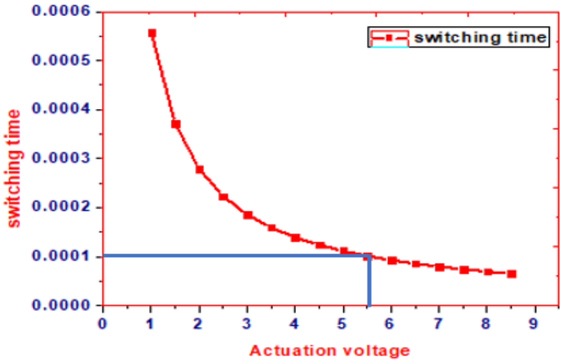

Fig. 8. Switching time analysis of the proposed switch.

The switching time for the designed device at resonant frequency where the beam undergone maximum displacement of 3µm is 0.10ms according to equation 3 as depicted in the fig. 8.

3.2.3 Capacitance Analysis

The capacitance formed due to the applied voltage between the actuation and ground electrodes is plotted by performing the electrostatic analysis. In general, the ideal dielectric material for electrostatic analysis is selected by opting a material having a relative permittivity in the range of 3.3 to 12.9. In the proposed device structure, silicon nitride is preferred as the dielectric material as it has a dielectric constant of 9.5. The upstate capacitance of the designed structure can be obtained by the following equation. [12]

$$C_u = \frac{\varepsilon_0 A}{g + \frac{t_d}{\varepsilon_r}} \quad (4)$$

In RF MEMS cantilever type switches, the beam and the di electric layer will be contacted directly thus forming a down stste capacitance formed from the equation.

$$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d} \quad (5)$$

Where, ε_0 is the permittivity of the free space, ε_r is the relative permittivity of the dielectric layer, A is the area overlapped by the two electrodes, t_d is the thickness of dielectric layer and g is the gap between the beam and the di electric layer.

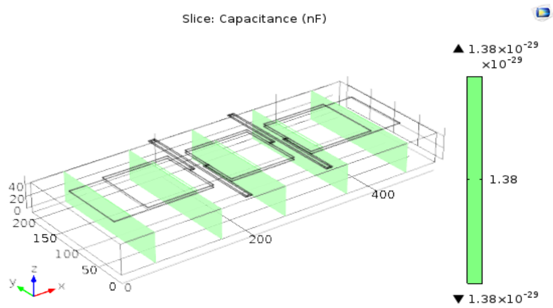

Fig. 9. Simulated capacitance result for the structure.

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The upstate and down state capacitance calculated analytically from equations above are 29.3fF and 3.05pF respectively. The capacitance obtained from the simulation of the device are 24.9fF and 2.77pF which is precisely equal to the theoretical values thus validating the capacitance analysis of the designed structure. An efficient capacitance ratio of 104.45 is obtained from the proposed switch.

3.2.4 Stress Analysis

The stress generated on the cantilever beam plays a key factor in the device performance. The effective force (F_e) is a parameter which shows the amount of stress that can be withstand by the beam of the RF-MEMS cantilever type switch. This effective force can be derived from the equation as follows [13]

$$F_e = \frac{\varepsilon_o A V^2}{2g^2} \tag{6}$$

Where ε_o is the permittivity of the free space, A is the overlapping area of the actuation electrodes, V is the pull-in voltage of the device and g is the gap between the actuation electrode and the ground electrode.

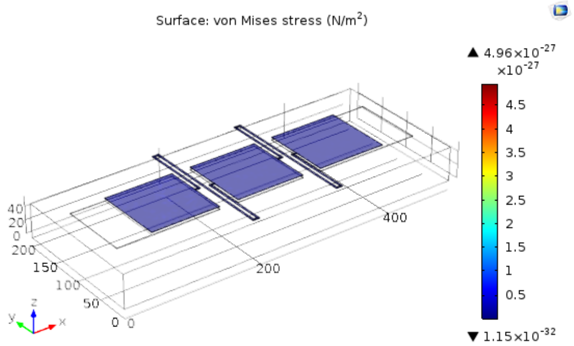

Fig. 10. Effective force developed on the cantilever beam.

The stress developing on the beam should be less than the effective force of the device so the the beam can withstand the stress formed due to the applying of the voltage. Otherwise there is a chance of breakdown of the switch[14].

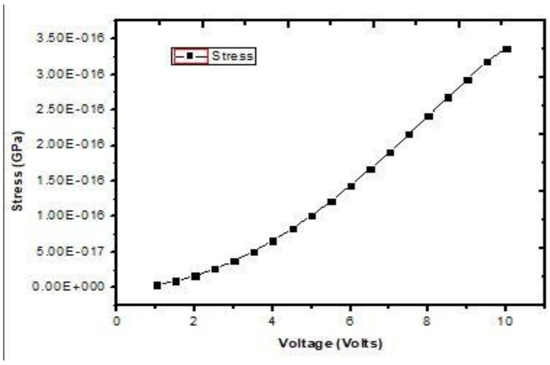

Fig. 11. Voltage vs stress distribution

3.2.5 Resonant Frequency Analysis.

The frequency at which the beam attains the maximum displacement is known as the resonant frequency. As the gap between the beam and bottom electrodes in the device is determined to 3µm, the frequency obtained at 3µm is considered to be the resonant frequency of the device [15]. The resosnant frequency of the switch is obtained analytically by the equation below:

$$F_r = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \tag{7}$$

Where K is the spring constant ant m is the effective mass of the beam structure.

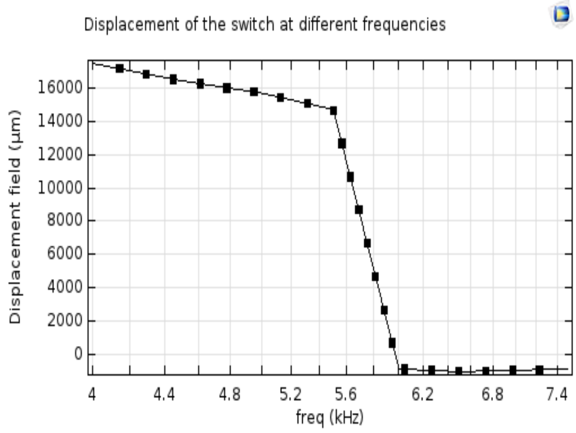

Fig. 12. Frequency Analysis of the proposed switch.

The simulated result for the resonant frequency has been obtained at 6KHz, which is almost same as the theoretical value obtained for the designed structure which is 5.6 KHz.

3.2.6 Quality Factor.

The quality factor or Q-factor of the switch is derived from the damping coefficient, resonant frequency and the spring constant of the device. The increase of the pull in voltage is occurred due to the damping of air over the beam of the device. The membrane structure plays a crucial role in analysing the damping coefficient. The minimization of the damping coefficient can be done by using various methods [14]. In this analysis the air between the beam and the pull down electrode is reduced by varying the measurements of the electrodes with respect to their widths. The damping coefficient is derived by equation below [17] is 0.033×10^{-3}

$$b = \frac{3}{2\pi}\frac{\mu A^2}{g^3} \tag{8}$$

Where µ is viscosity of air, A is the area overlapped by the actuation region and the pull down electrode and g is the gap between the beam and the ground electrode. Thus, the quality factor is given by

$$Q = \frac{K}{2\pi f_0 b} \tag{9}$$

Obtaining a quality factor of $0.5 \le Q \le 2$ depicts an efficient strucutre [1]. The switch performs at slower switching rate if the Q value is less than 0.5 and leads to long settling time when Q more than 2. In this designed device structure, the quality factor obtained is Q = 0.55 which proves that the designed device is effectively useful for switching applications.

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3.2.7RF PERFORMANCE ANALYSIS.

$|S_{21}|^2$ is used to depict the loss of signal by RF MEMS switch at Radio Frequency ranges, the decline in S_{21} is generally due to the loss of power of the switch but sometimes may be because of the rise in the reflected power of the switch ($|S_{11}|^2$)[16]. The S-parameters are helpful in determining the power loss of the designed structure.

$$Loss = 1 - |S_{11}|^2 - |S_{21}|^2 \qquad (10)$$

Where S_{11} represents the return loss when the device is in ON state and S_{21} represents the Isolation loss when the device is in OFF state. The isolation loss is obtained when the switch is in OFF state and the beam will be having no stress is obtained by the equation

$$|S_{21}|^2 = 4\omega^2 C_u^2 Z_0^2 \qquad (11)$$

Where ω is the angular resonant frequency, C_u is the upstate capacitance and Z_0 is the characteristic impedance (50Ω) [18]. The tip membrane of the beam comes in contact with the dielectric material in ON state. Thus forming a down state capacitance which creates return loss S_{11} from the equation

$$S_{11} = \frac{2jC_d Z_0}{1 + 2j\omega C_d Z_0} \qquad (12)$$

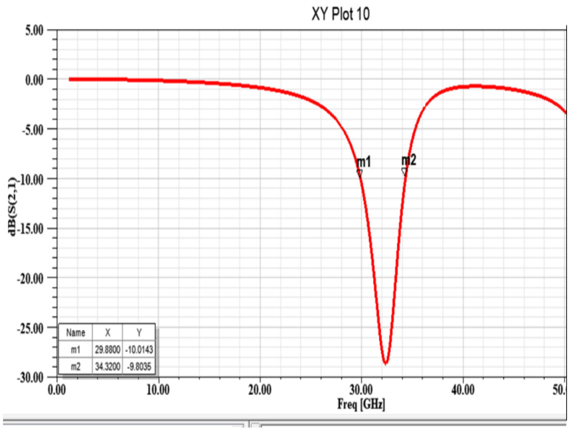

Fig. 13. Isolation loss of proposed switch.

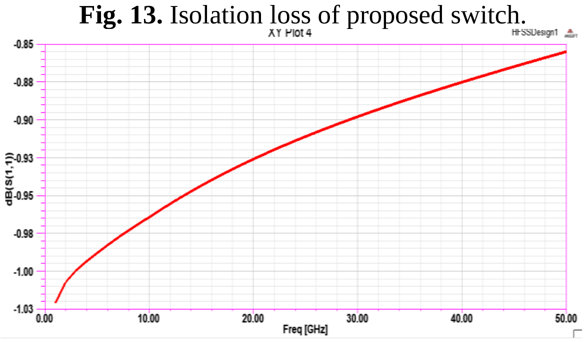

Fig.14. Insertion loss of proposed switch.

-28.6 dB and -0.89dB are respectively the isolation loss and the insertion loss achieved at 30 GHz frequency as shown in figures 13 and 14. Through the above analysis we can understand that the switch is best suitable in millimeter wave applications. Therefore this switch device can efficiently used in the design of reconfigurable antennas. In the present scenario, the mobile and satellite communication fields are providing more scope for rapid growth of RF MEMS. Series switches employing cantilever beam provides an excellent performance, when compared to the traditional PIN and FET diodes. In this work, RF MEMS switch of cantilever type model is designed and simulated by incorporating a notch on the same coplanar wave guide at the edge of the actuation area such that the stiction problem is reduced. Electromechanical analysis is performed to analyse various properties such as actuation voltage, spring constant, up-state capacitance, downstate capacitance, resonant frequency. The results are calculated theoretically and simulated results are obtained by using COMSOL and HFSS tools. The isolation losses are observed as – 28.6 dB at 30 GHz. whereas the insertion loss is obtained -0.89dB at 30GHz. The designed structure can further be analysed for communication applications upon integrating with the antenna applications.

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Compliance with ethical standards

Conflict of interest. The authors declare that they have no competing interests

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