Design and Simulation of MEMS based Varactor with High Tunability for Digital Communication Systems

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***Abstract*—This paper presents a novel design and simulation of 3-bit RF MEMS tunable capacitor for digital communication systems. Proposed varactor design consists of three parallel plate capacitors connected with truss beam. There are slices in parallel plates to increase the area tuning capability of varactors. A new beam design is proposed to reduce the stiffness of the beam which results in reduction of pull in voltage to 4.5 V. The length and width of beam is 718 µm and 80 µm. A standardized process is used for fabrication process. There are nine states of capacitance and at pull in voltage of 4.5 V maximum tunability is achieved that is 168%. Total varactor design dimensions are 900 µm × 750 µm. The beam has 2 µm thickness and low losses CPW made up of gold material. Mechanical simulation is done on INTELISUIT Software while electrical analysis done on CST microwave studio.**
Keywords— RF MEMS, fixed-fixed beam, Varactor

I. Introduction

Due to increase in demands of wireless communication system modern technologies require more sophisticated, reliable and efficient RF devices to make it useful for communication system. The performance parameters of RF MEMS technology over solid state devices has already been demonstrated [1]. In many applications conventional based switches has been replaced by RF MEMS varactors such as voltage-controlled oscillators (VCOs) [2], RF Filters [3,4] and RF matching networks [5]. All the given circuits are used for tuning or changing of operating frequency. For example, in tunable filters varactors are used to tune the pass band of filters. Implementations in conventional based varactors include off chip (GaAs p-n), silicon (Si on chip), MOS capacitors as well as junction diode suffer from low quality factor, non- linearity in CV response, resistive losses, low self-resonant frequency. RF MEMS varactor have many advantages on solid state-based varactor such as low power consumption, high linearity, light weight, small size and fast switching response [1].

Most RF MEMS varactor use electrostatic actuation to actuate the parallel plate capacitor. On comparison of MEMS varactor over MEMS capacitive switches and MEMS varactor they do not suffer from sticking. The close contact between moveable membrane and actuation electrode has been avoided. MEMS varactor also provide a continuous tuning range of signals although tuning range of such components is limited by some pull in effect. Different solution have been presented by different researcher to increase the tunability by modifying the device's mechanical design [6]. Several varactor design have been studied and fabricated [7,8].

There are three different method used to change the capacitance of parallel plate capacitors: area tuning method [9,10], gap tuning method [11-14], dielectric displacement method [15]. Different actuation mechanism for parallel plate capacitors has been used in literature: piezoelectric actuator [16], Thermal actuator [17], electrostatic actuator [18]. Due to fabrication compatibility and low power consumption of electrostatic actuator researchers use electrostatic actuation. Advantages of electrothermal is low actuation voltage and high tunability but its drawback is high power consumption. We are using electrostatic actuation which decreases the voltage requirement to make our design useful for digital communication systems. In [19], the proposed varactor is based on double actuation mechanism. It requires a high operating voltage to make it useful for microwave applications. Different approaches have been used to improve quality factor, tunability and low voltage requirements.

For broadband applications when capacitive switches or varactor are designed, designer should carefully consider the insertion loss, impedance, linearity of CV response for RF devices, for given frequency range quality factor, isolation and interconnection of circuits to additional components. There is a challenge to meet all requirements. Research shows that in a simplest design having small size, the electrostatic actuation and metallic electrode based on micromachine surface meet all above requirements. However, there is an issue of tunability. To achieve high tunability digital varactor should be utilized. In digital varactor design, many MEMS switches are arranged in parallel are in series in binary weighted scheme. Each switch can operate individually to produce maximum and minimum capacitance in upstate and downstate. Total capacitance can be obtained by summing all capacitance in varactors.

In this paper a new design of varactor is proposed. The main purpose of this work is to reduce the actuation voltage to make it useful for digital communication system. A new beam design is proposed that have low spring constant and exhibit low actuation voltage. This device is fabricated on high resistive silicon substrate by using standardized process.

II. RF MEMS VARACTOR DESGIN

A. Proposed structure

The proposed RF MEMS varactor is shown in Fig.1. It is based on electrostatic actuation mechanism. We have proposed a new design of tunable capacitor that requires a low actuation voltage and have high tunability. We can use this design for digital communication systems because of its low voltage requirement and high tunability. As shown in Fig.1 the proposed varactor design has three parallel plate tunable capacitor. The beam which is used is fixed-fixed truss beam which have dimensions: length 718 µm and width 80 µm and thickness 2 µm.

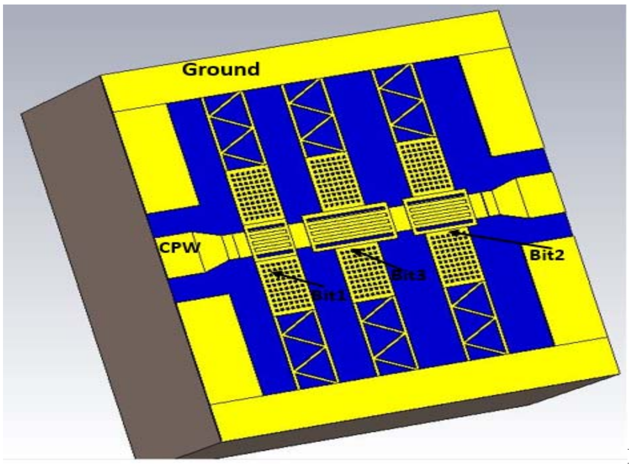

Figure 1. 3D CST Model of Proposed Varactor.

Cross section view is shown in Fig.2. Upper layer is suspended 2.7 µm above the CPW which is covered with oxide layer of 100 nm thickness. At zero biased there will be a gap of 2.7 µm. When there is no voltage applied, the upper layer remains in upstate position. When actuation voltage is applied an electrostatic force will be generated between the upper and lower plate which will force the upper plate to move downward results, decrease in gap between plates which yield the maximum capacitance.

Upper layer is of gold material having thickness of 2 µm and electrode is of polysilicon material having thickness of 0.78 µm. There are slices in capacitor plates to enhance the area tuning capability [20]. When actuation voltage is applied, upper layer moves downward, the gap between plates will be decreases as a result there will be increase in tunability. As shown in Fig.2 gap between plates reduces from x_0 to $xdown$.

B. Mathematical Modeling

At zero biase there is a gap of x_0 between upper plate and lower plate, the capacitance can be calculated as in equation (1) [1]

$$Cu = \frac{\varepsilon_0 A}{x_o + \frac{td}{\varepsilon_r}} + C_f, \qquad (1)$$

where x_0 , is initial gap between plates t_d is thickness of dielectric, ε_0 is free space permittivity, c_f is fringing field capacitance between silicon substrate and beams. After applying the voltage, plates will move downward decreasing the gap between plates from 2.7 to 1.8 results in increase in capacitance of capacitor. Fig.3 shows the front view of shunt capacitor.

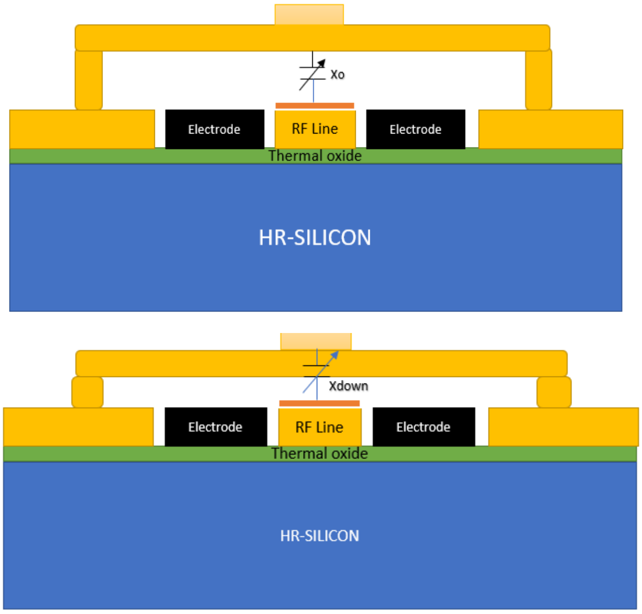

Figure 2. Cross section views of Varactor (ON state and OFF state)

When plates are in down state condition, capacitance can be measured by equation (2) [1],

$$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d}. \qquad (2)$$

Pull in voltage can be calculated by equation (3) [1]

$$V_p = \sqrt{\frac{8kx_0^3}{27\varepsilon_0 A}}, \qquad (3)$$

where k shows the stiffness of the beam, A is the area of electrode stiffness of beam that is calculated is 0.98 N/m. Tunability of varactor can be calculated by equation (4)[1]

$$T = \frac{C\,max - cmin}{cmin} \qquad (4)$$

III. SIMULATION RESULTS

A. Mechanical Analysis of RF MEMS Varactor

When electrostatic force is applied, the force is induced between the fixed and moveable plates of the actuator due to which gap between plates increases or decreases depending upon the value of applied voltages. Deflection of upper layer is analyzed which includes an initial deformation due to stresses by using intellisuite software. Upper layer material is of gold having young modulus of 79 GPa and poison's ratio 0.44. As shown in Fig.2 initially there is a gap of 2.7 µm when pull in voltage of 4.5 V is applied to the electrode, an electrostatic force will be generated between plates due to which membrane will move downward. During actuation stresses on beam structure are called von misses stress are measured these are 9.4 MPa at the end of beam to ensure that with applied force it can withstand without breaking as shown in Fig.7. This value is lower than the gold yield strength

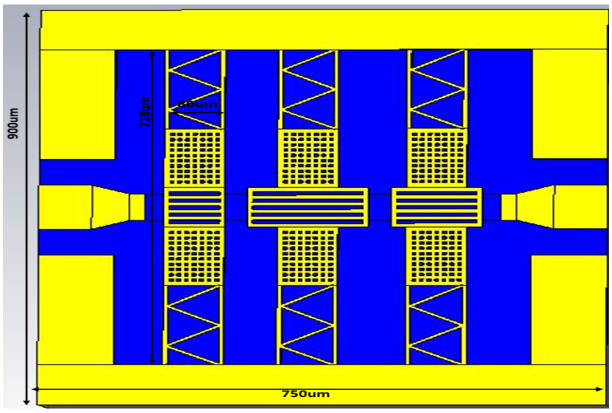

Figure 3. Front View of Proposed Varactor.

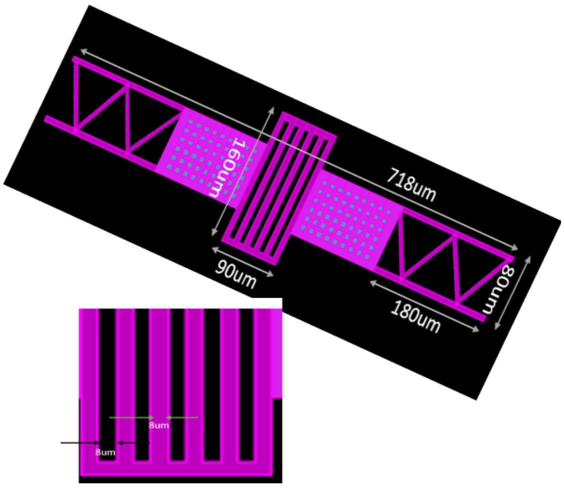

Figure 4. Schematic View of upper membrane

TABLE I. PARAMETERS OF PROPOSED VARACTOR

Parameters	Value (µm)
Contact Area	Bit 1 (90x80) Bit 2 (90x120) Bit 3(90x160)
Length of beam	380x80
Thickness of upper layer	2
Total device area	900x750
Thickness of thermal oxide	1
Polysilicon silicon	0.78
Gold thickness	2

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Fig. 5 shows the displacement with respect to applied voltage including residual stresses. By applying DC voltage to electrode, the initial gap between plates xo changes from 2.7 µm to x_{down} due to electrodes complete membrane snap down is avoided above the signal line.

Mechanical analysis of Proposed MEMS varactor has been done on Intellisuite software while RF characteristics is measured on CST microwave studio. There are three-bit RF MEMS varactor which means three plates connected in parallel, so we have 9 states of capacitance as shown in Fig.9. There are total 9 combination that can be used in any application for tunability of devices.

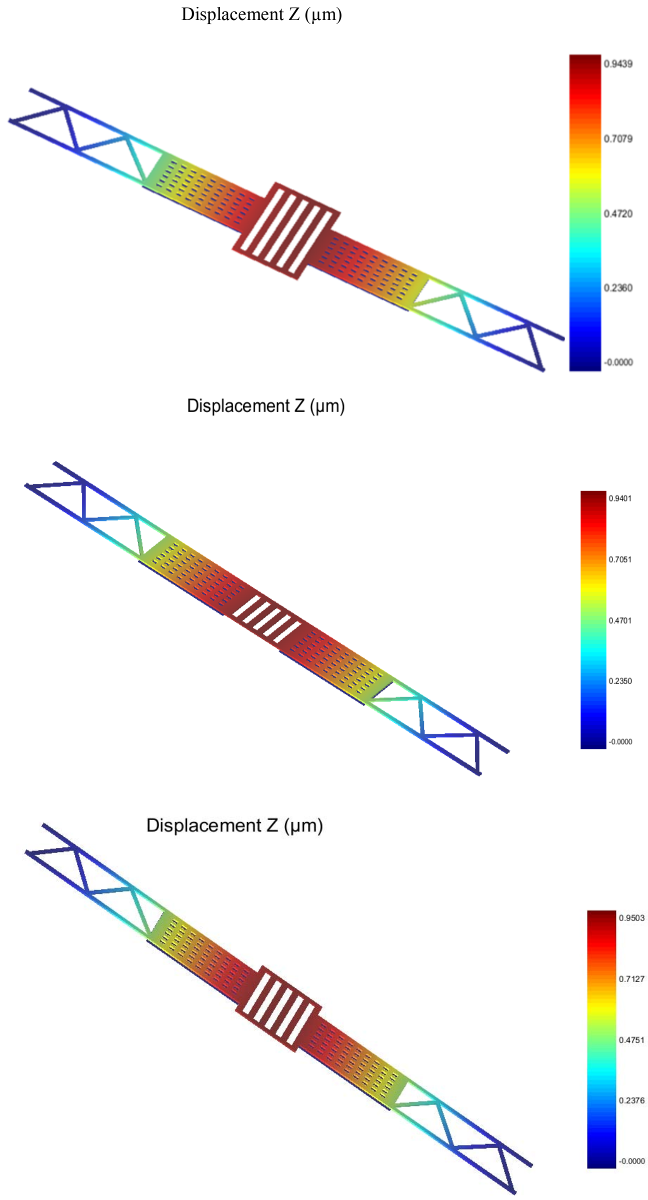

Figure 5. Displacement w.r.t Voltage

B. *Electrical Analysis of RF MEMS Varactor*

Proposed MEMS varactor have been modelled in CST microwave studio as shown in Fig.1 and 3, and dimensions are given in table 1. Ideally in OFF state when there is no voltage is applied return loses should be zero and insertion loses will be maximum as shown in Fig.10 & 11. The RF part of the proposed structure has been designed in CST software, where, the RF signal line is designed over the 525 µm thick resistive silicon layer. A dielectric layer of SiO_2 (silicon dioxide) is used because of its high dielectric constant over the silicon substrate. The dimensions of CPW are 80/70/80 µm, where signal width (S) is 70 µm and gap (G) between signal and ground is kept 5.5 µm. The standard port dimensions have been used to provide the input signal to the RF transmission line. The width of port is kept [3 x signal line width(w) + 2 x (spacing between ground & signal)], while minimum height (h) for the port is kept 4 x height of the substrate

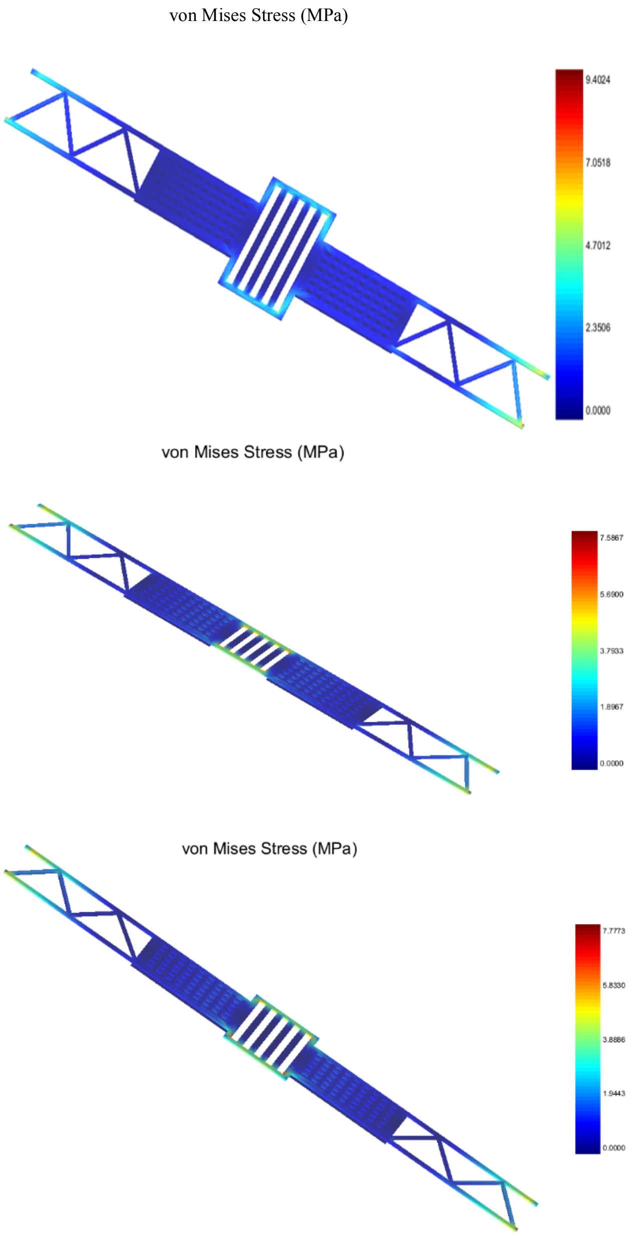

Figure 6. Stress analysis w.r.t Voltage

A high resistive silicon substrate is used to improve the performance of design. The input and output ports are designed to be 50 Ω to match the requirement of circuit. There are 9 capacitance state which shows the total change in tunability of 167% that is our capacitance is varying as shown in Fig.10. RF characteristics are measured from CST software as shown in Fig.10 insertion loses are very low from 0 to 10GHz.

There are slices are used in capacitor plate as shown in Fig.4 to increase area tuning capability of varactor [20]. Upper layer has been grounded. When voltage is not applied, the overlap area between slices of upper plate and lower plate is lower, so capacitance is low.

The minimum capacitance is achieved when all capacitor plates are in upstate condition and maximum capacitance when all plates are in down state that is achieved can be calculated by equation (5).

$$C = \frac{\varepsilon_0 A}{d} \qquad (5)$$

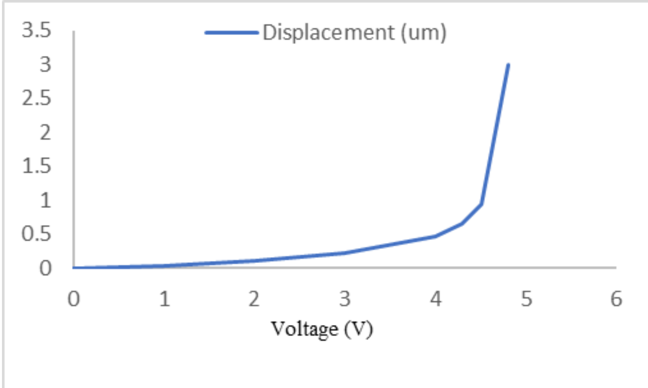

Figure 7. Upper layer displacement w.r.t applied voltage

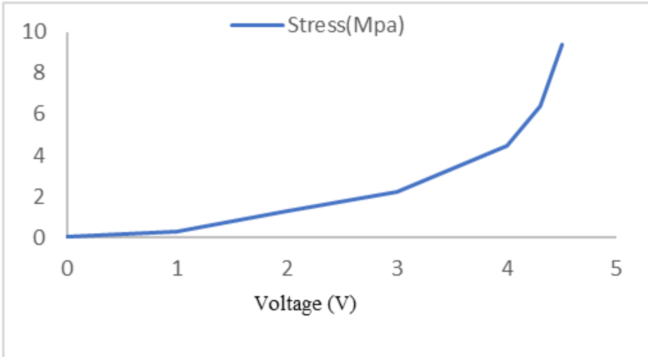

Figure 8. Von misses stress

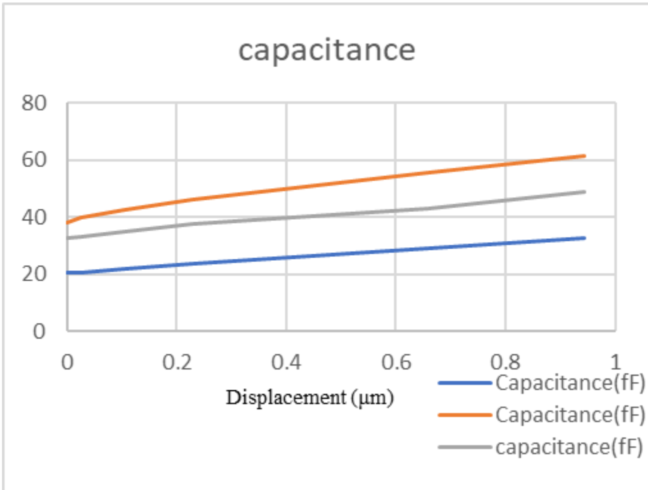

Figure 9. Capacitance value for 3 plates w.r.t to voltage.

Quality factor describes about energy loses in varactor. It depends on its impedance. Quality factor in varactor defines the loses S 1-1 can be calculated by [1]

$$Q = \frac{Im[z_{11}]}{Re[z_{11}]} \qquad (6)$$

According to equation 6 if impedance is known then quality factor can be calculated. Quality factor depends on S1-1. Lower the loses greater will be the quality factor.

Return loses, and insertion losses are shown in Fig 10 & 11. In actuated state varactor has good performance at 3.5GHz. Insertion losses are -0.01dB while return losses are -58dB.

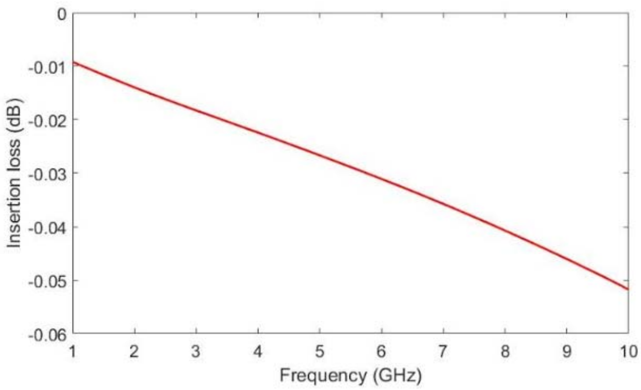

Figure 10. Insertion loses of MEMS varactor.

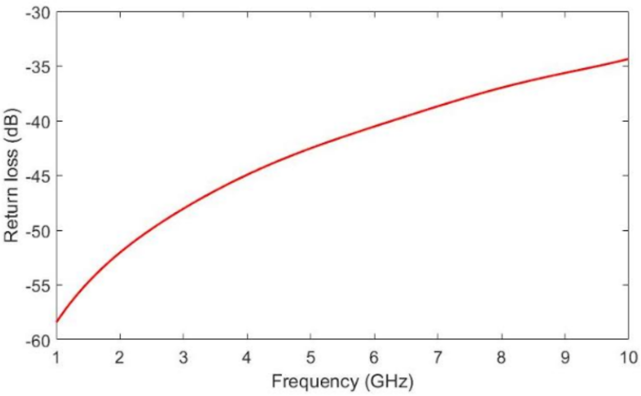

Figure 11. Return loses of MEMS varactor.

V. CONCLUSION

This paper presents a novel design and simulation of RF MEMS based varactor to enhance the tunability and reducing the voltage requirements to make it useful for digital communication systems. This device consists of 3-bit parallel plates capacitor of different dimensions results in increase in tunability of 168% at 4.5V and frequency is 3.5GHz. The proposed RF MEMS varactor is a promising choice for low voltage and high tunability.

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