Design and Analysis of a Uniform Meander RF MEMS Switch

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Abstract: This paper projected to uniform meander RF MEMS capacitive shunt switch design and analysis. The less pull in voltage is obtained in flexure type membrane by proposed RF MEMS Switch. The materials selection for the dielectric layer and beam is explained in this paper and also shown the performance depends on materials utilized for the design. The good isolation of -31dB is achieved for the pull-in voltage of 11.97V with a spring constant of 2.38N/m is produced by the switch and is obtained by the optimization process at a frequency of 38GHz.

Keywords: RF MEMS Switch, Meanders, COMSOL, HFSS.

1. Introduction

MEMS technology presents miniaturization than other technologies like CMOS and GaAs technology. They present good electrical performance with low Consumption of power and good linearity. [1-4] RF MEMS is promising technology, because of superior performance; they are spread widely in wireless communications. RF switches enable switching in transmission line they use mechanical switching Classification of MEMS switches is to be done in two different ways i.e. metal to metal. Capacitive contact switches. They best configured for high frequency applications; resistive configured switches are meant for low frequency applications [5]. Configuration is of two types’ series and shunt. Switch with shunt configuration produce improved performance. In actuated state capacitive contact was achieved by fixed–fixed switch that use metal membrane [6-9]. Capacitive contact switches have capability of power handling. When the switch is in actuated state it provides an excellent isolation. It shorts the RF signal to the ground. MEMS technology is the integration of mechanical and electrical components on single platform i.e. substrate [10]. From the literature, various researcher have proposed different RF MEMS Switch, but still there few challenges on optimization of the Switch for best performance.

To enhance the functional behavior of switch a much better optimization approach for the proposed switch is carried out at specified frequency of application in terms of low pull in voltage, better isolation and lowest possible insertion loss [11]. The switch dimensions are extracted through optimization using proposed method. The modified switch is to obtain lowest possible pull in voltage, spring constant and stiction problem, by introducing the meanders in the proposed structure. Two types of meanders i.e uniform and non uniform meandering techniques are used for the switch, [12-14]. For both the switches solid mechanical analysis and electromechanical analysis and also electromagnetic analysis are done. The dimensions and material for substrate and coplanar waveguides are used for the impedance matching. In order to lower the pull in voltage overlapping area is to be increased [15]. By maximum power transfer, impedance matching is obtained with low return loss using RF MEMS switch. The high frequency ka-Band has lot of advantages comparatively with low frequency like less interference and compact sizes [16].

The organization of the paper follows; in Section-2, the RF MEMS proposed Switch and its specifications. In Section-3, the theoretical parameters description of uniform meanders RF MEMS Switch and the materials selection for the proposed Switch. In Section-4, the electromechanical analysis carried out by COMSOL software and RF analysis carried out by HFSS software and followed by Conclusion in Section-V.

2. The RF MEMS proposed switch and its specifications

2.1. The Proposed structure of Uniform Meander RF MEMS Switch
Design and Analysis of a Uniform Meander RF MEMS Switch

2.2. The proposed Device Dimensions

Table 1. Dimensions of uniform meander switch

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Elements</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/S/G</td>
<td>Coplanar waveguide</td>
<td>56µm/95µm/56µm</td>
</tr>
<tr>
<td>H</td>
<td>Substrate Height</td>
<td>400 µm</td>
</tr>
<tr>
<td>W</td>
<td>The width of membrane bridge beam</td>
<td>186 µm</td>
</tr>
<tr>
<td>L</td>
<td>Length of a membrane bridge beam</td>
<td>558 µm</td>
</tr>
<tr>
<td>g₀</td>
<td>Air gap</td>
<td>3 µm</td>
</tr>
<tr>
<td>t₁</td>
<td>Dielectric thickness</td>
<td>0.2 µm</td>
</tr>
<tr>
<td>A</td>
<td>Square holes</td>
<td>6 µm×6 µm</td>
</tr>
<tr>
<td>A</td>
<td>Actuation area</td>
<td>186 µm×279µm</td>
</tr>
</tbody>
</table>

Table 2. uniform meander dimensions

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Length</th>
<th>Width</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>48µm</td>
<td>5µm</td>
<td>1.2µm</td>
</tr>
<tr>
<td>K2</td>
<td>55µm</td>
<td>5µm</td>
<td>1.2 µm</td>
</tr>
</tbody>
</table>

3. Theoretical parameters of uniform meander RF MEMS Switch

3.1. Effect of spring constant

There exist a direct relationship between Spring constant and pull-in voltage. The spring constant is to be very small to attain very low pull-in voltage [17]. Spring constant can be mathematically expressed as

\[ k = \frac{Ewt^3}{L^3} \quad (1) \]

Here K stands for Spring Constant stands for Young’s modulus, w,t,L stands for width, thickness and lengths respectively.

3.2. Effect of pull in voltage

The amount of voltage required for beam to pull down and make a contact with signal dielectric known as Pull in voltage. It can be calculated as [18].
\[ V_p = \sqrt{\frac{8Kg^3}{27\varepsilon_0 A}} \text{ Volts } = 8.04 \text{ Volts} \] 

Where \( g \) is the gap between electrode and beam, \( \varepsilon_0 \) stands for permittivity of free space; \( A \) stands for an actuation area.

3.3. Effect of ON state capacitance \( (C_{ON}) \)

The capacitance of a switch developed due to displacement of a beam with signal dielectric, i.e. gap is known as Upstate Capacitance \( C_{ON} \). It can be calculated by using

\[ C_{ON} = \frac{\varepsilon_0 \varepsilon_r xy}{g + \frac{t_d}{\varepsilon_r}} \text{ Farads} = 103 \text{ fFarads} \] (3)

\( x \) stands for beam width, \( y \) stands for beam length, \( g \) stands for gap from beam to dielectric, \( t_d \) stands for dielectric thickness, \( \varepsilon_r \) stands for beam material relative permittivity.

3.4. Effect of OFF state capacitance \( (C_{OFF}) \)

The capacitance of a switch developed when the when beam touches signal dielectric i.e. no air gap is known as downstate capacitance. It can be mathematically expressed as

\[ C_{OFF} = \frac{\varepsilon_0 \varepsilon_r xy}{t_d} \text{ Farads} = 7.03 \text{ pFarads} \] (4)

\( x \) stands for beam width, \( y \) stands for beam length, \( g \) stands for gap from beam to dielectric, \( t_d \) stands for dielectric thickness, \( \varepsilon_r \) stands for beam material relative permittivity.

3.5. Effect of Capacitance Ratio \( (C_{ratio}) \)

The ratio of the OFF capacitance to the ON capacitance is known as capacitance ratio.

\[ C_{ratio} = \frac{C_{OFF}}{C_{ON}} = 68.25 \] (5)

3.6. Effect of switching time analysis

The amount of time required for a switch for initiating a transition from ON state to OFF state and from OFF state to ON state is known as switching time [19] and is mathematically expressed as

\[ T_s = \frac{3.67 V_p}{V_o \omega_b} \text{ Seconds} \] (6)

\( V_p \) stands for pull-in voltage, \( V_o \) stands for supply voltage, \( \omega \) stands for resonant frequency. Therefore switch switching time equals to 0.14msec.

3.7. Effect of Quality Factor

The quality factor relates with spring constant, damping coefficient and resonant frequency. The technique used for minimizing it lives in choosing actuation electrode with different dimensions and fixed beam, so that the air gap between actuation electrode can be easily minimized[20]. The damping coefficient mathematically expressed as

\[ b = \frac{3 \mu A^2}{2\pi g^3} = 0.033 \times 10^{-3} \] (7)

\( \mu \) stands for viscosity of air, \( A \) stands for an overlapping area and \( g \) stands for gap between the electrodes. The quality factor is mathematically expressed as

\[ Q = \frac{K}{2\pi f_0 b} \] (8)

It is always better to choose quality factor of a switch between 0.5 and 2. The proposed switch achieve the quality factor of 0.55 which helps in enhancing switching activity.

3.8. Substrate Material selection

We chosen different possible suitable materials for substrate and the separate the graph between young’s modulus versus Poisson’s ratio. As shown in fig.6, substrate material as silicon has low Poisson’s ratio and high Young’s modulus which offers high stiffness. The switch performance is enhanced by the matching the impedance which relies on substrate material and dielectric constant [21].Silicon is chosen as a substrate material because of its phase velocity, maximum resistivity and cheap in cost[22-23]. High dielectric constant 11.9 offers low signal loss. The dimensions of CPW plays predominant role in RF signal transmission which is another important one (Figure 6).
3.9. **Dielectric Material Selection**

Different useful materials are fitting for the dielectric layer are considered and develop the graph against the electrical resistivity and dielectric constant. Whichever is the material is having max dielectric constant with moderate resistivity is chosen as a dielectric. Because of maximum dielectric constant HfO2 (Hafnium oxide) is chosen as material for the dielectric as shown in the fig.7. The dielectric constant of the material increases the pull-down capacitance is directly depends on the switch capacitance ratio and by increasing the pull-down capacitance and capacitance ratio we can easily attain the caring and stability of the switch (Fig.7).

**Figure 6.** Substrate material selection of switch

**Figure 7.** Dielectric material selection of switch

3.10. **Beam Material Selection**

**Table 4. Different beam Material Properties**

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>E (Gpa)</th>
<th>rho</th>
<th>$\sqrt{E}$</th>
<th>$\sqrt{E}/\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>79</td>
<td>19.3</td>
<td>8.88819</td>
<td>2.02318</td>
</tr>
<tr>
<td>Aluminum</td>
<td>70</td>
<td>2.7</td>
<td>8,3666</td>
<td>5.09175</td>
</tr>
<tr>
<td>Platinum</td>
<td>168</td>
<td>21.45</td>
<td>12.96148</td>
<td>2.7986</td>
</tr>
<tr>
<td>Si3N4</td>
<td>385</td>
<td>3</td>
<td>19.62142</td>
<td>11.14422</td>
</tr>
<tr>
<td>Ni</td>
<td>200</td>
<td>8.902</td>
<td>14.14214</td>
<td>4.73992</td>
</tr>
<tr>
<td>Si</td>
<td>196</td>
<td>2.3</td>
<td>14</td>
<td>9.23133</td>
</tr>
<tr>
<td>SiO2</td>
<td>73</td>
<td>2.27</td>
<td>8.544</td>
<td>5.67085</td>
</tr>
</tbody>
</table>
For beam material selection different suitable materials are examined and mark the graph with different indices against Poisson’s ratio and Young’s modulus. The material for beam is selected based on low Poisson’s ratio and moderate young’s modulus as shown in the above fig 8. Aluminum is the best material to be chosen. The Au (Gold) is costlier than Al (Aluminum), so we prefer beam material as aluminum here we preferred Al as the beam material as shown in (Figure 8).

Table 5. RF MEMS proposed Switch Material selection

<table>
<thead>
<tr>
<th>Selection</th>
<th>Type of Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Silicon (Si)</td>
</tr>
<tr>
<td>Coplanar Wave Guide</td>
<td>Aluminum (Al)</td>
</tr>
<tr>
<td>Dielectric Layer</td>
<td>Hafnium oxide (HfO₂)</td>
</tr>
<tr>
<td>Anchors</td>
<td>Aluminum (Al)</td>
</tr>
<tr>
<td>Fixed Fixed Beam</td>
<td>Aluminum (Al)</td>
</tr>
</tbody>
</table>

4. Results and Discussions
4.1. Uniform Meander Switch Electromechanical Analysis
Case i) Exchange of beam materials

Case ii) Exchange of gaps
Design and Analysis of a Uniform Meander RF MEMS Switch

**Figure 10.** Voltage Vs displacement for distinct gaps
*Case iii) Exchange of distinct dielectric materials*

**Figure 11.** Voltage Vs displacement by changing dielectric materials

**Figure 12.** Voltage Vs displacement

**Figure 13.** View of total displacement for pull in voltage through FEM tool

**Figure 14.** Simulated ON state capacitance
Figure 15. Simulated OFF state capacitance

Figure 16. C-V curve of uniform meander switch

Figure 17. Switching time for uniform meander switch

4.2. Stress Analysis
Aluminum is selected as a material for beam which exhibits a stress of 1.78E-5Pa and the force of 1.9606E-6N.

Figure 18. Stress distribution
4.3. Uniform Meander Switch Electromagnetic Analysis

**Return Loss:** It is existing because of impedance misalliance between the circuits. (Figure 19).

![Figure 19. Uniform meander switch Return loss](image)

**Insertion loss:** Other than frequency selection, critical to test insertion loss. At high frequencies power is expensive. So electromechanical switches provide lowest possible loss (Figure 20).

![Figure 20. Uniform meander switch Insertion loss](image)

**Isolation loss:** It is the degree of attenuation from an unwanted signal detected at the port of interest. It is important at higher frequencies (Figure 21).

![Figure 21. Uniform meander switch Isolation loss](image)

5. Conclusion:

This paper is an optimization model and is operated at 35GHz, which is modeled by Chen lei chu [5]. The existing switch dimensions are modified with optimization approach. The optimization yields enhanced operational characteristics with a isolation of -29dB for the pull in voltage of 9.36V for the existing switch. The proposed switch dimensions are modified with optimization approach. The optimization yields enhanced operational characteristics with a isolation of -31dB for the pull in voltage of 11.97V and the spring constant is 2.38N/m. The electromechanical analysis is carried out using COMSOL software for measuring Upstate and Downstate capacitance, Pull in voltage and stress analysis (Fig.9 to Fig 17). The RF MEMS proposed switch can be effectively integrated as a switching element within the antenna patches for achieving reconfigurability [9&19] at high frequency of 38GHz. Therefore switch is best suited for future 5G communication applications [10].

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