Modeling and simulation of multiport RF switch

1,2J.Vijay, 3Ivan Saha, 4G.Uma, 5M.Umapathy

1Student, Department of Instrumentation and Control Engineering, National Institute of Technology, Tiruchirappalli-620015, India.

2Email: vijay_j_2003@yahoo.com

3Scientist, Indian Space Research Organisation (ISRO), India.

4Lecturer, 5Assistant Professor, Department of Instrumentation and Control Engineering, National Institute of Technology, Tiruchirappalli-620015, India.

Abstract: This paper describes the modeling and simulation of “Multi Port RF Switch” where the latching mechanism is realized with two hot arm electro thermal actuators and the switching action is realized with electrostatic actuators. It can act as single pole single thrown as well as single pole multi thrown switch. The proposed structure is modeled analytically and required parameters are simulated using MATLAB. The analytical simulation results are validated using Finite Element Analysis of the same in the COVENTORWARE software.

1. Introduction

RF MEMS has been identified as an area, which has the potential to provide a major impact on existing system architectures in sensors and communication by reducing weight, cost, size, and power dissipation, by few orders of magnitude. Key MEMS devices for current RF architecture are switches in radar system and filters in communication systems. RF MEMS combine the advantage of traditional electro-mechanical switches such as low insertion loss, high isolation, extremely high linearity with those of solid state switches such as low power consumption, low mass, long life time. RF MEMS switch finds its application in satellite where less weight and more bandwidth is of high demand, smart phones and blue tooth, any radio frequency system.

This paper describes the modeling and simulation of “Multi Port RF Switch”, the proposed structure is modeled analytically and the required parameters are simulated using MATLAB. The analytical simulation results are validated using finite element analysis of the same in the MEMS simulation software COVENTORWARE.

2. Design of Multi Port RF Switch

A new design of a multiport RF switch with a latching mechanism is presented here. And this design has the following advantages.

- No power consumption at quiescent state
• Each cantilever beam can be either input port or output port
• It can be used to build multiport or switch matrix

RF MEMS series switch considered here uses a cantilever type electrostatic actuator and is actuated by induced electrostatic force between two parallel plates, here the cantilever beam by itself is considered as one conductive plate and other is on the nitride layer both are made of Polysilicon. The voltage induced force brings the two electrodes together bending the cantilever and causing the two end contacts to touch. The touching ends close the conduction path and allow transmission of an RF signal.

The considered RF Switch structure is shown in Figure 1. It includes two horizontal thermal actuators and a cantilever electrostatic actuator. The actuating sequence is as follows: first the horizontal thermal actuators are actuated. When plate A is moved away from plate B, the cantilever is actuated, it brings the plate B downward to the substrate. Then, the horizontal thermal actuators are released; they bring plate A back to the original position. After that, the cantilever (electrostatic actuator) is also released. Because plate A is brought back first and blocks the way of plate B, it cannot go back to its original position any more. Before actuation, plate A was under plate B, after actuation, plate A is above plate B, so two different states of plate B are generated, which are the two states of the switch. A closed view of the latching mechanism is shown in Figure 2. Detailed design of cantilever beam, meander and two-hot arm thermal actuators are explained below.

![Figure 1. Schematic of Multiport RF Switch](image1)

![Figure 2. Detail of latching mechanism](image2)

### 3. Optimization of RF switch components

Dimensions of the various components of the RF switch are optimized using analytical and numerical simulation to achieve the respective requirements as stated below. Cantilever beam dimensions are optimized to make the stiffness as low enough to have the actuation voltage less than 15V. Meander spring dimensions are designed to have stiffness approximately four times that of cantilever beam to keep the cantilever beam in contact position even after removal of actuation voltage. Dimensions of the two-hot arm thermal actuators are adjusted to have actuation displacement of more than the overlapping length.

#### 3.1. Optimization of cantilever beam stiffness

The Cantilever beam bends due to the electrostatic force generated between the electrodes. The electrostatic force acting over the overlap area of the electrodes can be expressed as a concentrated force in a geometric centre of the overlap. This assumption is utilized throughout the analytical
calculation. Hence the concentrated force is not acting at the end of the cantilever but it is acting in the middle of the overlap area of the electrodes. Therefore for the calculation purpose, the cantilever beam is divided into two sections: section-1, from the fixed end to the point of application of the equivalent concentrated force, and section-2, from the point of application of this force to the free end of the cantilever.

Deformation of the cantilever due to electrostatic force will vary along its length. Deformation of the cantilever from its fixed end to the point of force application, i.e. within section-1, can be represented by an elastic curve \[1\].

While deformations for the portion of the cantilever from the point of the force application to the free end, i.e. section-2 can be represented as a linear function of position. After applying law of conservation of force and the boundary conditions to the above equation yields the displacement profile with respect to the beam length.

\[
y(x) = \frac{F}{EI} \left( \frac{1}{6} x^3 - \frac{1}{2} L x^2 \right)
\]  

(1)

Where, \(y(x)\) - displacement of beam, \(x\)- length from the fixed end, \(L\)- total length of the beam, \(F\) - electrostatic force, \(E\) - Young’s modulus, \(I\) - moment of inertia of the beam.

Stiffness is obtained from equation (1) as

\[
K = \frac{8EI}{L^3}
\]

(2)

For the optimized dimensions given in the Table 1, analytically stiffness is found to be \(K=2.5965\) N/m. Using the same dimensions cantilever beam is modeled in MEMS simulation software (Coventorware®). Modal analysis on the cantilever beam gives generalized mass for the each mode frequencies. The modal analysis results are shown in Table 2.

| Table 1. Cantilever beam dimensions | Table 2. Modal analysis result for the cantilever beam |
|-------------------------------|-----------------------------------------------|
| **Parameters** | **Dimension (μm)** | **Mode** | **Frequency (Hz)** | **Generalized Mass (kg)** |
| Length of the cantilever, \(L\) | 220 | 1 | 2.497960E+005 | 1.368002E-011 |
| Length of the electrode, \(L_e\) | 160 | 2 | 8.117089E+005 | 1.338080E-011 |
| Gap between the electrodes, \(g\) | 2 | 3 | 8.597313E+005 | 8.158490E-012 |
| Distance from the fixed end to the electrode, \(L_o\) | 30 | 4 | 1.590816E+006 | 5.108374E-012 |
| Breadth, \(b\) | 32 | 5 | 1.701180E+006 | 1.309949E-011 |
| Height, \(h\) | 2 | 6 | 2.925562E+006 | 1.304124E-011 |

Stiffness is calculated from the generalized mass and mode frequency as \(K = \omega^2 m\). Stiffness from the model analysis for the first mode of vibration is \(K= 3.4321\) N/m.
3.1.1. Cantilever beam pull-in voltage calculation

Cantilever beam electrostatic actuator [3] is approximated to a parallel plate capacitor with spring attached at one end and fixed electrode at the other end. Where the spring constant represents the stiffness of the cantilever beam and the electrode area represents effective electrode area in the electrostatic actuator. It is assumed that electric field is uniform between the plates of the capacitor, and it is zero outside. Electric field creates the electrostatic force that tries to bring the plate together, which is given as

\[ F = \frac{Q^2}{2\varepsilon A} = \frac{V^2 A \varepsilon}{2g^2} = K \cdot z \]  

(3)

Where, \( F \) - electrostatic force, \( Q \) - magnitude of charge on each plate, \( A \) - overlapping area between the two electrodes, \( g \) - gap between the electrodes, \( K \) - stiffness of the cantilever beam, \( z \) - vertical displacement of the electrode.

For a physical model (Finite mass electrodes) mechanical restoring force is equivalent to electrostatic force until beam voltage reaches the pull in voltage or snap down voltage. Pull-in voltage is defined as voltage at which top electrode snaps down to the bottom electrode. Beam actuation will be stable when differential of net force acting on the model is less than zero, it will be marginally stable when the differential of net force acting is equal to zero, and becomes unstable when the differential of net force become greater than zero. Applying marginal stable condition to the equation (3) gives voltage at which the beam snaps-down.

\[ g = \frac{2}{3} g_o \]  

(4)

Where, \( g \) – gap at which beam snaps down, \( g_o \) – total distance between the electrode.

- **Figure 3.** Applied voltage versus displacement simulation result
- **Figure 4.** FEM Pull-in voltage of electrostatic actuator

Pull-in voltage equation is derived by applying equation (4) in (3), which is expressed as

\[ V_p = \sqrt{\frac{8Kg_o^3}{27A\varepsilon}} \]  

Where \( V_p \) – Pullin voltage.
Pull-in voltage calculated analytically is 11.652V. Finite element analysis of the cantilever beam results in pull-in voltage of 12.4V. Figure 3, Figure 4 shows analytical as well as the FEM pull-in voltage results.

### 3.2. Stiffness calculation of the meander spring

RF switch consist of meander [3] for the latching mechanism, the reason behind using meander is, having low stiffness with the less space. Serpentine spring plays an important role in the latching mechanism, for holding the cantilever beam in the ON state. It is designed such a way that its spring stiffness is greater than four times as that of the cantilever beam.

A single meander spring has 2 primary beams and 2 secondary beams. For the analytical calculation, it is assumed that all six degrees of freedom of the anchor point are fixed. Moreover, the guided-end boundary conditions are applied to the free-end point of the spring since this point is attached to the main switch body. Consequently, a moment and torsion are applied to this point to constrain the rotation angles around the end axes. Moments and torsions are calculated for the primary as well as the secondary beams from the fixed end. It is known that stiffness

\[
K_z = \frac{F_z}{\delta_z} = \left[ \frac{\partial U}{\partial F_z} \right]
\]

(6)

Where, \(K_z\) - stiffness of the meander in z direction, \(F_z\) - force acting in the z direction, \(U\) - total energy stored in the meander.

By applying equilibrium and boundary conditions to the above equation yields

\[
K_z = \left( \frac{8a^3 + 2b^3}{3EI_x} + \frac{(5a + b) ab}{GJ} \right) \left( \frac{a^2 \left( \frac{2a}{EI_x} + \frac{3b}{GJ} \right)^2}{2 \left( \frac{a}{EI_x} + \frac{b}{GJ} \right)} \right) \left( \frac{b^2 \left( \frac{a}{EI_x} + \frac{b}{GJ} \right)}{2 \left( \frac{a}{EI_x} + \frac{b}{GJ} \right)} \right)
\]

(7)

Where, \(G\) - shear modules, \(I_x\) - x-axis moment of inertia, \(I_z\) - z-axis moment of inertia, \(I_p\) - polar moment of inertia, \(J\) - torsion constant \(J = 0.413I_p\). The optimized dimensions are tabulated in the

| Table 3. Serpentine spring dimensions | Table 4. Model analysis |
|--------------------------------------|-------------------------|
| Parameter                            | Dimension | Mode Frequency | Generalized Mass |
| Primary meander length \(a\)         | 30        | 1 2.674161E05 | 2.191996E-12     |
| Secondary meander length \(b\)       | 70        | 2 3.714306E05 | 8.561884E-13     |
| Thickness \(t\)                       | 2         | 3 1.126582E06 | 2.916060E-12     |
| Beam width (both) \(w\)              | 10        | 4 1.503163E06 | 1.216178E-12     |
|                                      |           | 5 1.805775E06 | 9.771529E-13     |
|                                      |           | 6 2.248570E06 | 1.279823E-12     |

With the given dimensions, Z-direction stiffness is calculated analytically to be \(K_z=10.356\)N/m. For the same dimensions meander spring is modeled using MEMS simulation software and modal analysis is carried out, whose results are tabulated in Table 4. Stiffness calculated from modal analysis for the fourth mode of vibration is \(K_z=11.058\)N/m.
3.3. *Thermo-mechanical analysis two-hot arm thermal actuator*

Thermoelectric actuators are more attractive [4] as they can generate large deflection and force. Two-hot arm thermal actuators are used in latching mechanism, to hold the switch after release of the electrostatic actuation. The structure of which is given below in the figure 5.

Voltage applied between the outer and inner hot arm cause them to expand horizontally due to self heating, which causes the actuator to rotate about the flexure. The size of the cross section of the actuator is much smaller than the actuator length therefore; electro thermal analysis of the two-hot arm actuator is generally simplified as a one-dimensional problem. Heat dissipation through radiation to ambient is neglected in comparison with heat losses through conduction to the anchor substrate which is considered as a heat shrink, and heat losses through air to the substrate due to convection.

Small element of the actuator is considered for the modeling. At steady state resistive heating power generated in the element is equal to heat conduction and convection out of the element.

\[
-k_p w_s t \frac{dT}{dx} + J^2 \rho w_s t dx = -k_p w_s t \frac{dT}{dx} \bigg|_{x+dx} + \frac{S w_s (T - T_s) dx}{R_f}
\]

Where \( T \) and \( T_s \) are the beam and substrate’s temperatures respectively, \( k_p \) is the thermal conductivity of Polysilicon, \( J \) is the current density, \( \rho \) is the resistivity of Polysilicon, and \( S \) is the shape factor which accounts for the impact of the shape of the element to heat conduction to the substrate.

After applying thermal resistances and simplifying gives

\[
\frac{d^2T}{dx^2} = \frac{S(T - T_s)}{k_p R_f t} - \frac{V^2}{L^2 \rho \sigma k_p} \left(1 - \xi(T - T_s)\right)
\]

Where \( V \) is the applied voltage between outer and inner hot arms, \( L \) is the length of the arms through which the current passes, \( w_s \) width of the hot arm, \( t_s \) thickness of the hot arm, \( R_f \) thermal resistance.
Solving the above equation for the different boundary condition gives the temperature distribution throughout the two-hot arms. From the temperature distribution of the arms, the thermal expansion of the outer and inner hot arms, $\Delta L_1$ and $\Delta L_2$ where $\Delta L_1 = K \int_0^L (T_1 - T_c)dx$ ; $\Delta L_2 = K \int_0^L (T_2 - T_c)dx$

$T_1, T_2$ is the temperature distribution function of the outer and the inner hot arms with respect to the position. Deflection analysis of two hot-arm thermal actuator is carried out using “Force Method” and “Method of Virtual Work”. Total deflection of the actuator is expressed as.

$$u = \frac{1}{EI_b} \int_0^{1/2} \left( -\frac{\beta_a L_1^3}{3} + \frac{L_1 \beta_a - \beta_b}{2} L_1^2 + L_1^2 \beta_b \right)dx,$$

Where $\beta_a$ and $\beta_b$ are

$$\beta_a = X_1 + X_4 \quad \beta_b = X_1 (L_2 - L_1) - X_2 L_g - X_3 + X_4 (L_3 - L_1) - 2X_5 L_g - X_6.$$

$X_1, X_2, \ldots$ are the deflections of the actuator when it is analyzed as different beam elements. When 5V is applied, the deflection of the actuator is calculated to be 4.5 µm for the optimized dimensions. The finite element analysis of the two hot-arm thermal actuator was performed in Coventorware and the deflection is found to be 4.58 µm.

4. Conclusion

The proposed multiport RF switch was designed analytically using MATLAB and numerically using MEMS simulation software COVENTORWARE. From the results it is observed that the parameters designed using analytical and FEM is in close agreement. In this work, attempt has been made to optimize the mechanical design of the RF switch and its actuation voltage. However the design can be improved to optimize the insertion loss and the isolation.

| Components \ Results | Analytical modeling | FEA modeling |
|----------------------|---------------------|--------------|
| Cantilever stiffness (N/m) | 2.596 | 3.432 |
| Meander stiffness (N/m) | 10.356 | 11.058 |
| Pull-in voltage (V) | 11.652 | 12.4 |
| Displacement of thermal actuator (µm) | 4.520 | 4.580 |

5. References

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