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A micro level electrostatically actuated cantilever and metal contact based series RF MEMS switch for multi-band applications

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Abstract: In this paper, a micro level electrostatically actuated cantilever and metal contact based series RF MEMS Switch is designed and analyzed using Finite Element Method Tool. The designed switch is simulated and the performance is verified over the frequency range 0.8–20 GHz. In investigation, it is noticed that the performance of the RF MEMS Switch is decided by the actuation voltage, insertion losses, isolation losses and reliability. The switch designed in this paper achieved a constant insertion losses of −0.08 to −0.14 dB, isolation losses of −58 to −20 dB. This work also concentrated on the cantilever actuation voltage, and it is reduced to 3.55 V by using less weight polymer material like Poly Tetra Fluoro Ethylene (PTFE). The series metal contact based electrostatically driven switching is created in Microstrip Transmission line using cantilever structure associated with gold contact material. The designed RF MEMS switch is preferable in the design and implementation of reconfigurable communication devices like microstrip based antennas and RF filters.

Subjects: Materials Science; Nanoscience & Nanotechnology; Technology; Radio, Satellites, Television & Audio; Telecommunication; Semiconductors

Keywords: transmission lines; MEMS technology; RF switches; FEM tools

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PUBLIC INTEREST STATEMENT

Micro Electro Mechanical Systems (MEMS) is an eminent technology, which will facilitates miniaturization, low power consumption, high performance. Because of this reason the MEMS technology is adopted in many applications. Especially in RF applications like RF Switches, Phase shifters, Filters design MEMS technology is referred by many researchers.

• A micro level electro statically actuated cantilever and metal contact based series RF MEMS Switch is designed and analysed using Finite Element Method Tool.
• The designed switch is simulated and the performance is verified over the frequency range 0.8–20 GHz.
• In investigation, it is noticed that the performance of the RF MEMS Switch is decided by the actuation voltage, insertion losses, isolation losses and reliability.
• The switch designed in this paper achieved constant insertion losses of −0.08 to −0.14 dB, isolation losses of −58 to −20 dB.
1. Introduction

Nowadays, the micro-level RF switches are playing an important role in the design of reconfigurable communication circuits. The real challenge in the design of RF switches is creating switching in the electromagnetic transmission lines with good performance i.e. low insertion losses and high isolation losses. There exist different technologies like Complementary Metal Oxide Semiconductor (CMOS), Gallium Arsenide (GaAs), and Micro Electro Mechanical Systems (MEMS) which are useful to create the switching in transmission lines. Compared to other technologies MEMS technology-based switches provide good isolation losses, insertion losses and the major advantage with the MEMS technology is power handling which is in the range of 0.2–10 W. The operating frequency of the RF MEMS Switches is very high compared to other technology-based RF switches (Hashemi et al., 2013; Sleasman et al., 2016).

RF MEMS switches use a mechanical movement to create switching in Radio Frequency operating transmission lines (Rebeiz & Muldavin, 2001). RF MEMS switches are the specific micromechanical switches that are designed to operate at Radio frequency (0.3–300 GHz) (Raman, & Shanmugananatham, 2015; Rebeiz & Muldavin, 2001). In RF capacitive switches, the Upstate capacitance is sensitive to the power of RF signal and generates nonlinear effects. Nonlinear effects like Inter Modulation (IM) are negligible in MEMS devices compared to other switching components like PIN diode and FET Transistor (Dussopt & Rebeiz, 2003).

GaAs FET switches do not have sufficient isolation to minimize cross interference and signal jamming when the channels are in proximity. The major disadvantage with the PIN diode is it requires more operating power (Bakri-Kassem & Mansour, 2015; Demirel et al., 2016). RF MEMS series resistive switches provide high isolation losses when switch is open and low insertion loss when switch is closed with a very less operating voltage (Mercado, Kuo, Lee, & Lee, 2005). The performance of MEMS technology-based RF switch is good in Radio Frequency (Mercado et al., 2005). MEMS switches provide high isolation, which is required in communication base stations and satellite systems (Muldavin & Rebeiz, 2001). By using MEMS technology in different ways we can create the switching in microstrip and coplanar transmission lines (De Poolsis et al., 2016). Figure 1. shows the different ways to create switching in RF transmission lines (Ravirala et al., 2017; Srinivasa Rao, & Thalluri, 2016).

Dielectric is not required in resistive (or) metal contact RF MEMS switches, so there is no fringing field effect (Pelliccia et al., 2015). But the main drawback with the resistive switches is it will lead to stiction and long-term actuation because of this the switch reliability will effect.

As on investigation, we have referred in this paper a series, DC contact, cantilever (gold) structure, thickness 2.2 μm, length 75 μm, height of contact is 0.6 μm, offering insertion loss of 0.4–0.9 dB over the frequency 1–75 GHz, isolation losses of 30–8 dB over the frequency 1–25 GHz (Gong, Shen, & Barker, 2009). A metal contact series sliding anchor based switch with actuation voltage of 90 V offering an isolation losses of 55–25 dB, insertion losses of 40–9 dB over the frequency 1–8 GHz (Zareie & Rebeiz, 2014). A bridge structure (gold) based switch is achieved an isolation of 55–25 dB, 0.5–0.9 dB over the frequency 1–26 GHz (Casals-Terre et al., 2014).

In this paper, we have explained the theoretical and Mathematical analysis about the Series metal contact base electrostatically actuated RF MEMS switch in Section 2. Section 3 discusses the results and the improvements. Finally the paper is concluded in Section 4.

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**Figure 1. Classification of RF MEMS switches.**

| Actuation | Axis Deflection | Contact | Circuit Configuration | Structure |
|-----------|-----------------|---------|-----------------------|-----------|
| Electrostatic | Vertical | Capacitive | Series | Bridge |
| Thermal | Lateral | Resistive | Shunt | Cantilever |
| Piezoelectric | | | Series & Shunt | Diaphragm |
| Magneto Static | | | | |
2. Theoretical analysis

This paper concentrates solely on the design of electrostatically actuated, vertically deflected, resistive contact, series type, cantilever based RF MEMS switch which is suitable to operate in the frequency range of 0.8–20 GHz. This work tries to improve the insertion losses, isolation losses and actuation voltage. In resistive contact based RF MEMS Switches the insertion losses mainly depends on the contact material, which closes the gap in the transmission line. The isolation losses mainly depend on the length of the gap in the transmission line shown in Figure 3, and the actuation voltage depends on the cantilever structure which is used to create switching in the RF transmission line. The switch dimensions are in micro level as a Finite Element Method (FEM) tool is used for design and analysis.

2.1. MEMS actuation

In RF MEMS Switches the mechanical actuation can be created by using different mechanisms, like electrostatic (or) Thermal (or) Piezoelectric (or) Magneto Static (Rebeiz & Muldavin, 2001). Within these mechanisms, electrostatics is preferable (Rebeiz & Muldavin, 2001). Any electrostatically actuated mechanical structure can be characterized using the parameters like mass of the actuation structure \( (m) \), Spring Constant \( (K) \), Natural Resonant Frequency \( (\omega_0) \) and Pull in voltage \( (V_{pull,in}) \).

2.1.1. Actuation structure total mass

Cantilever is associated with the contact material and the top electrode, as shown in Figure 2. So, the total mass of the structure is considered as the sum of individual structure masses. In this electrostatically actuation, a Cantilever structure is associated with two sub structures i.e. a top electrode and contact material. Here, material preferred is a light weight polymer i.e. Poly Tetra Fluoro Ethylene (PTFE) as a cantilever. A high conductive material gold (Au) is used as top electrode and contact material. Finally the electrostatically actuated structure total mass is considered as a sum of cantilever mass \( (m_1) \), top electrode mass \( (m_2) \), and contact material mass \( (m_3) \) i.e.

\[
\text{Actuation Structure Mass} \ (m) = m_1 + m_2 + m_3 \ \text{in kg}
\]  

where: mass of cantilever \( = m_1 = l_1 \times w_1 \times t_1 \times \rho_1 \), cantilever dimensions = length-\( l_1 \); width-\( w_1 \); thickness-\( t_1 \); density-\( \rho_1 \), mass of top electrode \( = m_2 = l_2 \times w_2 \times t_2 \times \rho_2 \), top electrode
dimensions = length-$l$; width-$w$; thickness-$t$; density-$\rho$; mass of contact material =
$m = l \times w \times t \times \rho$; contact material dimensions = length-$l$; width-$w$; thickness-$t$; density-$\rho$.

2.1.2. Stiffness or spring constant ($K$)

From the Hooke’s Law it is clear that the required force for deformation is proportional to the spring
constant i.e. if the spring constant of the actuation structure is high, more actuation voltage or pull
in voltage is required to deform the structure. So, it is better to choose the actuation material with
low spring constant. In this work, a light weight polymer material is used as a deformable cantilever
material, so that the spring constant value is low. Because of the low spring constant, the required
deformation force also decreases and it will helps in the reduction of the actuation voltage. The
spring constant of rectangular cantilever can be expressed as

$$
K = \frac{2Ewt^3}{3l^3} \text{ in N/m}
$$

(2)

Here $E$ is Young's Modulus in Pa, $l$ is Length of Cantilever in $\mu$m, $t$ is the Cantilever Thickness in $\mu$m,
and $w$ is Width of the Cantilever in $\mu$m.

2.1.3. Natural resonant frequency ($\omega_0$)

If the switch is considered as a second order device, the output is a function of static sensitivity ($\zeta$),
damping ratio, and un-damped natural resonant frequency ($\omega_0$) (Hashemi et al. 2013; Payam et al.,
2014). The un-damped natural frequency of the actuation structure is useful to find the switching
time of the switch. The un-damped natural resonant frequency is directly proportional to the stiff-
ness of the actuation structure and is inversely proportional to the mass of the actuation structure.
The un-damped natural resonant frequency is expressed as

$$
\omega_0 = (K/m)^{1/2} \text{ in Rad/Sec}
$$

(3)

Here, $K$ is the spring constant in N/m; $m$ is the total mass of the actuation structure in kg.

2.1.4. Pull-in voltage ($V_{\text{pull-in}}$)

The basic principle of electrostatic RF MEMS Switch is, a significant voltage need to apply between
the electrodes as shown in Figure 2, to get the deformation in the rectangular cantilever. The mini-
imum actuation voltage required for structure deformation is known as pull-in voltage. For the rec-
tangular beam the pull-in voltage is expressed as

$$
V_{\text{pull-in}} = \sqrt{\frac{8K}{27Ae_0}d^3} \text{ in V}
$$

(4)

Here, $A$ is the effective area between electrodes, $d$ is the gap between the electrodes in $\mu$m, $e_0$ stands
for free space permittivity and is equal to $8.85 \times 10^{-12}$ F/m.

2.2. Microstrip transmission line with gap

Transmission lines are used to transmit the RF signal from one point to other point. In this paper, a
microstrip transmission line is taken with a gap ($g$) as shown in Figure 3, and switching is created
using electrostatically actuation structure as shown in Figure 5. The fabrication of micro level trans-
mission line suitable for RF MEMS switch is a real challenge.

Why MEMS technology to create the switching in the microstrip transmission line means, which
provides high isolation losses and minimum insertion losses. These two parameters mainly depend
on the gap ($g$) in the transmission line and the contact material which is used to cover the gap in the
transmission line.

There are two types of transmission lines which support PCB and IC technologies. One is microstrip
and the other is coplanar transmission line. These transmission lines are used to feed the microstrip
antennas. By creating switching in the microstrip transmission lines reconfigurable antennas, filters
can be designed.
Microstrip transmission line is a very good medium to transmit radio frequency signals. The design of these transmission lines requires placing of ultra thin metal strip on the top of a dielectric material with appropriate dielectric constant as shown in Figure 3. The real challenge in design of this transmission line is maintaining few losses and less distortion. The mode of RF signal transmission in this transmission line is quasi TEM, because the wave propagates through air and dielectric medium with different speeds (Schneider, Glance, & Bodtmann, 1969). Few materials suitable for dielectric and micro strip are listed with properties in the Table 1.

2.2.1. Characteristic impedance ($Z_0$)

The reflection losses in the transmission lines can be reduce by matching the source impedance and the characteristic impedance. In general the source impedance is 50Ω. The characteristic impedance of the microstrip transmission line is defined as the ratio of circular integration of electric field over the length to the circular integration of magnetic field over the same length i.e.

$$Z_0 = \frac{\int E \, dl}{\int H \, dl} \text{ in } \Omega$$

(5)

And the same characteristic impedance is expressed in terms dielectric height ($h$), width of the microstrip ($w$) by Bahl and Trivedi (1977) for two different conditions i.e. $w/h < 1$, $w/h > 1$. The characteristic impedance of a microstrip transmission line under the condition $w/h < 1$ is,

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{\text{eff}}}} \ln \left( \frac{8h}{w} + 0.25 \frac{w}{h} \right) \text{ in } \Omega$$

(6)

Under the condition ($w/h < 1$) the effective relative permittivity ($\varepsilon_{\text{eff}}$) can be expressed as:

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \frac{1}{\sqrt{1 + \frac{12h}{w}}} + 0.04 \left( 1 - \frac{w}{h} \right)^2 \right]$$

The characteristic impedance of a microstrip transmission line under the condition $w/h > 1$ is,

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{\text{eff}}}} \left[ \frac{w}{h} + 1.393 + \frac{2}{3} \ln \left( \frac{w}{h} + 1.444 \right) \right]$$

(7)

Under the condition ($w/h > 1$) the effective relative permittivity ($\varepsilon_{\text{eff}}$) can be expressed as

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \frac{1}{\sqrt{1 + \frac{12h}{w}}} \right]$$

(8)

The characteristic impedance of the microstrip transmission line depends on the relative permittivity ($\varepsilon_r$), height ($h$) of the substrate material, and the width ($w$) of the conductive material. In microstrip
transmission line, wave propagation happens in air and substrate. So the effective relative permittivity ($\varepsilon_{\text{eff}}$) should be measured to find the accurate characteristic impedance of the microstrip.

2.3. Series RF MEMS switch

When the cantilever is in upstate, because of the gap in the transmission line the RF input signal is unable to reach the RF output port. When a voltage is applied an electric field created between the electrodes, then the cantilever will come to down state and the contact material associated with cantilever covers the gap in the microstrip transmission line (Bahl & Trivedi, 1977). Therefore the RF signal applied to the input port is able reach the output port with less reflection (Figure 4).

2.4. Working principle

The working principle of the series RF MEMS switch designed in this paper is as follows, if the applied actuation voltage between the electrodes is 0 V, the structure (Cantilever) never deforms and it is always in upstate so the gap ($g$) in the microstrip transmission line creates good isolation. Under this condition RF input signal will not reach RF output port. When a significant actuation voltage is applied between the electrodes, some electrostatic force will be created between the top electrode and the bottom electrode. Then the structure (Cantilever) starts deforming and come to down state and covers the gap ($g$) in the transmission line. It acts as a channel to the RF signal. Hence the RF input signal reaches to the RF output port. The complete RF MEMS Switch designed in this paper is shown in Figure 5.

2.5. Design methodology

The series RF MEMS switch design is done in two phases, in the first phase a microstrip (gold) is placed on the top of substrate with significant dielectric constant. A small gap is created in transmission line for switching purpose. In the second phase an electrostatically actuated MEMS structure is placed on the top of the transmission line to cover the gap when required. In each phase required materials are assigned to the design structures.

3. Results and discussions

A miniaturized series RF MEMS switch is designed with the dimensions shown in Table 2, using a Finite Element Method (FEM) Tool COMSOL. The main aim of this work is design of high performance
series RF MEMS switch by improving the parameters like insertion losses, isolation losses and the actuation voltage. The RF transmission line means it is a medium used to transmit a high frequency signal from source point to destination point. Recent applications require transmission lines which need to carry ultra and super high frequency signals.

Microstrip transmission lines are appropriate when the transmission distance is of millimetre and micrometre range. In the design of these transmission lines it is important to maintain the characteristic impedance in the range of 50–150Ω range.

To maintain the characteristic impedance within the range the switch dimensions and dielectric material properties are important. This paper, principally analyses the variations in the characteristic impedance of microstrip transmission lines depending on dimensions and dielectric materials in micro level which are suitable to design RF MEMS Switches. Analysis is done with the mode of transmission in microstrip is quasi TEM mode.

**Table 2. Switch design dimensions, materials and properties**

| Type                  | Substrate type                  | Dimensions (μm) | Materials          | Material properties               |
|-----------------------|---------------------------------|-----------------|--------------------|------------------------------------|
| MEMS actuation section| Cantilever                      | Length (l₁) = 825 Width (w₁) = 40 Thickness (t₁) = 5 | Polytetrafluoroethylene (PTFE) | Young’s modulus (E) = 0.4 × 10⁹ Pa, Density (δ₁) = 2,200 kg/m³ |
| Top electrode         | Length (l₂) = 500              | Width (w₂) = 40 | Gold (Au)          | Density (δ₂) = 19,300 kg/m³        |
| Bottom electrode      | Length (l₃) = 500              | Width (w₃) = 450 Thickness (t₃) = 20 | Gold (Au)          | Density (δ₃) = 19,300 kg/m³        |
| Contact material      | Length (l₄) = 50               | Width (w₄) = 80 | Gold (Au)          | Density (δ₄) = 19,300 kg/m³        |
| RF section            | Microstrip transmission line with gap | Width (w) = 50 | Gold (Au)          | Electrical conductivity (σ) = 45.6 × 10⁶ S/m |
| Dielectric material   | Height (h) = 20                | Silicon Dioxide (SiO₂) | Dielectric constant (ε) = 3.8 |

![Figure 6. Cantilever in Up state, switch OFF.](image-url)
First the isolation losses mainly depends on the gap \((g)\) in the micro strip transmission line, here a 1 μm gap \((g)\) is created in the transmission line. If the voltage applied between the electrodes is 0 V, the cantilever structure is in upstate as shown in the Figure 6, which results an isolation loss in the range -58 to -20 dB over the frequency 0.8–20 GHz respectively as shown in the Figure 7. Under this condition the RF input signal is unable to reach to RF output port which is clearly shown in Figure 6.

The insertion losses depends on the contact material which is used to cover the gap \((g)\) in the transmission line, here in this work a gold (Au) material is used as a contact material to cover the gap in the transmission line. Whenever an actuation voltage of 3.55 V is applied between the electrodes, the structure will start deform as shown in Figure 8, and cover the gap \((g)\) in the transmission line.

Figure 7. Isolation losses \((S_{21})\), when cantilever is in Up state.

Figure 8. Cantilever deformation.

Figure 9. Cantilever in Down state, switch ON.
Now the RF input signal will reach to the RF output port as shown in Figure 9. Which resulting a constant insertion loss of −0.08 to −0.14 dB over the frequency range 0.8–20 GHz as shown in Figure 10. The parameter actuation voltage is mainly depends on the linear elastic material, here a light weight Polytetrafluoro ethylene (PTFE) polymer material is used, which is deformed 1 μm in downward direction for the actuation voltage of 3.55 V as shown in Figure 8. Few mechanical properties of the cantilever are theoretically calculated and listed in Table 3.

Table 3. Theoretical calculations

| Parameter                             | Theoretical value          |
|---------------------------------------|-----------------------------|
| Total cantilever mass (m) = m₁ + m₂ + m₃ | 19.842 × 10⁻¹⁰ kg           |
| Spring constant (K)                   | 2.375 × 10⁻¹ N/m            |
| Pull-in voltage                       | 0.2229 V                    |
| Resonant frequency                    | 0.173 kHz                   |

Microstrip transmission line is very good medium to transmit radio frequency signals. The design of these transmission lines require placing of ultra thin metal strip on the top of a dielectric material with appropriate dielectric constant. The real challenge in design of this transmission line is maintaining fewer losses and less distortion. The mode of transmission in this transmission line is quasi TEM, because the wave will propagate through air and dielectric medium with different speed.

Table 4. Different RF MEMS series switches comparison

| Parameter | Gong et al. (2009) | Zareie and Rebeiz (2014) | Casals-Terre et al. (2014) | Proposed         |
|-----------|--------------------|--------------------------|---------------------------|------------------|
| Type      | DC contact         | Metal contact            | Metal contact             | Metal contact    |
| Structure (Material) | Cantilever (Gold) | Sliding anchor           | Bridge (Gold)            | Cantilever (PTFE) |
| Structure thickness & length | 2.2 & 75 μm         | –                        | 1.8–3 & 580 μm           | 5 & 825 μm       |
| Actuation voltage | –                  | 80–90 V                 | 20 V                     | 3.55 V          |
| Transmission line | CPW                | CPW                      | CPW                      | Microstrip      |
| Gap       | 0.6 μm             | 0.9 μm                   | 2.37 μm                  | 1 μm            |
| Insertion losses | 0.4–0.9 dB @ 1–75 GHz | 0.25–0.5 dB @ 1–8 GHz | 0.5–0.9 dB @ 1–26 GHz | 0.08–0.14 dB @ 0.8–20 GHz |
| Isolation losses | 30–8 dB @ 1–25 GHz | 40–9 dB @ 1–8 GHz       | 55–25 dB @ 1–26 GHz     | 58–20 dB @ 0.8–20 GHz |

Figure 10. Insertion losses ($S_{21}$), when cantilever is in Down state.
In this paper, an analysis is done on the effect of young’s modulus ($E$) on the actuation voltage and it noticed that, if the young’s modulus ($E$) of the actuation structure increases then the strength of the structure also increases, therefore the required actuation voltage increase as shown in Figure 11. After comparing with the past work, as listed in Table 4, the cantilever switch discussed in this paper is provided a solution to reduce the actuation voltage ($\approx 3.55$) by using polymer material as actuation structure. Achieved low insertion losses of 0.08 dB, high isolation losses of 58–20 dB.

4. Conclusion

Recent communication applications need the things like micro strip antennas and filters with reconfigurable feature. From the investigation, it is clear that MEMS technology based switches are the best solution to design reconfigurable Radio Frequency devices. Series RF MEMS switches will fulfil the requirement in communication applications for transmission and reception of data in different frequency bands. In this paper, an electrostatically actuated, series, metal contact RF MEMS is designed and simulated over the frequency range 0.8–20 GHz. The main achievement in this work is high isolation losses in the range $\sim 58$ to $\sim 20$ dB. The switch is offering an insertion loss of $\sim 0.08$ to $\sim 0.14$ dB. Here a high conductive contact material like gold (Au) is used to cover the gap (g) in the transmission line. One more challenge in the MEMS technology based switches is requirement of high actuation voltage. This work tried providing the solution for it by referring a light weight polymer material as linear elastic material. Because of using the polymer material like Polytetrafluoroethylene (PTFE) with young’s modulus of 2,200 kg/m$^3$, the actuation voltage is restricted to 3.55 V for the deformation of 1 μm. The designed switch results show that the switch can give good performance over the frequency range 0.8–20 GHz, i.e. the switch can be referred for L, S, C, X, Ku band communication applications.

Nomenclatures

| Abbreviation | Description |
|--------------|-------------|
| MEMS         | Micro electro mechanical systems |
| RF           | Radio frequency |
| FEM          | Finite element method |
| TEM          | Transfers electro magnetic |

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