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Pi-shaped MEMS architecture for lowering actuation voltage of RF switching

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Abstract: A wide band low actuation capacitive coupling electrostatic RF MEMS switching device is presented in this paper. The device includes a pi-shaped matching architecture containing two switches connected by a high impedance short transmission line. The device can act as a switch for any desired frequency whilst requiring only 12 volts for actuation. By optimizing the length and the characteristic impedance of the transmission line, the switch can be tailored for desired frequency bands. The switch is calculated and simulated for Ka to V frequency bands demonstrating excellent improvements of RF characteristics.

Keywords: RF MEMS switch, actuation voltage, RF characteristics, pi matching architecture

Classification: Micro- or nano-electromechanical systems

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1 Introduction

RF switches are used in antenna pattern switching and signal routing, tuning filters, phase shifters, and several other applications. Switching networks provide flexible connection between various ports and channels and have essential affect on system redundancy. RF switches can facilitate optimum usage of available frequency bands. RF micro electromechanical systems (RF MEMS) can be fabricated with standard integrated circuit technology, providing the advantages of mass production with great uniformity in device characteristics.

RF MEMS switches offer superior RF characteristics as compared to other electronic and mechanical switches. Whilst mechanical switches have good RF characteristics, they are heavy and costly. Electronic switches are light but give poor RF characteristic and nonlinearity, and consume more power. The RF MEMS switches combine the advantages of both mechanical switches (excellent linearity, low insertion loss, and low noise) and electronic switches (light and low cost). However, RF MEMS switches have some disadvantages that researchers are trying to address: RF power handling [1], reliability and long lifetime [2], costly packaging [3], dielectric charging [4], and high actuation voltage.

2 Low actuation methods

The actuation voltage is very important for wireless systems. There exist several methods to improve the parameters of RF MEMS switches with primary emphasize on lowering the actuation voltage. Piezoelectric actuation is an attractive method used by several researchers including Kugeler et al. [5]. An extremely low actuation voltage (2.5 V) has been obtained. However, the access frequency band is narrow and also a complicated fabrication process is needed. Lowering the spring constant is another way to decrease the actua-

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tion voltage. The proposed switch uses the folded flexure beam [6], therefore the spring constant (k) is defined by:

$$k = Ew\left(\frac{t}{l}\right)^3 \tag{1}$$

where E is Young modules ($E = 80\,\text{GPa}$ for Gold), w is width of the beam ($w = 4\,\mu\text{m}$), t and l are thickness and length of the beam ($t = 1.5$, $l = 80\,\mu\text{m}$ respectively). Therefore, k can be achieved as $4.218\,\text{N/m}$ (see Fig. 1 (a)).

Decreasing the spring constant does not have any significant affect on the RF characteristics of the switch but reduces the pull-down voltage that is defined as [3]:

$$V_p = \sqrt{\frac{8kg^3}{27\varepsilon_0 w_1 w_2}} \tag{2}$$

where g is the height of the gap between membrane and transmission line, W_1 and W_2 are dimensions of contact plate of the membrane. Dai et al. [6] achieved an actuation voltage of 17.5 V by connecting four springs to the corners of the membrane. However, the switching time increased with lowering the spring constant that makes the switch usable only for low speed applications.

There are also various specific designs to lower the actuation voltage. Thermal actuation was used to achieve an actuation voltage of less than 5 V [7]. However, the design needs high current (35 mA) for actuation. Changing the pull-down mechanism from vertical to lateral driven [8] can lower the pull-down voltage but increases the switching time. The three-state position of the membrane reported by Touati et al. [9] reduces the actuation voltage to a value of 3.5 V. However, since the membrane is always under stress and also the gap is short, the life cycle and reliability are affected. Joo-Young et al. [10] employed a combination of electrothermal and lowering the spring constant for actuation. Due to the large upstates gap height ($200\,\mu$m), the switch has good RF characteristics in microwave frequency of up to 15 GHz but its energy consumption is too high.

3 Design principle

This work focuses on improving the RF characteristics of an RF MEMS switch with low actuation voltage. For an ideal shunt coupling capacitive switch in upstate position, there is no obstacle in the way of the signal propagation ($S_{11} = -\infty\,\text{dB}$). For a practical switch, however, there is an unwanted capacitance between membrane and transmission line that bypasses a part of the signal to ground and causes mismatch at the input and output of the switch. This can be verified by scattering parameters. To overcome this problem, the capacitance between membrane and transmission line should be decreased. This issue can be addressed by increasing the gap or decreasing the area of the membrane. Both these increments, however, can cause an excessive raise in the actuation voltage. In this work, we first calculated the area of membrane for the desired RF characteristics, and also minimum

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acceptable gap height for reliability and life cycle. However, the switch is only applicable at narrow band frequency. By using a π mach circuit, consisting of two switches and a piece of high impedance short transmission line between them, the capacitance is covered up for a very large frequency band. The equivalent inductance of the high impedance short transmission line is calculated to compensate for the upstate capacitance of the switches. By transmission line theory, the optimized value for the length and characteristic impedance of the high impedance short transmission line is determined for the desired frequency band.

4 Proposed π-shaped switch

The proposed switch includes a π-shaped matching architecture consisting of two switches connected by a high impedance short transmission line (Fig. 1 (b)). The two switches are placed in the line of RF signal resulting in the creation of a very high isolation in the off position. This high isolation paid by a negligible increase in the insertion loss in the on position especially for DC contact switches. In this work, the two switches are coupling capacitance and do not have significant losses.

Design Procedure:

1. Select the desired frequency band (20-40 GHz).

2. Calculate the upstate capacitance. For reasonable matching, $S_{11} \leq -10$ dB for the desired frequencies. Therefore,

$$S_{11} = \frac{-jwC_u Z_0}{2 + jwC_u} \tag{3}$$

For $f_0 = 30$ GHz, the value of $C_u = 50.3$ fF.

3. Calculate the size of the switch. To achieve a low actuation voltage and good reliability, the flexure membrane [3] is chosen. Moreover, to achieve good life cycle, the gap height is set as $2\,\mu$m. The area of membrane is calculated using:

$$C_u = k\frac{\varepsilon A}{g + \frac{t_d}{\varepsilon_r}} \tag{4}$$

where $k\,(1.2-1.4)$ is the coefficient due to fringing capacitance, A is the area of the membrane, g is the height of the gap, and t_d is the thickness of the dielectric. Therefore, $A = 9472\,\mu\text{m}^2$, $W_1 = 80\,\mu$m, and $W_2 = 118.4\,\mu$m. The actuation voltage is determined by Eq. (2) as 12 V.

4. Optimize the value of the high impedance short transmission line parameters to achieve a matching in the desired frequency band. Fig. 1 (c) shows the equivalent circuit of the switch. Neglecting the small value of the parasitic elements (R_p, L_s), the required inductance to match the switch can be calculated as follows:

$$Z_{in} = Z_o = \frac{1}{JC_u\omega_0} \| \left[\left(Z_0 \| \frac{1}{JC_u\omega_0}\right) + J\omega_0 L_{TL}\right]. \tag{5}$$

The equivalent high impedance short transmission line can be obtained by solving the wave equation:

$$\tan(\beta l_{st}) \approx \frac{L\omega_0}{Z_h} \tag{6}$$

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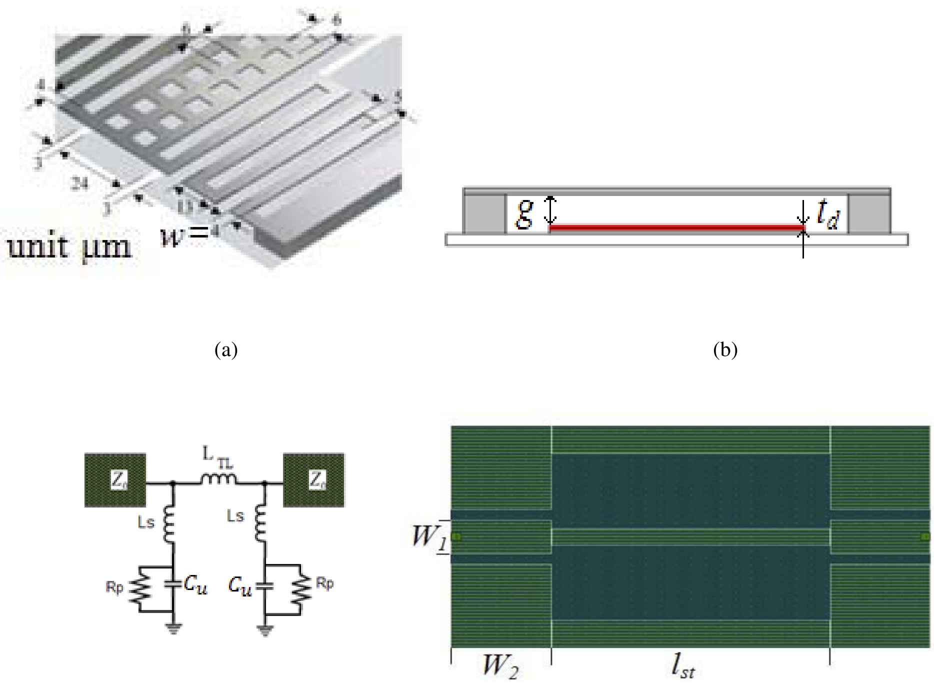
For small values, the length of short transmission line is

$$l_{st} = \frac{Lv_0}{Zh\sqrt{\varepsilon_{eff}}} \tag{7}$$

where $v_0 = 3 \times 10^8 m/s$ and ε_{eff} is dielectric constant of the substrate.

Eq. (6) states that for Z_h values that make βl_{st} close to $(2k+1)\frac{\pi}{2}$, (k is integer), the input impedance of the switch is very sensitive to frequency variation and the frequency band is very small. For, $\beta l_{st} = (2k+1)\frac{\pi}{2}$, the input impedance is infinite and the switch acts as a narrow-band stop filter. Therefore, for wide-band applications, the value of Z_h should make βl_{st} as low as possible. Moreover, for input impedances to be less sensitive to frequency variations, Z_h should be selected as large as possible. On the other hand, the large values of Z_h result in excessive widths of the short transmission line that is limited by technologic constraints. Hence Z_h should be optimized for these two constraints. Considering these, a reasonable value for Z_h is $90\,\Omega$. Using Eq. (6) and Eq. (7), the optimum length for the high impedance short transmission line is $l_{st} = 328\,\mu$m.



(a) (b) (c) (d)

Fig. 1. (a) Flexural supported springs [6]. (b) Architecture of the proposed switch. (c) Equivalent circuit of the proposed switch. (d) Co-planar waveguide of the proposed switch.

5 Simulation results

The co-planar waveguide of the switch (see Fig. 1 (d)) is designed and simulated using the EM3DS software. The scattering parameters of the proposed

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switch and a single switch for upstate and downstate positions are shown in Fig. 2. The reflection coefficient of the switch in upstate position is shown in Fig. 2 (a). As can be seen from the figure, S_{11} is much lower around the middle of the frequency band for the proposed switch. Therefore, excellent match exists between the proposed switch and its input and output ports. Moreover, there still exists significant improvement in the reflection coefficient for the entire desired frequency band. Fig. 2 (b) shows the insertion loss of the proposed switch in upstate position. The impressive results are due to perfect matching of the proposed switch at its ports. However there exists negligible increase in the insertion loss in very low frequencies in upstate position due to being out of the desired frequency band.

In down-state position, S_{11} is shown in Fig. 2 (c) and S_{21} is shown in Fig. 2 (d). As can be seen from the figures, the proposed switch is nearly an ideal short circuit and the output circuit is perfectly isolated from the input port. The entire incident power is nearly reflected at the input port in the desired frequency band. Simulation results show a good matching condition in the frequency band of 20 to 44 GHz which is consistent with the desired specification.

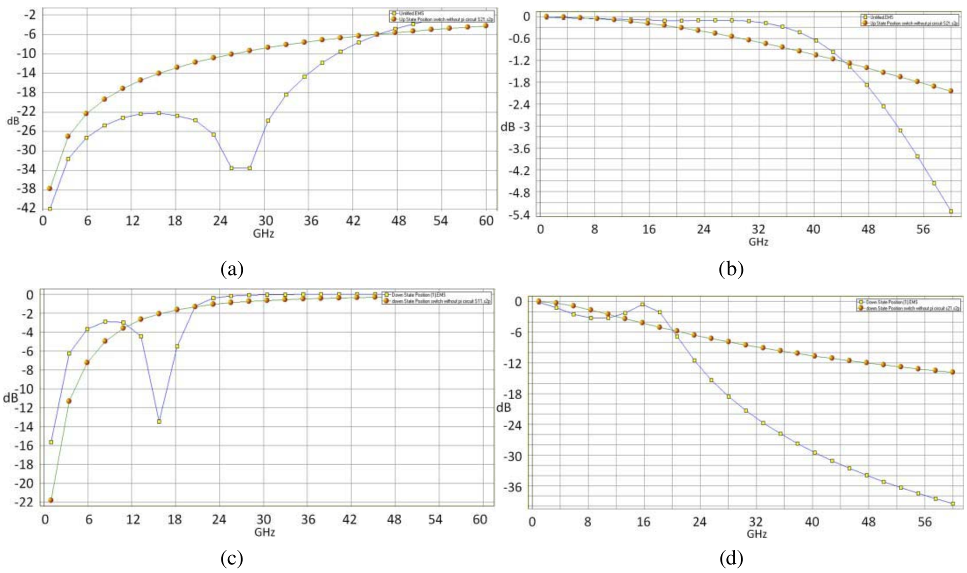

Fig. 2. Scattering parameters of the proposed switch. (a) S_{11} for upstate position. (b) S_{21} for upstate position. (c) S_{11} for downstate position. (d) S_{21} for downstate position. (Rectangle: Proposed switch. Circle: Single switch.)

The minimum improvement of S_{11} in the frequency band of 20-40 GHz is better than 5 dB. For the low value of S_{11}, there is a linear relation between C_u and S_{11}. Using Eq. (3), then Eq. (4), and finally Eq. (2), the calculated actuation voltage is 28.4 V for the single switch instead of 12 V for our proposed switch.

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6 Conclusion

The priorities of the proposed switch are summarized as follow: (i) Low actuation voltage is achieved (12 V), by choosing a proper spring and the physical properties of the switch. (ii) Life cycle and reliability are considered in the design, by choosing the capacitive coupling switch with a 2 μm gap height. (iii) In upstate position, the capacitance between membrane and transmission line is covered by the equivalent inductance of the high impedance short transmission line. Therefore, excellent RF characteristics are achieved. (iv) Switch can be designed for any wide frequency band by optimizing the parameters of the high impedance short transmission line. (v) Comparing with other low actuation voltage methods such as Piezoelectric actuation and electrothermal actuation, the proposed switch has capability of the integration in CMOS technology, and is cheap.

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