Design and optimization of a novel high isolation low insertion loss RF MEMS single-pole double-throw switch

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Abstract. This paper designs an RF MEMS single-pole single-throw and single-pole double-throw switch based on the Ka-band on the CPW. The electrodes of the switch are sandwiched by two dielectric layers. Each SPDT switch has a resonant frequency of approximately 35 GHz and a bandwidth of 20 GHz with an isolation greater than -38 dB and an insertion loss less than -0.8 dB. By changing the state of the SPDT switch, one is in the up state and the other is in the down state, it can achieve the function of switching on and off. The SPDT switch also operates at around 35 GHz with a return loss greater than -23 dB, an insertion loss of less than -1 dB, and an isolation greater than -38 dB.

1. Introduction
Compared with PIN diodes and FETs, RF MEMS switches have smaller size, lighter weight, are not sensitive to acceleration, have no DC loss at microwave frequencies, and have high isolation and low insertion loss [1], which is communication. The system is widely used in phased array radar [2], electronic warfare, satellite communications [3] and other important control units. Compared with the microstrip line, the CPW transmission line has the signal line and the ground line on the same side of the substrate. When the series and parallel circuit components are installed, the substrate is not required to be perforated [4]. These features are helpful for the wide application of CPW transmission line in the field of RF MEMS. Compared with other processing technologies, silicon-based MEMS processing technology is very mature. Therefore, the RF MEMS switch of silicon-based CPW transmission line has been a hot spot in international scientific research. For capacitive switches, the higher the capacitance ratio, the better the RF performance of the switch will be. The use of large beam displacements [5] and relatively thin dielectric layers can effectively increase the upper and lower capacitance ratios. However, the driving voltage of the MEMS switch increases significantly as the beam height increases; Secondly, a thin dielectric layer can cause the switch to break down and fail. High dielectric constant materials can increase the on-state capacitance of the switch and increase the insertion loss of the switching operating band. Therefore, the low-loss, high-isolation large capacitance is urgently needed to solve the key technology of the structural design of the RF MEMS switch. In the paper, Koul S K designed a high capacitance ratio parallel MEMS switch based on CMOS technology, which has a return loss of 12.7 dB-17 dB from 10 GHz to 20 GHz. The Ku-band (13 - 17 GHz) SPDT switch [6] for the T-module application proposed by Sukomal Dey et al. used a series-tap mode of operation; Deepak Bansal et al. proposed a Y-type anchorless slab SPDT switch using a single series capacitor switch mode of operation [7]; Although the above switch design has good switching performance, it is not suitable for the high frequency band, because the touch switch is easy to contact and generate electric spark at a higher
frequency, thereby shortening the switch life. Professor Gou et al form Harbin Institute of Technology have simulated SPDT switches based on microstrip line series MEMS and CPW parallel MEMS switches [8] and found that the impedance was difficult to match during the design process due to the complexity and asymmetry of the switch structure.

In this paper, some research on RF MEMS switches and CPW transmission lines have been carried out based on some of the above problems, and the details, analysis and simulation of the switch design are introduced. In order to solve the impedance matching problem of the discontinuous structure of Ka-band power distribution network, the transmission line theory is used to design a reconfigurable feeder power network model based on SPDT switch according to theoretical analysis, it is found that the switch has high isolation and low insertion loss in both operating states.

2. Circuit model of MEMS switch

The MEMS shunts switch can be integrated on a coplanar waveguide (CPW) or microstrip line if a 1/4 wavelength stub is to be connected to an anchor on the microstrip line. In this paper, a 50 ohms matched CPW transmission line is used for circuit model analysis. The center bandwidth of the CPW is W, the gap width is G, and the thickness is 1 μm, and 400 μm is used as the thickness of the silicon substrate. In the CPW transmission line, the thickness of the dielectric layer is t_d, and the dielectric constant is ε_r, where g is the distance of the switch beam from the dielectric layer. The beam has a length L, a width w, and a thickness t. These are some of the basic dimensions of RF MEMS switches. The side view of the MEMS capacitor parallel switch is shown in Figure 1.

![Figure 1. Side view of the MEMS parallel variable container.](image)

Typically, the MEMS switch beam is connected between the transmission line and ground, and the switch anchor area is connected to the CPW ground. When a DC voltage is applied between the MEMS beam and the CPW transmission line, the resulting static force causes the beam to bend downward, leaving the switch in the down state. When the DC bias voltage is not applied, the light beam returns to the initial state (down state) by the elastic restoring force.

The upper capacitor C_u of the switch is composed of a parallel plate capacitor C_p and an edge capacitor C_e. The edge capacitance is about 20% to 40% of the parallel plate capacitance, and its value varies with the height of the beam. In this paper, the structure of the double-layer dielectric clamped electrode is used as the dielectric layer. So the parallel plate capacitor C_p is equivalent to two capacitors in series. The parallel plate capacitance is given by the following equation (1), and the capacitance ratio is given by (2), where A_up and A_dn is the opposite area of parallel plates, and t_d is the dielectric layer thickness.

\[
C_{dn} = \varepsilon_0 (A_{dn} / \varepsilon_r)^{-1}/2
\]
\[
C_{up} = \varepsilon_0 A_{up} \varepsilon_r [g_0 \varepsilon_r + 2t_d]^{-1} + C_f
\]

When the edge effect is neglected, the ratio of the upper state C_up to the lower state capacitance C_dn of the above varactor can be approximated as:

\[
C_{dn}/C_{up} = \frac{A_{dn}}{A_{up}} \left[ 1 + \frac{g_0 \varepsilon_r}{t_d} \right] = 1 + \frac{g_0 \varepsilon_r}{2t_d}
\]
The upper state and the lower plate are equal in area, that is, $A_{up}=A_{down}$. According to the structural size of the equivalent CPW, the characteristic impedance can be calculated by the formula (4) [9], and the isolation is obtained by the formula (5).

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\varepsilon_r}} \ln \left( \frac{8d}{W} + \frac{W}{4d} \right) & \left( \frac{W}{d} \leq 2 \right) \\ \frac{120\pi}{\sqrt{\varepsilon_r}} \left[ \frac{W}{d} + 1.393 + 0.667 \ln \left( \frac{W}{d} + 1.444 \right) \right] & \left( \frac{W}{d} > 2 \right) \end{cases}$$ \hspace{1cm} (4)$$

$$S_{21} = \frac{1}{1 + j\omega C_d \frac{d_0}{2}}$$ \hspace{1cm} (5)

We use ADS software to simulate the circuit model of the MEMS switch in the Ka-band by typical values, then observe the simulation results of the scattering parameters to obtain high isolation and low insertion loss.

The beam elastic modulus of a MEMS beam is given by:

$$k = 4EW \left( \frac{t}{L} \right)^3$$ \hspace{1cm} (6)

![Figure 2. Vertical view of MEMS beam.](image)

After the elastic coefficient is obtained, the magnitude of the driving voltage can be calculated according to the formula (7). The parameters in equation (7) are given in Table 1.

$$V_P = \sqrt{\frac{8kg_0^3}{27WLw_B \varepsilon_0}}$$ \hspace{1cm} (7)

### 3. Structure and design of RF MEMS switch

The material of the CPW transmission line and the MEMS switch including the beam and the anchor is known as gold. We use Si3N4 as the dielectric layer. We can deform the switch beam because increasing the complexity of the beam deformation can effectively change the inductance. The resonant frequency of the switch increases as the inductance increases. We can use the above method to adjust the resonant frequency of the switch. All parameters used in the RF MEMS switch model are shown in Table 1. Figure 3 shows the structural model of the switch.

| Symbol | Describe                               | Value         |
|--------|----------------------------------------|---------------|
| $W_b$  | width of the beam                      | 120μm         |
| $L_b$  | length of the beam                     | 300μm         |
| $W_h$  | width of the releasing hole             | 15μm          |
| $L_h$  | length of the releasing hole            | 15μm          |
| $W_{d1}$ | width of the up dielectric layer        | 130μm         |
| $L_{d1}$ | length of the up dielectric layer      | 140μm         |
| $W_{d2}$ | width of the down dielectric layer     | 140μm         |
| $L_{d2}$ | length of the down dielectric layer    | 150μm         |
| $t_{d}$ | thickness of the dielectric layer      | 0.2μm         |
| $W$    | width of center transmission line      | 100μm         |
| $G$    | width of the gap                       | 60μm          |
| $L_a$  | length of the anchor                    | 300μm         |
4. Theoretical Analysis and Design of MEMS Single-Pole Double-Throw Switch

In this paper, the T-shaped CPW transmission line is used to design the SPDT switch. The two incident waves can be obtained by equation (8) through a transmission line with a characteristic impedance of 70.7ohms to make the output wave in impedance matching. From this we can get the width W1 of the segment of the transmission line. We place the two switches at a symmetrical position of 1/4 wavelength from the point of convergence. When the switch is in the down state, it is actually equivalent to an open circuit at the point of convergence, as shown in equation (9). Therefore, theoretically, there is no energy loss. Wherein \( Z_l = 0 \), \( l = \lambda/4 \), therefore \( Z_{in} = \infty \) which is close to open circuit.

\[
Z_c^2 = Z_{in}Z_l
\]  
(8)

\[
Z_{in} = Z_c e^{-jZ_cZ_l \beta l}
\]  
(9)

Assuming that the switch is in an ideal state, the insertion loss and isolation can be obtained by formula (10) [10], where \( y_1 \) and \( y_2 \) represent the normalized admittance of two ports and \( \theta \) is the phase difference. In fact, the single-pole double-throw switch can not achieve the ideal turn-on and turn-off, so when calculating the attenuation of one port, the influence of the other port cannot be ignored. The two switches are each 1/4\( \lambda \) to the branch, so \( \theta \) can be taken as 90°. Therefore, according to the formula (10), the insertion loss of the single port Port1 can be directly written as formula (11). Finally, the optimum position of the switch can be obtained by inserting the loss versus the admittance (the reciprocal of the impedance) and then the extremum of the distance \( l \). The same algorithm can obtain
the isolation. Figure 5 shows the structural model of the SPDT switch and the parameters in Figure 5 are given in Table 2.

\[
L_{dB} = 10 \log_{10} \left| \frac{1}{4} (2 + y_1 + y_1 y_2) \cos \theta + j (2 + y_1 + y_1 y_2) \sin \theta \right| ^2
\]

\[
L_{dB} = 10 \log_{10} \left| \frac{1 + 2y_1 + y_1 y_2 + y_2}{2y_1} \right|^2
\]

Table 2. Optimal configuration of SPDT.

| Symbol | Describe | Value   |
|--------|----------|---------|
| \(W_1\) | width of 70.7Ω impedance transmission line | 60μm   |
| \(L_1\) | length of 70.7Ω impedance transmission line | 130μm |
| \(L_2\) | length of 50Ω impedance transmission line | 300μm |
| \(W\)  | width of center transmission line | 100μm |
| \(G\)  | channel width | 60μm   |

Figure 5. SPDT Switch Model.

5. Results Fabrication, Measurement, and Results

We then measure the model and observe the S-parameter results (as shown in Figure 7, 9). For SPST switches, the insertion loss is greater than -0.6dB when the switch is in the upper state, and the isolation is less than -38dB when the switch is in the lower state at 35 GHz. For SPST switches, it can be seen that when one switch is in the upper state and the other switch is in the down state, the return loss is -23dB in 35GHz. The insertion loss is -1dB and the isolation is less than -35dB.
Figure 8. Processed SPDT switch.

Figure 9. S parameters of SPDT switch.

6. Conclusion
This paper introduces the design and analysis of RF MEMS SPDT switches, and proposes a model structure sandwiched by two dielectric layers. This special structure can increase the contact area between the electrode and the beam, and can also make the capacitance ratio of the switch up and down state higher, which can make the switch get better performance. The SPDT switch selection function is realized by controlling the two switches of the T-type CPW to be in different states. Due to the small size and high performance characteristics, the proposed switch design can be used in the mode of reconstructing antenna feed network.

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