A New Double-Bridge RF MEMS Switch with Low Actuation Voltage and High Isolation

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ABSTRACT: This paper presents a new dual beam RF MEMS capacitive shunt switch with low voltage, low loss and high isolation for K-band applications. In this design, we have proposed the step structure to reduce the air gap between the bridge and the signal line, thus the actuation voltage is reduced to 2.9V. Furthermore, to reach more isolation, we used Aluminum Nitride (AlN) as a dielectric layer instead of conventional dielectric materials such as Sio_2 and Si_3N_4which has more ε_r led to increase the down-state capacitance and increase the isolation of switch. The results show that the switch in up position involve S_{11} less than -10 dB from 1 to 40 GHZ and S_{21} more than -0.72 dB from 1 to 22 GHZ. In down state, switch has an excellent isolation at the frequency range of K-band. The maximum isolation of -58 dB is obtained at resonance frequency of 27 GHZ. Furthermore, we used the π-match circuit to improve the reflection and isolation of switch. In this case, the double-bridge switch has the return loss of around -12 dB at the range of 1-31 GHZ. The insertion loss of switch is less than -0.8 dB at the range of 1-27 GHZ. The isolation around -40 dB is obtained at the range of 15-40 GHZ. The proposed dual beam switch is the wideband and low-loss switch that appropriate for applications of K-band frequencies.

KEYWORDS: RF MEMS, dual beam switch, actuation voltage, isolation

1. INTRODUCTION

RF MEMS switches are the most important components. Many MEMS switches have been reported with different geometries and characteristics such as low insertion loss and high isolation which are suitable for microwave applications[1]. These devices can be employed in radio frequency (RF) from 30 KHZ up to 300 GHZ applications. They can be used for cell phones, short range communication including WLAN and Bluetooth, automotive industry, biomedical applications. The MEMS switches showed a better performance than the conventional FETs and PIN switches specially when used in microwave applications[2]. This is due to their good linearity, low noise, low power consumption, high electrical isolation, and ultra wide frequency band[1]. MEMS switches can be categorized in electrical configurations (series or shunt), mechanical structures (cantilever or fixed-fixed) beam and actuations (electrostatic, electromagnetic, electrothermal and piezoelectric actuation)[3 − 6]. Due to the nearzero power consumption and linearity, electrostatic actuation is most widely used, in which electrostatic force is generated between fixed electrode and movable membrane for switching operation. Some applications, such as mobile communication systems, WLANs, electronically steerable antennas (ESA), and automatic test equipment, demand RF switches with both low insertion loss and very high isolation performance[7]. If the isolation characteristics of the switches are low, then more intermediation is produced due to leakage of signals from another channel, thus the RF system performances will be debased[8]. In recent years, several RF MEMS shunt capacitive switches have been designed and fabricated. In[9], a MEMS capacitive switch was designed which has a return loss about -35 dB and insertion loss about -0.4 dB from 5 to 20 GHZ. The isolation of this switch is -45 dB at 14 GHZ. The proposed switch in [10] with air gap of 2μm is placed on a silicon substrate. It has a return loss less than 10 dB for the frequencies more than 20 GHZ, and the isolation about 25 dB at 9GHZ. In[11], the MEMS capacitive switch has the insertion loss about 0.034 dB and the isolation about 41 dB at the frequency of 21 GHZ. The actuation voltage of the switch was obtained 9.7 V. The RF MEMS capacitive switch in[12] with the air gap of 2μm that the thickness of golden bridge is 0.5 μm was proposed. The actuation voltage of this switch is 4.8 V. It has the insertion loss 0.55 dB and isolation 47.63 dB at 40 GHZ.

In this paper, a RF MEMS switch using shunt capacitive topology and electrostatic actuation is proposed. To reduce the actuation voltage of switch, we have designed the step structure to reduce the air gap of switch. Moreover, to reach the higher isolation, have tried to choose the materials with appropriate properties.

2. THE MEMS SHUNT CAPACITIVE SWITCH

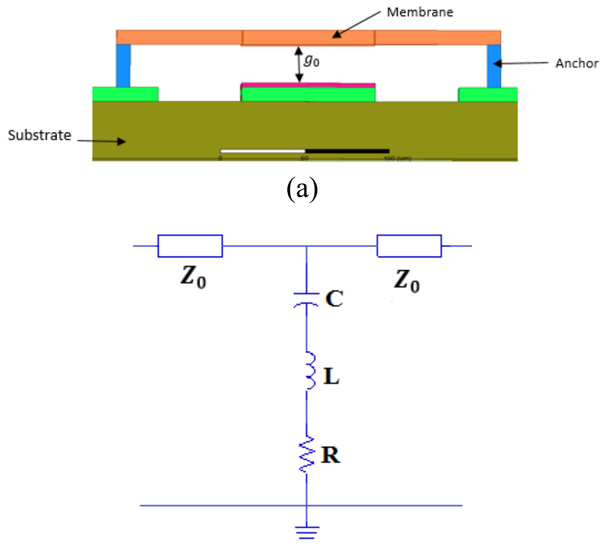
The standard RF MEMS shunt capacitive switches consist of a thin metallic bridge which suspended over the CPW line. The coplanar waveguide (CPW) consists of one signal line in the middle and two infinite grounds beside the transmission line.

2.1. The Structure and Electrical Model of MEMS Shunt Capacitive Switch

The schematic of the MEMS capacitive switch is shown in Figure1a. When there is no actuation voltage across the beam, the RF MEMS shunt switch is ON and the signal passes from the input to the output. While the switch is actuated, the bridge collapses on the CPW transmission line and the signal is disconnected from input to output due to short circuit. The actuation voltage, V_p, of MEMS switch is given by

$$V_p = \sqrt{\frac{8k}{27\varepsilon_0 A} g_0^3} \tag{1}$$

where g_0 is the zero-bias air gap, A is the area of electrodes, ε_0 is the permittivity of free space and k is spring constant. The RF performance of the switch is quantified by its insertion loss, return loss and isolation. Basically, it is desirable to have a low insertion loss and return loss and high isolation in order to improve the RF performance; therefore it is necessary to modify the bridge design of the switch. The RF capacitive switch can be modeled by a transmission line with characteristic impedance, $Z_0 = 50\ \Omega$, and a lumped series resistor-inductor-capacitor model of the bridge, as shown in Figure 2b.



(a)

(b)

Fig.1: (a) RF-MEMS capacitive shunt switch (b) lumped electrical model

The metallic bridge of the switch is represented mainly by the bridge resistance R, bridge inductance L, and variable bridge capacitance C. The variable bridge capacitance changes according to the actuation state of the switch. The impedance of the bridge, Z, is given by

$$Z = R + j\omega L + \frac{1}{j\omega C} \tag{2}$$

where $C = C_u$ or C_d, depend on the actuation state of the RF capacitive switch; C_u is the up-state capacitance, and C_d is the down-state capacitance. At up state, the switch is modelled as a single capacitor between transmission line and bridge because the operation frequency is much lower than the cut-off frequency (THZ). At down state, the switch needs to be modelled by C_d, L, R. C_d depends on the overlap between the membrane, signal line and thickness of the dielectric, L depends on the overlap between the membrane and gap between ground and signal line. R depends on transmission line and bridge resistivity. The resonant frequency, f_0, is given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

The impedance of the switch depends on operation frequency is approximated by Equation (4)

$$Z = \begin{cases} \frac{1}{j\omega C} & \omega \ll \omega_0 \\ R & \omega = \omega_0 \\ j\omega L & \omega \gg \omega_0 \end{cases} \tag{4}$$

The CLR model behaves as a capacitor for frequencies below resonant frequency and as an inductor on frequency higher than that. At resonance frequency, the CLR model behaves as series resistance. The reflection coefficient of the switch in up-state is given by

$$|S_{11}|^2 = \frac{\omega^2 {C_u}^2 {Z_0}^2}{4} \tag{5}$$

$$C_u = \frac{\varepsilon_0 A}{g_0 + \frac{t_d}{\varepsilon_r}} \tag{6}$$

Where t_d is the dielectric thickness,g_0 is the air gap between transmission line and bridge, and ε_r is the permittivity of dielectric material. The isolation in down state is given by

$$|S_{21}|^2 = \begin{cases} \frac{4}{\omega^2 {C_d}^2 {Z_0}^2} & f \ll f_0 \\ \frac{4R^2}{{Z_0}^2} & f = f_0 \\ \frac{4\omega^2 L^2}{{Z_0}^2} & f \gg f_0 \end{cases} \tag{7}$$

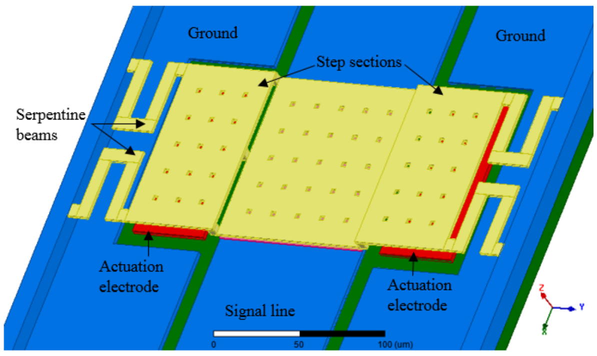
Wheref_0 is the LC resonant frequency of the switch in the down state. The down-state capacitance can be calculated by

$$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d} \tag{8}$$

2.2. Design of a Novel RF MEMS Shunt Switch

To design of switch, the quartz is chosen as a substrate, because the quartz has high melting point compared with silicon and it can withstand high temperatures than the silicon. The MEMS switch consist of quartz substrate with $\varepsilon_r = 3.78$, signal line width, W, and distance between signal line and ground, G, of 100µm and 11.2µm respectively, and the thickness CPW of 2µm. We selected Aluminum (Al) as a CPW, bridge and the actuation electrodes that led to less loss and excellent isolation. They are placed over the quartz substrate. A very thin dielectric layer of Aluminum Nitride (AlN) with $\varepsilon_r = 9.5$ is placed over the center conductor of proposed switch. Most of the conventional MEMS switches used silicon dioxide (Sio_2) or silicon nitride(Si_3N_4) with $\varepsilon_r = 3.9$ and $\varepsilon_r = 7.5$ respectively as dielectric material. AlN has good dielectric properties, high thermal conductivity, and non reactive with normal semiconductor process chemicals and gases. The dielectric provides a capacitive path for RF signal while avoid short circuit of transmission line to ground. The dimension of MEMS switch is given in Table 1.

Figure 2 shows the new switch with step beam. The thickness of beam is 0.5µm. It is connected to the ground of CPW via four serpentine beams. Two actuation electrodes have been used for electrostatic actuation that placed under the bridge at two sides of the CPW. Top view of the switch is shown in Fig.2a. The center section of the switch is placed over the CPW with gap of 0.7µm and the gaps of two step sections from the actuation electrodes are 2.2µm.The pull-in occurs at $\frac{g_1}{3}$. If $g_2 \leq \frac{g_1}{3}$, the maximum travel distance of membrane will be g_2. Therefore, the pull-in will not occur. The close view of the step structure is shown in Fig2b. The geometrical parameters are shown in Figure 2c and Figure 2d shows the cross section view of the proposed switch.



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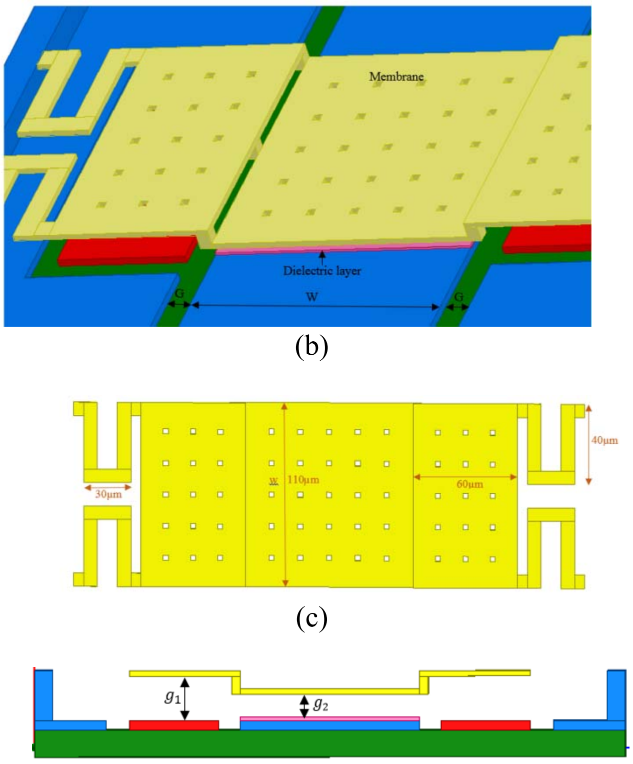


(b)

(c)

(d)

Fig.2: (a) Overall view (b) Close view (c) Geometric parameters (d) Cross-section view of the proposed switch

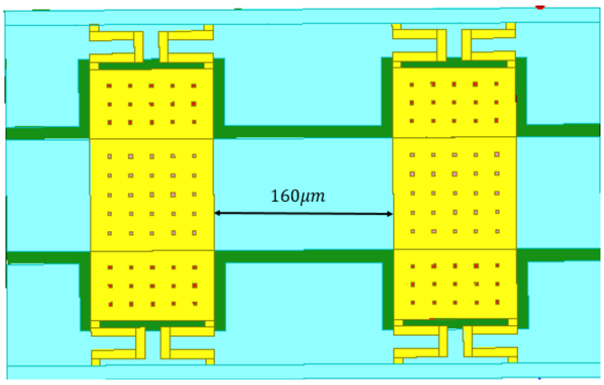
Table1. RF MEMS switch parameters

Parameter	Value
Membrane width (w)	110µm
Signal line width (W)	100µm
Gap between signal line and ground (G)	11.2µm
Overlap area	110× 100 μm^2
CPW thickness	2µm
Dielectric thickness	0.1µm
Gap between actuation electrodes and membrane (g_1)	2.2µm

Gap between transmission line and membrane (g_2)	0.7μm
Bridge thickness	0.5μm

Some square holes with diameter of 4μm are formed on the beam to facilitate the etching of the sacrificial layer. These holes not only help for release processing but also improves the dynamic performance of the switch by reducing the air damping, stickiness and hence the switching time.

In many applications, higher isolation and broader bandwidth compared to the ones achieved by a single-bridge switch are desired. A two-bridge switch consisting of two metallic bridges with serpentine folded suspensions has been designed and is presented in Fig.3a. Both bridges have the same dimensions. The separation distance between the two bridges is 160μm. Fig.3b shows the circuit model of the two beam switch. The model is constructed using two 50Ω transmission lines at the ports, two shunt CLR branches for modeling the beams and a short section of transmission line of 50Ω for separating the shunt branches. In this design, meanders supporting the beam introduce additional inductance thus increasing the beam inductance.



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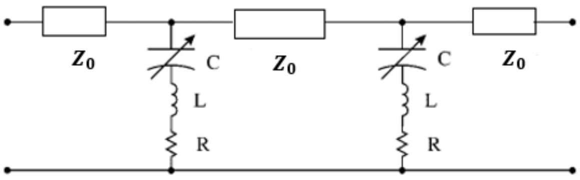


(b)

Fig.3: (a) Double-bridge switch (b) CLR circuit model of the double-bridge switch

2.3. Results and discussion

The finite element method (FEM) is utilized to evaluate the mechanical and electric behaviors of the RF MEMS switch(single-bridge) using Intellisuite MEMS tool and the microwave characteristics are considered using HFSS software. The material of the switch is aluminum with a young modulus of 70 GPa, Poisson's ratio of 0.33 and mass density of 2700 $\frac{kg}{m^3}$,. A DC voltage of 2.9 V was applied between membrane and actuation electrodes. It causes the membrane pulls down on the dielectric layer thus the switch is OFF (seeFig.4). It clearly shows that the membrane has uniform displacement.

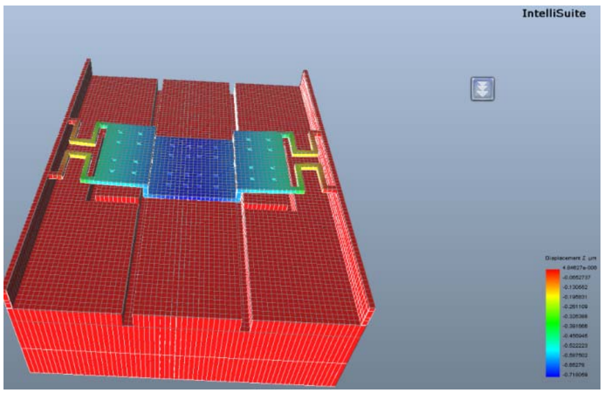
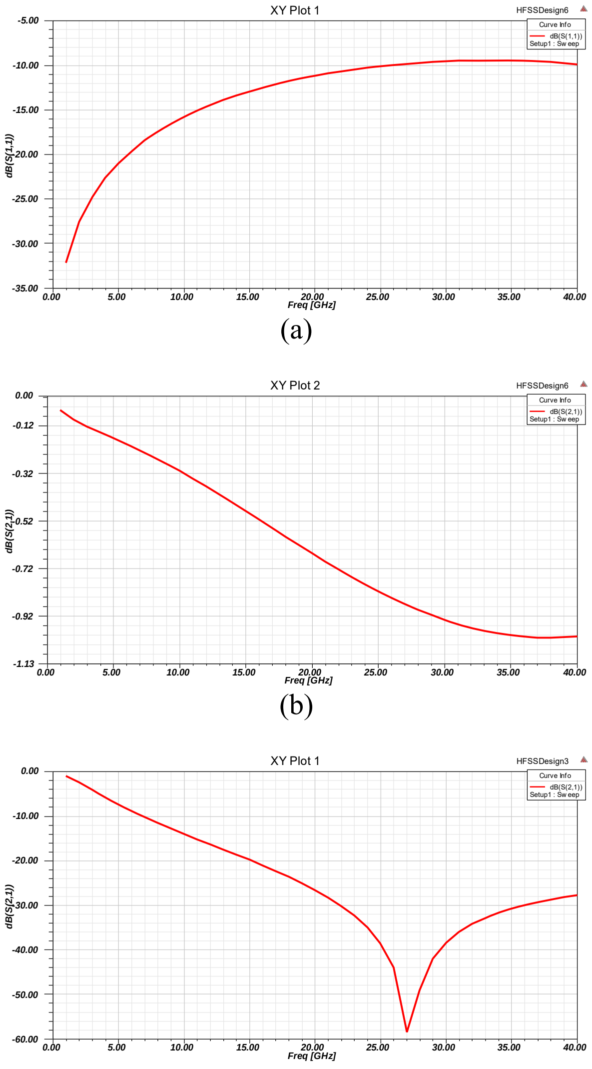


Fig.4: Displacement of membrane of RF MEMS switch

The isolation loss, return loss and insertion loss of the proposed switch is measured using ANSYS HFSS v15. RF performance of the switch is observed between frequencies 1 GHZ to 40 GHZ. The scattering parameters of proposed switch are desirable for K band. At the up state, the S_{11} is less than -10 dB for the frequencies from 1 to 40 GHZ (see Fig.5a). Furthermore, there is an excellent matching at 3 GHZ that$S_{11}$is less than -25 dB. Figure 5b shows the insertion loss of -0.92 dB from 1 to 30 GHZ. Also, at down state, the isolation of MEMS switch is less than -30 dB from 22 to 36 GHZ. The maximum isolation of -58 dB is occurred at resonant frequency of 27 GHZ (see Fig.5c).



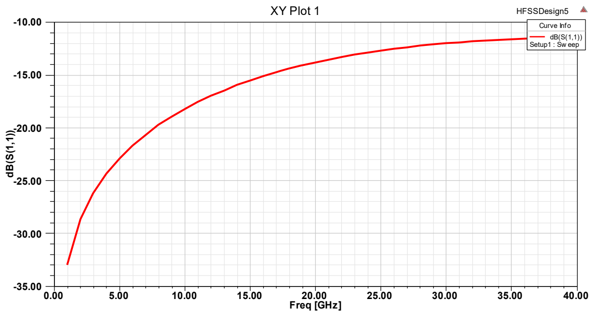
(a)

(b)

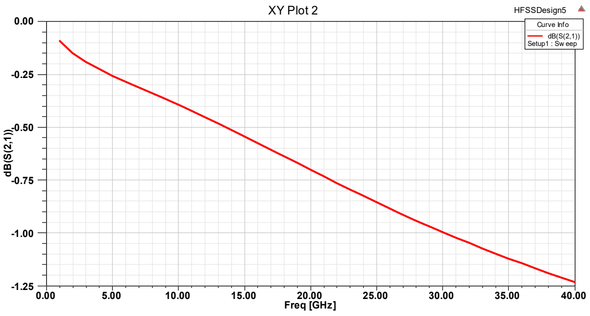
(c)

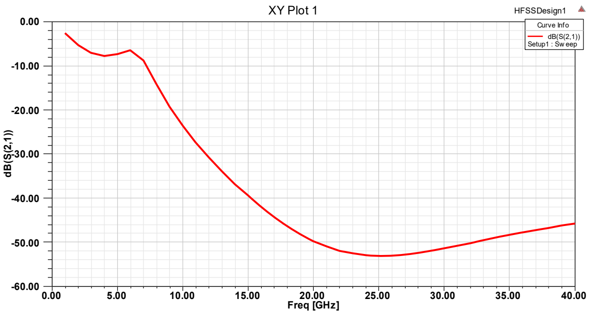
Fig.5: (a) Return loss (b) insertion loss of switch in up-state (c) Isolation of single-bridge switch in down-state

The simulated RF performance of the double-bridge switch is also shown in Fig.6.



(a)





(b)

(c)

Fig.6: (a) Return loss (b) insertion loss of double-bridge switch in up-state (c) Isolation of double-bridge switch in down-state

The simulated S-parameters of the designed double-bridge switch that presented in Fig.6, shows reasonable results for return loss and insertion loss. The isolation of double-bridge switch is much better than the single-bridge switch. In this case the isolation is around -40 dB in the range of 15 to 40 GHZ, thus the bandwidth is much broader. The comparison between the isolation of single-bridge and double-bridge switch is shown in Fig.7.

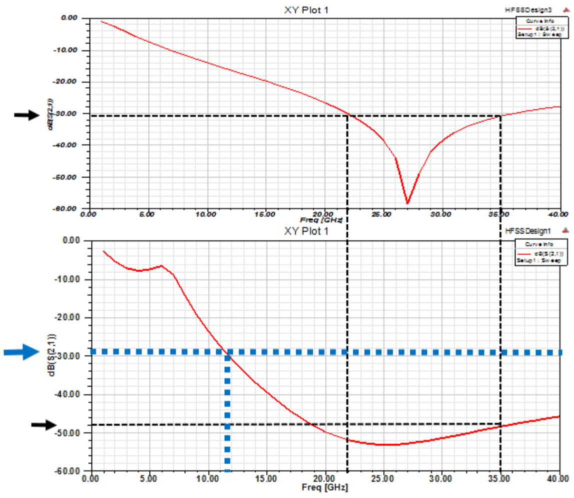


Fig.7: The comparison of isolation of single and double-bridge switch

Table 2 shows the comparison of proposed single-bridge switch with previous works. It can be seen that the proposed switch has excellent performance in high frequency than the other switches.

Table 2. Comparison of proposed switch with previous works.

Parameters	Ref. [11]	Ref. [12]	Ref. [13]	Proposed switch
Metal bridge	1-2μm (Au)	0.5μm (Au)	1.5μm (Au)	0.5μm (Al)
Air gap	3μm	2.0μm	3.0μm	0.7 and 2.2μm
Dielectric	0.5μm (Hfo_2)	0.15 μm (Si_3N_4	0.35μm (To_2O_5)	0.1μm (AlN)
Insertion loss	0.034 dB	0.55 dB	0.8 dB	0.8 dB
Return loss	0.3 dB	12 dB	-	10 dB
Isolation	41 dB	47.63 dB	40 dB	58 dB
Actuation voltage	9.7 V	4.8 V	15-20 V	2.9 V

3. CONCLUSION

In this paper, anew RF MEMS capacitive shunt switch with low actuation voltage, low loss and high isolation is presented for K band applications. To obtain low actuation voltage, small air gap is needed, therefore the step membrane has been designed for switch. In proposed switch, Aluminum Nitride (AlN) as a dielectric layer has been used instead of conventional dielectric materials such as silicon dioxide and silicon nitride to increase the down-state capacitance and improve the isolation. The results show that the actuation voltage is reduced to 2.9V, and the switch in up position involve S_{11} less than -10 dB from 1 to 40 GHZ and S_{21} more than -0.72 dB from 1 to 22 GHZ. In down state, switch has an excellent isolation at the frequency range of K-band. The maximum isolation of -58 dB is obtained at resonance frequency of 27 GHZ. Furthermore, we used the double-bridge switch to improve the reflection and isolation of switch. The proposed dual beam switch is the wideband and low-loss switch that appropriate for applications of K-band frequencies.

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