Optimization in MEMS Switch Designing for K_u/K_a Applications

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Abstract — This article describes various optimization techniques, essential for designing RF-MEMS Capacitive type switch to cater entire K-band applications. The optimal dimension of the package has also been determined here. The design is based upon high resistive Silicon Substrate (ρ > 8 KΩ-cm)and analysis was done using commercially available MoM and FEM based EM solvers.

***Keywords*—Air bridge, Ground notching, T-matching, RF packaging.**

I. INTRODUCTION

In now-a-days world, MEMS technology shows enough promising features to manifest multiple microwave applications as compared to already established VLSI, Ferrite or solid-state devices. Numerous advantages are obtained with MEMS [1-3].Considering high frequency applications and other fabrication intricacies, shunt capacitive switches are comparatively preferred than series categories.

Here, a standard dimension of RF switch is chosen and analysed for 6" high resistive Silicon substrate of 675 µm thickness . The dielectric constant (ε_r) of the substrate is taken as 11.8 and the loss tangent is assumed to be 0.01, whereas resistivity of the substrate is higher than 8 KΩ-cm. The physical dimension of the switch is depicted in Table-I.

RF switch is used for various multipurpose applications like- Phase shifter, phased array antenna, reconfigurable devices, switching matrices, etc. Different applications demand varieties of optimization techniques as per the desired RF performances ,like-for phase shifter applications users claim minimum phase-error along with loss criteria. Another important aspect of designing RF switch is, practical implementation of actuation mechanism and its associated parasitic, hindering the RF performances.

This article is summarized into four sections, separately explaining the criteria for substrate choosing, air-bridge optimization, T-matching, notch incorporation and finally packaging effect.

Here, we present the various strategies of designing a K-band RF Switch utilizing Finite Ground Conductor Backed Coplanar waveguide (FG-CB-CPW) configuration on high resistive silicon (HRS).

II. CHOICE OF SUBSTRATE

The performance of the transmission lines has the limitation particularly at K-band frequencies due to radiation loss, surface wave propagation and dispersion associated with them. Radiation loss is caused by the circuit discontinuities and is worse for the thicker substrate with low permittivity. Dispersion and surface wave propagation are caused by substrate-air discontinuity. Dispersion affects high-frequency broadband performance and surface-wave propagation contributes to signal loss. Increasing the substrate permittivity and thinning the substrate reduce the losses; however thinned wafers are very much fragile. In a structure, dominant mode propagation has to be much below cut-off frequency. So, for desired quasi-TEM mode propagation, the height of the substrate (HRS, ρ > 8 KΩ-cm) is chosen as 300 µm, which gives a cut-off frequency as 80 GHz. And at this substrate thickness, a best trade-off is achieved between bandwidth and loss.

TABLE I
Physical constants & Notations

Symbol	Parameter	Selected Value
f_c	Centre Frequency	30 GHz
Z_o	Characteristic Impedance	50 Ω
ε_r	Dielectric constant	11.8 for Silicon
h	Substrate thickness	270 µm
Selected Dimensions		
W	Width of the centre conductor CPW line	80 µm
G	Gap between centre conductor & ground plane of CPW	46 µm
t	Thickness of the membrane	1 µm
w	Width of the membrane	100 µm
l	Length of the membrane	272 µm
g_0	Initial gap between the switch and CPW	2.5 µm

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III. Air-Bridge Optimization

To facilitate the DC biasing of the RF switch, splitting in CPW ground line is often employed. But, this splitting introduces extra discontinuity in the structure and also causes coupled slot wave propagation. Two ground planes may not face same potential at the same instant, which may support odd-mode propagation, unpredictable at higher frequencies. To eliminate these problems, air-bridges are incorporated between two grounds. Air bridges are nothing but a MAM capacitor, which doesn't undergo any electrostatic actuation like RF switches. Increasing the number of bridges not only enhances the fabrication complexity (especially stiction), but also affects the RF performance (insertion phase) significantly. Table-II shows the optimization results for number of air-bridges. It clearly depicts that, in a splitted ground CPW structure three numbers of air-bridges are sufficient to compensate all parasitic effects. Further this number can be reduced by providing a thin slit for continuation in RF ground, as shown in Fig.1. Here, all the analysis has been carried out with 150 µm long & 20 µm wide air bridges. Simulation shows that a change in RF ground width of 20 µm can affect a change in insertion phase of ~ 1°.

TABLE II
Comparative study of the effect of number of the air-bridges on RF performance

Type of Structure		S_{11}(dB)	S_{21}(dB)	Phase(S_{21})
Basic CPW structure		-26.48	-0.169	-92.28
Splitted ground	Single air-bridge	-17.40	-0.273	-96.63
	Two air bridges	-21.29	-0.206	-93.72
	Three air bridges	-25.01	-0.183	-92.28

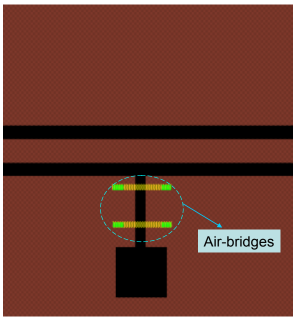
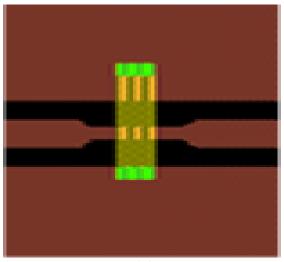


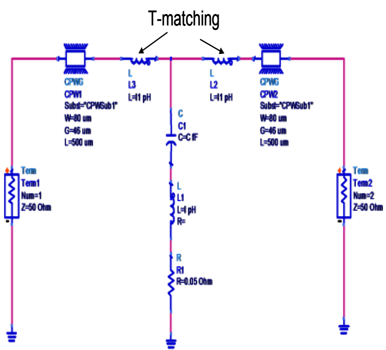
Fig 1. Reduction technique of number of air bridges.

IV. T-Matching

Switch insertion introduces extra capacitance and degrades the RF performance of the CPW line. Due to the low height (0.12 to 2.5 µm) of the membrane layer, a significant additional capacitance is present between the inner conductor of the CPW and the short-circuited anchored strip. This modifies the characteristic impedance of the line and the effective dielectric constant in the bridged region [1]. As we know that, for a loss less transmission line the characteristics impedance is given by the square root of the ratio of the line inductance to capacitance. So, introduction of switch increases the line capacitance significantly. To compensate this, tapering of Tx-line beneath membrane is done to enhance the line parasitic inductance. By tapering the t-line beneath the membrane, the degradation in return loss is minimized leaving marginal phase deviation, which can be taken care in the T-matching. Basically, two short high-impedance sections of t-lines before and after the bridge are introduced, which behave as series inductors and provide an excellent match at the desired frequency [2]. Fig.2 shows the layout of the T-match circuit along with its equivalent diagram.



(a)



(b)

Fig 2. Layout for the T-match circuit (a) and equivalent circuit (b).

Table-III shows the parametric study of the inductive matching by varying the length and the width of the tapering in the live line of the CPW.

Table-III
Parametric study of the T-match circuit

Width = 34 µm

Tapering Length(µm)	L(pH)
100	36.91
120	39.12
150	41.85
200	49.93

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Length = 120 µm

Tapering Width(µm)	L(pH)
30	13.05
32	14.37
34	39.12
38	41.85

Fig.3 shows a comparative study between a switch inserted simple CPW structure and a structure with inductive matching. The T-matching enhances the return loss performance by around 20 dB in Ka-band, leaving the insertion loss behaviour more or less same.

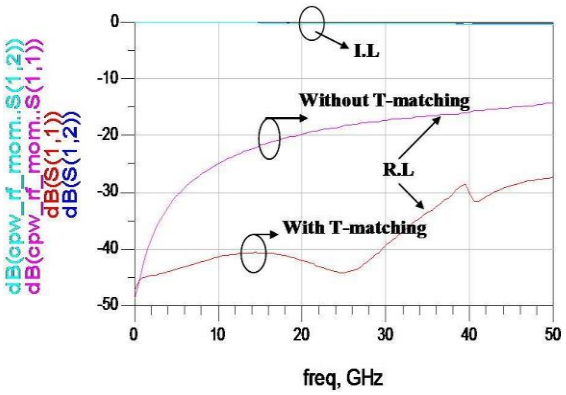

Fig 3. Improvement of RF performance by T-match circuit

V. NOTCH INCORPORATION

In various occasions, notches are introduced (to increase inductance) at the membrane ends to compensate the parasitic. Fig.4 shows a notch introduced RF switch structure. A detailed simulation is carried out in Ka-band by varying the width and length of the notch structure, shown in Fig.5. And Table-IV shows a parametric study of the notch structure on high frequency performance. It depicts that, changing the length of notch much affect in RF performance rather than its width change.

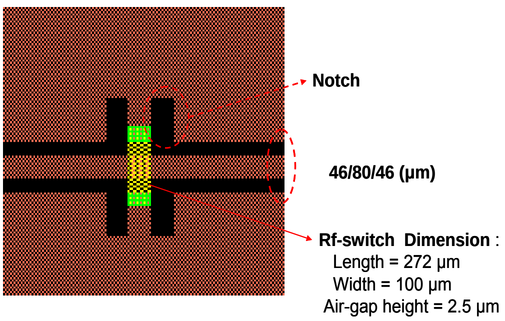

Fig 4. Notch introduced capacitive type shunt RF-switch structure

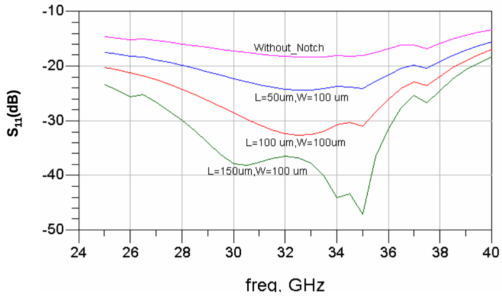

Fig 5(a). Return loss performance with fixed width/variable length notches.

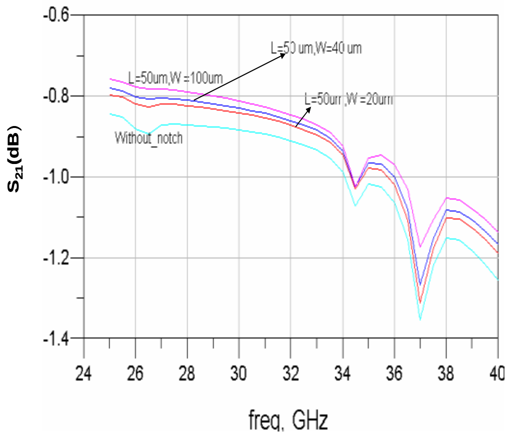

Fig 5(b). Insertion loss performance with fixed width/variable length notches.

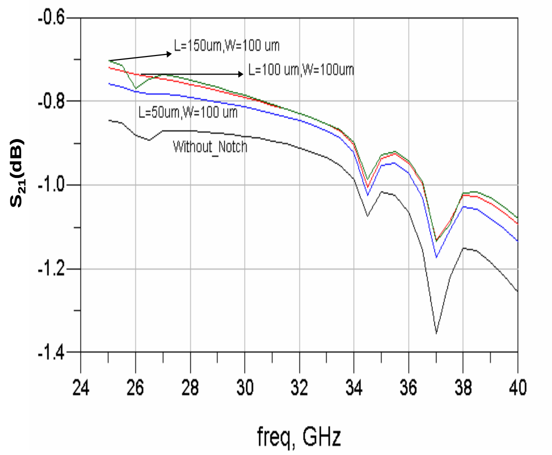

Fig 5(c). Insertion loss performance with fixed width/variable length notches.

Ground notching can also be incorporated beneath the membrane to facilitate the DC biasing arrangement of switches, as shown in Fig.6. Here, notches not only improve the loss parameters as per the above discussion, but also allow to employ bigger size actuation pad beneath the shunt switch, which results in reduction of pull-down voltage.

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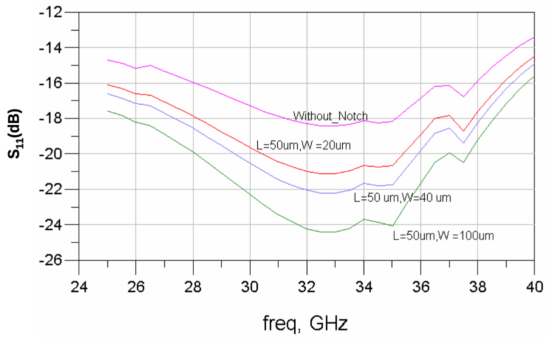

Fig 5(d). Return loss performance with fixed length/variable width notches.

But, with single bias arrangement actual beam size becomes longer to maintain the axial symmetry with respect to the actuation pad. This problem can be resolved with the use of dual bias technique, where simultaneously two DC pads are utilized for electrostatic actuation, as shown in Fig.7. Here, beam length is reduced and notching isn't required beneath the bridge, avoiding fabrication complexity. Rather, notching has been added to the structure far away from the switches but contributing the same RF performance like previous one. Reducing the beam length decreases the pull-down voltages, as well as increases the mechanical strength of the hanging structure.

Table-IV
Parametric study of the notch structure

Length =50 μm

Width(μm)	S11(dB)	S21(dB)	Phase(S21)
20	-19.6	-0.840	-111.882°
40	-20.6	-0.830	-112.210°
100	-22.3	-0.813	-112.539°

Width =100 μm

Length(μm)	S11(dB)	S21(dB)	Phase(S21)
50	-22.3	-0.813	-112.539°
100	-28.6	-0.791	-115.620°
150	-37.9	-0.786	-118.513°

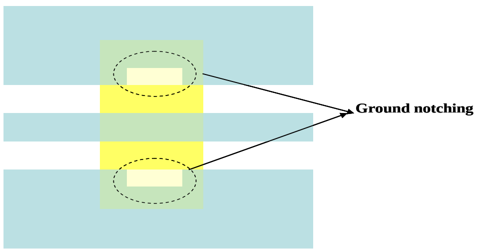

Fig 6. Layout of RF-switch with notched ground beneath it.

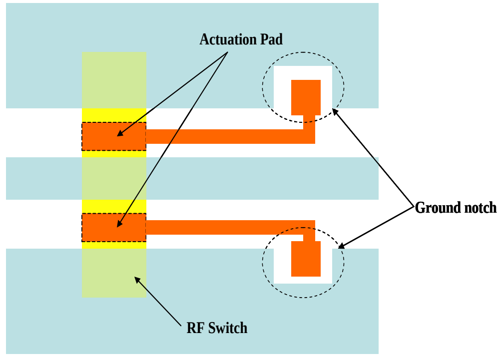

Fig 7. Layout of RF-switch with dual biasing arrangement.

VI. PACKAGE SIMULATION

Packaging is one of the major concerns for developing MEMS devices. Similar to other MEMS devices the shielding/package provides hermetic environment for its working as well as protection from EMI/RFI [4]. Initiating this work with microstrip line gives a clear picture to determine the physical dimension of the RF package. The physical separation of the lateral wall of the package is placed $\lambda/4$ apart from the central RF circuits and the top wall of the package can be placed at the $\lambda/8$ distance. The short circuited $\lambda/4$ line behaves as open circuit, avoiding the effect of abrupt termination of electric fields emanating from the RF circuits inside the shields. Table-V shows the effect of metallic enclosures placed at the aforesaid distances for the Ku and Ka band respectively. Fig.8 shows the placement of a RF switch in the metallic enclosure, which has been analysed using the FEM based EM solver. The switch is studied for its two distinct states-open and closed state. Table-VI demonstrates the analysed result for the same.

In addition to that, the effect of bond-wire is also studied here. As bond-wire plays an important role for die-attaching at different critical situations, it also has some detrimental effect on the RF performance. Specially, parasitic inductance and inter-wire capacitances come into picture. In this study, we consider 2 mil diameter gold-wire for bonding. Studying the FEM analysis, it can be concluded that at least six numbers of bond-wires are essential to cope up the nearby actual RF characteristics for 500 μm gap coupled transmission lines, shown in Fig.9. Results have been summarized in Table-VII. This study is targeted for conventional wire-bonding process employed in the embedded I/O pads/connectors of the package and the DUT's I/O lines.

Table-V
Effect of metallic shield on Simple transmission Line(Microstrip/CPW)

Frequency band (GHz)	Centre Freq. (GHz.)	Without shielding		With shielding	
		R.L(dB)	I.L(dB)	R.L(dB)	I.L(dB)
15-19	17	-50	-0.5	-47	-0.25
28-32	30	-19.8	-0.75	-19.0	-0.71

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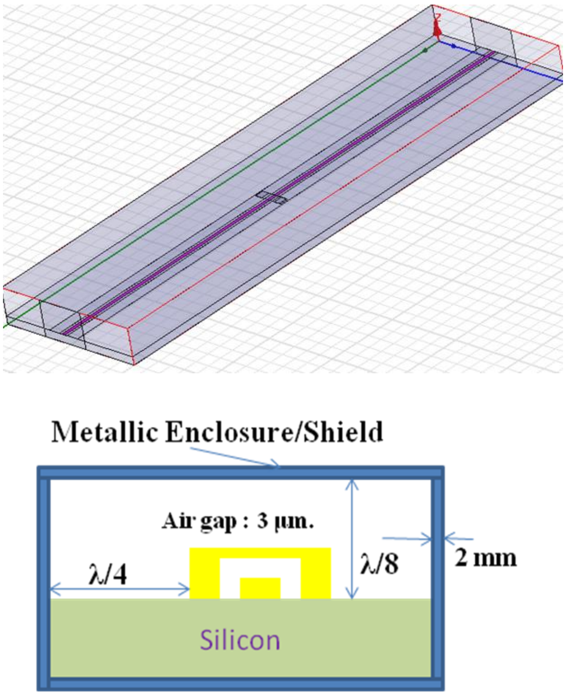

Fig 8. Placement of the RF Switch inside the package boundary.

Table-VI
Effect of metallic shield on RF Switch

Up-state

Frequency band (GHz)	Centre Freq. (GHz.)	Without shielding		With shielding	
		R.L(dB)	I.L(dB)	R.L(dB)	I.L(dB)
28-32	30	-27	-0.6	-30	-0.41

Down state

Frequency band (GHz)	Centre Freq. (GHz.)	Without shielding		With shielding	
		R.L(dB)	I.L(dB)	R.L(dB)	I.L(dB)
28-32	30	-27	-0.6	-30	-0.41

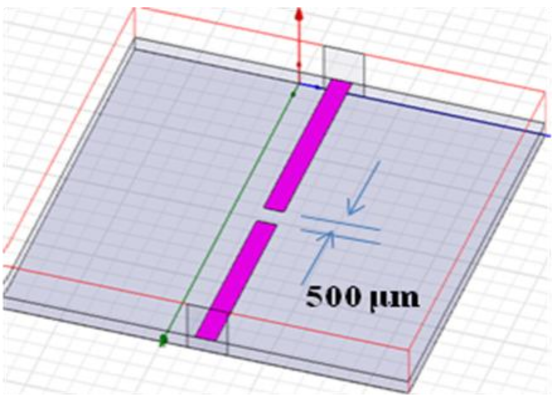

Fig 9(a). Gap coupled Transmission line

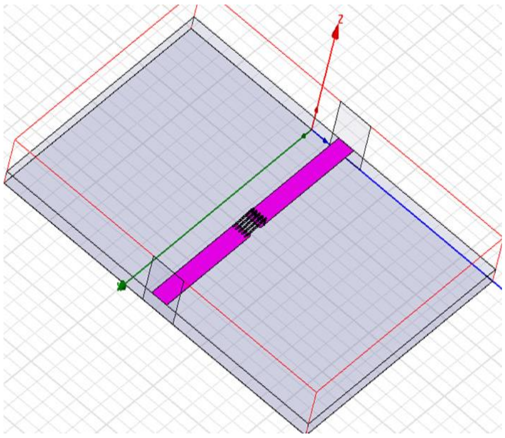

Fig 9(b). Bond-wires attached to the gap-coupled t-line.

Table-VII
Effect of bond wire

Frequency band (GHz)	Centre Freq. (GHz)	Without shielding		With shielding		
		R.L(dB)	I.L(dB)	Number of bond-wires	R.L (dB)	I.L(dB)
28-32	30	-30	-0.6	1	-2.3	-5
				2	-4.2	-3.2
				3	-5.6	-2.2
				5	-11	-0.9

VII. CONCLUSION

Designing RF switch at K_u / K_a-band is a challenging task for a RF engineer. Because, at this frequency parasitics get much importance, which may reflect adversely system performance. Proper optimization is essential from design as well as fabrication point of view. This paper details about various optimization techniques. The authors feel that this article will provide useful database for the designers involved in the RF field, who are interested to start designing RF switch and its derived circuitry at K_u/K_a-band.

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