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Tuned Dual Beam Low Voltage RF MEMS Capacitive Switches for X – Band Applications

E.S.Shajahan[1], Shankaranarayana M Bhat[2]
Department of Electronics and Communication Engineering
National Institute of Technology Karnataka
Mangalore, India
[1]shajes2007@gmail.com, [2]msbhat@ieee.org

***Abstract*—This paper presents a low voltage, low loss tuned RF MEMS (Radio Frequency Micro Electro Mechanical Systems) capacitive shunt switches for use in X – band. The tunable switch is designed using two shunt beams with meander springs. The switch achieved low actuation voltage along with small up state capacitance. Simulation using CoventorWare shows the actuation voltage as 7.5 Volts and up state capacitance of 47fF. HFSS simulation reveals the insertion loss in the range of (0.1 – 0.2) dB and up state return loss better than -25 dB in the X-band (8-12 GHz). The switch offers down state isolation of 60 dB at 12 GHz and is better than 40 dB in the frequency range 8-25 GHz.**

I. INTRODUCTION

Recent research has demonstrated beyond doubt the role of low loss RF MEM (Radio Frequency Micro Electro Mechanical) switches in millimeter and microwave applications [1]. This is because of the numerous advantages RF MEMS switches have over their semiconductor counterparts (PIN and FET switches) in terms of their low power dissipation, transmission loss, high quality factor, better isolation and very low inter modulation products [2]. Disadvantages include low switching speeds (10-20μs), high actuation voltages (15-60 V) and hot switching in high power applications and failure due to stiction phenomenon. Despite better performance over other competing technologies such as PIN or FET switches, reliability issues hamper the commercialization of RF MEMS capacitive switches.

This study discusses the design of low voltage, low loss tuned Micro Electro Mechanical (MEM) switches for use in X – band. To reduce the actuation voltage, low spring constant meander springs have been employed to connect the capacitor plates to the anchors. Vast majority of the switches in the literature typically require pull-in voltage of the order of 40-100 V. These ranges are quite challenging for handheld devices and wireless devices that rely on low voltage power supplies. Goldsmith *et al.* [4] have experimentally observed significant lifetime improvement for every volt drop in pull-in voltage. Thus, reducing the actuation voltage not only broaden the range of applications but also improves their performance.

II. DESCRIPTION OF THE X – BAND RF MEM SWITCHES

The dual beam tuned switch is constructed over CPW transmission line with a characteristic impedance of 50 Ω. The tuned switch is designed to be a low voltage, low loss and high isolation RF switch for operation in the X – band (8-12 GHz). The switch is found to have satisfactory RF characteristics in K_u band as well. This tunable switch design employs two thin metal membranes with meander springs for switching action. The MEMS switches are separated by a high impedance transmission line of characteristic impedance 60 Ω. The transmission line separating the switches can be made shorter if its impedance is higher than at the ports. The length as well as the impedance of the transmission line can be adjusted such that the reflections from the two switches are out of phase and thus gets cancelled at the input port thereby improving the up state return loss.

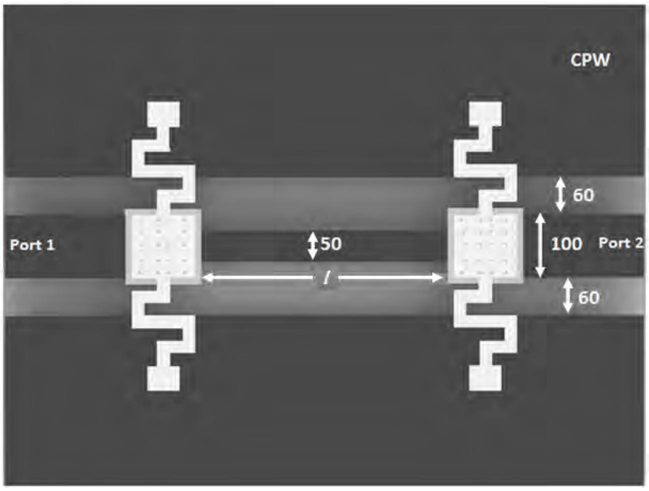

Fig. 1. Dual beam tuned switch – top view

Fig. 1 shows the top view of the dual beam switch. Meandered beams have been used not just to lower the actuation voltage alone but to lower the LC resonant frequency to the X-band. In MEM switches, thin metal membranes are made to shunt the CPW transmission line. A thin dielectric layer over the transmission line and below the beam provides a capacitive path for the RF signal to ground. Unlike in solid state switches, here in MEMS, switching action is due to the mechanical deformation of the metal membrane.

III. SPRING CONSTANT AND ACTUATION VOLTAGE

A. Switch Design

The mechanical design of the electrostatically actuated switches is dictated by the required actuation voltage. When

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designing switches with low actuation voltage, the choice of membrane material and of the support design is critical. Equation (1) showed below presents a widely cited formula for calculating the pull-in voltage (V_p) for fixed-fixed beams [1]

$$V_P = \sqrt{\frac{8K_{eff}\,g^3}{27\varepsilon_0 A}} \tag{1}$$

K_{eff} is the effective spring constant of the movable structure, g is the air gap, ε_0 is the free-space permittivity and A is the switch area. A meandered spring supported beam shown in Fig. 3 is used to reduce the effective spring constant. DC simulation shows the pull-in voltage as 7.5 V

B. *Spring Design*

As shown in Fig., the switch is connected to the anchors through four meander springs, two on each side. The effective spring constant, $K_{eff,}$ of the entire MEMS switch can be determined by combining the simple spring equations. Since the mathematical details have been analyzed in [1] and [2], just the equations are presented here. Fig. 2 shows the dimensions of single meander spring of spring constant, K_m

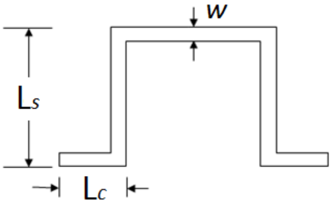

Fig. 2. Meander spring dimensions

For the meandered spring, spring constant, $K_{m,}$ [1] is given by

$$K_m = \frac{Ew\left(\frac{t}{L_c}\right)^3}{1+\frac{L_S}{L_c}\left[\left(\frac{L_S}{L_c}\right)^2 + 12\frac{1+\nu}{1+\left(\frac{w}{t}\right)^2}\right]} \tag{2}$$

where E is Young's modulus, ν is poisons ratio, w is width of meander, L_S is overall width of meander and L_C is the distance from end of spring to start of meander. Non meandered spring constant $K_{n\text{-}m}$ [2] is given by

$$K_{n-m} = 32EW\left(\frac{t}{L}\right)^3 \tag{3}$$

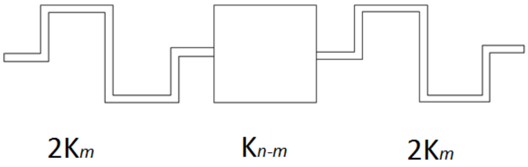

Fig. 3. Switch with meanders

The effective spring constant, $K_{eff,}$ of the membrane shown in Fig. 3 can be derived as in [2]

$$K_{eff} = \frac{K_m K_{n-m}}{K_m + 4K_{n-m}} \tag{4}$$

All the necessary dimensions and material constants of this design are given in Table I and Table II

TABLE I

PARAMETERS AND DIMENSIONS OF THE SWITCH

Parameters	Values
CPW dimensions (µm)	60/100/60
Width of the membrane W (µm)	100
Distance between membranes X (µm)	400
Dimension of Dielectric (µm)	120x120
Dielectric constant of Si_3N_4 (ε_r)	7.4
Thickness of membrane, t (µm)	1.0
Thickness of Dielectric, T (µm)	0.1
Air gap, g (µm)	3.0
Relative dielectric constant of Si substrate	11.7
Young's modulus of gold (E)	80 GPa
Poisson's ratio of gold (ν)	0.44

TABLE II

DIMENSIONS OF THE MEANDER SPRING

Dimension	Values
Overall width L_S (µm)	60
Length L_C (µm)	20
Width of the spring w (µm)	20
Thickness of the meander spring t (µm)	1
Length of the non-meander spring L (µm)	120

IV. CIRCUIT MODEL OF THE TUNED SWITCH

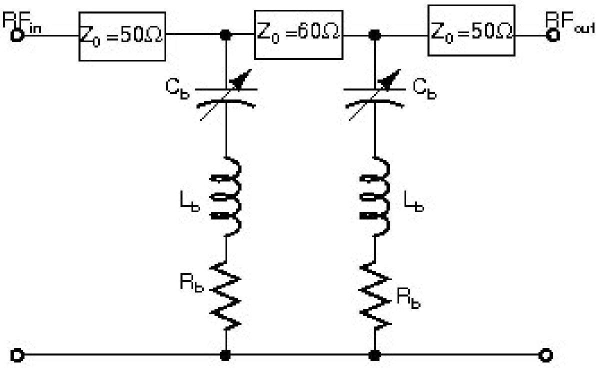

Fig. 4. CLR circuit model of the dual beam switch

Fig. 4 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 high impedance transmission line of 60Ω for separating the shunt branches. In this design, meanders supporting the beam introduce additional inductance thus increasing the beam inductance. To operate the switch in X–band, the LC resonant frequency is decreased by increasing the beam inductance. The LC resonant frequency is given by [5]

$$f = \frac{1}{2\pi\sqrt{L_b C_b}} \tag{1}$$

Resonance frequency in the vicinity of 35GHz for single beam switches is brought down to X - band frequency by employing meandered spring beam geometry. This is inductive tuning [7]. The switch is designed for a down capacitance C_d of 6.7 pF and the extracted beam inductance L_b from the isolation characteristics is 24pH. Thus it is evident that LC resonant frequency can be reduced by increasing bridge inductance even if the capacitance is kept the same due to process limitations. Increased inductance increases Q resulting in reduced bandwidth and increased isolation around the resonant frequency

V. S- PARAMETERS OF THE SWITCH

The simulated S-parameters of the designed dual beam switch are presented in Fig. 5- Fig.7. Simulation has been carried out for various physical lengths of the high impedance transmission line between the membranes. Table III shows the results of the RF and DC simulation. The insertion loss (S_{12}) of the switch in the up state is shown in Fig. 5. S_{12} is 0.1-0.15 dB in X-band for a high impedance transmission line length of 600 μm between the membranes. This dual beam design gives a reflection coefficient of (S11 in up-state) less than – 25 dB in X- band. The frequency of cancellation of reflections from the switches for transmission line lengths of 400, 500 and 600 μm are found to be 24.4, 30.7 and 33.4 GHz respectively. This is illustrated in Fig. 6.

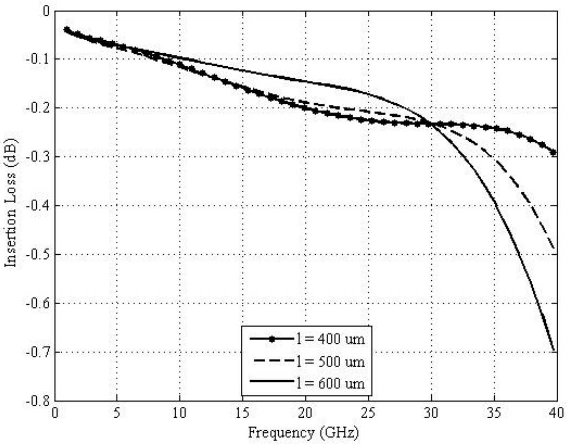

Fig. 5. Insertion Loss in Up- state

TABLE III
S - PARAMETERS OF THE DESIGNED SWITCH

S11 Up-State	S12 Up-State	S12 Down-State	Frequency GHz	Pull-in voltage
> 25 dB	< 0.2 dB	> 45 dB	8-20	7.5 V

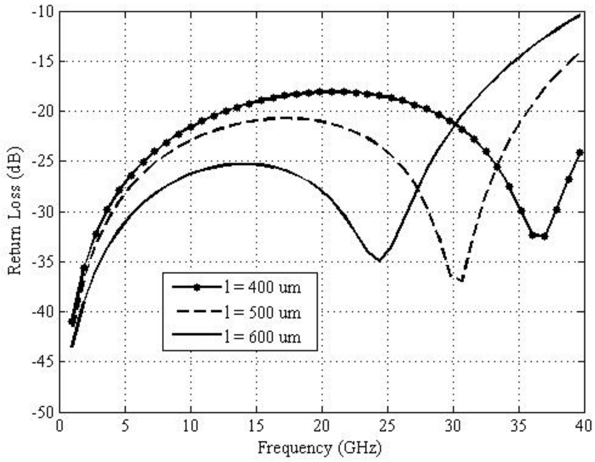

Fig. 6. Return Loss in Up- state

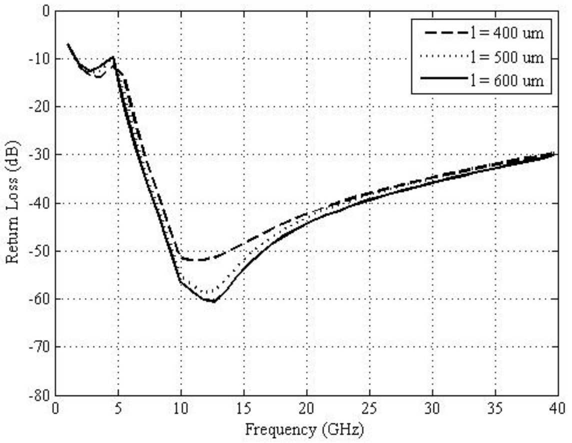

Fig. 7. Isolation

A capacitance ratio (C_d/C_u) of over 100 is achieved with 3 μm air gap between the membrane and transmission line which results in isolation better than -50 dB in X-band. The isolation of the switch is limited by the downstate capacitance (C_d) for frequencies less than LC resonance and by the beam inductance (L_b) for frequencies higher than the resonant frequency. The bandwidth of the switch is specified by isolation performance dictated by these values.

VI. LOSS CHARACTERISTICS WITH SUBSTRATE RESISTIVITY

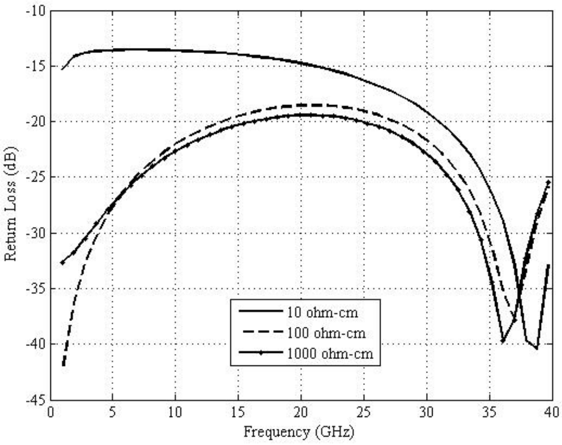

Fig. 8. Return Loss with substrate resistivity

Insertion loss in RF MEMS switches includes substrate loss, conductor loss due to skin effect and reflections due to mismatch. Radiation losses are significant only when the device dimensions become comparable to one tenth of the RF signal wavelength. Conductor loss due to skin effect can be minimized by making the CPW conductor thickness greater than twice the skin depth. Since skin depth of gold at 10 GHz is 0.7 μm, CPW conductor thickness is chosen to be 2μm in this work. It has been observed from simulation that substrate resistivity influences the S–parameters. It is highly likely that the signal penetrates deep into the substrate and gets absorbed if it is highly doped. This is substantiated by the simulation results. The total loss tangent [3], $\tan \delta_t$, of a lossy dielectric medium is given by

$$\tan \delta_t = \tan \delta_l + \tan \delta_d$$

$\tan \delta_l$ is the intrinsic loss from the polarization loss of the intrinsic silicon substrate and $\tan \delta_d$ is the extrinsic loss due to the finite conductivity of the silicon substrate.

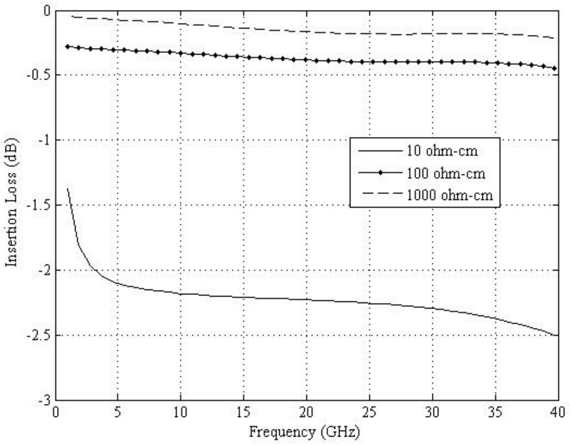

Fig. 9. Insertion loss with resistivity

Therefore, the total loss increases with conductivity of the substrate. The insertion loss is 2-2.5 dB and up-state return loss is better than -15 dB with a substrate resistivity of 10 Ω-cm and the insertion loss improves to 0.1-0.2 dB with a return loss better than -20 dB when the substrate resistivity is increased to 1000 ohm-cm as shown in Fig.6 - Fig.7. From these results, it is inferred that for millimeter wave (mm-wave) switching applications, low loss, and low dielectric constant substrates like glass or quartz would yield better loss characteristics. Another possible alternative is to use micro-machined high resistive silicon (1000 Ω-cm) [6].

VII. CONCLUSION

A low voltage low loss dual beam tuned RF MEM capacitive shunt switch suited for applications in the X- band (8-12 GHz) is presented. Meandered spring supported beam is used to lower the actuation voltage (7.5 V) and the increased beam inductance reduced the LC resonant frequency to X-band range. Thus actuation voltage of 7.5 V is achieved with an air gap of 3 μm between the CPW conductor and the membrane. The length of the high impedance transmission line separating the beams is fixed to be 600 μm for better RF characteristics in the X-band.

RF simulation shows that the designed tuned switch could achieve high isolation in down state and better return loss in upstate. Results reveal an insertion loss of 0.1-0.2 dB and return loss in excess of -25 dB in up-state and isolation better than -50 dB in X- band. Possible reasons for observed losses are discussed in detail. Detailed RF simulations are being carried out to arrive at better results. Work is also underway with regard to fabricating the device with the final goal of demonstrating the switch for real applications. The results of these studies will be reported in literature in near future.

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