International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249 – 8958, Volume-3 Issue-2, December 2013

Design and Analysis of a Low Voltage RF MEMS Shunt Switch for Reconfigurable Antennas

Jija Rajmohan, M.R.Baiju

Abstract ***RF MEMS switches can be used to achieve reconfigurability of various RF systems and in particular, that of miniaturized antenna structures. In the case of micromachined antennas, which involve low voltage signals, RF MEMS switches with low actuation voltage are required for achieving reconfigurability . The capacitive shunt switch derives its switching property from the significant difference of its capacitance in the up-state and down-state. The actuation voltage of RF MEMS switches mainly depends on the spring constant of the switch membrane. In this paper, a low actuation voltage capacitive shunt switch suitable to be used along with micromachined antennas, is presented . A process flow for the fabrication is designed and simulated using Intellisuite . The electromechanical analysis results are presented and compared with that of a fixed- fixed flexure based switch membrane to establish the low actuation voltage characteristics of the proposed design.***

Index Terms—RF MEMS Switches, Actuation voltage, Reconfigurablity

I. INTRODUCTION

Radio Frequency (RF) systems designed for single predefined mission use antennas with fixed characteristics such as frequency band, radiation pattern, polarization, and gain. Applications such as cognitive radio system, Multiple-input multiple-output (MIMO) channels and satellite communication need antenna with the reconfigurable parameters [1, 2].

Reconfiguring of antenna is achieved through changing its frequency, polarization or radiation characteristics by using Radio-Frequency Micro Electro Mechanical Systems (RF-MEMS), PIN Diodes, Varactors and FETs [1-7].Even though they have slow switching speed, unlike the other switching devices, RF MEMS switches are mechanical switches electronically controlled and have near zero power consumption, low insertion loss and high isolation.[8-13]. This mechanical movement is achieved using electrostatic, piezoelectric, magnetostatic or thermal actuation[8].

Even though electrostatic method requires a high actuation voltage it is the most prevalent one due to its near zero power consumption, small electrode size, thin layers and short switching time[9].On the basis of contact mechanism and the position with respect to transmission line, RF MEMS switch can be classified as capacitive or ohmic and series or shunt [14-16].The shunt RF MEMS switches are capacitive in nature where the mechanical movement of the switch membrane introduces a variable capacitance between the signal line and the ground [17,18].

Manuscript received December, 2013.

Jija Rajmohan, National MEMS Design Centre, Department of Electronicsand Communication, College of Engineering, Trivandrum, Kerala, India..

M.R.Baiju National MEMS Design Centre, Department of Electronics and Communication, College of Engineering, Trivandrum, Kerala, India.

The capacitive RF MEMS switches used along with CPW and integrated with RF circuits to achieve reconfigurability requires low actuation voltages[19-22]. The actuation voltage of the RF MEMS switches can be reduced so as to make it compatible with the associated control circuits by varying the spring constant, actuation area or the gap between the switch membrane and the actuation electrode[9,20].Lowering the spring constant by using different geometric structures for the switch membrane can reduce the spring constant and the actuation voltage [9,14,20].

In this paper an RF MEMS capacitive switch operating at a low actuation voltage of 1 Volt is presented. A process flow has been designed for the proposed switch and tested in IntelliFab. The mask files for the fabrication are designed and results of electromechanical analysis of the proposed design are presented.

RF MEMS SWITCHES

RFMEMS switches can be classified as capacitive or ohmic on the basis of circuit configuration and as series or shunt based on the nature of contact. The ohmic contact switch consists of a thin metallic strip fixed at one end, suspended over the metallic transmission line with a gap of few microns. A metallic electrode is attached between the transmission line and the fixed end to act as a pull down electrode and makes a direct metal –metal contact. The capacitive switch does not involve physical contact of the conductors and hence can have low ohmic losses

A. Capacitive Shunt Switch

Fig.1 shows a RF MEMS capacitive shunt switch consisting of a movable metal bridge, suspended at a height 'g_0' above the dielectric layer on the transmission line mechanically anchored and electrically connected to ground of the coplanar waveguide (CPW). The width of the signal line is 'W'µm and the length of the switch is 'L'µm. The dielectric layer is used above the centre conductor, which is also the actuating electrode, so that the switch membrane does not come into contact with the centre electrode during the actuated state. The DC actuation voltage is applied on the centre conductor of the CPW (signal line), which will require a DC bias line routed to the center conductor.

The switch can be modeled as a capacitor between central conductor and ground with the centre conductor as one electrode, the other electrode being the switch membrane. The parallel plate capacitance of MEMS shunt switch in the up-state is $C_{pp} = \frac{\varepsilon_0 A}{g + \frac{t_d}{\varepsilon_r}}$ where t_d is the dielectric thickness, ε_r the relative permittivity . In the downstate position, the capacitance is calculated using $C_d = \frac{\varepsilon_0 \varepsilon_r A}{d}$. The capacitance ratio, C_{pp} to C_d is $1 + \left(\frac{g}{t_d}\right)\varepsilon_r$. A high down-state capacitance and a low up-state capacitance implies high isolation in the down state and a low insertion loss in the up state, and hence is an important parameter for the shunt switch.

Actuation Mechanism

In order to actuate the switch the central conductor of the switch is dc biased with respect to ground and an electrostatic force is induced on the beam. This electrostatic force on the beam is

$$F_e = \frac{\varepsilon_0 A V^2}{2g^2} \quad (1)$$

where ' ε_0 ' permittivity of free space, 'A' area of the electrode, ' V ' the applied voltage and ' g_0 ' is the gap between beam and electrode. The mechanical model of the switch consists of a bottom plate which is fixed and a top plate held by a spring with a spring constant k. The induced electrostatic force is balanced by the stiffness of the beam Fs = $k(g_0 - g)$, where 'g' is the instantaneous position of the beam from the original position, g_0 is the zero bias bridge height and ' k' is the spring constant . Therefore

$$\frac{\varepsilon_0 A V^2}{2g^2} = k(g_0 - g) \quad (2)$$

and $$V = \sqrt{\frac{2kg^2 (g_0 - g)}{\varepsilon_0 A}} \quad (3)$$

When the voltage is increased, the electrostatic force increases and pulls the beam down towards the lower electrode resulting in an increase in the associated capacitance. When the beam height is $\frac{2}{3} g_0$, the electrostatic force is greater than the restoring force and the beam position becomes unstable and collapses to the down state position. This is referred to as pull in and the voltage at which the top electrode touches the bottom electrode is called the pull- in voltage,

$$V_p = \sqrt{\frac{8k\, g_0^3}{27\, \varepsilon_0 A}} \quad (4)$$

A voltage greater than the a pull-in voltage is used for actuating the switch.

II. RF MEMS SWITCHES FOR RECONFIGURABLE ANTENNAS

A.Reconfigurable Antennas using MEMS

Reconfigurable antennas make use of limited area as multiple functions are possible in a single antenna. Integration of RF MEMS switches with antennas makes the antenna smaller and cheaper. A major issue involved when RF switches and antennas are on the same substrate is the size of the substrate. The RF circuits require thin substrates with high value of dielectric constant for compactness and to reduce losses from radiation whereas the radiation characteristics of the antenna are degraded due to this high value of dielectric constant. These conflicting requirements can be met by Micromachining technology . By selectively etching part of the substrate from underneath the antenna, a low permittivity region is created for the antenna resulting in an increase in the bandwidth and radiation efficiency. Antennas with the ability to dynamically reconfigure their radiation characteristics also have been realized through micromachining techniques [4-7, 20 -22]

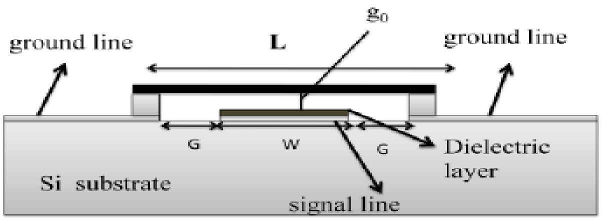


Fig.1(a) : RF MEMS shunt switch in the UP state

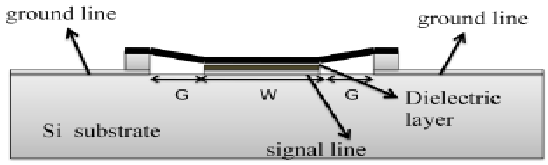


Fig 1(b) : RF MEMS shunt switch in the DOWN state

B. Low Actuation Voltage Switches

Generally RF MEMS switches are actuated using electrostatic method which requires a high actuation voltage. But in the case of miniature antennas like micromachined antennas which involve low signal levels, low actuation voltage is a desirable requirement. The actuation voltage of the RF MEMS switch can be reduced by increasing the actuation area, reducing the gap height and reducing the spring constant. Increasing the actuation area lowers the actuation voltage but is a threat to the design of miniaturized circuits. Reducing the air gap reduces the actuation voltage but adversely affects the switch creating a high insertion loss in the up state and low isolation in the down state. Of these parameters, the maximum design flexibility is offered by controlling the spring constant ' k ' of the switch membrane.

III. DESIGN OF THE PROPOSED LOW ACTUATION VOLTAGE RF MEMS SWITCH

In the present work, the switch is designed for an actuation voltage of 1Volt. The CPW dimensions for the proposed design are chosen as 50/100/50 µm. The width of the beam is chosen 100 µm so that the area of the actuating electrode (area of the center conductor), is 100 x 100 µm, As per Eqn. (3) , the proposed design should have a spring constant 1.0.

In the present work, a low actuation voltage of 1 Volt is achieved by using a switch membrane with an appropriate serpentine structure. The switch membrane is supported by four serpentine flexures which lower the spring constant of the switch membrane. The serpentine spring consists of rectangular turns of conductors, referred to as meander, as shown in Fig. 3. One meander consists of four adjacent beams, two vertical and two horizontal ones, the horizontal beam of length 'a' and vertical beam of length 'b'. An 'N' meander spring will have 2N horizontal beams and 2N vertical beams.

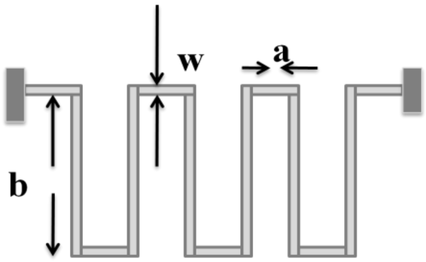


Fig 2 : The structure of a typical meander flexure

In the present work the meander structure to achieve the required spring constant is found using the following equation [19],

$$k_s \sim \left[\frac{(8N^3 a^3) + 2Nb^3}{3EI_x} + \frac{abN[3b + (2n+1)(4N+1)a]}{3GJ} - \frac{Na^2 \left[\left(\frac{2Na}{EI_x} \right) + \frac{(2N+1)b}{GJ} \right]}{2\left(\frac{a}{EI_x} + \frac{b}{GJ} \right)} - \frac{Nb^2}{2} \left(\frac{a}{GJ} + \frac{b}{EI_x} \right) \right]^{-1} \qquad (4)$$

The effective spring constant k_s of the serpentine structure depends on the number of meanders N , horizontal beam length 'a', vertical beam length 'b' , E the Young's Modulus, 'ν' the Poisson's ratio, 'w' the thickness, $I_x = wt^3/12$, $I_y = t w^3/12$ the moment of inertia along the x axis and y axis Sheer modulus 'G' = E/2(1+ν) , $I_p = I_x + I_y$ the polar moment of Inertia and Torsion Constant ' J '= $0.413 I_p$.

.

TABLE 1: Structural parameters of the proposed design of RF MEMS switch

Parameters	Values
CPW Dimensions	50/100/50
Length of the switch membrane	300µm
Width of the switch membrane	100 µm
Gap height	1 µm
Horizontal beam length (a)	12.5µm
Vertical beam length (b)	45 µm
Switch thickness	2.5 µm

The switch is designed with the structural parameters shown in TABLE 1. The other design parameters of the switch membrane are calculated and shown in TABLE 2. Using these parameters, the meander horizontal beam length 'a' and vertical beam length 'b' are chosen as 12.5 and 45 µm respectively, based on the Eqn(4).

TABLE 2 : Design parameters of the proposed design.

Parameters	Values
Young's modulus (E)	69MPa
Poisson's ratio(ν)	0.35
Sheer modulus (G)	25.55×10^{6}
x- axis moment of Inertia(I_x)	0.2×10^{-24}
y-axis moment of Inertia(I_y)	1.3×10^{-24}
Polar moment of Inertia (I_p)	1.5×10^{-24}
Torsion Constant (J)	0.6×10^{-24}

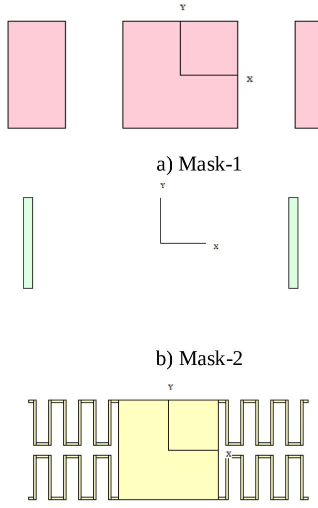
V.RESULTS AND DISCUSSION

A. Fabrication

A process flow is designed for fabrication of the proposed switch on a silicon substrate. The proposed fabrication process is designed using three masks shown in Fig.3. The masks for the proposed design are generated in IntelliMask . Mask-1 is used for two processes, to etch the CPW in Aluminum and to etch the dielectric layer in Silicon Nitride . Mask-2 is used to etch the posts for the membrane (Aluminum) and Mask-3 is used to create serpentine switch membrane in Aluminum.

The process flow is designed and simulated using IntelliFab/FabViewer and the important stages of the process flow for the proposed design are shown in Fig.4.

The fabrication process starts with the evaporation of thin metal films of 1 µm Aluminum onto the silicon substrate. The metal film is patterned using Mask-1 shown in Fig. 3 (a) with a photo resist, followed by reactive ion etching to realise the structure as shown in Fig. 4(a). In all the processes sacrificial etching of the photo resist is performed. A silicon nitride layer is deposited on top of the Aluminum to act as an isolating structure between the switch membrane and the central conductor of the CPW line. The dielectric layer is deposited using chemical vapor deposition(CVD) and patterned using Mask-1. A layer of Aluminum is evaporated on to the dielectric layer to form the post and patterned using Mask-2 shown in Fig.3(b) followed by etching of Aluminum. To create the gap between the CPW and the switch membrane, a sacrificial layer of PSG is deposited with planarization as the mode of deposition. Aluminum is deposited on the planarized sacrificial layer of PSG and patterned using Mask-3 shown in Fig. 4(c).

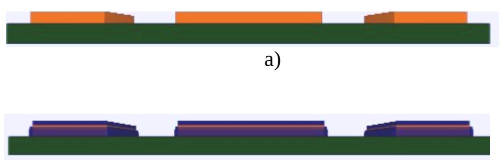


a) Mask-1

b) Mask-2

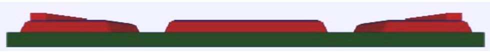
c) Mask-3

Fig 3: a) Mask-1 is used to etch the coplanar waveguide(CPW)and dielectric layer b) Mask-2 to etch the post c) Mask-3 to etch the switch

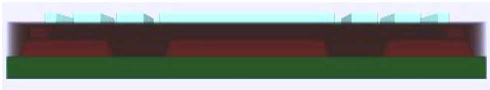


a)

b)

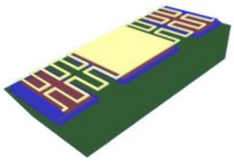


c)



d)

e)



f)The proposed serpentine structure

Fig.4 : Process flow for the proposed design simulated in Intellifab. a) Conformal Deposition of Aluminum on Silicon substrate b)Deposition of Silicon nitride for dielectric layer c)planarization of Aluminum on dielectric for post d)Serpentine membrane e) Release d structure

The Aluminum layer is partially etched off to realize the serpentine switch membrane. Finally, the switch membrane structural element is released by the performing the etching of the PSG sacrificial layer. The top view of the proposed serpentine structure after sacrificial etching is shown in Fig. 4(g).

B. Analysis

Fig.5 to Fig.7 show the results of the electromechanical analysis of the proposed switch using TEM Module of Intellisuite. Fig. 5 shows the result of the pull-in analysis and the maximum possible displacement of 1μm is obtained for 1.0 V. It may be noted that a switch with same dimensions and using a fixed -fixed flexure for the switch would need actuation voltage as high as 5V as evident from Fig.6. Fig.7 shows the deformation experienced when 1.0 V is applied to the central conductor of the CPW (which acts as the lower electrode), and the maximum displacement is seen for the centre part of the switch membrane, as evident from the color scheme.

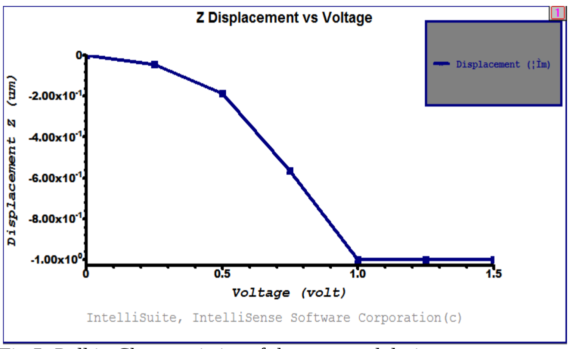


Fig 5: Pull in Characteristics of the proposed design

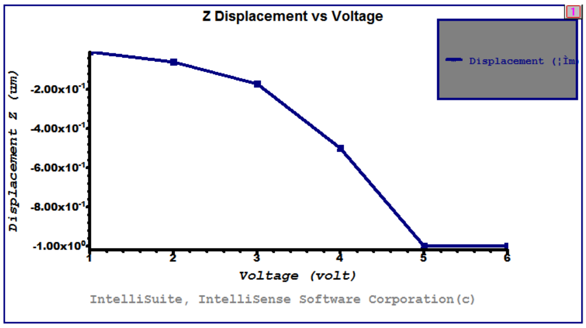


Fig.6 Comparative study : Pull in characteristics of the fixed- fixed flexure

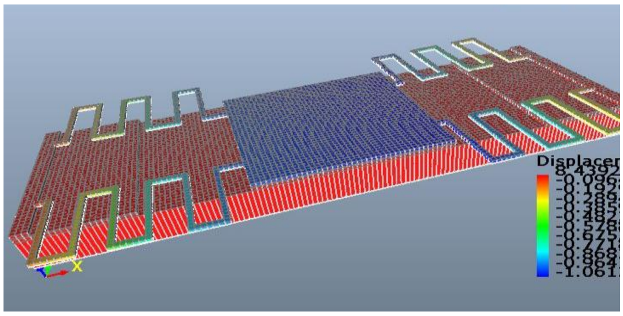


Fig.7 Z displacement of the serpentine flexure: Results of the Electromechanical Analysis in Intellisuite

Fig.8 shows the variation of the capacitance formed by the upper switch membrane and the lower electrode (centre conductor of the CPW). As the actuation voltage increases the switch membrane is pulled towards the bottom electrode, thereby resulting an increase in the capacitance. The capacitance increases many times after the pull in as the switch membrane gets snapped to the lower electrode. Fig.8 shows that after pull-in, the capacitance remains at 1306fF and this is the down state capacitance of the switch. In the upstate position of the switch, that is when no actuation voltage is applied, the capacitance is seen to be 103fF. Therefore, the capacitance ratio for the proposed design is 12.67. The results of the electromechanical analysis of the proposed design are summarized in TABLE 3 .

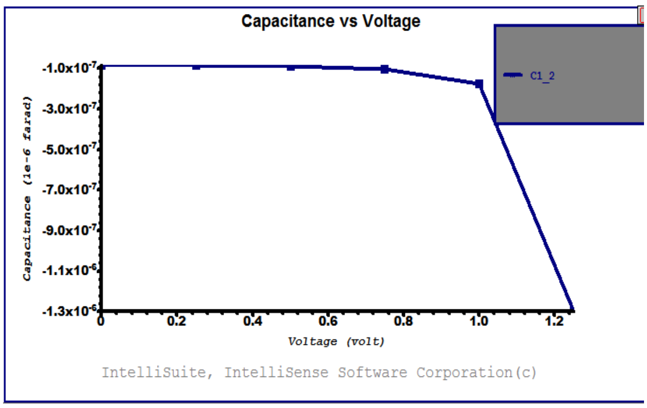


Fig.8 Variation in capacitance of the proposed switch before and after actuation

TABLE 3 :Summary of the results of the various parameters of the proposed design

Parameters	Designed Value	Simulated Result
Pull in voltage (V)	0.9	1.0
Up-state capacitance (fF)	83	103
Down-state capacitance (fF)	1345	1303
Capacitance ratio	16.20	12.67

VI.CONCLUSION

A low actuation voltage RF MEMS capacitive switch, suitable for achieving reconfigurable micromachined antennas is presented. A serpentine geometry for the flexures holding the switch membrane results in reducing the spring constant sufficiently low as to have a pull in voltage of 1.0V. A process flow is designed and fabrication files with appropriate masks are generated. The electromechanical analysis is performed and results are presented.

REFERENCES

[1] Christos G Christodolou,Youssef Tawk,Steven A Lane and Scott R Erwin," Reconfigurable antennas for wireless and space applications ",Proceedings of the IEEE Vol 100 No .7 ,July 2012.
[2] Harvey S.Newmann ,"RF MEMS Switches and Applications ", 40th Annual International Reliability Physics Sympopsium ,Dallas ,Texas,2002.
[3] N.Haider,D Caratelli and A.G.Yarovoy ," Recent developments in Reconfigurable and Multiband and Antenna technology", Microwave Sensing,Signal and Systems,DelftUNiversity of Technology,January 2013.
[4] Chang won Jung, Ming-jer Lee, G. P. Li, and Franco De Flaviis,"Reconfigurable Scan-Beam Single-Arm Spiral Antenna Integrated With RF-MEMS Switches," IEEE Transactions on Antennas and Propagation, vol. 54, no. 2, February 2006.
[5] Greg H. Huff, and Jennifer T. Bernhard,"Integration of Packaged RF MEMS Switches With Radiation Pattern Reconfigurable Square Spiral Microstrip Antennas" IEEE Transactions on Antennas and Propagation, vol. 54, no. 2, february 2006
[6] Jennifer .T .Bernhard, Reconfigurable antenna s,Morgan and Claypool publishers.
[7] Nakul Haridas, Ahmet T. Erdogan, Tughrul Arslan, Anthony J. Walton,Stewart Smith, Tom Stevenson, Camelia Dunare, Alan Gundlach, Jon Terry, Petros Argyrakis, Kevin Tierney, Alan Rose and TonyO'Hara, Reconfigurable MEMS Antenna
[8] E. R. Brown, "RF-MEMS switches for Reconfigurable Integrated Circuits", IEEE Trans. Microwave Theory Tech., vol. 46, p p. 1868-1880, Nov. 1998.
[9] Gabriel M.Rebeiz and Jeremy .B.Muldavin ," RF MEMS Switches and Switch circuits ", IEEE Microwave magazine,December 2001.
[10] Gabriel .M.Rebeiz,"RF MEMS Switches :Status of the Technology", 12th International Conference on Solid state Sensors,Actuators and microsystems,,June 8-12,2003.
[11] V. Ziegler, C. Siegel, B. Schönlinner, U. Prechtel, H. Schumacher,"Switching Speed Analyssi of low complexity RF-MEMS switches ," European MicrowaveWeek, Paris, France, October 2005.
[12] Mingxin Song, " Design and analysis of a novel low actuation voltage capacitive RF MEMS switches", Proceedings of the 3rd IEEE International conference on Nano/Micro Engineered and Molecular systems,January ,2008
[13] P.D.Grant and M.W.Denhoff," A Comparison between RF MEMS Switches and Semiconductor switches ", Proceedings of the 2004 International Conference on MEMS ,Nano and smart systems.
[14] Haslina Jaafar, Othman Sidek, Azman Miskam and Shukri Korakkottil, "Design and Simulation of Microelectromechanical SystemCapacitive Shunt Switches," American J. of Engineering and Applied Sciences 2 (4): 655-660, 2009 ,ISSN 1941-7020 © 2009 Science Publications
[15] Lianjun Liu ," High Performance RF MEMS Series Contact switch -Design and Simulation", Electronic Components and Technology Conference ,p.p 158-164 ,2007.
[16] Jeremy B Muldavin and Gabreil .M Rebeiz ,"High Isolation CPW MEMS shunt switches - Part1:Modelling ", IEEE Transactions on Microwave Theory and Techniques ,Vol 48,No:6,June 2000.
[17] Jeremy B Muldavin and Gabreil .M Rebeiz ,"High Isolation CPW MEMS shunt switches - Part2:Design ", IEEE Transactions on Microwave Theory and Techniques ,Vol 48,No:6,June 2000.
[18] Jeremy B Muldavin and Gabreil .M Rebeiz ,"Inline capacitive and DC Contact MEMS shunt switches ", IEEE Microwave and Wireless components letters ,Vol 11,No:8,August ,2001.
[19] Mai O. Sallam, Ezzeldin A. Soliman, and Sherif Sedky "Reconfigurable Micromachined Antenna with Polarization Diversity for mm-Wave Applications",6th European Conference on Antennas and Propagation (EUCAP), 2011.
[20] Dimitrios Peroulis, Sergio P. Pacheco, Kamal Sarabandi, and Linda P. B. Katehi, " Electromechanical Considerations in Developing Low-Voltage RF MEMS Switches" IEEE transactions on microwave theory and techniques, vol 51,pp. 259-269,J January 2003.
[21] G. Huff, J. Feng. D Zhang, J.T. Bernard, A Novel Radiation Pattern and Frequency Reconfigurable Single Turn Square Spiral Microstrip Antenna, IEEE Microwave and Wireless Components Letters, Vol. 13, No. 2, February 2003, pp. 57-59.
[22] H. Pan, J.T Bernhard, V.K. Nair, Reconfigurable Single-Armed Square Spiral Microstrip Antenna Design, IEEE International Workshop on Antenna Technology SmallAntennas and Novel Metamaterials, 2006, March 6-8, 2006,pp. 180 – 183.

Jija Rajmohan graduated in 1999 from TKM College of Engineering, Kerala and had her Masters from Anna University, Tamil Nadu. She is with the Faculty of Mar Baselious College of Engineering and Technology, Trivandrum and currently working towards her PhD Degree at Department of Electronics and Communication,College of Engineering Trivandrum ,India.

M.R.Baiju graduated from College of Engineering Trivandrum in 1988 .He did his Masters and PhD at Indian Institute of Science, Bangalore in 1997 and 2004 respectively. He is now Professor at Department of Electronics and Communication, College of Engineering Trivandrum, India. His fields of interest are MEMS and Power Electronics.