Robust Design of RF MEMS Switch Design with Reduced Buckeling Effect

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ABSTRACT

RF MEMS switches are used in many applications and also can be used to achieve reconfigurability of various RF systems and in particular, that of minute sized antenna structures and systems. In the case of micro machined antennas, which usually have low voltage signals, RF MEMS switches with low actuation voltage are highly 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. We have presented a highly reliable RF MEMS switch. We have used various small beams to achieve reliably. Basically the stiction and buckling effect can be reduced by using such a structure. The actuation voltage of RF MEMS switches mainly depends on the spring constant of the switch membrane. A low actuation voltage capacitive shunt switch, is presented. A process flow for the fabrication is designed and simulated using HFSS. The EM analysis results are presented and compared with that of a fixed-fixed flexure based switch membrane to establish the low actuation voltage. Reliable can be seen from the vertical structure [22-26].

General Terms:

MEMS Switch, Buckling Analysis

Keywords:

RF MEMS, Switch, Low Voltage, Antennas, Electrostatic Actuation

1. INTRODUCTION

Radio Frequency (RF) systems designed for 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].
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].
The reliability of RF MEMS switches is a major concern for various applications and is currently the subject of an high research effort. In Metal to metalcontact switches, the reliability is strongly related to the contact area used, whereas in capacitive or shunt switches, the reliability is limited by dielectric charging or dielectric breakdown. In both the cases, the RF power has a strong effect on the reliability of RF MEMS switches. The mechanical failure basically metal fatigue or fracture in switches of well-designed MEMS cantilever or fixed"fixed membrane is not a problem because the beams are 70"300 um long and are deflected by only 1-4 um. Basically, many MEMS switches have been tested up to 100 billion cycles with no observed mechanical failure around the anchors (the location of maximum stress or strain).
The designed capacitive switch has low actuation voltage, This designed RF MEMS switch is suitable for achieving stiction less operation of micro machined antennas or other devices. A mesh like thick geometry for the flexures holding the switch membrane results in reducing the spring constant sufficiently low as to have a pull in voltage of 4.0 V. A process flow of designing and fabrication are also discussed. RF performance of the designed switch is excellent and shows potential for applications in space and radar applications and best use of this reliable switch is in reconfigurable antennas.

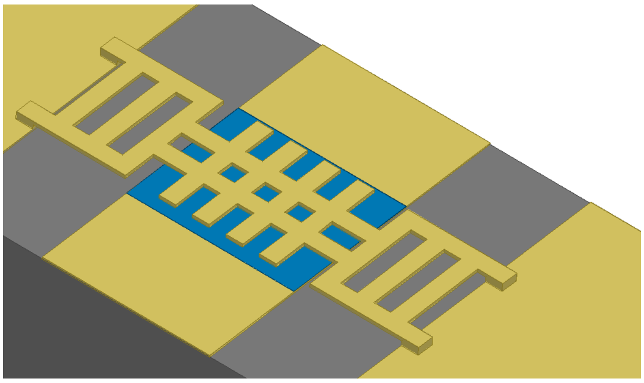

Fig. 1. Proposed Highly Reliable RF MEMS Switch

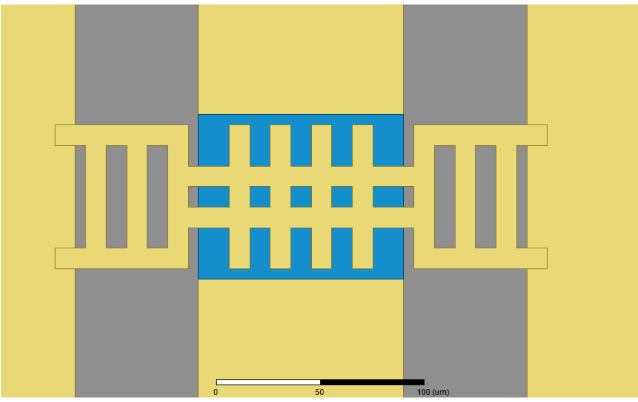

Fig. 2. Top view of proposed RF MEMS switch

2. SERIES/SHUNT 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.

2.1 Shunt RF MEMS Switches

An RF MEMS capacitive shunt switch consisting of a movable metal bridge, suspended at a height 'g0' 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"'m and the length of the switch is 'L' um. 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

$$C_{pp} = \frac{\epsilon_0 w W}{g_0 + t_d/\epsilon_r} \tag{1}$$

where, t_d is the dielectric thickness, ϵ_r is the relative permittivity. In the downstate position, the capacitive is calculate using

$$C_d = \frac{\epsilon_0 \epsilon_r w W}{t_d} \tag{2}$$

The capacitance ratio can be calculated by

$$C_r = \frac{C_{pp}}{C_d} \tag{3}$$

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.

2.2 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 [29]

$$F_e = \frac{\epsilon_0 w W V^2}{2 g_0^2} \tag{4}$$

where, ϵ_0 is the permittivity of free space, 'A' area of the electrode, ' V ' the applied voltage and ' g0 ' 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

$$F_s = k(g_0 - g) \tag{5}$$

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 the voltage can be calculated analytically [22-25].
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. 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 [30, 31],

$$V = \sqrt{\frac{8 k g_0^3}{27 \epsilon_0 w W}} \tag{6}$$

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

3. HIGHLY RELIABLE SWITCHES FOR RECONFIGURABLE ANTENNAS

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

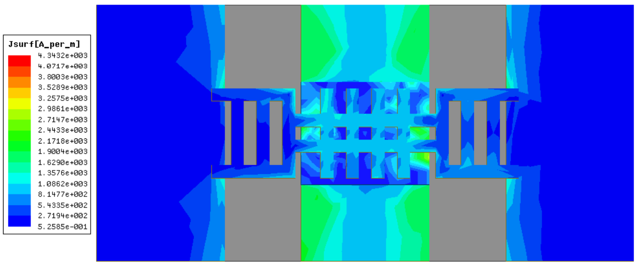

Fig. 3. Current Density in proposed switch

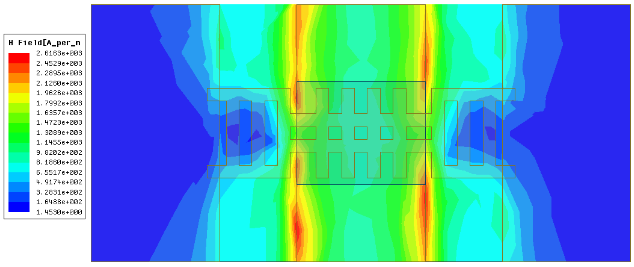

Fig. 4. Magnetic field in RF MEMS switch

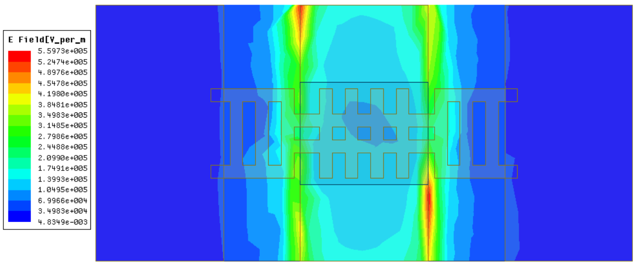

Fig. 5. Electric Field in RF MEMS switch

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 Fig. 1. 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]

3.1 Failure Mechanism of MEMS Switches

The reliability of capacitive or shunt switches is basically dominated by stiction between the dielectric layer and the metal layer due to the larger contact area of the switch (approximately 100 by 100 um2). The stiction is due to the injection of charge and trapping of charge in the dielectric layer used underneath the bridge or membrane. Trapping mechanisms or charge trapping in oxide layers have been investigated for 32 years because it is essential to the proper operation of MOS transistors in CMOS logic. There are basically three trapping areas in the MEMS capacitive switch: The interface traps between the metal and the dielectric layer, the bulk traps in the oxide layer, and the surface traps on top of the oxide layer. Several well-known properties of oxide charging are detailed below:

The charging of dielectrics is due to the application of stress, whatever its nature: mechanical, ionizing, thermal, or electric field stress, Electrons are trapped at low fields (2-5 MV/cm) and detrapped at high fields, while trapped positive charges are typically observed at high fields (7-10 MV/cm) [2]. and interfaces, which are areas where defects are concentrated, will be areas where charges are preferentially trapped. There is no direct relationship between an insulator conductivity and its charging properties. The trapped electrostatic charge is not only due to the insulating nature of the material (ionic or covalent), but is due to defects, either from its crystallographic structure or from defects due to tooling (dislocation, nonstoichiometry), or due to radiation under ionizing beams (electron, photon, or ion bombardment of SiO2). Dielectrics will break down at any high electric field, provided that they are stressed long enough. The breakdown will always occur beyond a certain amount of injected charge [3].

3.2 Designed MEMS Switch

Generally RF MEMS switches are actuated using electrostatic method which requires a high actuation voltage. But in the case of miniature switches like micromachined switches which involve low signal levels and have very small dimensions, low actuation voltage is a desirable requirement. We have designed the switch with thicker rectangular menders as it can be seen in the geometry also, by using this type of structure, one can get low actuation voltage and high reliability. As in the case of reliability and failure mechanisms. By using larger gaps, first of all we are decreasing contact resistance and secondly, whenever the beam will bend in downward direction, the stress component would be of smaller value instead of going towards its ultimate tensile strength of the switch. 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.

4. DESIGN OF RF MEMS SWITCH FOR RELIABLE OPERATION

In the present work, the switch is designed for an actuation voltage of 4 Volt. The CPW dimensions for the proposed design are chosen as 50/100/50 um. The width of the beam is chosen 100 um so that the area of the actuating

5. RESULTS AND DISCUSSIONS

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 Ansoft HFSS. 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.

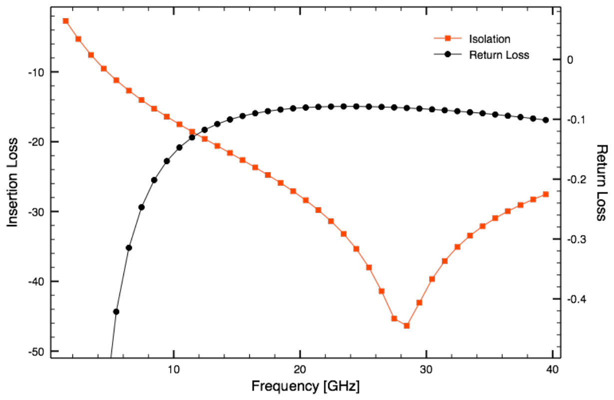

Fig. 6. OFF state S Parameters showing Isolation and Return Loss

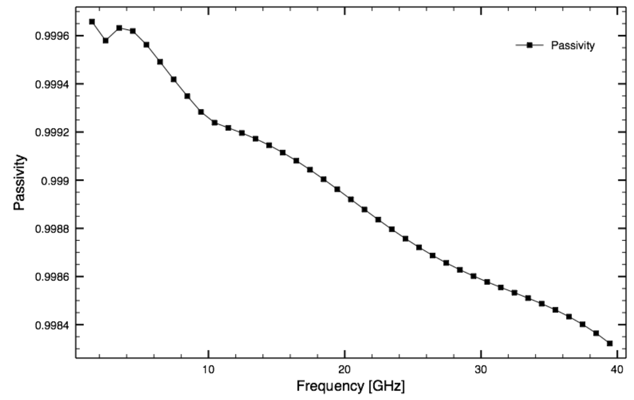

Fig. 8. Plot showing passivity more than 0.999 for designed RF MEMS switch

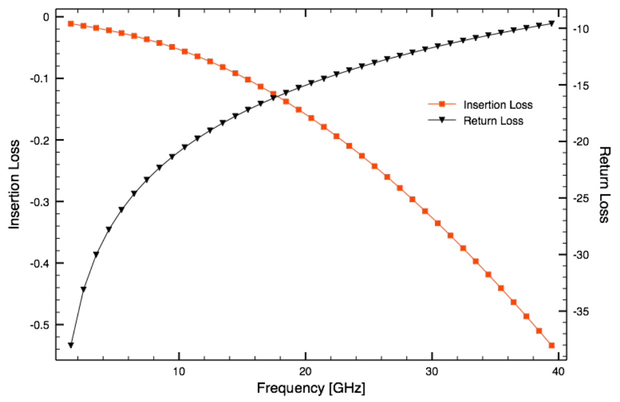

Fig. 7. ON State S Parameters showing Insertion Loss and Return Loss

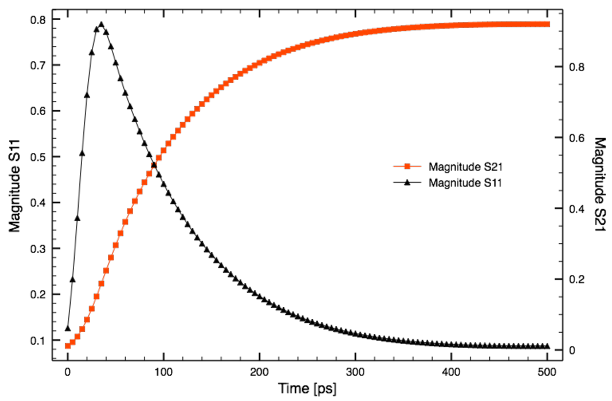

Fig. 9. Magnitude of S11 and S21 in OFF state of RF MEMS switch

The fabrication process starts with the evaporation of thin metal films of 1 um Aluminum onto the silicon substrate. The metal film is patterned using Mask-1 with a photo resist, followed by reactive ion etching to realise the structure. 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 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. 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 [22, 23, 24].
Fig.6 to Fig.7 show the results of the EM analysis of the proposed switch using HFSS. Fig. 5 shows the result of the pull-in analysis and the maximum possible displacement of 1 um is obtained for 4.0 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 4.0 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.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 [25, 26]. Fig.8 shows that after pull-in, the capacitance remains at 130.6 fF 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 103 fF. Therefore, the capacitance ratio for the proposed design is 12.67. The results of the electromechanical analysis of the proposed switch are described in Table 3. [27, 28]

6. CONCLUSION

A highly reliable RF MEMS with the mechanism of reduction in buckling effect is proposed. The designed capacitive switch has low actuation voltage, This designed RF MEMS switch is suitable for achieving stiction less operation of micro machined antennas or other devices. A mesh like thick geometry for the flexures holding the switch membrane results in reducing the spring constant suf-

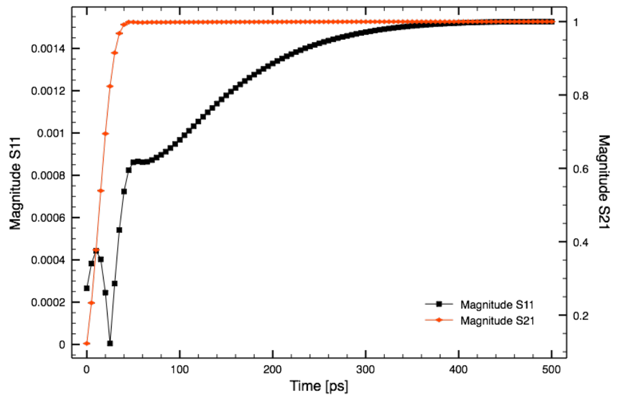

Fig. 10. Magnitude of S11 and S21 in ON state of RF MEMS switch

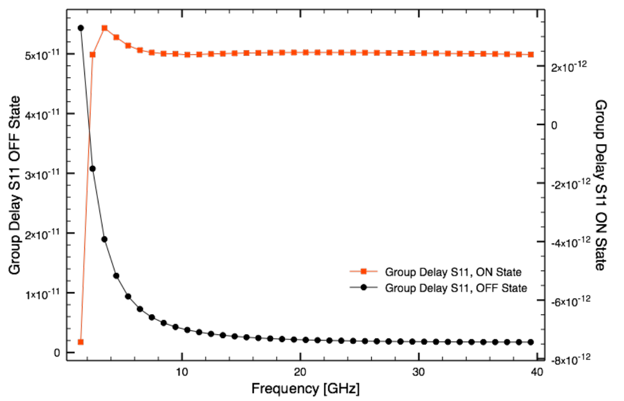

Fig. 11. Group Delay S11 in ON and OFF state of RF MEMS switch

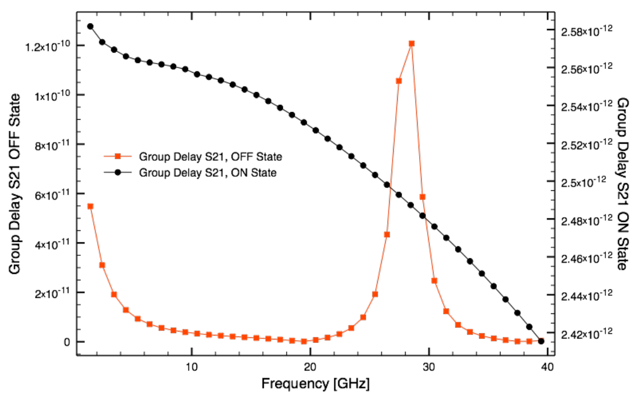

Fig. 12. Group Delay S21 in ON and OFF state of RF MEMS switch

ficiently low as to have a pull in voltage of 4.0 V. A process flow of designing and fabrication are also discussed. RF performance of the designed switch is excellent and shows potential for applications in space and radar applications and best use of this reliable switch is in reconfigurable antennas.

Table 1. Structural Parameters

Parameter	Value
CPW Lines	50/100/50
Length of Membrane	300 um
Width of Membrane	100 um
Gap	1.5 um
Beam length (Horizontal)	13 um
Beam length (Vertical)	40 um
Thickness of Beam	2 um

Table 2. Mechanical Components

Parameter	Value
Young's Modulus	70 MPa
Poisson's Ratio (v)	0.35
Sheer Modulus (G)	26e6
X-Axis Moment of Inertia (Ix)	0.2e-12
Y-Axis Moment of Inertia (Iy)	1.3e-24
Polar Moment of Inertia (Ip)	1.5e-24
Torsional Constant (J)	0.6e-24

Table 3. Simulation Results

Parameter	Value
Pull in Voltage (Vp)	4 V
Up State Capacitane	103 fF
Down State Capacitance	1.3 pF
Capacitance Ratio	13

7. 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 Symposium, 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, Delft University of Technology, January 2013.

[4] Chang won Jung, Mingjer 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] E. R. Brown, "RF-MEMS switches for Reconfigurable Integrated Circuits", IEEE Trans. Microwave Theory Tech., vol. 46, pp. 1868-1880, Nov. 1998.

[8] Gabriel M.Rebeiz and Jeremy .B.Muldavin ," RF MEMS Switches and Switch circuits", IEEE Microwave magazine,December 2001.

[9] Gabriel .M.Rebeiz,"RF MEMS Switches :Status of the Technology", 12th International Conference on Solid state Sensors,Actuators and microsystems,,June 8-12,2003.

[10] V. Ziegler, C. Siegel, B. Schnlinner, U. Prechtel, H. Schumacher,"Switching Speed Analyssi of low complexity RF-MEMS switches," European Microwave Week, Paris, France, October 2005.

[11] 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

[12] 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.

[13] 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

[14] Lianjun Liu ," High Performance RF MEMS Series Contact switch -Design and Simulation", Electronic Components and Technology Conference ,p.p 158- 164 ,2007.

[15] 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.

[16] 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.

[17] 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.

[18] 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.

[19] 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.

[20] 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.

[21] H. Pan, J.T Bernhard, V .K. Nair, Reconfigurable Single-Armed Square Spiral Microstrip Antenna Design, IEEE International Workshop on Antenna Technology Small Antennas and Novel Metamaterials, 2006, March 6-8, 2006,pp. 180 " 183.

[22] Tejinder Singh and Kamal J Rangra, "Compact Low-Loss High-Performance Single-Pole Six-Throw RF MEMS Switch Design and Modeling for DC to 6 GHz," *Microsystem Technologies*, 2015, pp. 1-10, January 2015. DOI: 10.1007/s00542-015-2411-0.

[23] Tejinder Singh, "Design and Finite Element Modeling of Series-Shunt Configuration based RF MEMS Switch for High Isolation Operation in K-Ka Band," *Journal of Computational Electronics*, vol. 14, no. 1, pp. 167-179, March 2015.

[24] Tejinder Singh and Farzaneh Pashaie, "Finite Element Modeling of a Ti based Compact RF MEMS Series Switch Design for Harsh Environment," *Microsystem Technologies*, 2015, pp. 1-7, September 2014. DOI: 10.1007/s00542-014-2329-y.

[25] Tejinder Singh and Farzaneh Pashaie, "Circuit Modeling and Eigenfrequency Analysis of Poly-Si based RF MEMS Switch Designed and Modelled for IEEE 802.11ad Protocol," *Journal of Computing Science and Engineering*, vol. 8, no. 3, pp. 129-136, September 2014.

[26] Tejinder Singh, "From Theory to Development: Role of Multiphysics Modelling and its Effect on Education in Electronics," *Electronics*, vol. 17, no. 2, pp. 105-109, December 2013.

[27] Simran Rana and Rajesh Mehra , "FPGA Implementation of Open RISC using Hyper Pipelining Technique", *International Journal of Advanced Computing*, Volume 47, pp. 2051-0845, 2014.

[28] Harmanpreet Kaur, Kirandeep Kaur, Rajesh Mehra, "Adaptive Filter For Audio Signal Enhancement Using Leaky And Non Leaky Algorithms", *International Journal of Electrical and Electronic Engineering and Telecommunications*, Volume 3, pp. 1-9, 2014.

[29] J. Rajmohan and M. R. Baiju, "Design and Analysis of a Low Voltage RF MEMS Shunt Switch for Reconfigurable Antennas", *International Journal of Engineering and Advanced Technology*, Volume 3, no. 2, pp. 414-418, 2013.

[30] A. Chaurasia and R. Mehra, "Design and Performance Analysis of Capacitive RF MEMS Switch for Low Voltage Reconfigurable Antennas", *International Journal of IT, Engineering and Applied Sciences Research*, Volume 3, no. 9, pp. 12-17, 2014.

[31] G. M. Rebeiz, "RF MEMS: Theory, Design and Technology," John Wiley and Sons, ed. 1, 2004.