Conjoined Rectangular Beam Shaped RF Micro-Electro-Mechanical System Switch for Wireless Applications

R.Raman[1] and T.Shanmuganantham[1]*

[1]*Department of Electronics Engineering, Pondicherry University, Puducherry, India*
email: shanmuga.dee@pondiuni.edu.in

Abstract. A conjoined rectangular shaped cantilever beam switch is designed to operate in the frequency range from 2 to 12 GHz. The proposed switch exhibits good RF characteristics with low pull-in voltage which makes it ideal for various wireless mobile applications. The switch is designed in terms of electrostatic actuation mechanism with the optimization of the beam gap, switch beam thickness, and low actuation voltage. The switch shows excellent RF characteristics, low actuation voltage using a simple cantilever beam structure over a reliable contact. The proposed design is investigated by using IntelliFab v8.7[@] software for electromechanical and EM software for electromagnetic analysis. The developed RF-Microelectromechanical system (MEMS) switch was actuated with a very low pull-in voltage of 5V and the maximum Mises stress under actuated condition is 16.7012 MPa. Its insertion loss is -0.25 dB to -3.56 dB at 2 GHz to 12 GHz and isolation is about -74.55 dB to -57.65 dB at 2 GHz to 12GHz.

Keywords: RF MEMS, pull-in voltage, electrostatic actuation, electromagnetic analysis, isolation

1. Introduction

In high performance wireless systems RF-Microelectro-mechanical system (MEMS) technology plays a vital role as it has the ability to realize almost an ideal microwave switches for its applications [1]. With the advancement in RF MEMS devices it is possible to discover new architecture and configurations which were not possible in the existing technologies. Its applications can be extended to defence related products to personal communications devices by combining its advantages such as high performance, low cost, and ultra-low power consumptions. The MEMS DC metal contact switch is one of the most promising MEMS devices and has the same principle of a mechanical moving switch to manipulate an electrical signal. The performance of these RF MEMS switches is superior to the existing solid state switches. RF MEMS switches exhibit excellent performance in terms of insertion loss, isolation, and linearity. Several vertical RF MEMS switches were developed in the last decades due to their excellent RF performance [2]. In last few years many researchers reported the ohmic contact RF switches [3-9]. In general a low voltage of 4-5 V is required for the operation of all the wireless mobile devices, but a complex charge pump circuitry is required for the operation of RF MEMS switches with high actuation voltage in the range of 40-100V [10,11]. The proposed RF switch design approach is to achieve a low actuation voltage in order to avoid the large circuitry.

In this paper, we have discussed about the design approach, fabrication process, and the simulated results of the proposed switch in detail. The switch is a cantilever beam designed on a silicon substrate. The main feature of the proposed design is an optimized conjoined rectangular beam structure with low actuation voltage, high RF performance, high reliability, and long life time. In section 2 the design considerations of the proposed switch and its specifications is given in detail. Section 3 illustrates the virtual fabrication process involved in the design of the proposed switch. Section IV discusses the simulated results.

2. Design consideration

The mechanical and electrical characteristics of RF MEMS switch depends upon its structural parameters. So it is important to design and optimize the structure of the RF MEMS switch. The micro-cantilever structure results in high temperature stability and reliability [1]. RF Switch with optimized cantilever beam has lower actuation voltage and higher dynamic structure [2]. Proposed design is a RF MEMS DC-metal contact series switch with conjoined rectangular beam structure. One of its ends is fixed and the other free end is covered with metal layer to open/connect the RF signal line. The proposed RF MEMS switch is shown in the Figure1.

The switch design parameters are given in the Table1. A conventional coplanar waveguide on a dielectric substrate consists of a center strip conductor with semi-infinite ground planes on an either side of the structure as it supports quasi-TEM mode of propagation [3]. The coplanar waveguide (CPW) offers several advantages over conventional microstripline, first it simplifies fabrication, and second it facilitates easy shunt as well as series surface mounting of active and passive devices. Our switch is a CPW series switch; consist of a cantilever with conjoined rectangular beam structure. The proposed RF MEMS switch has a coplanar waveguide (CPW) line of 1µm thickness made of aluminium for RF signal transmission on a 50 µm thick silicon substrate. A 0.1µm thickness of Silicon Nitrate (Si_3N_4) is deposited over the electrode at the bottom to avoid direct metal contact. The cantilever beam with length of 350 µm and width of 200 µm is fixed to the anchor with the conjoined rectangular structure. The cantilever beam is made of aluminium.

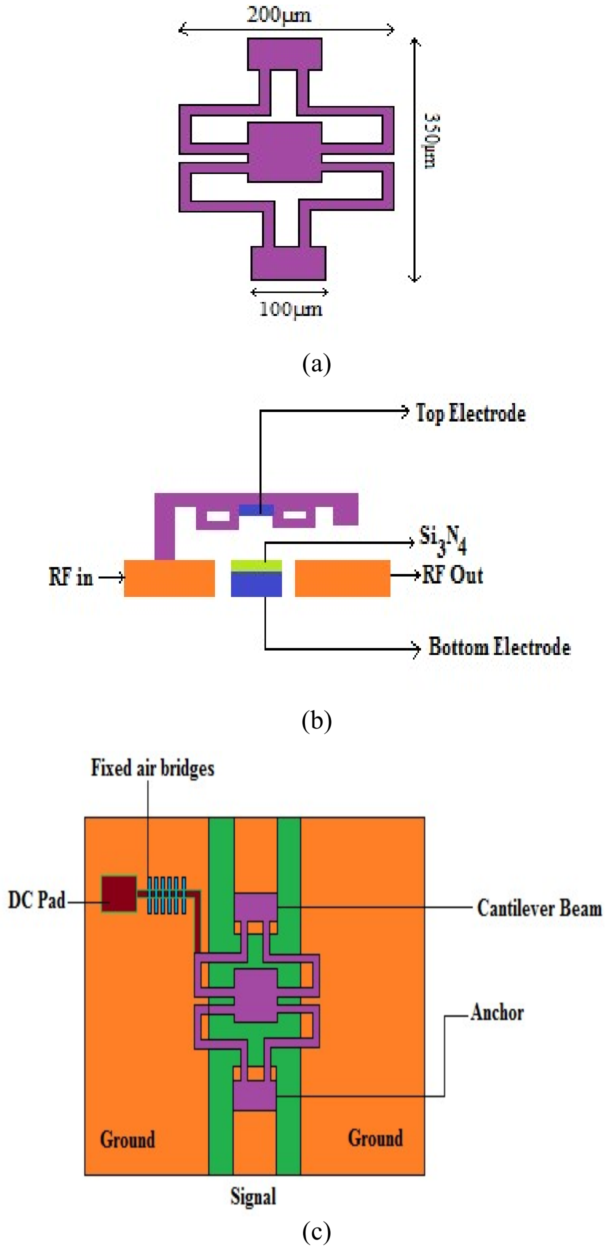

Fig.1 Geometry of the proposed switch: (a) Conjoined beam structure, (b) Side view, and (c) Front view

The switch is actuated using electrostatic actuation. When a voltage is applied between the cantilever beam and the strip line, an electrostatic force is created and the beam is pulled down to the signal line and a metal to metal contact is made, the switch is now in ON state. The RF signal is propagated form input port to the output port at this state. On the contrary without the applied voltage the beam is in upstate position, so the RF signal cannot be propagated. The switch is in OFF state. The force applied is directly proportional to mass and acceleration. The mass of the switch can be calculated by multiplying the area of the switch with the density of the aluminium. The pull-in voltage can be calculated using the equation (1)

$$V_p = \sqrt{\frac{8kz_0 a}{27A\varepsilon_0}} \qquad (1)$$

where k is the spring constant of the cantilever beam, z_0 is the initial gap height between the beam and the signal line, ε_0 is the permittivity of air, 8.854×10^{-12} F/m and A is the area of the beam namely the width (w) and the length (l) $w \times l$.

Table 1: Geometric parameters of the proposed switch

Beam length, l	350µm
Beam width, w	200µm
Beam thickness, t	1µm
Air gap, z_0	2µm
Length of CPW Line	1000µm
CPW Gap	80µm
Young's Modulus of Aluminum	70GPa
Poisson's ratio of Aluminum	0.44
Dielectric constant of silicon nitride	7.6

The actuation voltage is directly proportional to the spring constant of the beam. It can be varied by changing the dimensions of the beam and the materials used. It is expressed as in equation (2).

$$k = \frac{2E^t wt^3}{l^3} \qquad (2)$$

Where E is the Young's modulus of the beam, w is the width of the beam, t is the thickness of the beam and l is the length of the beam.

Moreover the moment of inertia of the cantilever beam is given by equation (3)

$$M = -EI\frac{d^2y}{dx^2} \qquad (3)$$

$$\text{where } I = \frac{WT^3}{12} \qquad (4)$$

The electrostatic moment applied at the beam tip represents the electrostatic force F along the beam multiplied by the resulting beam tip deflection α.

From this equation the moment of inertia is calculated and the stress is obtained from the equation (5)

$$\alpha(z) = E\tau \qquad (5)$$

$$\text{where } \tau = \frac{12M}{EWT^3} \qquad (6)$$

The closing time of the switch depends on the actuation voltage and the opening time depends on the mechanical properties of the switch. By scaling the MEMS devices the switching time is also scale downs, as equation (7)

$$t_s = 3.67\frac{v_p}{v_s\omega_0} \qquad (7)$$

$$f_0 = \sqrt{\frac{k}{m}} \qquad (8)$$

Where (ω_0, f_0)) is resonant frequency, V_p is pull in voltage and V_s is the applied voltage.

3. Virtual fabrication process

The fabrication is carried out using surface micromachining techniques by using IntelliFab, a process simulation module in Intellisuite[@] [12]. The virtual fabrication process flow is shown in the Figure 2. Silicon of 50µm thickness was used as the substrate. A 3.5 µm of PR-S1800 is used as the photo resist material for masking by spin coating. The first metal aluminium of 1µm thickness for CPW is deposited through E-beam evaporation and patterned. Si_3N_4 (Silicon nitride) layer of 0.1µm thickness is deposited using plasma-enhanced chemical vapor deposition [PECVD] and patterned over the actuation electrode. The anchor is realized by using the sacrificial layer. The beam structure with 1 µm thickness is realized using RF sputter deposition of aluminium. The sacrificial layer is etched out using plasma etching.

4. Results and discussions

4.1. Mechanical characteristics

The fabricated structure in IntelliFab module is simulated using ThermoElectroMechanical module in Intellisuite. The variation of displacement with the applied voltage was studied to determine the pull-in voltage of the switch.

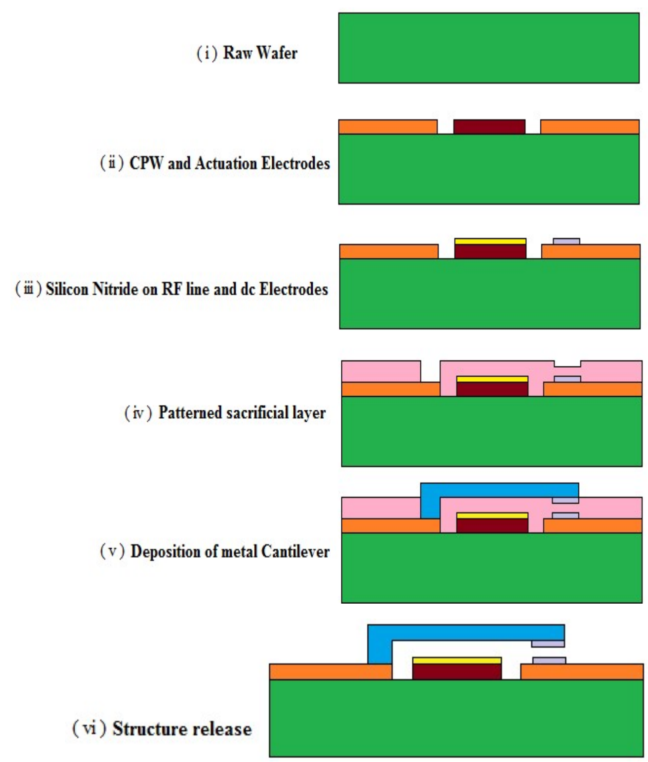

Fig.2. Fabrication process flow.

The switch shows a maximum displacement of 0.00493149 µm as shown in Figure 3 with an actuation voltage from 0 to 10 V. Pull-in voltage of the switch is calculated when the gap between the beam and the signal line is (2/3)Z_0 which is also called as critical gap height in ON state. The pull-in voltage of the switch was found to be 5V from the simulated graph displacement versus Voltage as shown in Figure4.

Mises stress is determined to check whether the design withstands to the given load conditions. The stimulated Misses stress is shown in the Figure5. The maximum Misses stress under actuated condition is found to be 16.7012 MPa.

The dynamic response of the switch is carried out using frequency analysis to find the structural resonance frequency. The structural resonance frequency was found to be 2.887 kHz. Figure6 shows the simulated values of the resonance frequency for the first three modes.

4.2. RF analysis

The RF performance of the switch was measured by stimulating the structure using EM software in the frequency 2 to 12 GHz.

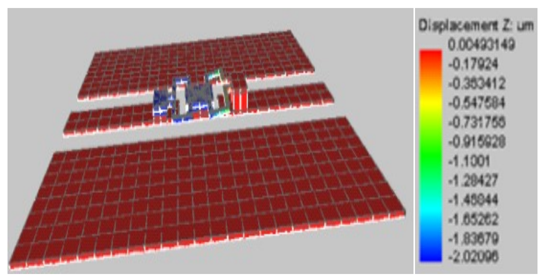

Fig. 3. Displacement of the switch

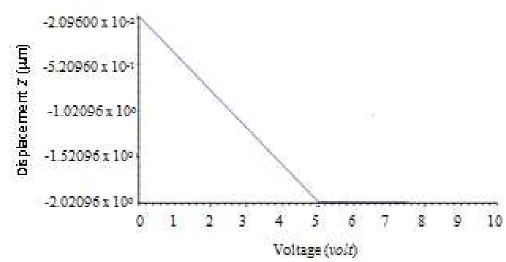

Fig.4. Displacement Vs Voltage

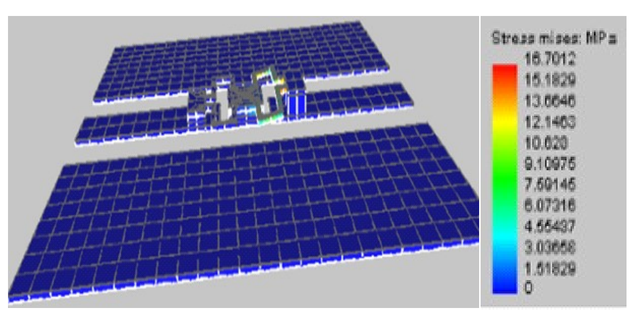

Fig. 5. Stress Analysis.

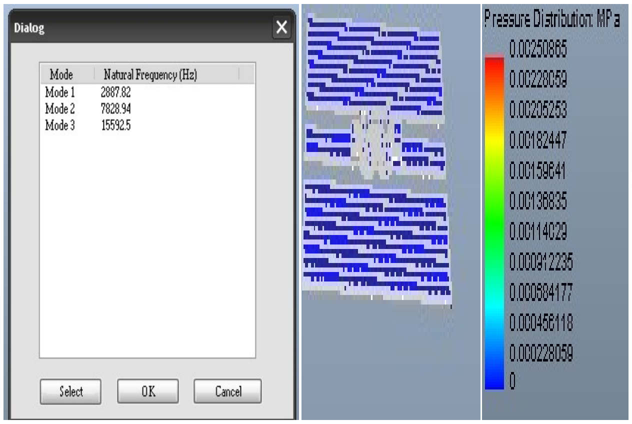

Fig. 6. Modal frequency analysis

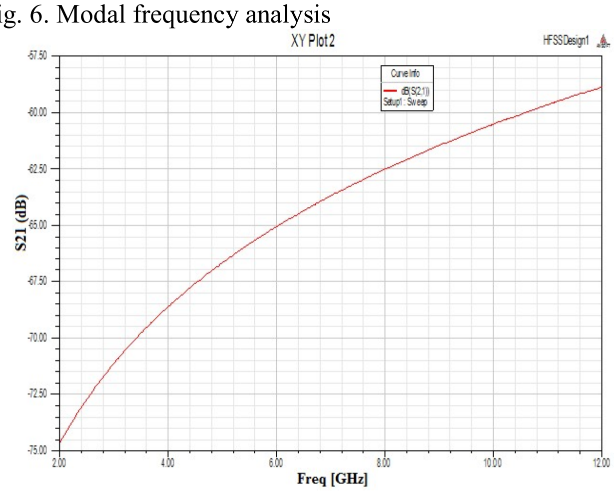

Fig.7. Isolation S_{21} in OFF state

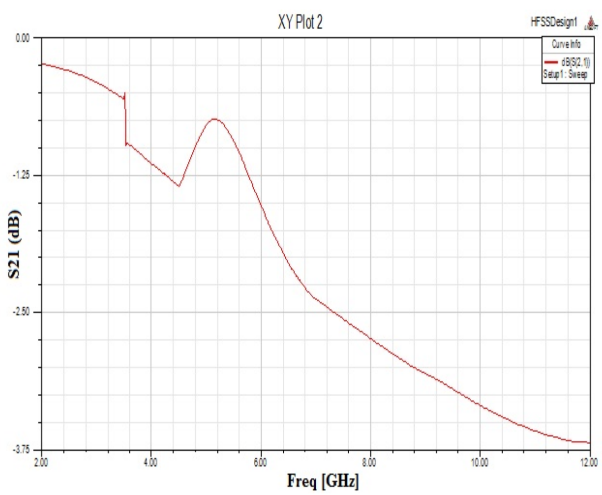

Fig. 8. Insertion loss S_{21} in ON state

Figure7 shows the stimulated result of isolation of the switch in off state. The switch had an isolation of -74.55 dB at 2 GHz and -57.65 dB at 12 GHz.

The insertion loss of the switch is shown in Figure8. The insertion loss was found to be -0.25 dB at 2 GHz and -3.56 dB at 12 GHz.

The reflection coefficient (S_{11}) of the switch is shown in Figure9. The reflection coefficient in OFF state is found to be -9.71 dB at 12 GHz and -3.45 dB at 12 GHz in ON state.

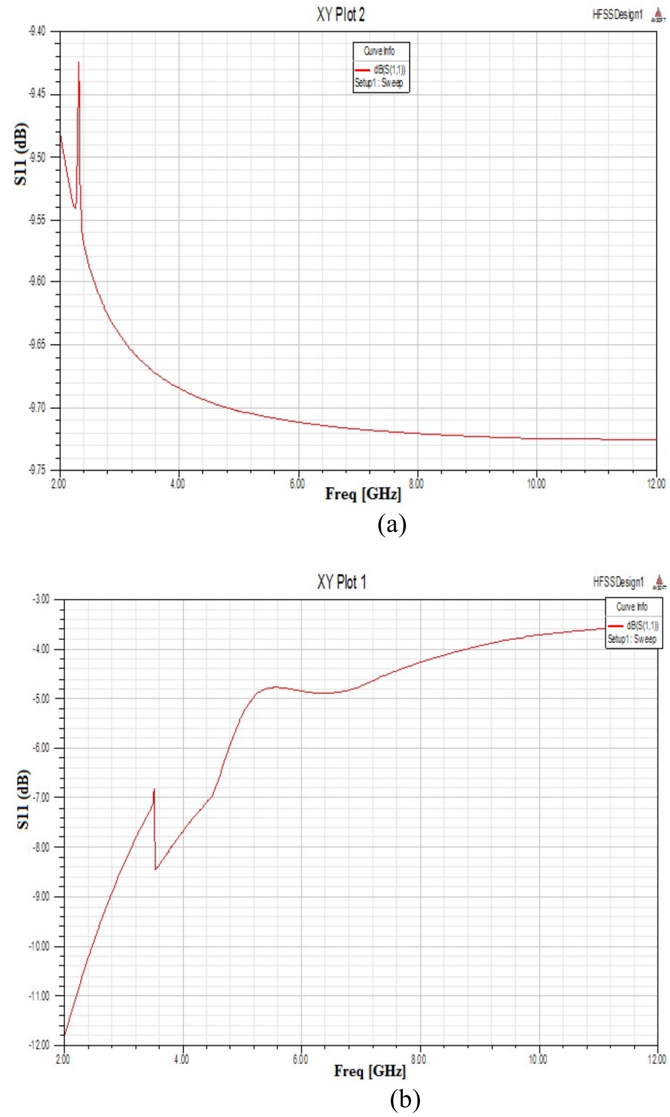

Fig. 9. Reflection coefficient (S_{11}): (a) ON and (b) OFF state

5. Conclusion

A metal contact RF MEMS switch with conjoined rectangular cantilever beam structure has been simulated, designed and virtually fabricated. The conjoined rectangular beam structure was successful for achieving low stress and high spring constant. The switch exhibited an insertion loss of -0.25 dB to -3.56 dB from 2 to 12 GHz. The isolation of the switch was found to be -74.55 dB at 2 GHz and -57.65 dB at 12 GHz. The pull-in voltage of the switch was found to be 5V. The maximum stress Misses under actuation condition was 16.7012 MP. The results of this proposed switch makes it suitable for wireless applications.

References

[1] De Santos, H. J., S. Rassoulian, and J. Maciel, MEMS for future microwave systems, *IEEE MTT-S International Microwave Symposium Digest*, pp. 6–8, 2005.

[2] A. Q. Liu, *RF MEMS Switches and Integrated Switching Circuits Design, Fabrication, and Test*. Springer, New York, 2010 .

[3] Yao, J. J. and M. F. Chang, A surface micromachined miniature switch for telecommunications applications with signal frequencies

from DC up to 4 GHz, *International Conference on Solid-State Sensors and Actuators Digest*, pp. 384–387. Stockholm, Sweden, 1995.

[4] J. B. Muldavin, and G. M. Rebeiz, Inline capacitive and DC-contact MEMS shunt switches, *IEEE Microwave Wireless Components Letters,* vol. 11, pp.334–336, 2001.

[5] Hyman, D.,Mehregany,M.: Contact physics of gold micro contacts for MEMS switches. *IEEE Transaction on Componenets Packaging Technology,* vol. ***22***, pp. 357–364, 1999.

[6] P. M. Zavracky, N. E. McGruer, R. H. Morrison, and D. Potter, Microswitches and microrelays with a view toward microwave applications. Int. J. RF Microwave and Computer-Aided Engineering, vol. 9, pp. 338–347, 1999.

[7] Sakata, M., Y. Komura, T. Seki, K. Kobayashi, K. Sano, and S. Horike, Micromachined relay which utilizes single crystal silicon electrostatic actuator, *12th IEEE International Conference on Microelectromechanical Systems*, pp. 21–24, 1999.

[8] Spasos, M., N. Charalampidis, K. Tsiakmakis, and R. Nilavalan, Analysis and design of an all metal in line series ohmic RF MEMS switch for microwave applications, *Symposium on Design Test Integration and Packaging of MEMS/MOEMS (DTIP)*, pp. 27–32, 2010.

[9] E. R. Brown, “RF-MEMS Switches for Reconfigurable Integrated Circuits,” in *IEEE Transactions on Microwave Theory and Techniques*, Vol.46, No.11, pp.1868-1880, November 1998.

[10] Fujiwara, T., T. Seki, F. Sato, and M. Oba, Development of RFMEMS ohmic contact switch for mobile handsets applications, *42nd European Microwave Conference (EuMC)*, 2012.

[11] Basu A., R. Hennessy, G. Adams, and N. McGruer, Leading and Trailing Edge hot switching damage in a metal contact RF MEMS switch, *Transducers 2013, Barcelona, SPAIN*, 16-20, June 2013.

[12] www.intellisense.com

Biography of the authors

R.Raman received B.E. degree in Electronics and Communication Engineering from Anna University, M.Tech degree in Electronics and Communication Engineering from Pondicherry University. He is pursuing his Ph.D in the area of RF MEMS under the guidance of Dr.T.Shanmuganantham. He has 4 years of teaching experience at CK college of Engineering and Technology. His research interest includes RF MEMS and Antennas. He is a life member of ISTE.

T. Shanmuganantham received B.E. degree in Electronics and Communication Engineering from University of Madras, M.E. degree in Communication Systems from Madurai Kamaraj University and Ph.D. (Gold Medal) in the area of Antennas from National Institute of Technology, Tiruchirappalli, India under the guidance of Dr. S. Raghavan. He has 15 years of teaching experience in various reputed Engineering colleges such as SSN College of Engineering, National Institute of Technology and Science. Presently he is working as Assistant Professor in. Department of Electronics Engineering, School of Engineering & Technology, Pondicherry University, Pondicherry. His research interest includes Microwave/Millimeter-Wave Circuits and Devices, Microwave Integrated Circuits, Antennas. He has published 125 research papers in various national and International level Journals and Conferences. He is a member in IEEE, Life Member in IETE, Institution of Engineers, CSI, Society of EMC, OSI, ILA, ISI, and ISTE.