Modeling Method of Finite Element Modeler and Electromagnetic Solvers for Education and Research in RF MEMS

Tejinder Singh, Wael M. El-Medany and Kamal J. Rangra

***Abstract*—Field of electronics engineering is the most captivating among students, researchers and academicians now-a-days. With the passage of time the requirement of advance tools for engineering is increasing. Many institutions and universities around the globe provide quality education to various engineering domain. Students although study theory courses but they also need exposure that how theory can be related to actual devices. Simulations play an important role for relating theoretical components to the virtual practical environment. Students of Radio Frequency (RF) domain and especially students that are studying Microelectromechanical Systems (MEMS) as courses, due to the extreme complexity of these devices, students need multiple tools to simulate the performance parameters. This paper highlights the most prominent tools that are used in the industry to design and implement RF MEMS structures. The role of Electromagnetic (EM) solvers and Finite Element Modeller (FEM) and its impact on electronics engineering education is demonstrated. Modeling approach of these tools are also explained. These tools and due to there huge advantages, electronics graduates should study these tools in their course curriculum to know how to tackle various types of RF problems and through case studies, it is demonstrated that how these tools can aid shift from just theoretical study to virtual practical environment.**

***Index Terms*—EM solver, FEM, electronics engineering, education, simulation environment.**

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I. INTRODUCTION

MANY a times, graduate engineering students or graduate research students face variety of challenges in designing and modeling the problems that are spanned in multiple disciples of engineering and applied sciences [1]. Streamlined computational methods and techniques that combine the technologies and that can handle engineering problems are required to precisely model the issues and accurately predict results before manufacturing or fabrication [1], [2]. Most of the electronic engineering programmes offer domain specific simulation and modeling methods on a very limited basis.

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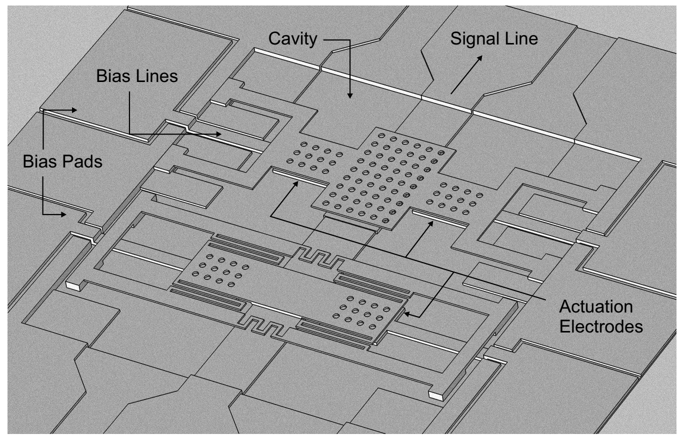

Fig. 1. T. Singh [5] proposed the RF MEMS switch based on series-shunt configuration, both membranes are incorporated inside the cavity. Bias pads demonstrate the actuation signal routing beneath the membranes. [Copyright © 2014, Springer Science, NY]

Our primary focus is on group of graduates that are into RF MEMS/antenna designing. RF MEMS [3] is a very fast growing field of research. Students usually face challenges in modeling and simulating RF MEMS systems [4]. We have encountered many questions on technology forums and through emails, students that just entered into this industry wonder that which tools are most prominent for simulating these micro structures.

Fabricating RF MEMS devices [6], [7] is a cumbersome process, hence simulations is the best bet to get approximate near to actual response. Theoretically it said that RF MEMS systems show excellent performance like high isolation and low insertion loss. But, to model the response, complex mathematical derivations need to be solved prior to check performance. EM solvers, provide comprehensive solution to all these RF or microwave related issues. Including, radiation field analysis, near and far fields, S, Y and Z parameters to name a few. If taught as core curriculum with hands on experience with these tools, fresh grads can usher in the industry. FEM on the other hand solves multi domain physics problems and provide solutions as per the requirement. Hence, companies are now opting for multi-physics modeling or finite element modeller (FEM) [8], [9] to save costs and to reduce computing resources. One tool can handle various physics problems. By this way, students not only learn their field specific solvers, instead they also get experience to couple various physics problems that may include, particle trajectories, flow analysis, damping analysis, stress or fracture analysis, doping concentration, charge flow and many more. Universities should focus on these issues and add finite element modeling in the course curriculum of graduate engineering students [2], [10].

Basically, FEM environment require the basic knowledge of the problem that one is going to tackle as a prerequisite. Once, the governing equations of the problem is provided, then using FEM computation methods, the FEM, thus ask for boundary conditions and finally computes those governing equations for specified boundary conditions [1], [4], [11], [12]. It takes a very little time if the basics are strong and clear. EM solvers are a boon to RF engineers, couples with FEM is just icing on the cake. These tools takes the theoretical inputs and do all the simulation and testing in between the framework of theory to actual development.

Engineering curricula in good universities offer design and research experience of various tools to better teaching and practical exposure. An electronics graduate student may require FEM techniques to solve electric field issues as well as overall device level issues like mechanical stresses or chemical process if the system is on same chip or base. This paper presents the need of these tools as an electronics engineering graduate course curricula that should covers the most of the methods and techniques relating to theory courses [11], [12].

Mostly, graduate engineering students become active participants in concept based learning than their theory counterparts. More generally, These tools not only teach them how to solve physics problems but also make them understand in very efficient manner. The introduction of the concept (need of simulation methods as a course) is explained in introduction followed by a section on impact of research tools on education and core technologies behind these tools. The statements are supported by our prior research work, by providing two case studies, in which Section IV, covers RF performance simulation using commercially available EM solvers followed by Section V, that reports the use of FEM on the design and analysis of RF MEMS. We have provided simulation process flow in Section III as well. The concluding remarks are given in Conclusion section.

II. Impact of Research Tools on Education and Core Technologies

There are many industrial grade tools for simulation depending on the problems. Now-a-days, tools are developed that we can also couple the physics from different domains for analysis [4], [13]. Modeling tools provides an environment for engineers in which they can design, analyse/simulate, compare the results and optimise various factors depending on the type of application [14]. Students after their engineering education, definitely look for engineering jobs. It is always advantageous for students to learn and practise these tools in whichever field they want to pursue their careers [15].

Our primary focus of this paper if for the graduates, who are studying antennas, RF engineering, microwave engineering, microelectromechanical systems or micro systems course in their curriculum, can get advantage to implement the theoretical designs and concepts in these tools. Thus by this methodology and practise graduates not only learn in an efficient manner, but also can understand better and comply with the industry requirements. Many a times, students face the issues that what to do with the mathematical formulas, that they are studying as theory [15]. Even in our classes, during lecture delivery, we show them the simulations that how those mathematics come into picture when we solve real world problems.

Universities might not have industrial grade testing labs or research centres, but either a lab related to the research tools or simulations along with lecture delivery can make students learn and understand in an efficient way. As, we have implemented this methodology from last few months, we have seen that students now learn and understand mathematical concepts in better way. They remember the things if we relate it to real world problems.

In this paper, we provided two case studies, that clearly relates the use of engineering tools, specially EM solvers and FEM in the field of Antennas, microwave theory and the most prominent research area RF MEMS.

A. *Aid of Simulation Tools*

As discussed in the previous section, we have designed an RF MEMS switch and relating the computed parameters from mathematical formulas to implementing in EM solver and FEM to check how accurate these tools are and how these tools can save abundant of time.

Solving partial derivatives and many other complex mathematical equations are not practical for engineering field. Such tools provide, ready to use solving algorithms and provide the results that are very close to the actual solutions. Simulations act as a mid way in between theory to development. It plays a very crucial role, providing ample space to optimise and check the solution to the problem.

In RF industry, performance and size of the devices are limiting factor especially for RF MEMS [16], [17]. For RF MEMS Switches, scattering parameters are analysed to check its RF performance. Other that that we are interested in how E field and H field of RF signal travels in the RF MEMS switches or subsystems. Then there comes the analysis of current density, J, temperature, leakage, resistant, capacitance, inductance, q-factor to name a few. That can be easily simulated in commercially available EM solvers like Ansys HFSS, Sonnet, CST Microwave Studio, EM3D and many more. These are many different types of EM solvers available in the market based on requirements.

Then to check the issues like stress gradient, voltage requirement, spring constant, switching time, damping, fracture analysis etc, finite element modeller are used. FEM like COMSOL or Ansys Workbench provides sophisticated solution in a close proximity to the real world fabricated designs. FEM divides the problem into finite elements of very small or desired size called the *Mesh* and solve the governing equations relating to that particular problem.

Fabricating RF MEMS switches and subsystems needs million dollar machinery, time, knowledge and engineering. Hence, these tools before going into actual experiment or fabrication run, provides relatively exact solutions. That saves time and money, thus increase productivity.

Students, if they would be knowing the tools before entering into industry, they can perform better and their initial performance in industry would be impactful on peers.

Briefly, in the following sections, we have presented the Series-Shunt based RF Switch, we have analysed the RF performance and Stress distribution. The comprehensive study of the RF MEMS switch is given in [5]

III. Simulation Process Flow and Design Properties

Till now, We have discussed that simulation represent an invaluable link between theory and practice in modern engineering. In this section, the simulation process flow is demonstrated.

A. Process Flow using Ansys HFSS

1) Geometry: Geometry can be created in 3D environment layer by layer. After setting the units to appropriate scale, one can start designing the geometry of product (RF MEMS Switch as used in this case). Geometry can be imported or exported in variety of formats to exchange with different simulation tools.

2) Material Assignment: After creating the geometry, material has to be assigned to different layers, as an example, bulk of Silicon (Si), is used mostly followed by a deposition of dielectric layer of different material. Once the material selection is complete, one can proceed to next section.

3) Ports Excitation: I/O Ports have to be assigned. We have to design the CPW lines to characterise it for 50 ohm for ease in coupling with coaxial cables. In this case study, typically for RF MEMS Switch, we have used Port 1 and Port 2 as input and output port with Wave Port assignment to both ports.

4) Analysis Setup: After setting up the model, we have to setup analysis. We have provided a linear frequency sweep of DC to 40 GHz with step size of 0.1 GHz to simulate RF performance of the designed switch. We have used smaller step size to get precise results. Although, less the step size, can affect computation time. Although, this tool provides the provision of High performance computing concept, such that we can use all the licenses available with us to get results in less time. Parts of the projects is usually simulated by using the computation power of different machines and then it automatically combine the results in host machine.

5) Checking the Results: After the completion of analysis, results can be plotted using Rectangular 2D plot option. Then, we can easily check the performance of switch while plotting S11 as Return loss [dB] and S21 as Isolation [dB] of the switch.

B. Process Flow using COMSOL Multiphysics

Although, Multiphysics environment provides, realistic approach to solve various physics problems. We can couple the physics to get best of both worlds. But, just to highlight the advantage of EM solver, we have simulated RF performance in Ansys HFSS and mechanical modeling in COMSOL Multiphysics. RF performance can also be simulated using COMSOL Multiphysics only. But, from our experience, it takes much more time to compute the same problem, thus we have chosen HFSS as our dedicated EM Solver.

1) Geometry: We have to check the mechanical issues like stress gradient, spring constant and pull-in voltage required to deflect the beam for particular gap height, g_0. We have to set the units to micrometers. In this, we need only metal membrane instead of complete geometry to ease the computational load. Hence, we imported membrane only in multi physics environment to start investigating the issues further.

2) Material Assignment: In COMSOL, huge library of materials is already provided with details like Poisson Ratio, Elasticity, Permittivity, Permeability, Density, Young's modulus, thermal coefficient and many more. We then assigned "*Au*" material from category MEMS, as the only material for this switch membrane.

3) Physics: We have chosen, Electromechanics (emi) physics and stationary study for this particular problem. This physics allows to compute pull-in voltage and deflection of membrane.

4) Boundary Conditions: For this model, we have assigned inner membrane as Linear Elastic Material, while the fixed constraints are bottom side anchors of membrane. Then, we have to choose Boundary Load and we have applied boundary load as Contact Pressure as a predefined variable followed by Prescribed Mesh Displacement. At last, we have applied boundary conditions: Voltage Terminal and Ground Terminal.

5) Mesh: COMSOL Multiphysics offer physics controlled mesh depending on the complexity of geometry or we can optimise the mesh to reduce computation time. for this model, we have chosen Mapped mesh and Swept the mesh in complete geometry.

6) Solver: COMSOL offer variety of solvers, but we have optimised the solver for our model. We chose Full couples solver and under Method and Termination section, we chose Nonlinear method to select Automatic (Newton). Finally under "Direct" option, we chose PARDISO solver.

7) Computation and Results: After setting up the model, we computed it and plotted the results as desired in Results section. In that section, we can plot 3D, 2D or 1D results depending on the requirement.

The correctness of simulation results with experimental results can be seen from the work of [3], [18], in which researchers have fabricated the designs and compared the performance.

IV. Case Study I - RF Performance Estimation using EM Solvers

The most critical parameter for any RF system or device is to analyse its RF performance. RF performance is the most important factor that primarily shows the performance of MEMS that it is intended for. The isolation loss, return loss and insertion loss of the RF MEMS switch is simulated using commercially available EM solver Ansys HFSS. RF performance of the switch is observed between frequencies 1 to 40 GHz. Fig. 2 shows the peak isolation S_{21}, of 75 dB at 28 GHz in OFF state, although the switch has very large bandwidth of 30 GHz, i.e., it can be used for K–Ka band applications. From the results, the performance of switch is excellent for said frequency bands. Two bandwidths a and b are considered, Bandwidth a is 30 GHz and has the complete frequency range of K and Ka band that shows more than 60 dB of isolation and bandwidth, b is 7 GHz narrow bandwidth that shows excellent isolation of above 70 dB from 25 GHz to 32 GHz. The solution to the RF problems thus can easily be solved by using EM solver as demonstrated [19].

Numerically the S–parameters S_{11}, S_{21} in both switching states can be computed using the Y and Z–matrix data from EM solver and by plugging the values in equations given below. To determine the ON state parameters, Y_{11-x} is required, where $x = 1$ for switch in ON state and $x = 0$ for switch in OFF state.

$$S_{11-x} = \left(\frac{Y_z^2 - Y_{11-x}^2 + Y_{21-x}^2}{\left(Y_{11-x} + Y_z\right)^2 - Y_{21-x}^2} \right) \tag{1}$$

where S_{11-x} is the ON or OFF state return loss depending on the variable x, $Y_z = 1/Z_0$, $Y_{11-x} = j\omega C_{down}$ for $x = 0$ i.e., in OFF state and $Y_{11-x} = j\omega C_{up}$ for $x = 1$ i.e., in ON state. $Y_{21-x} = -j\omega C_{down}$ for $x = 0$ and $Y_{21-x} = -j\omega C_{up}$ for $x = 1$ i.e., in OFF and ON state respectively. Isolation S_{21-0} and insertion loss S_{21-1} can be analysed by using

$$S_{21-x} = \left(\frac{-2Y_{21-x}^2 Y_z}{\left(Y_{11-x} + Y_z\right)^2 - Y_{21-x}^2} \right) \tag{2}$$

For the switch in ON state, the return loss, S_{11} and insertion loss, S_{12} is computed. Fig. 3 shows the return loss of 24 dB and Fig. 4 shows low insertion loss of 0.13 dB at 28 GHz with markers for complete 30 GHz bandwidth for K and Ka bands.

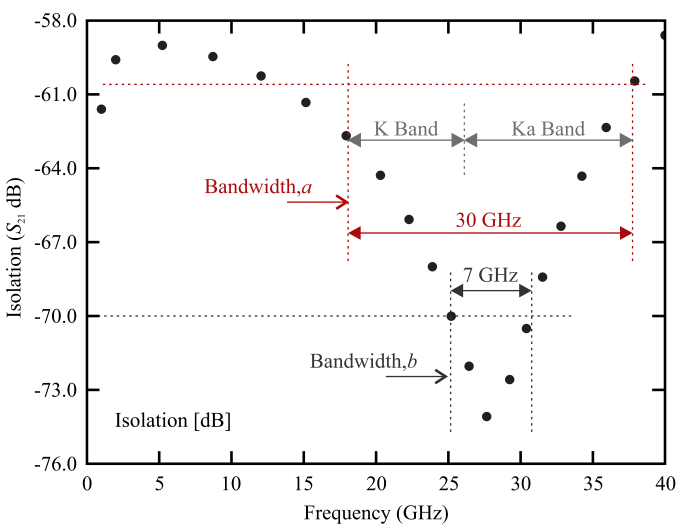

Fig. 2. Simulation of Isolation [dB] performance for combined switch in series–shunt configuration. The simulation is done for frequency sweep of 1–40 GHz and results in maximum peak isolation of 75 dB at 28 GHz. Two bandwidths are considered for this switch, Bandwidth (a) 30 GHz is very large with above 60 dB of isolation and bandwidth (b) 7 Ghz has excellent isolation of above 70 dB. Parameters are for the RF MEMS switch shown in Fig. 1, courtesy T. Singh [5]

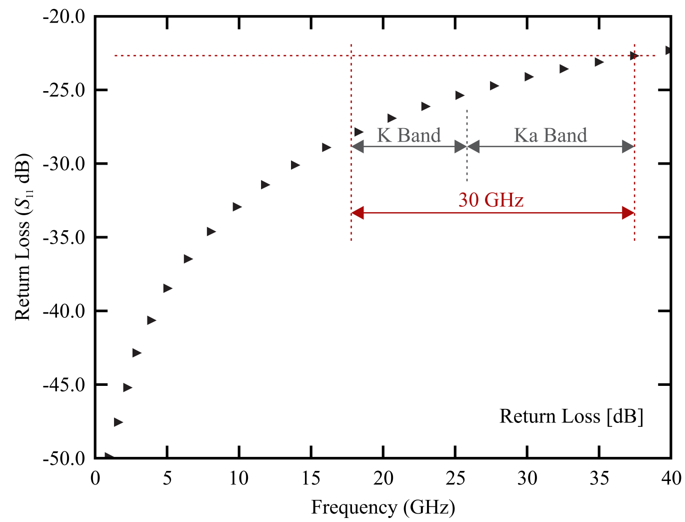

Fig. 3. Return loss [dB] for switch in series–shunt configuration. The simulation results are analysed for frequency sweep of 1–40 GHz and demonstrates the maximum peak return loss of 50 dB at 1 GHz and 24.5 dB at 28 GHz.

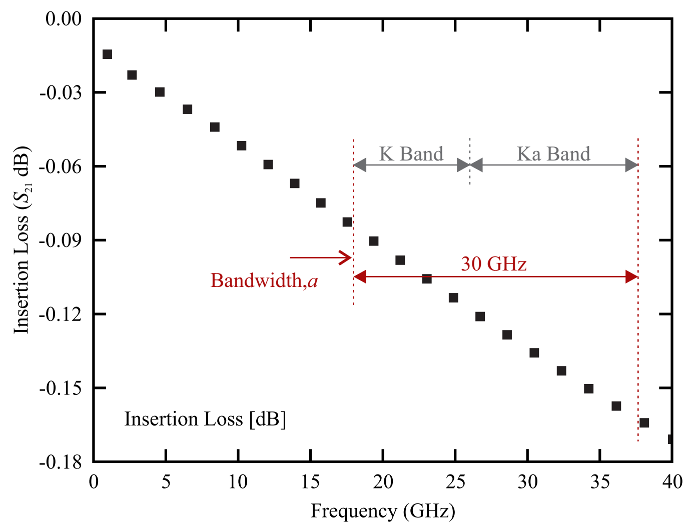

Fig. 4. Insertion loss [dB] simulation for complete switch in series–shunt configuration. The simulation is carried out for frequency sweep of 1–40 GHz and demonstrates the maximum peak insertion loss of 0.015 dB at 1 GHz and 0.13 dB at 28 GHz.

V. Case Study II - Finite Element Modeling for RF-MEMS

RF MEMS switches or subsystems are highly regarded for their better RF performance in microwave regime than their semiconductor counterparts. RF MEMS switches have huge advantage including; excellent isolation, low insertion loss, negligible power consumption, very compact structure, low cost of manufacturing [20]. But these tiny intelligent devices suffer from reliability issues including stiction and high voltage requirements [13], To overcome these problems, researchers and designers has to model and analyse the issues first and then optimise the design accordingly. In this case study, we have reported that how FEM is useful in estimating the stress gradient to help determining how the membrane of RF MEMS can handle stress for reliable operation [5].

The design and modeling parameters are reported in [5], [20]. We have presented the stress analysis for two different membranes. We have also reported the spring constant estimation and pull-in voltage analysis of these switches by using FEM. Although, RF performance is analysed by EM solver and is given in the previous section. There is a need of FEM (Finite Element Modeling) to check various parameters before fabrication of devices [16]. For this proposed switch, the spring constant, stress and pull-in voltage required for actuation is analyzed as discussed in [5], [20]. COMSOL Multiphysics is used as finite element modeler for analyzing the parameters [17], [20]. This section deals with the coupled physics, electrostatic + magnetic problem solving. Analytical calculations of spring constant for complex structures are not possible, because the formulas presented till now are for simple beams or for beams with simple meanders. The complex geometries can be better analyzed using FEM. To calculate the spring constant and stress in membranes, sweep of force is applied over the area of electrodes. Both the membranes are analyzed one by one for the same force and displacement sweep.

As the membranes are made of gold, the gold can withstand stress of 100 MPa and it fails for values higher than that. The effective stress can be seen in membranes from Fig. 5 and 6 respectively. The von Mises stress analysis is mandatory to check the maximum stress level. If the maximum stress increases for a given gap height from the stress a material can withstand, then it is an alert for failure in design. But the redesigned membranes can withstand stress for assigned gap height and have margin to take twice of more stress. The ohmic membrane is designed to reduce the spring constant and stress. The side view of ohmic membrane is shown in Fig. 7. It depicts that the sides of membrane are not making any contact with signal line and it helps to keep the inner membrane straight for better contact and better switching speeds. It increases the reliability of switch as well. The spring constant for ohmic and capacitive switch membranes are shown in Fig. 8

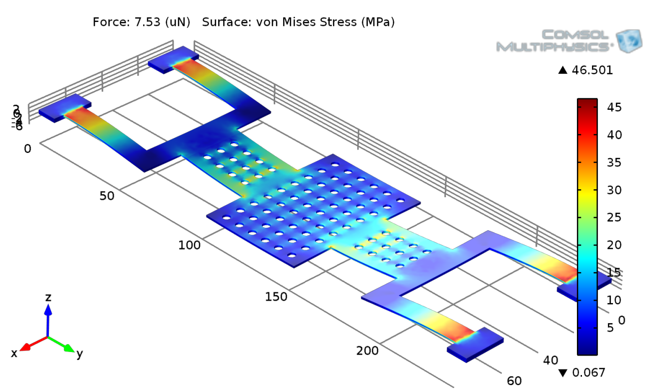

Fig. 5. Capacitive / Shunt switch membrane stress analysis for 2.5 μm gap height, showing maximum stress of 46.5 MPa. [Copyright ©2014, Springer Science, NY]

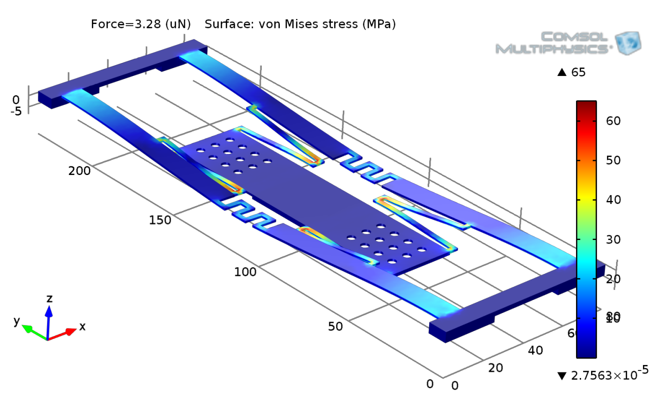

Fig. 6. Results by T. Singh [5] Ohmic / Series switch membrane stress analysis for 3 μm, showing maximum stress of 65 MPa. [Copyright ©2014, Springer Science, NY]

The actuation voltage is analyzed by plotting a curve of applied voltage vs. deflection of beam. The voltage required for desired gap height is shown in Fig. 9. The ohmic switch membrane works properly on 3 μm gap and capacitive switch membrane on 2.5 μm. The pull–in voltage required is same for both membranes as shown in plot.

Theoretically, determining the fundamental mode of operation is also required for certain analysis. The equation of motion of the thin metal beam that is under harmonic force is considered. In single degree of freedom, the harmonic motion of the mass-spring system is fundamentally modelled with the 2^{nd} order differential equation as

$$m_{\text{eff}} \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + \gamma_{\text{eff}} \frac{\mathrm{d}x}{\mathrm{d}t} + k_{\text{eff}} x = F_e \tag{3}$$

where m_{eff} is the beam's effective mass, γ_{eff} is the effective coefficient of damping of dielectric material, F_e is the electrostatic force and k_{eff} is the effective spring constant. m_{eff} is of gold material, effective mass of inner movable beam i.e., 8.52 ng. Effective spring constant k_{eff} is composed of k' and k''. According to [3] the component of biaxial residual stress k'' can be neglected due to the crab type flexures design, perforation i.e., holes are added to release the biaxial residual stress in membrane. γ_{eff} can be estimated by computing Eq. 3 by fitting all the remaining values.

The spring constant is simulated for the membrane and shown in Fig. 8. For the serpentine flexures, the numerical values of spring constant can be analysed by using

$$k' \approx \frac{48GJ}{l_a^2 \left(\dfrac{GJ}{EI_x} l_a + l_b \right) n^3} \quad \text{for } n \gg \frac{3 l_b}{\dfrac{GJ}{EI_x} l_a + l_b} \tag{4}$$

where n is the number of meanders in the serpentine configuration, $G = E/2\,(1+v)$ is the torsion modulus, $I_x = wt^3/12$ is the moment of inertia, and the torsion constant is usually

Fig. 7. Vertical defection in ohmic switch membrane showing deflection in Z–direction, from this side–view image, the straight contact over signal line and contact area on electrodes can be seen.

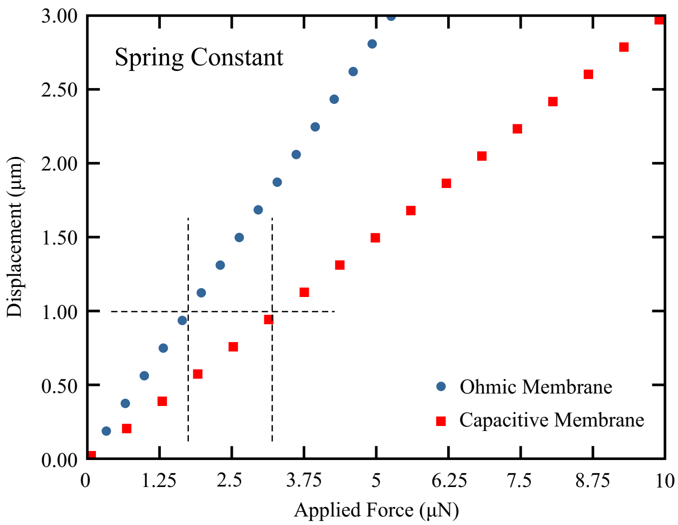

Fig. 8. Spring contact analysis for ohmic and capacitive switch membranes for displacement sweep of 0.3 – 3.3 μm vertical displacement in Z–direction

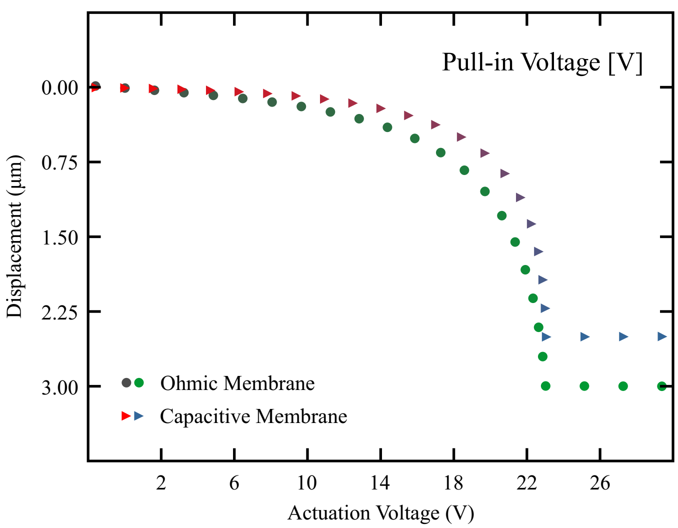

Fig. 9. Simulation of actuation voltage requirement by series and shunt membranes. The voltage is simulated for the maximum 3.5 μm displacement. The maximum voltage required are optimized to use same potential for different gap height of 2.5 μm for series and 3 μm for shunt membrane.

given by

$$J = \frac{1}{3}t^3 w \left(1 - \frac{192}{\pi^5}\frac{t}{w}\sum_{\substack{t=1,\\ i=odd}}^{\infty}\frac{1}{i^5}\tanh\left(\frac{i\pi w}{2t}\right)\right) \tag{5}$$

The effective spring constant k_{eff} can be determined by plugging material values like Young's modulus E and moment of inertia I_x in Eq. 4. The combined spring constant k_{eff} for the membrane is 1.5 N/m for ohmic and 2.7 N/m for capacitive membrane.

The natural frequency of the membrane depends on the equivalent spring constant and the effective mass, the natural frequency f_0 is given as

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_{\text{eff}}}{m_{\text{eff}}}} \tag{6}$$

Next higher mode of eigenfrequency f_1 can be determined by using

$$f_1 = \frac{1}{2\pi}\left[\frac{15.418}{L^2}\right]\sqrt{\frac{EI_x}{\rho}} \tag{7}$$

where; ρ is the mass density (mass/length), L is length of membrane

VI. Assessment Results

To check the understanding of concepts by introducing simulation environment to students, we have conducted a survey of 3 Grad classes and 2 Undergrad classes. While, teaching the subject RF MEMS theoretically, we have presented the simplistic flow of simulation and explained its use among students. They students first of all became more attentive in the class, and whatever they have learned using tools i.e., results computed using simulation environment were more regarded by students. A simple exercise of comparing the simulation results with analytical results provides a good method of learning among students. They started relating the numerical concepts in correct manner. By teaching using simulations, brain become more attentive to see the actual working of analytical equations on products/designs. Students tend to learn and understand things faster.

We have conducted a survey by demonstrating few simple electromagnetic related problems and their computed solutions by numerically and using computationally, and finally found that more than 90% of undergrad and grad students wanted faculty to teach using these kind of tools for their better understanding. We then taught about a simple physics problem numerically or analytically in one section consisting more than 60 students with their average academic standing of grade A. Simultaneously, we taught about same physics problem by introducing simulation tools to the students with average academic standing of grade B.

After that session, we conducted a test based on that problem and found the score of test of students taught using simulation tools scored way better than other section. Students enjoyed learning about the concepts if taught using computational tools.

VII. Conclusion

The role of EM solvers and finite element modeller for researchers in RF MEMS domain is discussed by citing two case studies from our previous research work. Our primary focus in this paper is to relate the industrial requirements to the electronics engineering students. Students who are working or want to work in antennas or RF MEMS industry can take advantage, if they would learn these tools in their course curriculum. The capabilities of these tools in solving engineering problem is demonstrated in both case studies. It is clear that the capabilities of these tools are tremendous for any cross-coupled physics problems. The learn curve might be steeper for some, but once mastered it cam drastically reduce the designing and testing time. As only engineers can develop efficient and advanced products that can serve the needs of humanity and it can be possible with the quality engineering education.

APPENDIX – I

Design parameters and material parameters are given in Table I and in Table II respectively for the RF MEMS switch designed for Case study in this paper. These parameters are for the design elaborated in depth by T. Singh [5]

TABLE I
SPECIFICATIONS OF THE RF MEMS SWITCH

Component	Length μm	Width μm	Depth μm	Material
Substrate	412	412	200	Quartz
Substrate Dielectric	412	412	0.5	HfO_2
CPW (G S G)	126	31.5	1	Gold
Cavity	245	245	3	–
Series Membrane	235	80	1	Gold
Shunt Membrane	245	80	1	Gold
Electrode $\times 4$	35	40	1.5	Gold
Series Contact Pad	35	31.5	0.5	Gold
Meanders width	A (10)	B (3.5)	C (2.5)	Gold
Signal Line Dielectric	80	31.5	0.25	HfO_2

In value column, first value is for ohmic membrane and second is for capacitive unless otherwise specified. The parameters are given in Table. II. Some parameters are given in the specification table as shown in Table. I.

TABLE II
RF MEMS SWITCH – MATERIALS PROPERTIES

Parameter	**Notation**	**Value**
Young's Modulus	E	70 GPa
Density	ρ	$19,300$ Kg/m^3
Poisson's Ratio	ν	0.44
Dielectric Constant	ε_r	25
Spring Constant	k	$1.5, 2.7$
Initial Gap	g_0	$2.5, 3.0$ μm
Holes Radium	r_0	3.8 μm
Mean Free Path	λ	70 nm
Mass of Membrane	m	$8.52, 11.3$ ng

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