Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

Design of Miniaturized RF MEMS Based Single-Bit Phase Shifter

Amrita Chakraborty[1*], Avra Kundu[1], Sayan Chatterjee[1] and Bhaskar Gupta[1]
[1]Department of Electronics and Telecommunication Engineering, Jadavpur University, Kolkata-700032.
*Corresponding author: amrita.chakraborty2@gmail.com

Abstract: This paper presents a novel design of single-bit RF MEMS phase shifter. The novelty introduced for phase shifter design in this case is scaling down of the lateral dimensions of the conventional RF MEMS shunt switch by 10 times. Hence, in terms of overall area coverage, 100-150 times reduction can be achieved. Such miniaturized switches, operated individually, provide minimal phase shifts of 3^0-4^0. Hence, single-bit phase shifters have been designed by cascading several similar RF MEMS switched capacitors so as to exhibit considerable amount of phase shift, yet keeping the lateral dimensions well within limits. Mechanical and Electromechanical analysis of the designed miniature miniaturized phase shifter is conducted using COMSOL Multiphysics v.3.5a which primarily consists of Static Analysis, Modal Analysis and Transient Analysis respectively. Analysis yields an actuation voltage of 12.16V and a switching time as low as 180nsec only.

Keywords: Miniaturization, Static Analysis, Modal Analysis, Transient Analysis.

1. Introduction

The recent developments in the field of RF MEMS technology has proved to be highly beneficial since the RF MEMS based devices such as switches, varactors, inductors, tunable filters, pressure and temperature sensors call for substantial DC power reduction for space-based, airborne and even low-power portable telecommunication and radar systems [1]. However, this paper concentrates on the basic discussion of the design of RF MEMS phase shifting unit cell based on the periodic placement of MEMS shunt switches on a CPW (coplanar waveguide) transmission line. This type of phase shifter, known as the Distributed MEMS Transmission Line (DMTL) type, is one of the most common phase shifter design strategies adopted nowadays.

RF MEMS switches suffer from certain inherent limitations such as limited speed of operation, higher actuation voltage and certain associated reliability issues such as stiction, dielectric charging problems and buckling of the beam. All such limitations can be overcome by introducing the concept of miniaturization as a novel design strategy. RF MEMS based phase shifters, having conventional dimensions, as reported in [2], requires an overall area of (8.39×0.49) mm^2 for K_u band applications, and the unit cell occupies a lateral dimension of 660 μm, which leads to huge wastage of real estate. However, the phase shifting unit cell reported in this paper is miniaturized with respect to the standard switch dimensions, yet yielding a phase shift of 15^0 for K_u band frequencies. RF characterization of the unit cell has been carried out using Ansoft HFSS v. 12® [3] in order to obtain loss performance i.e., S11 (Return Loss) and S21 (Insertion Loss) for the entire range of frequencies in the K_u band and the corresponding differential phase shift values.

Hereafter we report the simulation results carried out in COMSOL Multiphysics v. 3.5a ® [4]. Static Analysis, Modal Analysis and Transient Analysis of the miniaturized RF MEMS beam have been performed to yield-

(i) the value of actuation voltage in volts, required to realize the down (actuated) state,
(ii) the value of the mechanical resonant frequency (in MHz) of vibration of the beam and its various deformed shapes,
(iii) the value of the switching time (in nsec) required by the miniaturized beam to undergo full up and down state transition once.

An actuation voltage of 12V with a switching time of only 180 nsec is achieved.

2. Phase Shifting Unit Cell Structure

The basic unit cell structure consists of a CPW based transmission line structure having G/W/G dimensions corresponding to 9.5/5.5/9.5μm respectively. The dimensions have been chosen in such a way so as to result in a characteristic impedance of 70 ohms, when the transmission

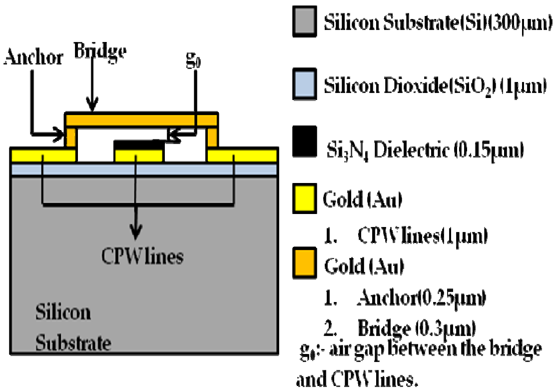

Figure 1 (a) Cross-sectional view of the unit cell structure

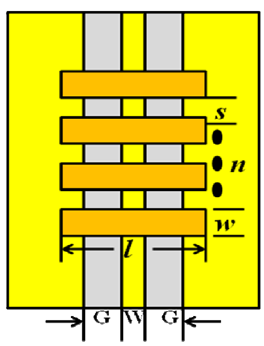

Figure 1 (b) Top-view of the unit cell structure

line is in unloaded state (devoid of the presence of any MEMS bridges). CPW lines, 1μm thick, made of gold, are fabricated on a high resistivity (10kΩ-cm) Si-substrate, 300μm thick. Four gold bridges, (0.3μm in thickness) are connected to the CPW ground planes, by means of fixed anchors, which are 0.25μm in height. Figure 1(a) and (b) [5] depict the cross-sectional view and top-view of the unit cell. Length *'l'*, width *'w'* and thickness *'t'* of the miniaturized bridge corresponds to 32μm, 12μm and 0.3μm respectively. A Si_3N_4 insulator, 0.15μm thick, acts as an isolator in between the CPW central line and the MEMS bridges. Each miniaturized bridge yields a minimal phase shift of 3^0 only, which is negligibly small. Hence, the number of bridges in a unit cell have been optimized to four, so that, a considerable amount of 15^0 phase shift is obtained at a frequency of 15GHz, yet keeping the loss-performance well within limits. Optimization is highly recommended as the amount of phase shift is directly proportional to the loss suffered and care should be taken to result in the maximum value of phase shift, in addition to low-loss output.

3. Use of COMSOL Multiphysics

This paper emphasizes on the usage of COMSOL Multiphysics as the basic MEMS tool to perform Static Analysis, Modal Analysis and Transient Analysis respectively.

3.1 Static Analysis

Static Analysis refers to the plot of displacement vs. voltage applied to a switch when it is being subjected to an externally applied electrostatic actuation. It aids in obtaining the amount of actuation voltage required to achieve the down (actuated) state configuration from the up (un-actuated state). For simplified theoretical analysis, the governing equations of the problem have been enumerated as under.

$$V = \sqrt{\frac{8k}{27\varepsilon_0 W w} g_0^{\ 3}} \qquad (1)$$

$$k = 32Ew\left(t/l\right)^3 \qquad (2)$$

where, V=actuation voltage required,
k= spring constant of the beam (23.73N/m),
ε_0= permittivity of free space= 8.854×10^{-12}F/m,
W=width of the central conductor in the CPW based transmission line (5.5μm),
w=width of the miniaturized beam (12μm),
g_0= height of the air gap in between the CPW central line and the MEMS bridge (0.25μm),
E= Young's Modulus of gold= 75G Pa,
t= thickness of the MEMS bridge (0.3μm),
l= length of the MEMS bridge (32μm).

However, in order to perform accurate simulated Static Analysis in COMSOL Multiphysics, the various application modules used are-

1) **MEMS Module**
   - Structural Mechanics
     - Solid, Stress-Strain
       - Static Analysis

2) **COMSOL Multiphysics**
   - Deformed Mesh
     - Moving Mesh (ALE)

Static Analysis

3) **MEMS Module**
Electrostatics

It is to be noted that under application mode properties, 'Large Deformation' should be kept 'on'; whereas the weak constraints should be kept under 'off' conditions.

The 3D block diagram of the fixed-fixed beam is enclosed on all sides by an air block and the corresponding sub-domain and boundary conditions are applied for each application mode. On successful completion of Static Analysis, an actuation voltage as low as 12.16V is obtained. Figure 2 shows the deformed shape of the beam when subjected to the required actuation voltage. Figure 3 shows the Displacement (nm) vs. Electric potential (V) curve showing an actuation voltage of 12.16V.

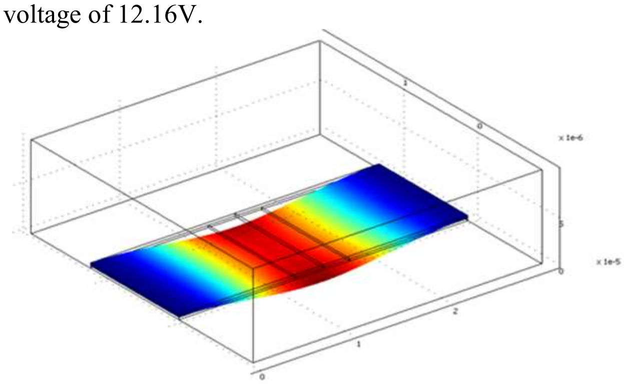

Figure 2 shows the deformed shape of the beam during Static Analysis

Figure 3 shows the Displacement (nm) vs. Electric potential (V) curve yielding an actuation voltage of 12.16V.

3.2 Modal Analysis

Modal Analysis [6] or rather, the Eigen frequency analysis refers to the calculation of natural frequencies of vibration of the beam. Modal analysis is the study of the dynamic properties of structures under vibrational excitation. The Eigen values are used to determine the natural frequencies (or Eigen frequencies) of vibration, and the eigenvectors determine the shapes of these vibrational modes. Modal Analysis aids in computing the values of these mechanical resonant frequencies of vibration of the beam. FEM simulations employing COMSOL Multiphysics provides the deformed shapes of the beam when subjected to the various modes of vibration.

The simplified governing equation has been written as under-

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \text{..........(3)}$$

$$m = 0.35(lwt)\rho \text{.........(4)}$$

where, f_0=natural frequency of vibration (in Hz),
k=spring constant of the beam (eqn. 2),
m=mass of the beam (in kg),
l=length of the beam (32µm),
w=width of the beam (12µm),
t=thickness of the beam (0.3µm),
ρ=density of gold=19,320kg/m^3.

In order to perform accurate Modal Analysis in COMSOL Multiphysics, the various application modules used are-

1) **MEMS Module**
Structural Mechanics
Eigen frequency analysis

2) **COMSOL Multiphysics**
Deformed Mesh
Moving Mesh (ALE)
Static Analysis

According to eqn. (3), the fundamental frequency of vibration is 2.67MHz, whereas, that obtained from simulations conducted in COMSOL Multiphysics is 2.265MHz. Hence, the results are in close agreement.

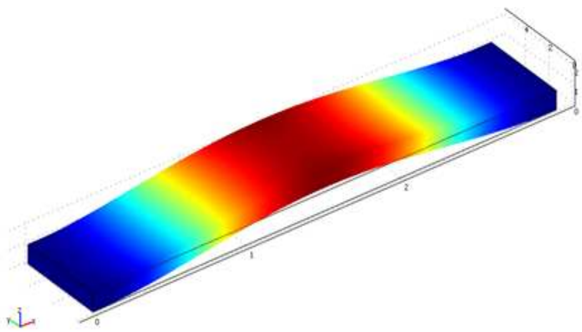

Figure 4(a) Fundamental mode of vibration (2.265MHz)

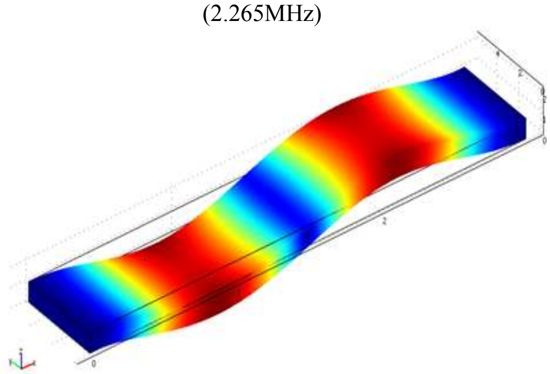

Figure 4(b) Second mode of vibration (6.185MHz)

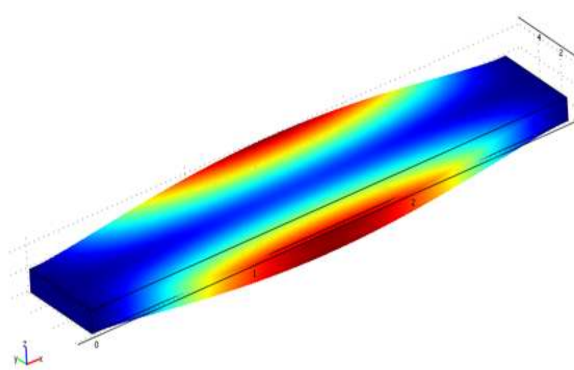

Figure 4(c) Third mode of vibration (7.07MHz)

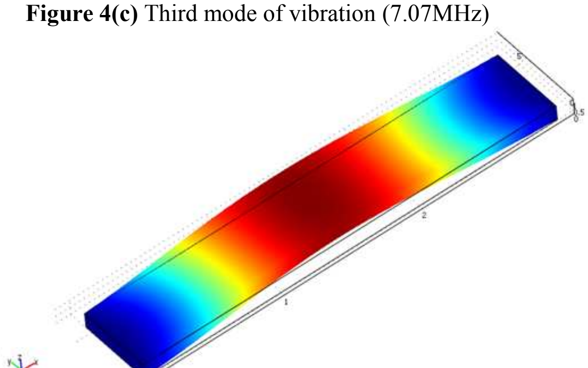

Figure 4(d) Fourth mode of vibration (9.95MHz)

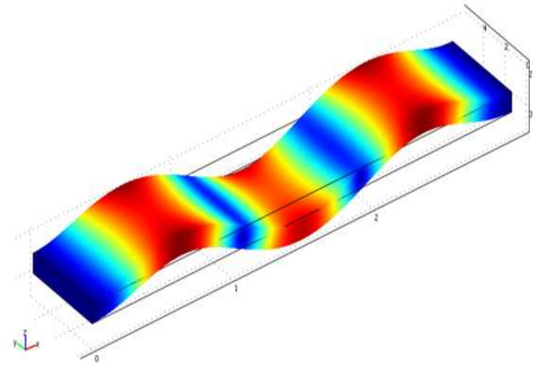

Figure 4(e) Fifth mode of vibration (12MHz)

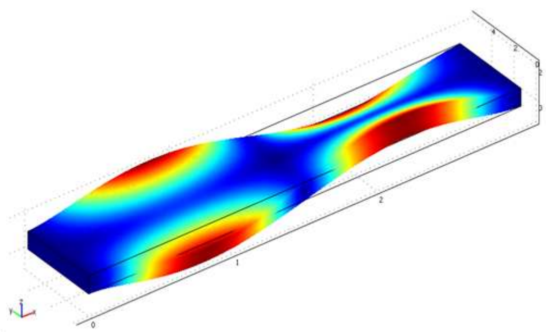

Figure 4(f) Sixth mode of vibration (14.52MHz)

Figures 4(a), (b), (c), (d), (e) and (f) respectively show the various deformed shapes of the miniaturized beam when subjected to the fundamental and higher order vibrational modes. It is seen that, six different deformed shapes are obtained, each corresponding to a higher order harmonic of the fundamental frequency of vibration.

3.3 Transient Analysis

Transient Analysis refers to the curve of displacement (nm) vs. time (nsec) so as to obtain the required switching time of operation. Transient Analysis is also known as the dynamic response of a system and it employs a non-linear equation called D' Alembert's principle [1] as the primary governing equation.

The equation has been written as under for convenience-

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F_e = \frac{1}{2}\frac{\varepsilon_0 A V_s^{\,2}}{(g_0 - x)^2} \quad \text{............(5)}$$

$$b = (3/2\pi)\left(\mu A^2 / g_0^3\right) \ldots\ldots\ldots(6)$$

where, m=mass of the beam (refer to eqn. (4)),
k=spring constant of the beam (refer to eqn. (2)),
Vs = 1.25Vp,
A = Area of the contact surface (Ww),
E = Young's Modulus of gold = 75GPa,
ρ = density of gold =19,320 kg/m^3,
μ = Coefficient of viscosity = 1.218×10^{-5} Pa-s.
x=displacement of the beam.

The different application modules used while performing Transient Analysis are as follows-

1) **MEMS Module**
   Structural Mechanics
   Solid, Stress-Strain
   Transient Analysis

2) **COMSOL Multiphysics**
   Deformed Mesh
   Moving Mesh (ALE)
   Transient Analysis

3) **MEMS Module**
   Electrostatics

Transient Analysis carried out in COMSOL Multiphysics yields a switching time of only 180 nsec, whereas, that exhibited by MEMS switches of standard dimension is about 1-20µsec or so. Figure 5 denotes the deformed shape of the beam

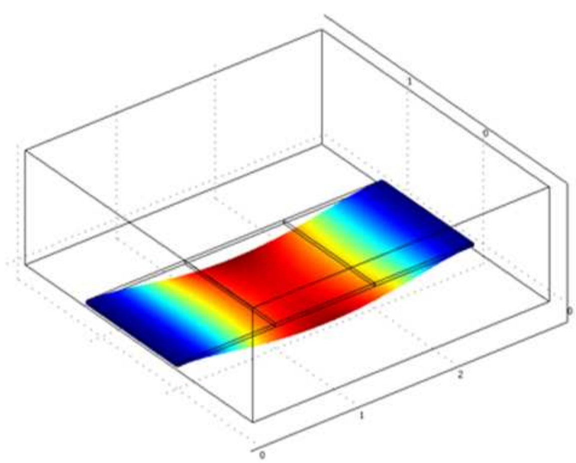

Figure 5 Deformed shape of the beam after performing Transient Analysis

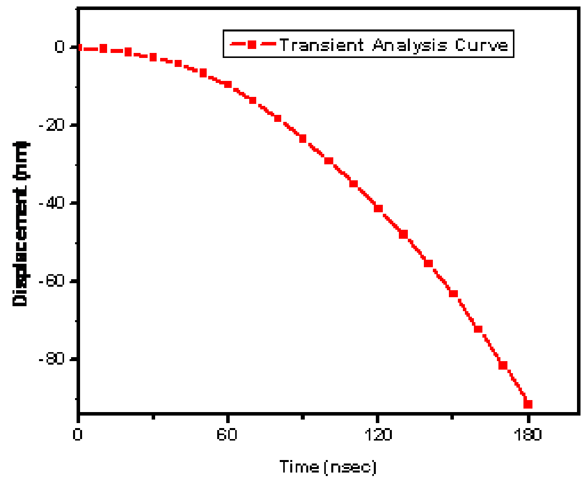

Figure 6 Displacement (nm) vs. Time (nsec) curve showing a switching time of 180nsec only.

on performing Transient analysis in COMSOL Multiphysics. Figure 6 shows the displacement (nm) vs. time (nsec) curve, evidently depicting the switching time.

4. Conclusion

This paper highlights the contributions of COMSOL Multiphysics in understanding the basic requirements of the simplest member amongst all RF MEMS based structures, i.e., the RF MEMS based switch. COMSOL Multiphysics is highly beneficial in providing the necessary outputs related to Static Analysis, Modal Analysis and Transient Analysis and the results obtained are quite close to those obtained by analytical formulae. This designed miniaturized switch based phase shifter not only provides a low actuation voltage of 12.16V, but also yields a very fast switching time of the order of 180 nsec only.

5. References

[1] Gabriel M. Rebeiz, "RF MEMS: Theory, Design, and Technology", *John Wiley & Sons Ltd*, Chapters 1, 9 and 10, pp.1-20, 259-324, 2003.

[2] Benjamin Lacroix, Arnaud Pothier, Aurelian Crunteanu Pierre Blondy, " Phase Shifter Design Based on Fast RF MEMS Switched Capacitors",

2008 *IEEE 3rd European Microwave Integrated Circuits Conference*, pp. 478-481.

[3] http://www.ansoft.com/products/hf/hfss

[4] http://www.comsol.com/

[5] Amrita Chakraborty, Avra Kundu and Bhaskar Gupta, “Compact K-Band Distributed RF MEMS Phase Shifter Based on High-Speed Switched Capacitors”, Mediterranean Microwave Symposium, Tunisia, Sept. 2011.

[6] http://en.wikipedia.org/wiki/Modal_analysis

6. Acknowledgement

The authors would like to thank Indian space Research Organization (ISRO) for their necessary support.