World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:11, No:3, 2017

Open Science Index, Electronics and Communication Engineering Vol:11, No:3, 2017 publications.waset.org/10006819.pdf

Analysis of Thermal Damping in Si Based Torsional Micromirrors

R. Resmi, M. R. Baiju

Abstract**—**The thermal damping of a dynamic vibrating micromirror is an important factor affecting the design of MEMS based actuator systems. In the development process of new micromirror systems, assessing the extent of energy loss due to thermal damping accurately and predicting the performance of the system is very essential. In this paper, the depth of the thermal penetration layer at different eigenfrequencies and the temperature variation distributions surrounding a vibrating micromirror is analyzed. The thermal penetration depth corresponds to the thermal boundary layer in which energy is lost which is a measure of the thermal damping is found out. The energy is mainly dissipated in the thermal boundary layer and thickness of the layer is an important parameter. The detailed thermoacoustics is used to model the air domain surrounding the micromirror. The thickness of the boundary layer, temperature variations and thermal power dissipation are analyzed for a Si based torsional mode micromirror. It is found that thermal penetration depth decreases with eigenfrequency and hence operating the micromirror at higher frequencies is essential for reducing thermal damping. The temperature variations and thermal power dissipations at different eigenfrequencies are also analyzed. Both frequency-response and eigenfrequency analyses are done using COMSOL Multiphysics software.

Keywords**—**Eigen frequency analysis, micromirrors, thermal damping, thermoacoustic interactions.

I. INTRODUCTION

MICROMIRROR systems are part of small Micro-Electro-Mechanical Systems (MEMS) systems for integrated scanning in telecommunications and consumer applications. MEMS technology processes can create submicron features with high precision, low power consumption and low cost per unit [1]. Torsional micromirrors are widely used in different applications like head up displays of automotives, medical imaging, scanners, fiber optics etc.

The micromirrors are movable micro optical components used for spatial manipulation of light [2]. These devices are commonly classified based on their operating modes. In torsional mode, micromirrors can deflect the incident light in the required direction by tilting along its axis while piston mode micromirrors are used to change the phase of the light by means of vertical displacement [3]. Low energy consumption is an important criterion in the design of these micromirror systems particularly in applications with limited power sources [4]. However, energy dissipation occurs in micromirrors since its dynamic displacement leads to a structural resonance resulting in damping.

Due to the integration constraints of scanning micromirrors; their design, modeling and fabrication have been investigated for the past decades in order to miniaturize and improve the performances. Energy dissipation mechanisms existing in microstructures are classified as extrinsic and intrinsic. The main intrinsic dissipation mechanisms are Akhieser Dissipation and Acoustic Thermoelastic Damping where as extrinsic sources of damping include anchor loss, air-damping, squeezed-film damping and surface loss.[5] In order to achieve a high Q factor, careful consideration of the extrinsic and intrinsic dissipation mechanisms are needed. Energy loss due to different damping mechanisms are controlled by changing the geometric design or working conditions. Air-fluid damping is reduced by operating the structure under vacuum. Anchor loss (support loss) is eliminated by designing nonintrusive supports. Energy loss like thermal damping imposes a strict upper limit on the performance of the micromirrors [6].

The dynamics of MEMS devices involves air–structure interactions to varying degrees. Some devices such as vibrating micromirrors generally work with ambient air surrounding them [7]. The thin layer of air between the planar structures having relative motion can significantly alter the dynamic characteristics of these devices by adding stiffness and damping to the system. The dynamic response of these devices can be studied efficiently by finite element modeling [8].

This paper deals with the analysis of the interaction between a thin layer of air and vibrating MEMS micromirrors. Dissipation of energy in the surrounding air of vibrating micromirror is presented which includes the effects of inertia, viscosity, compressibility and thermal conductivity. Finite element modeling is used which enables fully coupled acoustoelastic calculations to evaluate the dissipation of energy in the layer.

II. THEORY OF THERMAL DAMPING

Thermal damping is due to the varying thermal conduction between the gas surrounding the torsional micromirror and the vibrating structure. In addition to the thermal damping there exists a viscous damping due to viscous forces at the interface. The total damping is explained by the losses originating from these two processes and the total damping constant is the sum of the damping constants due to the abovementioned energy loss mechanisms. The damping constant is inversely proportional to the Q factor of the system.

Resmi R is with the LBS Institute of Technology for Women, Kerala University, Kerala, India (phone: 9446136613 e-mail: resmilbs@gmail.com).
M.R. Baiju is with Kerala University, Kerala, India (e-mail: mrbaiju@gmail.com).

$$\frac{1}{Q} = \delta = \delta TH + \delta VISC \qquad (1)$$

where δ_{TH} is the thermal damping constant and δ_{VISC} is the viscous damping constant.

The number of cycles required for the amplitude of the motion to reduce to $e^{-\pi}$ of its original value is the Q of the system. Zener predicted that thermal losses may be a limitation to the maximum Q factor of a resonator [9]. Basically, the principle of thermal damping is the following: In a torsional mode micromirror when vibration occurs, in the surrounding regions of micromirror compressive stress and tensile stress occur. Accordingly, compressed regions heat up and stretched regions cool down. Hence, a temperature gradient is formed between different parts of the system surrounding the vibrational micromirror. In torsional mode, vibration persists indefinitely when damping is absent. But local temperature gradients lead to irreversible flow of heat which is an energy loss mechanism and attenuates the vibration amplitudes. This irreversible flow of heat and entropy generation leads to damping of the system. Thermal resistance exists surrounding the vibrating structure which accounts for power dissipation and this accounts for Q limiting energy loss mechanism [10]-[13].

An important parameter in vibrating structures is the thickness of the viscous and thermal boundary layers also called the penetration depths. The thermal boundary layer thickness is the distance from the vibrating structure at which the temperature is 99% of the temperature found from an inviscid solution. The ratio of the viscous boundary layer thickness and thermal boundary layer thickness is governed by the Prandtl number [14].The Prandtl number is the ratio of the viscous diffusion rate to the thermal diffusion rate expressed as the ratio of kinematic viscosity to the thermal diffusivity. In boundary layer theory, the magnitude of the Prandtl number determines whether the thermal boundary layer is larger (Pr<<1) or smaller (Pr>>1) than the viscous boundary layer. If the Prandtl number is 1, the two boundary layers have the same width. The thickness of the thermal boundary layer δ is shown in Fig. 1 which is accountable for energy dissipation in vibrating MEMS structures.

III. DESIGN OF VIBRATING MICROMIRRORS USING FINITE ELEMENT METHOD

A. Modeling of Micromirrors

A sketch of the idealized micromirror system modeled is shown in Fig. 2. The mirror is made up of silicon and is surrounded by air. Fig. 2 shows the modeled micromirror which is 0.5 mm by 0.5 mm and only half is shown because of symmetry and thickness is 1μm. The center frequency selected for analysis is 10.5 KHz and Δf is 500 Hz.

The solid mirror is modeled using shell elements and the surrounding air is modeled using thermoacoustics. A pressure acoustics layer is used to truncate the computational domain.

One goal with the model is to get a correct assessment of the damping the mirror experiences. Therefore, the detailed thermoacoustics is used to model the air domain surrounding the micromirror. The interface includes thermal and viscous damping explicitly as it solves the full linearized Navier-Stokes, continuity, and energy equations [15].

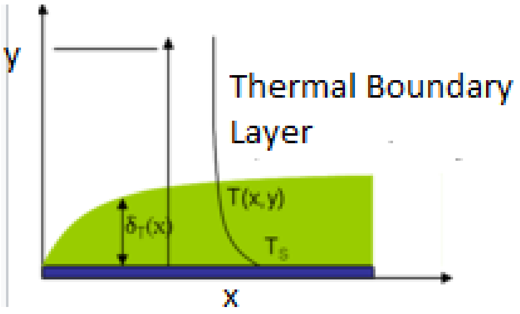

Fig. 1 Thermal Boundary Layer

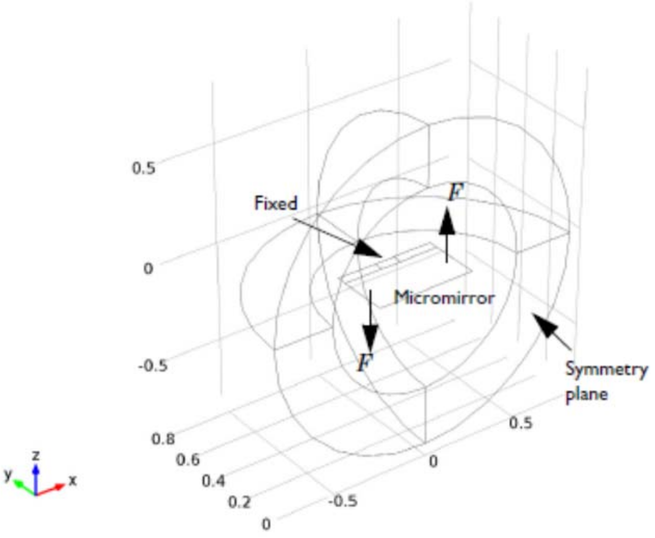

Fig. 2 Geometry of the modeled vibrating micromirror

B. Finite Element Analysis

Finite element modeling and simulations were performed using COMSOL Multiphysics to better understand the behaviour of the vibrating micromirror. The finite element model is shown in Fig. 3. The model combines the Shell interface, the thermoacoustics, and the frequency domain interface. The three physics interfaces are set up and combined using multiphysics couplings: The acoustic-thermoacoustic boundary coupling and the thermoacoustic-structure boundary coupling features, respectively. The thermal boundary layer thickness values and temperature variations are found out by Finite Element Analysis.

The vibrating micromirrors can be analyzed by the subdivision of the mathematical model into disjoint (non-overlapping) components of simple geometry called finite elements. A high velocity region is seen near the edge of the micromirror. The extent of this region into the surrounding air is given by the scale of the thermal boundary layer (also known as the thermal penetration depth). Heat transfer to and from the micromirror takes place within the boundary layer and it is responsible for the thermal energy loss.

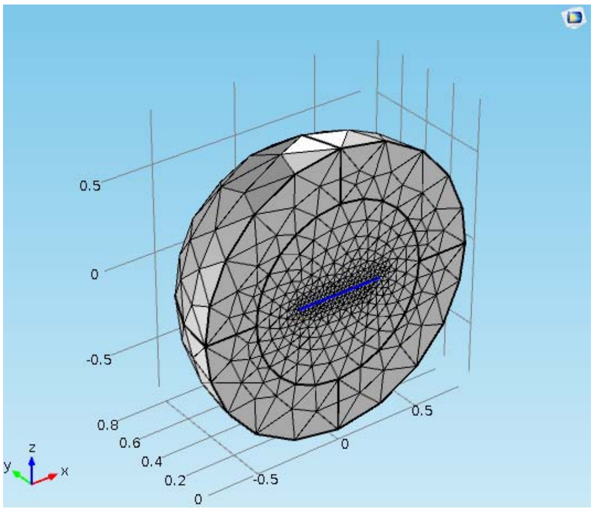

Fig. 3 Finite Element Modeling of Micromirror

IV. RESULTS AND DISCUSSION

A. Thermal Penetration Depth (δ) and Damping Analysis

In order to find out the thickness of the thermal boundary layers or Thermal Penetration Depth (δ) into the surrounding air an eigenfrequency analysis is done and structural modes are investigated. The thickness of the thermal layer is very crucial since energy is mainly dissipated in thermal boundary layers. From the analysis, it is clear that as the eigenfrequency increases the width of the thermal boundary layer decreases and so energy loss decreases with high frequencies. Operating the device under high frequencies substantially alleviates energy loss due to thermal damping by reducing the thermal penetration depth. Fig. 4 shows the variation of thickness of thermal boundary layer or penetration depth with eigenfrequency.

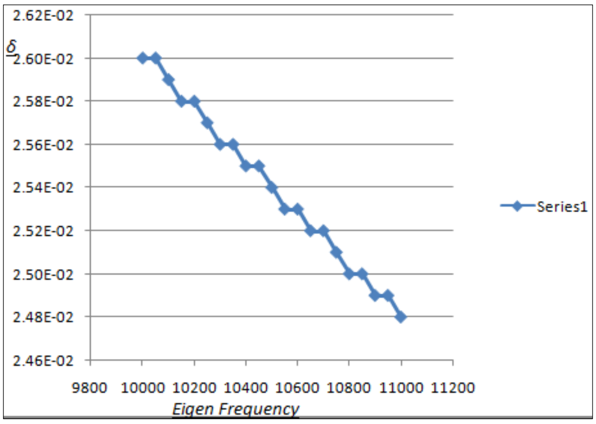

Fig. 4 Thermal Penetration Depth Vs. Eigen frequency

B. Thermal Power Dissipation

The analysis of Thermal Power Dissipation is also done by eigenfrequency analysis. Dissipation is the result of an irreversible process that takes place in inhomogeneous thermodynamic systems. In a dissipative process, energy is transformed from some form to another form and capacity of the final form to do mechanical work is less than that of the initial form. According to the second law of thermodynamics, temperature and entropy are directly proportional. Thermal heat dissipation reduces the capacity to do mechanical work, but never decreases in an isolated system. This process is irreversible and produces entropy. The dissipated power is given by the entropy production rate times ambient temperature. The thermal boundary layer incorporates a thermal resistance and the heat flow through such a boundary layer dissipates thermal power and generates entropy.

The variation of thermal power dissipation is shown in Figs. 5-7.

Fig. 5 shows the distribution of thermal power in the surrounding air of the vibrating micromirror. It is found that at 10 KHz the thermal power dissipation density is 4.2×10^{-15} W/m^3. The colour chart at the right side of the figures indicates the scaling and distribution of the various parameters simulated.

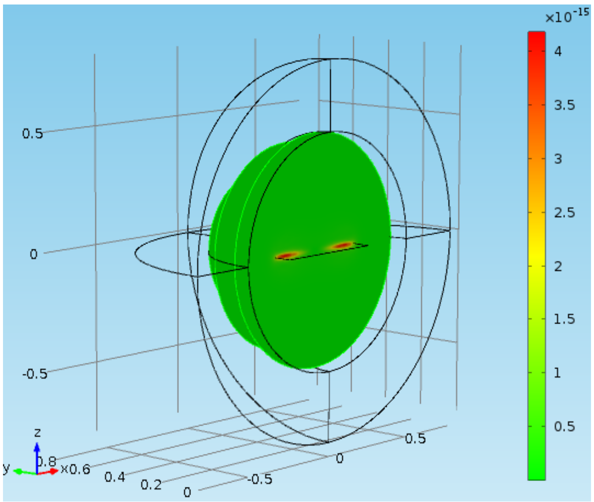

Fig. 5 Thermal Power Dissipation Density in the boundary layer at 10 KHz

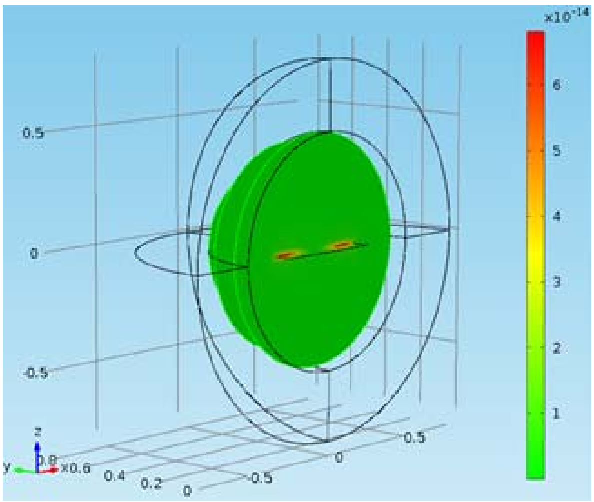

Fig. 6 Thermal Power Dissipation Density in the boundary layer at 10.5 KHz

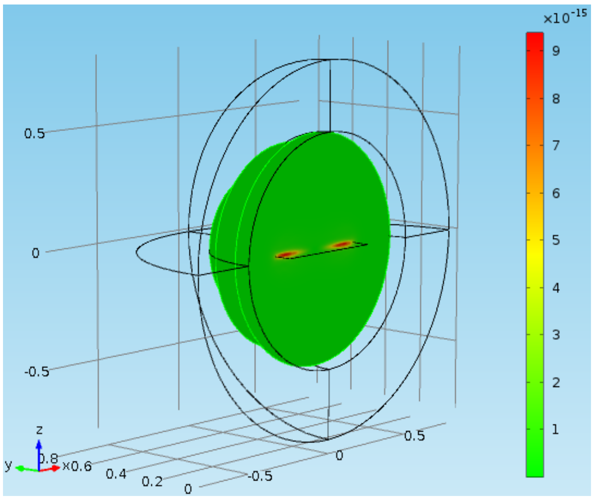

Fig. 7 Thermal Power Dissipation Density in the boundary layer at 11 KHz

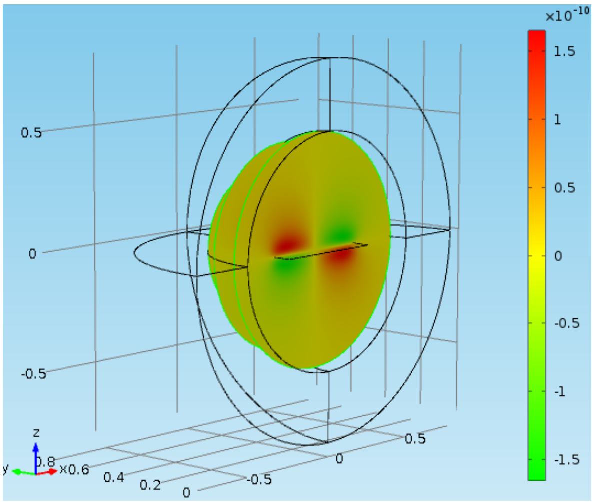

Fig. 8 Temperature variations of the surrounding area of micromirror at 10 KHz

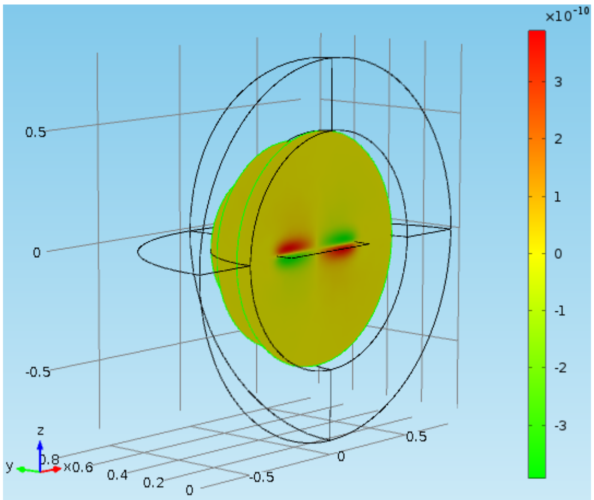

Fig. 9 Temperature variations of the surrounding area of micromirror at 10.5 KHz

Fig. 6 shows the distribution of thermal power density at 10.5 KHz and maximum value found to be 6.9x10^{-14} W/m^3.

The thermal power dissipation density in the thermal boundary layer at 11 KHz is shown in Fig. 7 and the maximum value found to be 9.2x10^{-15} W/m^3.

C. Temperature Variation

The acoustic temperature variations at different eigenfrequencies are shown in Fig. 8. The entropy production rate times ambient temperature gives the dissipated power. The maximum thermal dissipation power is obtained at a frequency of 10.5 KHz and the maximum temperature variation is also obtained at the same eigenfrequency.

Fig. 8 shows the variation of temperature in Kelvin at 10 KHz and it is found to be 1.7x10^{-10} K. The temperature variation is found to be 3.9x10^{-10} K at 10.5 KHz as shown in Fig. 9.

Fig. 10 shows the temperature variations surrounding the vibrating micromirror at 11 KHz and it is found to be 2.3x10^{-10} K. The temperature variations and thermal power dissipation density are found to be maximum at a frequency of 10.5 KHz.

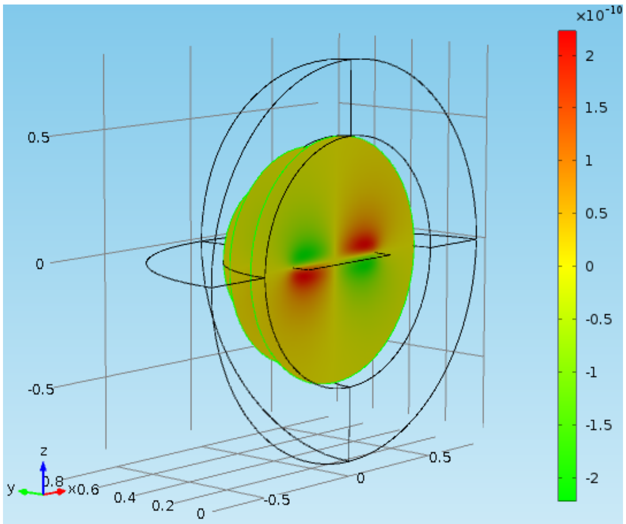

Fig. 10 Temperature variations of the surrounding area of micromirror at 11 KHz

V. CONCLUSION

In this paper, the thermal penetration depth around the vibrating micromirror which accounts for the thermal dissipation power at different eigenfrequencies is analyzed. It is found that as eigenfrequency increases thermal boundary layer thickness or thermal penetration depth decreases. The thermal penetration depth is accountable for thermal damping in a vibrating micromirror and estimation of its thickness is essential for designing high performance systems with minimum energy loss. The variation in temperature at different eigenfrequencies is also found out by eigenfrequency analysis. The potential of micromachined mirrors over conventional scanning mirrors – high scan speed, small size, and low cost with diffraction-limited optical performance find extensive applications in MEMS industry.

REFERENCES

[1] Olav Solgard, Asif A. Godil, Roger T. Howe, Luke P. Lee, Yves-Alain Peter, Hanes Zappe, *"Optical MEMS: From micromirrors to complex systems,"* Journal of Micro Electro Mechanical Systems, vol. 23, no.3, June 2014.

[2] R. Sulima and S. Wiak, "*Modeling of vertical electrostatic comb-drive for scanning micromirrors,"* Int. J. Comput. Math. Electr. Electron.Eng., vol. 27, no. 4, pp. 780–787, 2008.

[3] Xingguo Xiong and Hanyu Xie, *"MEMS dual-mode electrostatically actuated micromirror,"* Proceedings of Zone 1 Conference of the American Society for Engineering Education (ASEE Zone 1), 2014.

[4] David A. Ditmars and George T. Furukawa "*Detection and Damping of Thermal-Acoustic Oscillationsi n Low-temperature Measurements"* Journal of Research of the National Bureau of Standards-C. Engineering and Instrumentation, Vol. *69C,* No. I, January-March 1965.

[5] Srikar Vengallatore, "Analysis of thermoelastic damping in laminated composite micromechanical beam resonators", J. Micromech. Microeng. 2398-2404,2005.

[6] Minikes A, Bucher I and Avivi G, *"Damping of a microresonator torsion mirror in rarefied gas ambient,"* J Micromech Microengg 15:1762–1769K., 2005.

[7] Hamid Moeenfard, Mohammad Taghi Ahmadian, and Anooshiravan Farshidianfar, *"Modeling squeezed film air damping in torsional micromirrors using extended Kantorovich method lateral shift,*" Meccanica, 48:791–805, 2013.

[8] Tilmans H A C, "*Equivalent circuit representation of electromechanical transducers: Lumped-parameter systems,* J. Micromech. Microeng. 6 157–76, 1996.

[9] C. Zener, "Internal friction in solids II: General theory of thermoelastic internal friction," *Phys. Rev.*, vol. 53, no. 1, pp. 90–99, Jan.

[10] T.V. Roszhart, *"The effect of thermoelastic internal friction on the Q of micromachined silicon resonators",* Tech. Dig. Solid-State Sens. Actuator Workshop, Hilton Head, SC, 13-16, 1990.

[11] H. Tijdeman "*Energy Dissipation in Thin Air Layers"* ISMA 21 Conference on Noise and vibration Engineering, WB 26/TM 1582, 1996.

[12] T. Veijola, A. Pursula and P. Raback, *"Surface extension model for MEMS squeezed-film dampers"* in Proc. DTIP'05, pp. 235, 2005.

[13] R. Lifshitz and M. L. Roukes, *"Thermoelastic damping in micro- and nanomechanical systems*", Physical review B, Vol. 6, No 8, Feb. 2000, 5600-5609, 2000.

[14] Yusuke Kawai, Jin-Hyeok Kim, "Parametrically Actuated Resonant Micromirror Using Stiffness Tunable Torsional Springs" Sensors and Materials, Vol.28 No.2131-139, 2016.

[15] M. Gologanu, C.G. Bostan, V. Avramescu, O. Buiu, **"***Damping Effects in MEMS Resonators",* Sensors and Wireless Lab Bucharest (SWLB), IEEE Conference, pp: 67-74,2012.

Resmi R received B.Tech Degree in Electronics Engineering from Cochin University of Science and Technology, India in 2000 and M Tech. Degree from Kerala University in 2011.She is currently working as an Assistant Professor in LBS Institute of Technology for Women, Kerala, India. Her research interests include RF MEMS Resonators and Energy Dissipation in MEMS components. She is pursuing her PhD in Kerala University.