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REVIEW PAPER

Radio Frequency Microelectromechanical Systems in Defence and Aerospace

D.V.K. Sastry

Research Centre Imarat, Hyderabad-500 060

ABSTRACT

For all onboard systems applications, it is important to have very low-loss characteristics and low power consumption coupled with size reduction. The controls and instrumentation in defence and aerospace continually calls for newer technologies and developments. One such technology showing remarkable potential over the years is radio frequency microelectromechanical systems (RF MEMS) which have already made their presence felt prominently by offering replacement in radar and communication systems with high quality factors and precise tunability. The RF MEMS components have emerged as potential candidates for defence and aerospace applications. The core theme of this paper is to drive home the fact that the limitations faced by the current RF devices can be overcome by the flexibility and better device performance characteristics of RF MEMS components, which ultimately propagate the device level benefits to the final system to attain the unprecedented levels of performance.

Keywords: RF MEMS, microsystems, MEMS in defence, MEMS in aerospace, instrumentation, RF systems, micromechanical components

1. INTRODUCTION

Presently, microelectromechanical systems (MEMS) are gaining lot of popularity from industries, defence, and aerospace sectors due to the advantage of size reduction without compromising on the system performance[1-3]. In the modern communication arena, there is a need to have a technology solution that can push the operating frequencies higher, provide larger bandwidths, and handle multiple broad band signals, all within the same device. Today, radio frequency microelectromechanical system (RF MEMS) technology is rapidly advancing, offering solutions to these challenges. The most widely recognised advantages are low loss, high isolation, near-perfect linearity, and large instantaneous bandwidth that conventional mechanical and semiconductor technologies fail to offer. Broadly, the applications in the field of defence fall in the categories of communication, phased array radars, and reconfigurable antennas. In addition to strategic sector applications, RF MEMS technological solutions are being sought in high volume in areas like automotive and mobile phone applications.

The basic blocks of RF MEMS systems are the micromechanical components like tunable capacitors, high quality inductors, microresonators, high performance filters and switches which have the potential to replace the conventional discrete components. These devices are fabricated using MEMS structures like cantilevers, air bridges, membranes and inter-digital structures. This paper reviews the importance of RF MEMS, their salient features, and possible applications.

2. RADIO FREQUENCY MICROELECTRO-MECHANICAL SYSTEMS

The wide application spectrum of RF MEMS devices[4] classified as per the application domain is shown in Fig. 1. The popular RF transceiver architecture has been in existence since second world war largely due to its uncomplicated design methodology. The transceiver architecture is divided into three main blocks, the RF front-end block consisting of antenna, single-pole double- throw switch (SPDT), high performing band-pass filter, RF amplifier, voltage controlled oscillator (VCO)[5], mixer, IF filter block and base band block, where analog-to-digital signal conversion takes place. While a lot of technological evolution has helped in the integration of millions of transistors without significant

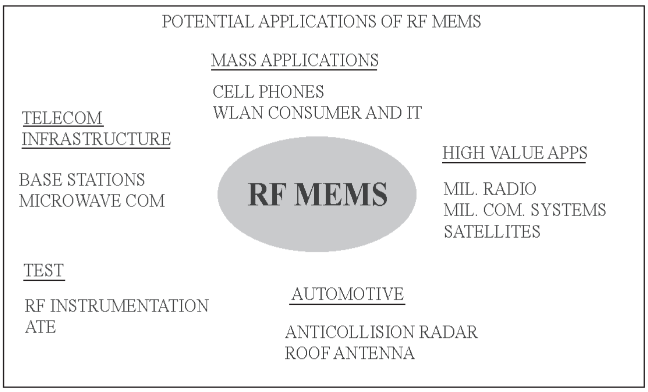

Figure 1. Application spectrum of RF MEMS devices.

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increase in digital block size, the RF front end still continues to rely on discrete, bulky off-chip components that interface with the digital block at PCB level. In essence, these off-chip components are becoming bottleneck for system-level miniaturisation. The search for technological solutions that offer miniaturisation of off-chip components without compromising on the performance continues. After years of effort, it now appears that the RF MEMS can offer solutions to the system-level challenges presented by transceivers.

The RF MEMS provide components with reduced size and weight, very low loss, low power consumption, wide bandwidth, higher linearity, lower phase noise, better phase stability and high isolation. Wherever the application demands these features, MEMS can be conceptualised to provide solutions to replace either components or circuits or the subsystems employing the components.

There are a variety of RF MEMS components which are either used directly for replacement or integrated to form a microsystem along with other semiconductor devices. The components can also go along with silicon technology or *GaAs* technology and the MEMS components can be integrated to provide a system solution. The limitations faced by the normal RF integrated devices can be overcome by the flexibility and better device performance characteristics of RF MEMS components, which ultimately propagate the device level benefits to the system to attain the unprecedented levels of performance. The component level to system level development of a typical communication system using RF MEMS devices is shown in Fig. 2.

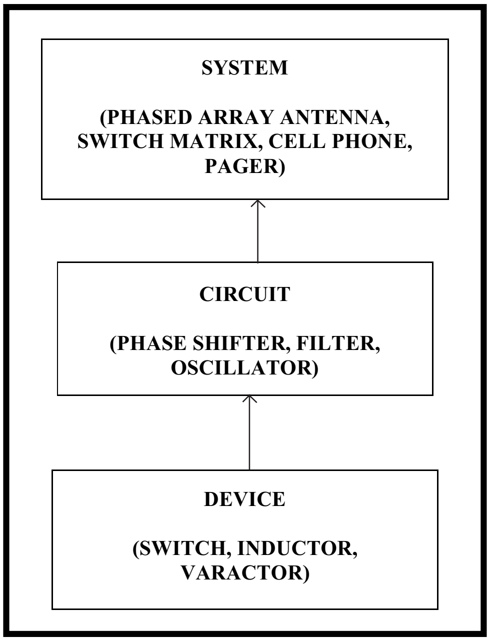

Figure 2. Schematic of RF MEMS system flow.

2.1 Radio Frequency Microelectromechanical Systems Components

The probable candidates which can give leverage over the conventional components in terms of high quality, low power consumption and wider operational frequency range are the tunable capacitors, high Q inductors, high performance filters, oscillators and mixers (Table 1). These components can be fabricated either by way of pre-CMOS or post-CMOS approaches to integrate the MEMS components on the same wafer.

One of the key advantages offered by MEMS is the precision tunability and the tuning ratio where in the conventional components fall apart[6]. This provides the ability to fine tune the circuits to the best optimum level and achieve the highest performance. Re-configurability is another desirable feature used to reconfigure the same antennas for various frequencies without shifting from one antenna to another. This helps in faster scanning and better directivity of the antennas. The switches, which are characterized by very low loss, low actuation voltages and better reliability are widely used for reconfiguring the antennas, routing networks, tunable filters, etc. The RF MEMS devices have extremely high linearity, which means that these create less harmonics and this feature makes them excellent candidates for broad band communication system applications, especially needing high dynamic range of operation.

2.1.1 Tunable Capacitors

The standard semiconductor IC technology can provide a fixed capacitance with a sandwiched dielectric layer between two conductive electrodes In this case, the parasitic capacitance and the series resistance will result in losses and reduction

Table 1. Classification of radio frequency microelectromechanical systems devices as per the application domain

Devices	Wireless	WLAN	GPS	Instrumentation	RFID	Radar	Missiles
Switch	***	***	**	***	**	***	***
MEMS Inductors	**	**	***				
Tunable Capacitors		**	**		**	***	***
Resonators		***	***	***	*	***	**
T-Lines						**	
MEMTENNA					*	***	**
Phase shifter						***	***
VCOS				***			**

Requirement: * ‘medium’, ** ‘large’, *** ‘very large’ in quality factor. Requirement for achieving very high capacitances also demands a very large chip area. The off-chip components provide better solution where in high dielectric materials can be used to achieve better values of capacitance.

Tunability of the capacitors is required in some of the analog circuits like voltage controlled oscillators and tuning circuits which are normally met using reverse-biased semiconductor *p-n* diode junction. However the semiconductor varactor diodes suffer from nonlinearity and losses, thus not very suitable for applications involving stringent requirements imposed by defence and aerospace applications. The micromachined tunable capacitors meet the requirements to a great extent.

The tunable capacitors can be realised either by surface micromachining or by bulk micromachining. However the surface micromachined capacitors[7,8] are simple and basically implemented by having a bottom electrode on the substrate and a suspended electrode on the top with an air gap. The tunability is achieved by the displacement of the top membrane by applying an electrostatic force between the two plates. The top membrane is suspended by means of meander beams which act like springs and provide the deflection. The tuning range, tuning voltage, quality factor, and self-resonant frequency are the factors to be considered during the design. Various configurations of micromachined tunable capacitors are shown in Fig. 3.

Tunable capacitors are made either using suspended membranes with meander[9] anchors to provide better spring constant, and thereby, low actuation voltage requirement. Various configurations of meander lines like single, double beams are used depending on the other dimensions of the structures.

Alternatively, the bulk micromachined interdigitated structure or comb structures are also used to achieve good tunable capacitors. The SEM photograph of an interdigital varactor is shown in Fig. 4. In this configuration, a spring supports a set of movable fingers that mesh with a set of stationary fingers. When a dc voltage is applied, the electrostatic force attracts the movable fingers to increase

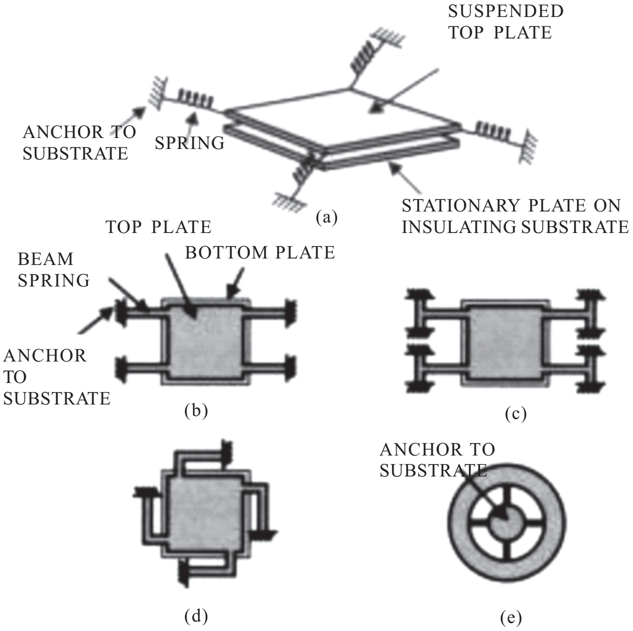

Figure 3. Surface micromachined tunable capacitors: (a) basic scheme, (b) top view of straight springs, (c) top view of 'T' shaped springs, (d) top view of 'L' shaped springs, and (e) top view of centre-anchored design.

the length of overlap and thus the capacitance between the fingers. The capacitance scales linearly with the number of fingers and finger thickness and is inversely proportional to the gap. Obtaining perfectly parallel fingers of the comb and release of the comb structure are the critical issues in realising the high quality device. The DRIE process is used to achieve high aspect ratio trenches which give raise to large capacitance per unit area. The process flow of DRIE is shown in Fig. 5.

The tunability is achieved by varying the bias voltage which results in the reduction of the gap between the top membrane and the bottom electrode or the gap between the two fingers in the case of IDT. The tunability ratio and the nominal capacitance are to be optimised during the design taking into account specific requirement. For very

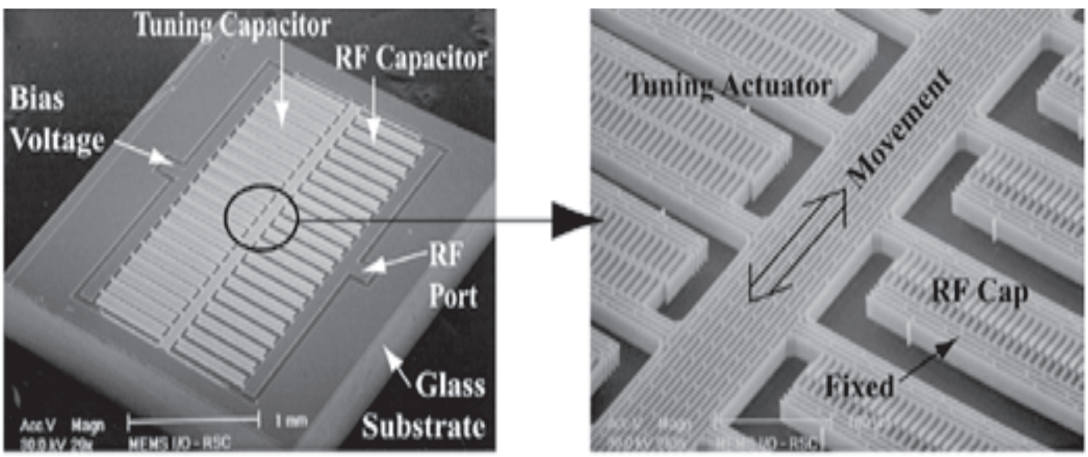

Figure 4. SEM picture of inter-digital varactor

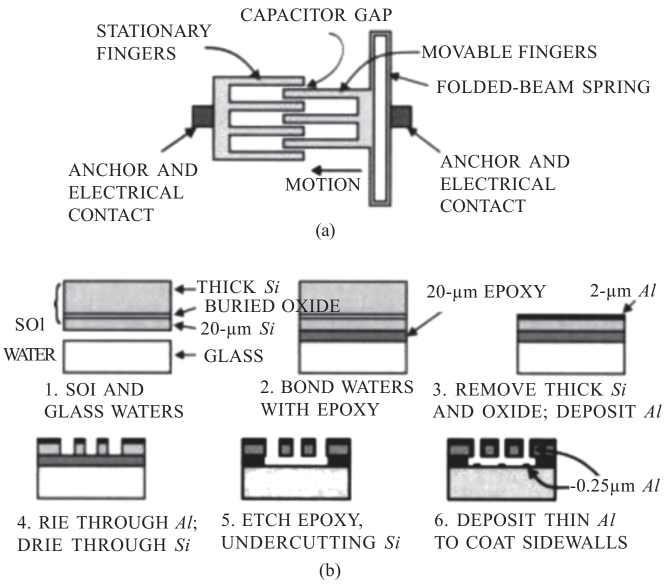

Figure 5. (a) Inter-digital structure (comb type) and (b) fabrication process flow.

high capacitance values, a suitable dielectric with high dielectric constant can be employed in the place of air between the two plates. The parasitic capacitance can be lowered and Q can be increased by changing the low resistivity substrate like silicon to high-resistivity material like quartz.

Another characteristic common to all the devices having mass and spring structures is the influence of external forces, such as acceleration and vibration which induce movement on the flexible membranes and causing corresponding change in capacitance. This result in noise and the allowed changes are application dependent.

For the sake of better damping, perforation is provided in the top electrode which also aids to remove the sacrificial layer conveniently during the process.

2.1.2 RF MEMS Switches

The RF MEMS switches have immense potential in consumer electronics, communication, defence and aerospace. The applications include phase shifters, switchable capacitors, tunable filters, switch matrix for routing and phased array antennas[10-13]. Ideally, switches are the components whose job is to perform signal routing without causing any power loss to signal. The MEMS switches have many potential applications in electronics. The desirable parameters in RF switches are low insertion loss and return loss in the closed state, high isolation in the open state, high linearity, high power handling capability during switching, low operating voltages, high reliability, small size, and low cost. The concept of switch mechanism is illustrated in Fig. 6: (a) in the open state, metal line acts as a waveguide with the sides being ground and the signal propagating down the centre line, and (b) in the closed state, application of a dc voltage pulls the top ground membrane to short the signal line. If there is a dielectric layer, the impedance is low only at high frequency.

There are different configurations in RF MEMS switches depending on the application requirements. Normally a series ohmic switch is used while transmitting the RF signals in the frequencies dc to few GHz. For higher frequencies, the ideal solution is to use a shunt switch which provides very good isolation[14]. Some times, the combination of these switches are conveniently used to meet wider bandwidth of operation. The key parameters considered while designing a switch are the losses, switching speeds, actuation voltages, RF power handling, and life cycles. Though various actuation mechanisms are available for actuating the MEMS membranes/ bridges/ cantilevers, the widely used mechanism in switches is the electrostatic actuation where the potential is applied between the two electrodes to bring in the displacement of the free beam. Most of these switches have a membrane or a cantilever containing one contact which is suspended over the substrate supporting another contact.

The low actuation voltages are desired, though it is a trade-off between the actuation voltage and the speed. A dielectric layer on the bottom electrode serves to cause electrostatic force to pull down the top beam. The RF MEMS switches are supposed to give better RF characteristics compared to conventional silicon *p-i-n* diodes or *GaAs* FETs and traditional relays, in terms of losses, isolation, and return loss. This makes routing of RF signals possible with much lower loss, giving RF systems better noise figure and sensitivity. The insertion loss will be affected by mismatch which comes from the beam's characteristic impedance being different from 50 Ω as well as conductor losses of the beam and dielectric losses. The isolation, on the other hand, will be affected by the beam to substrate separation that defines the 'OFF' state parasitic capacitance. The parameters, i.e., the beam to substrate separation, beam stiffness (spring constant), actuation voltage, dielectric thickness, switching speed are inter related and needs to be optimised to achieve the most desired operational parameter.

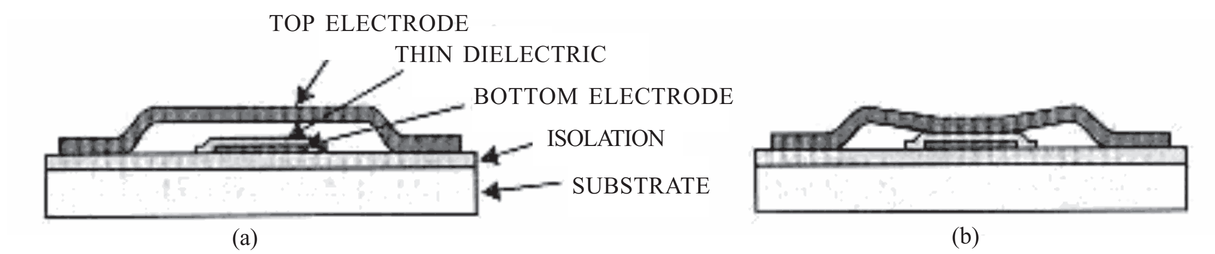

Figure 6. Illustration of a membrane switch in: (a) open state and (b) close state.

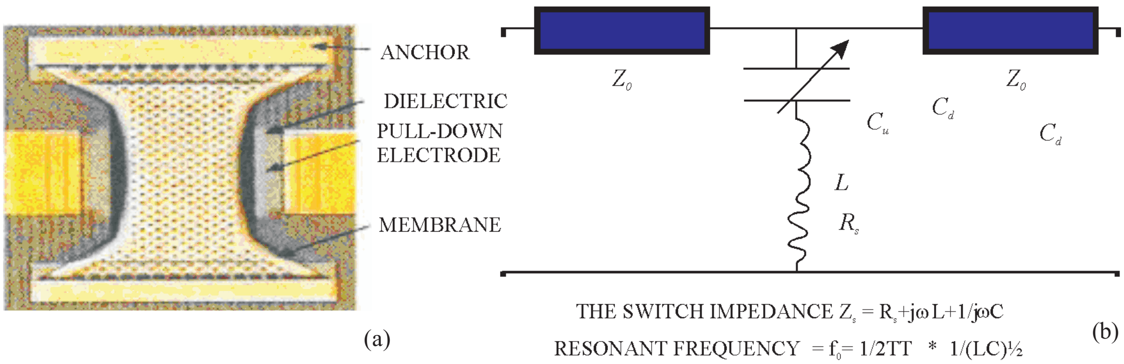

Figure 7. (a) Top view and (b) equivalent circuit of the RF MEMS switch.

A trade-off exists between the actuation voltage and the resonant frequency for improved device performance, as low switching voltage implies low switching speeds. Also, the voltage and speed depend on switch dimensions. The voltage and resonant frequency depend inversely on the beam length. The voltage can be reduced by reducing the gap between the electrodes, but the constraint is that the off state parasitic capacitance becomes high as the gap is reduced.

A detailed study on RF MEMS switches has been done at Research Centre Imarat (RCI) in designing various configurations. The RF MEMS switches in ohmic configuration were designed in the frequency range dc- 7 GHz. Various configurations were tried and with different beam lengths (450-540 µm) keeping the beam width (50 µm) and thickness (1.5 µm) constant. The schematic cross-sectional view of different shunt switch configurations (single actuation pad, double actuation pad, and common actuation and transmission line) are shown in Fig. 8(a) wheras the 3-D model of the series, shunt, and combination of series and shunt switches is shown in Fig. 8(b).

The insertion loss, return loss, and isolation were simulated using HFSS. The modal analysis was carried in the mechanical domain using Coventorware software and the resonant frequencies were studied for different modes which falls around 12-20 KHz for different structures. Electromechanical analysis was performed and the pull-in and contact voltages were obtained. The switches were optimised to work with actuation voltages of <15V. The summary of the simulation results carried out at RCI is shown in Tables 3(a)and 3(b).

2.1.3 *MEMS Inductors*

Inductors are the key elements determining the performance of the tuned circuits, in particular impedance-matching networks, low-noise amplifiers and voltage-controlled oscillators (VCOs). MEMS variable inductors find wide applications in the RF MEMS-based communication systems. The large parasitics associated with normal on chip planar inductors contributing to their lower quality factor *Q* can be eliminated by employing the micromachined inductors which lay above the substrate. The VCOs are potential candidates wherein MEMS inductors find place along with the tunable capacitors. In normal planar

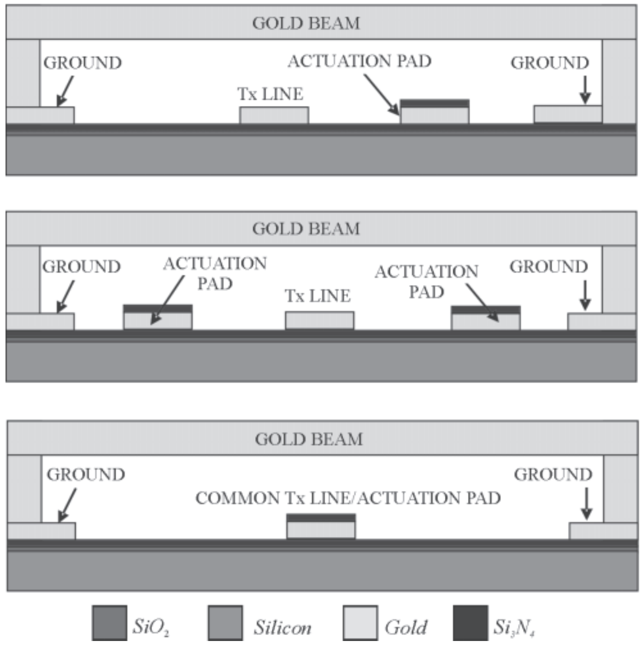

Figure 8. (a) Cross-sectional view of three types of shunt switch configurations.

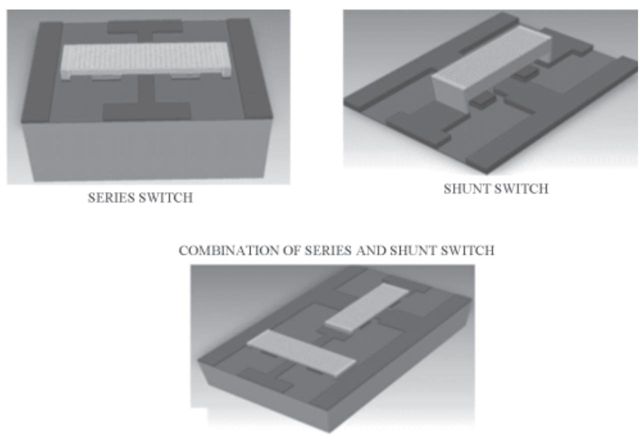

Figure 8. (b) 3-D pictures of switch structures.

Table 2. Performance comparison of switches

Switch type	Isolation	Insertion loss	Power handling	Power consumption	Switching speed
p-i-n diodes	Medium	Medium	Medium	High	Medium
GaAs FETs	Medium	Medium	Low	Medium	High
MEMS switch	High	High	Medium	Low	Low

Table 3(a). Summary of switch simulation results in electromechanical domain

Switch configuration	Suspended bridge dimensions (μm) (l x w x th)	Pull-in voltage (V)	Contact voltage (V)	C_{down} / C_{on}
Asymmetric	540 x 50 x 1.5	5.0	5.5	35.2
	450 x 50 x 1.5	12.0	12.5	
Symmetric	540 x 50 x 1.5	5.25	5.5	35.2
	450 x 50 x 1.5	8.75	9.0	
Common RF / actuation pad	540 x 50 x 1.5	3.0	6.25	41.25
	450 x 50 x 1.5	5.0	7.5	

Table 3(b). Summary of switch simulation results in RF domain

Switch configuration	Suspended bridge dimensions (μm) (l x w x th)	Frequency range (8 – 26 GHz) (dB)		
		Insertion	Isolation	Return loss
Asymmetric	540 x 50 x 1.5	-0.09 – -0.16	-31.24 – -23.85	-20.49 –-19.74
	450 x 50 x 1.5	-0.09 – -0.21	-32.10 – -24.47	-19.52 – -18.01
Symmetric	540 x 50 x 1.5	-0.02 – -0.17	-31.44 – -21.65	-33.93 – -27.61
	450 x 50 x 1.5	-0.02 – -0.22	-32.13 – -21.65	-32.07 – -28.86
Common RF / actuation pad	540 x 50 x 1.5	-0.05 – -0.36	-26.17 – -20.00	-24.62 – -12.24
	450 x 50 x 1.5	-0.05 – -0.34	-27.60 – -20.60	-25.46 – -12.75

inductor, the resistive metal lines and the dielectric losses in the substrate, contribute for the degradation of the Q factor and also cause fringing and parasitic capacitances. The micromachined inductors with suspended metal structures offer very high Q factor resulting in high frequency performance of the systems.

The inductors can be designed in two configurations either suspended spiral or as a solenoid as shown in Fig. 9. The inductor consists of a planar spiral made in one layer of metal and a connection to the center of the spiral in another layer of metal[14]. In both the configurations, the dielectric losses due to the substrate as well as the parasitic capacitances and fringing due to the metal lines in the substrate can be avoided by suspending the structure over the substrate. In the case of solenoid, the magnetic field cannot be strictly confined in the solenoid due to small dimensions and there will be fringing magnetic fields in the substrate which induces eddy currents, leading to more losses The suspended spiral overcomes this as the metal spiral is suspended over the substrate at a reasonable height so that there cannot be any fringing effect giving rise to losses. Another way of reducing the effect of fringing is using a very high resistive silicon substrate (20000 Ω-cm). Micro machined inductors are used in low-noise oscillators, high-gain amplifiers, and matching networks. The nominal inductances will be around few nH and the Q factors around 20-30 are achieved using MEMS inductors.

2.1.4 MEMS Resonators

Quartz is very commonly used in most of the electrical resonant circuits as the integrated electronic oscillators cannot reach the quality factors that matches quartz, which is necessary for the stable operation of frequency in selective communication systems. When one takes the normal electrical

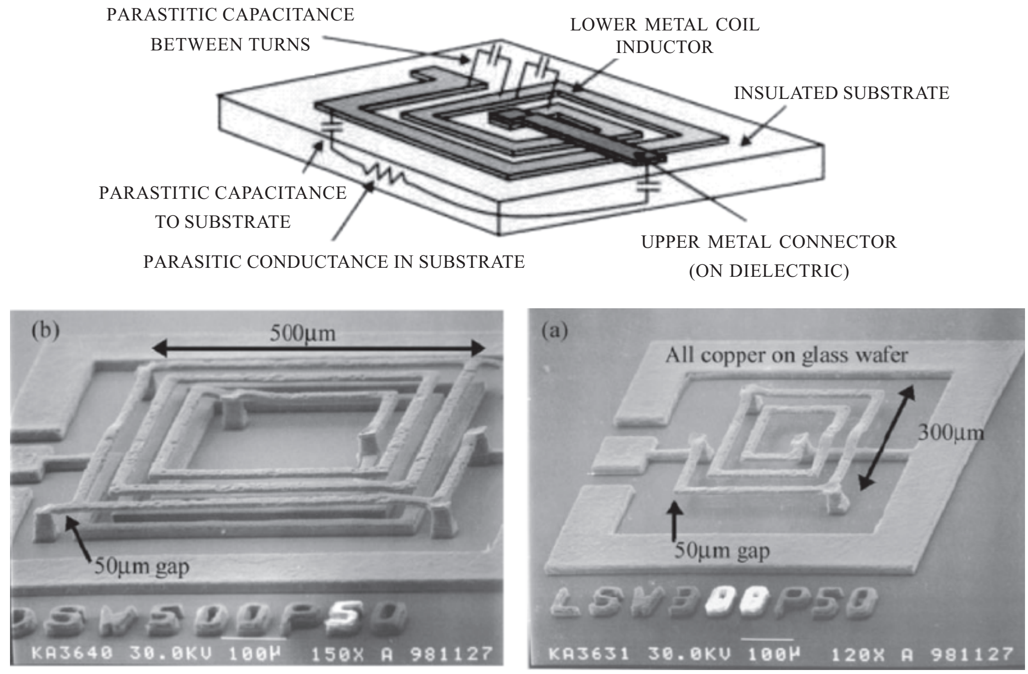

Figure 9. Planar on-chip inductor with parasitic noted.

RLC circuits, the quality factor is limited to < 100 because of the parasitic resistive losses in the circuit. This has also an impact on the insertion losses due to which the signal suffers an undesirable attenuation. The micromachined resonators with Q factors much above 1000 over a wide range of tunable frequencies when used in conjunction with the integrated electronics will result in highly stable communication system. The frequencies of interest cover the range between 800 MHz and 2.5 GHz for front-end wireless reception as well as the intermediate frequencies at 455 KHz and above.

The bulk cavity resonators exhibit a very high Q exceeding 10,000. However, dimensions are very large especially in the low frequency range up to few hundreds of MHz. The micromachined resonators[15-19] can be realised in dimensions that are order of magnitude smaller than cavity resonators, at the same time, meeting the high quality requirements in addition to low loss and high linearity.

There are two types of MEMS resonators, one with the vertical excitation using cantilever beams and the other with lateral excitation using comb like structures. The inter-digitated-finger comb drive structures shown in Fig. 10 are commonly used in many of the devices. The applied voltage generates electrostatic force between the left anchor comb and the shuttle comb and pulls the shuttle plate to the left varying the overlap area resulting in a change in

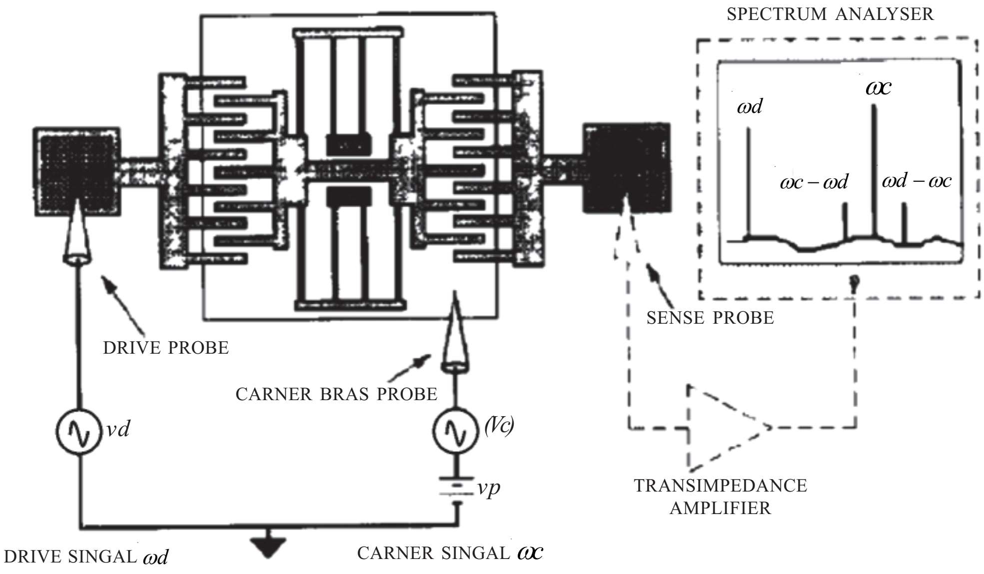

Figure 10. Illustration of comb resonator structure.

capacitance. But both these suffer from the limitation of operational frequency which can be extended only up to few hundreds of MHz only.

The limitation in this comb structure is that the self-resonant frequency is restricted and related to spring constant and motional mass. The spring constant can be increased to some extent by changing the dimensions of the beam width (increase) and the beam length (decrease). The resonant frequency can also be increased using materials with high stiffness-to-mass ratio, such as aluminum, titanium or may be silicon carbide.

Another class of resonators is the beam resonator with higher self-resonant frequency achieved through bulk micromachining. This type of resonators can give higher self-resonant frequencies, better linearity in frequency variation with temperature and smaller size. A simple beam resonator is shown in Fig. 11. When a dc voltage is applied between the beam and the underlying drive electrode, the centre of the beam deflects downward and the capacitance between the flexible beam and the drive electrode varies with the deflection.

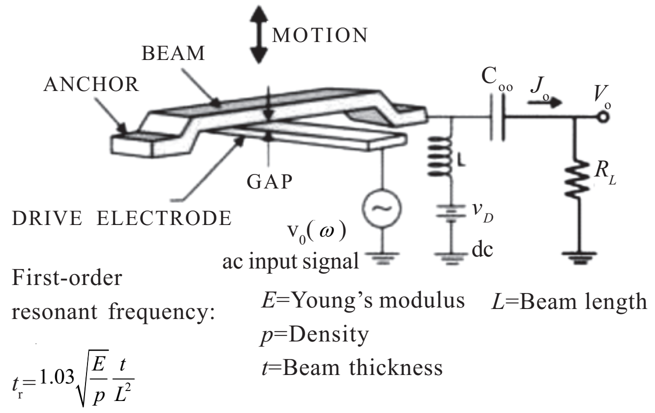

Figure 11. Illustration of transverse resonator structure.

Both the above configurations have the limitation to achieve higher frequencies. For applications requiring higher frequencies, that is up to few GHz, the film bulk acoustic resonator (FBAR) offers better solution. An FBAR basically consists of a thin layer of piezoelectric material, sandwiched between two electrodes. An alternating electrical potential is applied to its surfaces. Depending on the electric field and polarisation of piezoelectric layer, the thickness of the stack will change and an acoustic wave is generated in the bulk of the film. At certain frequencies, the piezoelectric layer will show resonating behaviour similar to that of the quartz material and can be used for oscillator/filter applications. This type of resonators can go upto 2 GHz with quality factors reaching over 1000.

2.2 RF MEMS Subsystems

Various subsystems have been conceived using the RF MEMS components with superior performance characteristics which cumulatively leads to the higher performance of the system. These MEMS components can be put as drop in replacement in the system or can be made an integral part of the system by fabricating the components on the same wafer. Whatever may be the approach, the systems are going to derive the benefits of these MEMS components and a number of applications are envisaged using this technology. A few applications which have a great impact on defence and aerospace are phase shifters, transreceivers, and antennas.

2.2.1 Phase Shifters

A phase shifter is a two port network, wherein the phase difference between output and input signal can be controlled by a control signal, usually dc bias. Phase shifters with low insertion loss, low drive power, continuous tunability and low production cost are the key to the development of light weight phased array antennas. The phased array antennas are widely used for telecommunications and Radar applications serving both the civilian and military needs. Presently the phase shifters are based on ferrite materials, *p-i-n* diodes or FET switches providing a good planar solution for application in microwave frequencies (However they introduce high losses which are undesirable while conceiving strategic systems).

There are two approaches to realise the MEMS phase shifters, one with switched line and the other with distributed MEMS transmission line (DMTL). The phase shifter[20-22] with switched line approach has MEMS switches in the configuration which when selectively actuated results in desired phase shift while the DMTL phase shifter can be optimised to achieve low insertion loss over a wide frequency band. The phase shifters based on RF MEMS switches results in substantial reduction in losses than their solid state counter parts. This is highly favored for systems meant for onboard applications where in the power demand is a constraint. The reduction in losses reduces the demand for the MW power and thereby reduces the size apart from offering better performance. This means that one can eliminate an amplifier stage in the Tx/Rx chain. Though this may not be an issue for ground based systems, for airborne systems and space based systems this is definitely a big advantage. The well established approach is to simply replace the solid state switches with MEMS switches.

The phase shifters are designed using the delay lines and the MEMS switches to introduce the desired delay by correspondingly activating the relevant switches in the

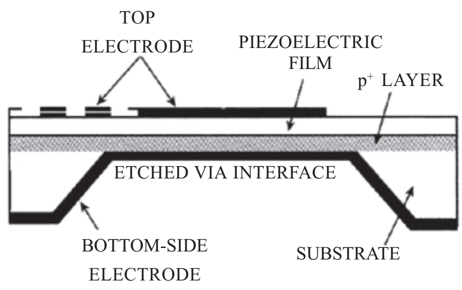

Figure 12. Cross-sectional view of film bulk acoustic resonator structure.

transmission line. The number of bits depend on the resolution required and no. of steps required which will be achieved by different combinations of the delay bits. For example, a 3-bit phase shifter is based on the 45/90/180 set of delay networks and can provide phase shifts of 0º, 45º, 90º, 135º, 180º, 225º, 270º, and 315º depending on the combination of bits used. The scanning resolution and side lobe levels of a phased array antenna is directly related to the number of bits employed. High performance systems may require higher number of bits like a 5-bit or 6-bit phase shifters. The insertion loss, linearity, phase accuracy and band width requirements are taken into account while designing the device. Figure 13 shows a 5-bit phase shifter designed by authors laboratory to achieve a 360º phase shift in 32 steps. The frequency of operation is in Ku band.

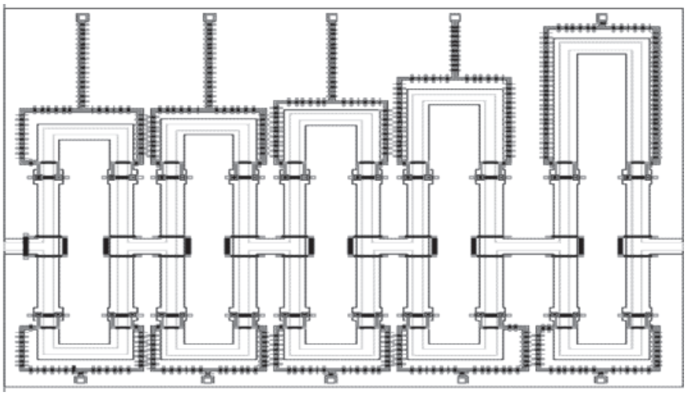

Figure 13. Switched line phase shifter.

The MEMS switches are used in each segment of the delay line and are actuated separately by providing dc bias. The effect of MEMS switches in phase shifter design is that they result in lower loss phase shifters at any frequency especially from 8 GHz to 100 GHz. Also since MEMS switches have very small up-state capacitances, they result in wider band performance than similar designs using solid state devices. The switches are shunt switches designed and optimized for best RF properties, which cumulatively contributes for the overall phase shifter performance. Finally, MEMS switches can be fabricated directly with the antenna element on ceramic, quartz, or teflon-based substrates, thereby resulting in low-cost phased arrays.

The switched path phase shifters are inherently digitally switchable with only a finite number of discrete states and become cumbersome with increasing switched paths.

Distributed MEMS transmission line (DMTL) is another approach to realise a phase shifter where in the transmission line is capacitively loaded periodically with MEMS bridges along the line and the phase velocity and phase shift can be varied accordingly. The gap between the air bridge and the bottom T line can be varied by applying electrostatic force. By controlling the bridge height, the distributed capacitance on the T line, phase velocity and phase shift can be varied and a phase shift of 0-360^0 can be achieved. Here, the phase can varied continually (analog) and is more rugged than switch based .They offer very wideband performance and can work well at very high frequencies (W band and beyond). This type of phase shifter can be used to continuously vary the phase shift depending on the phase shift per unit length.

The phase shifters find application in telecommunication and military radars. Our interest in phase shifters stems from its application for the electronically scanable antennas which can replace the conventional mechanically steered antennas. They have very broad applicability for both commercial and military applications including advanced military radars, satellite communication, cellular base stations and automotive anticollision radars. Electronically scanned phased array antennas have many benefits over its mechanical counterpart in terms of faster scanning rates, reduced mechanical complexity, ability to host multiple antenna beams on the same array, wider operational frequency apart from higher reliability.

The phase shifters are highly potential devices and these are extensively used in phased array antennas in defence for a variety of applications like smart munitions, missile communication, drones, missile radar seekers, aircraft and helicopters, ground electronic steerable antennas (ESA).The requirement runs into few millions over the few years when this is fully exploited for the defence applications.

2.2.2 RF MEMS Transceiver

Another possible application of RF MEMS is their implementation in transceivers in wireless systems[23]. The demand for portable wireless systems with more functionality is facilitating rapid growth in the technology to come out with newer devices with greater functional density and with integratability into the system. RF MEMS have made their impact with their potential in transceivers associated with very low power consumption, high quality factor, and size reduction. Infact, applications like personal communication systems (PCS), wireless networking, radars are being fully exploited by MEMS to reduce the parts count, power consumption, and lighter weight coupled with superior RF performance. Several types of RF MEMS devices such as switches, variable capacitors (varactors), inductors, and filters, have been developed and the technology is maturing to the

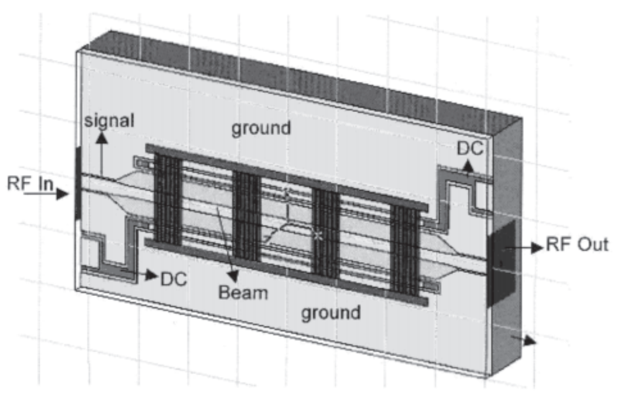

Figure 14. 3-D view of designed DMTL phase shifter at RCI.

level of deployment in commercial systems. Though these RF MEMS devices can be developed as discrete components, using many RF devices will increase the size of RF transceivers. Another problem is related to packaging. These RF devices containing movable parts have to be individually packaged which will result in the increase of overall size. The solution to exploit fully the benefit of RF MEMS is to go for the integrated RF MEMS on a single wafer and wafer level encapsulation process can be used for the packaging in an optimum size. The configuration for integrated RF MEMS technology is conceptually shown in Fig. 15.

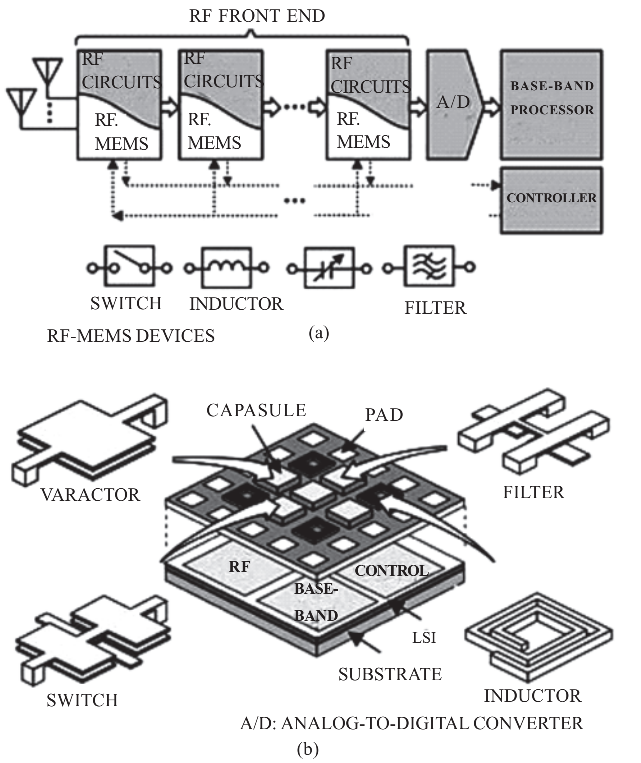

Figure 15. Conceptual design of integrated RF MEMS front-end receiver.

This configuration reduces the volume consumed by discrete packaging of the devices and allows the use of a lot of devices without increasing the number of off-chip components. RF MEMS devices such as switches with movable parts are protected by a device scale capsule to prevent their destruction during packaging. This technology will lead to the fusion of RF-MEMS and circuit technologies and to the development of single-chip reconfigurable RF transceivers.

The general block diagram of transceiver for RF communication indicating the possible application of RF MEMS components is shown in Fig. 16. This will result in systems with better RF performance, multi-band communicability, smaller size and with lower power consumption. The focus on this technology is primarily because of its large potential in future mobile communication enabling the device to carry out multifunctions.

3. RF MEMS PACKAGING

Packaging of MEMS is another critical bottleneck area

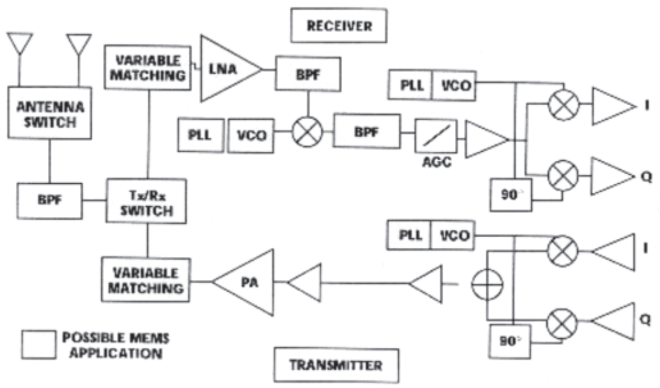

Figure 16. Conventional receiver architecture indicating the possible MEMS application.

in the realisation of MEMS product. Unlike the case of ICs, MEMS are sensitive to environmental conditions. The free-standing structures are fragile and must be properly encapsulated. An effective package protects the movable structure as well as prevent particles and contaminants from hindering their operation. The purpose of the package is to protect the device from all aspects of environment while interfering with the device performance in minimal way. For RF devices, it means the package needs to be invisible in the desired signal path (low insertion loss), be opaque to RF in every other possible signal path (good isolation, low cross-talk), defend the device from internal and external heat problems(including solderability, temperature cycling, power handling, etc.), defend it from environmental problems (fatigue, shock, vibration) and defend the device from internal and external contamination (hermiticity, gettering, etc.). In some cases, it also calls for vacuum sealing as the air causes viscous damping leading to reduction of Q factor in RF MEMS components. The package aspects are designed to ensure RF performance and at the same time provide the levels of operational characteristics like life time, repeatability, reliability, and ruggedness which are points of high concern for military and space applications.

In addition to ensuring of unwanted resonances and electromagnetic interference and coupling, RF MEMS packaging techniques aim at preventing moisture and particulates, which may impair the movement of freestanding MEMS structures, leading to change in resonant frequencies and more losses.

4. RELIABILITY OF MEMS

Reliability of MEMS is still a topic of concern, especially while conceiving systems for defence and aerospace applications. There are no uniform standards established for MEMS as the scenario is complex than the integrated circuit systems. This is because each device is unique in its nature and needs to employ separate procedures. In MEMS various materials, fabrication methods, process techniques are employed which are specific for each device and also these devices are sensitive to environmental parameters like moisture, contamination, gases, radiation, vibration etc making it more complex to evolve uniform qualification procedures.

The devices involve various moving parts, rubbing surfaces, impacting surfaces, which lead to various failure mechanisms. The failure also occurs due to stress, strain, and fatigue mechanisms of thin films which can be attributed to the type of deposition method and materials used. The accelerated life testing is tedious in MEMS unlike in other electronic systems where thermally activated process is used solely. In addition to mechanical failures , MEMS also suffers electronic failures due to micromechanical structures performing the electronic functions. The failure modes include short and open circuits, arcing across the small gaps, ESD, dielectric charging and corrosion. Presently the reliability and quality procedures are evolved for each device depending on the application environment and specific to the user.

5. CONCLUSIONS

The RF MEMS is poised to bring out a significant change in the field of communication in the years to come. The defence and aerospace has enormous potential for this technology in military communication, radar communication, phased array antennas, and instrumentation. With the upcoming national programms like micro-vehicles, pico-satellites, precision guided munitions, missile clusters, hit-to-kill weapons. RF MEMS will be a dominant technology playing a significant role in these programms. A trememndous amount of work is going on all over the globe , and more so, due to their potential for strategic applications in defence sector. A broad outline of RF MEMS brought out in this paper will show the prominence of this technology which should be exploited for implementation in our future programms. The final products that envisaged for defence systems are micromechanical resonators, MEMS inductors, BAW resonators, switches, tunable capacitors, micro-machined antennas, electronically scanned antennas, transceivers and MW transmission lines in the frequency range starting from dc to 90 GHz (the frequency range varies for different types of components).

Considerable research and development work is going on at RCI in collaboration with academic institutes like IISc, IIT (M), IIT (D) and with other centres like CEERI, Pilani, SCL, Chandigarh, and BEL, Bangalore for the development of MEMS-based RF devices.

REFERENCES

1. Yao, J.J. RF MEMS from a device perspective. *J. Micromech. Microeng.*, 2000, **10**, R9-R38.
2. De Los Santos, H.J. Introduction to microelectromechanical (MEM) microwave systems. Artech House, Norwood, MA,1999.
3. Pamidighantam, Sayanu. RFMEMS. Encyclopedia of Sensors, ASP, 2005.
4. Lucyszyn, S. Review of radio frequency microelectromechanical systems technology. *IEE Proc. Sci. Meas. Techn.*, 2004, **151**(2), 93-103.
5. Dec, A. & Suyama, K. Microwave MEMS based voltage-controlled oscillators. *IEEE Trans. Microwave Theo. Techn.,* 2000, **48**(11), 1943-949.
6. Dec, A. & Suyama, K. Micromachined electromechanically tunable capacitors and their application to ICs. *IEEE Trans. Microwave Theo. Techn.*, 1998, **46**(12), 2587-506.
7. Young, D.J. & Boser, B.E. A micromachined variable capacitorfor monolithic low Noise VCOs. Solid-state Sensors and Actuator Workshop, Technical Digest, Hilton Head, NC, June 1996. pp. 86-89.
8. Yao, J.J.; Park, S. & Denatale, J. High tuning ratio MEMS based tunable capacitors for RF communications applications. Solid-state Sensors and Actuator Workshop, Technical Digest, Hilton Head, SC, June 1998. pp.124-27.
9. Yao, J.J., *et al*. A low power/low voltage electrostatic actuator for RF MEMS applications. Solid-state Sensors and Actuator Workshop (Technical Digest), Hilton Head, SC, June 2000, pp. 246-49.
10. Brown, E.R. RF-MEMS switches for reconfigurable integrated circuits, *IEEE Trans. Microwave Theo. Techn.*, 1998, **46** (11), 1868-880.
11. Danson, J.; Plett, C. & Tait, N. Design and characterisation of a capacitive switch for improved RF amplifier circuits. *In* Proceedings of IEEE Custom Integrated circuits, Sept. 2005. pp. 251-54.
12. Pothier, A., *et al*. Low-loss 2 bit tunable band pass filter using MEMS DC contact switches. *IEEE Trans. Microwave Theo. Techn.,* 2005, **53**(1), 354-60.
13. Lacroix, B., *et al*. Sub-microsecond RF MEMS switched capacitors. *IEEE Trans. Microwave Theo. Techn.,* 2007, **55**(6), 1314-321.
14. Madim, Maluf; & Kirt, Williams. An introduction to microelectromechanical systems engineering, Ed. 2. Artech House, Inc, 2004.
15. Muldavin, J.B. & Rebeiz, G.M. High-isolation CPW MEMS shunt switches-Part 1: Modelling. *IEEE Trans. Microwave Theo. Techn.,* 2000, **48**(6), 1045-052.
16. Bannon, F.D.; Clark, J.R. & Nguyen, C.T.C. High-Q HF microelectromechanical filters. *IEEE J. Solid-state Circ.*, 2000, **35**(4), 512-26.
17. Wang, K.;Wong, A.C. & Nguyen, C.T.C. VHF free-free beam high-Q micromechanical resonators. *J. Microelectromechanical Sys.*, 2000, **9**(3), 347-60.
18. Hsu, W.T. & Nguyen, C.T.C. Stiff compensated temperature-insensitive micromechanical resonators. 15th IEEE Conference on Micro Electro Mechanical Systems, Technical Digest, Las Vegas, NV, 2002. pp. 731-34.
19. Mercier, D. & Blomdy, P. Millimeter-wave tune-all band pass filters. *IEEE Trans. Microwave Theo. Techn.*, 2004, **52**(4), 1175-181.
20. Nguyen, C.T.C. & Howe, R.T. Quality factor control for micromechanical resonators. International Electron Devices Meeting, Technical Digest, San Francisco, CA, 1992, pp.505-08.
21. Rabeiz, G.M.; Tan, G.L. & Hayden, J.S. RF MEMS phase shifters: Design and applications. *IEEE Microwave,*

2002, **3**(2), 72-81.
22. Barker, N.S. & Rabeiz, G.M. Optimisation of distributed MEMS transmission-line phase shifters-U band and W band designs. *IEEE Trans. Microwave Theo. Techn.*, 2000, **48**, 1957-966.
23. Nagra, A.S. & York, R.A. Distributed analog phase shifters with low insertion loss. *IEEE Trans. Microwave Theo. Techn.*, 1999, **47**, 1705-711.
24. Abidi, Asad A.; Pottie, Gregory J. & Kauser, Williams J. Power-conscious design of wireless circuits and systems. *Proceedings IEEE,* 2000, **88**(10).

Contributor

Dr D.V.K. Sastry obtained his PhD in semiconducting thin films and their characterisation, from S.V. University, Tirupati, Andhra Pradesh, in 1981. He joined Defence Research and Development Organisation as a Scientist in 1984. Presently, he is working as the Group Director, Microsystems Laboratory, Research Centre Imarat, Hyderabad, and is involved in the development of RF MEMS devices and circuits for radar and communication systems. His areas of research are: Development of hybrid microwave integrated circuits, polymer thin films, plasma treatment of polymers for improving adhesion, and electro-optical sensors.