CHAPTER 1

INTRODUCTION

In this chapter the recent progress of RF MEMS phase shifters for space, military and communication applications has been reported. The advantage of RF MEMS over conventional technology has been discussed. The distributed MEMS transmission line (DMTL) is broadly studied due to its outstanding performance in the millimeter-wave frequency range.

1 General Introduction

In the developing world of technology it is essential to have low consumption of available resources and energy, highly efficient, highly reliable with better performance. For such systems, micro-electro-mechanical-systems (MEMS) bring out the solution with small, high power efficient, reliable actuators and systems. MEMS technology is the miniaturization of mechanical and electro-mechanical elements, fabricated using compatible IC-fabrication technique and can be classified into various sub-areas like, RF MEMS (Radio Frequency MEMS), BIOMEMS (Biological MEMS), NEMS (Nano-Electro-Mechanical -Systems) and MOEMS (Micro-Opto-Electro-Mechanical-Systems) etc.

RF MEMS offers advanced attributes of semiconductor in terms of low insertion loss, low DC power consumption, high linearity which makes them potential contender for hand-held devices, satellite as well as military applications [1]. So far there are only three generic types of RF MEMS components ever been reported: (i) switch (ii) variable capacitor (iii) antenna [2]. However, the main component among all is the switch because of large number of applications such as circuits (e.g. phase shifter, attenuators impedance tuner, filters etc) and subsystems (e.g. redundancy switch network for signal routing). For commercialization of MEMS
switches, it is necessary to have a product with high reliability and better performance.

MEMS devices use similar semiconductor processing technologies to fabricate 3-Dimensional (3D) mechanical structures. In Bulk micromachining, 3D devices are defined by selectively etching of silicon substrate whereas in surface micromachining, devices are crafted by deposition, patterning and etching of thin films on substrate.

RF MEMS switch or varactor is the basic building block for RF MEMS phase shifter, has superior dominating properties of both mechanical and semiconductor switches in terms of RF performance i.e. low insertion loss, better isolation, nearly perfect linearity. Larger the capacitance ratio \( \frac{C_{\text{down}}}{C_{\text{up}}} \) better is the RF performance. The RF switches are typically used for communication applications with frequency range 0.1 to 100 GHz. The switches are further categorized based on the frequency e.g. ohmic contact switches (DC - 10 GHz) and capacitive contact switches (above 10 GHz). In ohmic contact switches a metal armature makes contact with the transmission line in order to pass the RF signal from input to output. In capacitive switches, metal armature is pulled down onto a dielectric layer to form a capacitor. At high frequencies, capacitor acts like a short circuit. Further ohmic and capacitive contact switches can be categorized in terms of armature placement (series or shunt), actuation mechanisms and armature movement (broad-line and in-line). Like other switches, MEMS switches also have two stable states. Switching between these two states can be achieved through various actuation techniques, including thermal, piezoelectric, electrostatic and magnetostatic. Electrostatic actuation technique is often preferred for mechanical movement due to almost zero power consumption, small electrode dimensions, ease of fabrication and better compatibility with IC fabrication techniques.

The phase shifter is basically a circuit which allows the tuning or control of signal's phase angle. The difference in phase angle between the input (incident) and output (reflected or transmitted) signals in single state, is expressed by the insertion
phase angle, \( \phi \) [2]. This phase angle is a function of gap between the capacitor plates, which is changed by actuating a fixed – fixed suspended beam through external DC bias. Hence, *relative phase shift*, \( \Delta \phi \), is defined as the difference between two insertion phase angles, such that \( \Delta \phi = \phi_2 - \phi_1 \). An important application of phase shifter is in phased-array antennas, where up to several thousand radiating elements are assembled, each having signals that are controlled in both amplitude and phase angle [3-5]. To date, this technology has been essentially confined to military and space communication and radar applications because of the high cost of such complex subsystems. Phase shifters are also being employed in new reconfigurable antenna architecture, currently under development. Other applications of phase shifters include RF and microwave measurement instrumentation and small-shift frequency translators [2].

1.1 RF MEMS over Conventional Technology

The advantage of RF MEMS over conventional technology has been discussed; addressing fabrication compatibility, RF performance, miniaturization, low-cost etc. The fundamental unit cell of phase shifter i.e. switch is also reviewed in brief for research as well as application prospect. The electrical performance of RF MEMS phase shifter is compared with commercially available phase shifters. The distributed MEMS transmission line (DMTL) has been discussed and also its two working modes: *Analog and Digital* are explored and analyzed in detail for reliability point of view.

1.1.1 Fundamental unit cell: Switch

The conventional microwave switches such as mechanical and semiconductor switches are presently occupied in the microwave industry [1]. Mechanical coaxial switches offer benefit of low insertion loss but are bulky and occupy large area. In contrast, semiconductor switches for example FET and p-i-n diodes afford considerably faster switching speed and are much smaller in size. However, they
have low-grade insertion loss, isolation and power handling than mechanical switches.

The major advantage of semiconductor switches over electromechanical relays is that they have no mechanical movement and which results in no welding of contacts [6]. Even though semiconductor switches are more expensive than electromechanical relays. Thus they find application where product lifetime is more important than manufacturing cost i.e. motor vehicles, industrial automation, etc. Beside this semiconductor switches have drawback of non-linearity. As reported in article [6], radar as well as communication systems demand for high linearity where semiconductor switches could not impart as a potential candidate.

On the other side, MEMS switches demonstrate ultra-low loss and thus challenging the present technology: GaAs or silicon based for analog switching. The performance is defined by a figure of merit (FOM) which is a function of the on-state resistance and off-state capacitance [2]. Unlike semiconductor switches, MEMS switches are perfectly linear because they do not contain junction [7].

MEMS switches show low switching speed (i.e. microseconds) as compared to the semiconductor devices (i.e. nanoseconds). However, semiconductor switches introduce a large amount of RF losses. Jorge et al. [8] illustrated monolithic GaAs based SPST switch with insertion loss of -1.7 dB and an isolation -50 dB at 2 GHz. Danny et al. [9] demonstrated GaAs Ku-band monolithic SPDT FET switch with -1.4 dB insertion loss and -18 dB isolation over 14 to 18 GHz. Large number of papers addressing RF MEMS switches with low losses and zero power consumption have been reported in literature: LG Korea [10-11] demonstrated capacitive switch with insertion loss of -0.08 dB at 10 GHz and isolation of -42 dB, DTIP [12] has developed switch with insertion loss of -0.65 dB and isolation of -25 dB at 24 GHz, Raytheon [14] has developed shunt capacitive switch with insertion loss and isolation of -0.07 dB (10-40 GHz) and -35 dB (at 30 GHz), respectively. University of Michigan [15] has developed low actuation voltage capacitive switch with an isolation of -25 dB (at 30 GHz) and an insertion loss of -0.1 dB (1 - 40 GHz),
Rangra et al. [13] have fabricated symmetric toggle switch with insertion loss and isolation -0.25 dB and -35 dB, respectively for 10 GHz etc. The major advantage of MEMS devices over PIN diode and FETs is that they exhibit extremely low resistance i.e. 0.1 to 0.3 Ω instead of 2 to 6 Ω, also they consumes almost zero power consumption in the order of μW as compared to mW [7]. MEMS switches can be utilized in phase shifters which results in better performance with low losses for any frequency range, especially from 8-120 GHz [16].

1.1.2 Phase Shifter

Electronically variable phase shifters are crucial components in wireless, radar and satellite broadband communication systems and can be controlled electrically, magnetically or mechanically [7]. Phase shifters based on semiconductor technology have been extensively used in modern phased array systems [17]. However, they have high loss even which are commercially available: around -8 to -9 dB at 35 GHz [17] and -4 to -6 dB at 12-18 GHz [17], analog phase shifter shows -8 dB up to 10 GHz and -4 dB over 10 to 18 GHz [18], 8-bit phase shifter shows -18 dB over 2 to 18 GHz [19] by planar monolithic industries, digital phase shifter by SAGE millimeter exhibits -9 dB over 6 to 18 GHz [20].

MEMS technology based phase shifters have higher linearity over a wide frequency range, low insertion loss, and zero power consumption compared to semiconductor technology. On the other side ferrite based phase shifters show better performance from 3 GHz to 60 GHz [7], but cannot be easily incorporated and are more expensive to manufacture than MEMS technology [21]. Also ferrite phase shifters are slower than MEMS phase shifters [22].

Phase Shifter based on RF MEMS switches or varactors have been widely studied since 1990s because of the strong necessity of these circuits in modern phased-array antennas and dramatic improvements in the performance that can be carried by RF MEMS technology [2]. The reduction in losses within phased-array antennas, such as those used in military radars, has a strong impact on the power consumption and cost of such system. Future applications in the commercial domain (e.g. automotive
radars and wireless communications) depend on the progress in reliability and cost reduction [2]. The main types of phase shifters comprise of:

- **Reflect-Line**
- **Switched Line**
- **Distributed MEMS Transmission Line (DMTL) phase shifters**

The RF MEMS DMTL phase shifter lure ever more attention because of its better properties such as small size (in millimeter), compact, low insertion loss, low power dissipation and wide-frequency range characteristics [21].

The next section discusses two common types of millimeter-wave MEMS phase shifters: (a) MEMS-switched-line true-time delay (TTD) phase shifter [25], and (b) distributed MEMS transmission line (DMTL) phase shifter [23].

1.1.2.1 MEMS-Switched-line True-Time Delay (TTD) phase shifter

MEMS switched line TTD phase shifters comprise of numerous unit cells (designed for specific phase shift) in a cascade arrangement. For desired phase shift, particular RF MEMS switch should be in on-state in order to transmit signal in transmission line. In switched line phase shifter, RF MEMS switches are required to provide connection between different transmission lines. This phase shifter possesses all the benefits of RF MEMS capacitive switches. However, switched line phase shifters are not appropriate for millimeter wave frequencies for example U-band, because essential lengths of the transmission line deteriorate performance [21].

M.C. Scardelleti, et al. [26] have described 1-bit Ka-band MEMS TTD phase shifters using SPDT switches. Stehle et al. [27] have explained a 3-bit switched line phase shifter that comprises of unit cells of 45 °, 90 ° and 180 °, with the return and insertion loss of -12 dB and -5.7 dB at 76.5 GHz respectively. B. Lakshminarayanan et al. [25] have illustrated the phase shifter with an insertion
loss of nearly -2.65 dB, measured ΔΩ/ΔB (phase shift/loss) of 150 °/dB, and return loss better -19 dB at maximum frequency of 110 GHz.

1.1.2.2 Distributed MEMS Transmission Line (DMTL) Phase shifter

The DMTL phase shifter is designed by periodically loaded transmission line with MEMS varactors [28]. On applying a bias voltage, capacitance is varied and thus the propagation coefficient of the transmission line and the signal phase angle between the input and output of the phase shifter are changed. The transmission line impedance is changed by varying the capacitance of the line which results in change in the phase velocity [29].

As compared to switched line phase shifter, DMTL phase shifters usually have outstanding performance in the millimeter-wave frequency range [21]. Transmission line can be loaded in two ways:

- **Analog**: where air gap is varied between MEMS bridge and transmission line
- **Digital**: where on-off states have been occurred due to discrete capacitor placed in series with bridge capacitor.

Higher capacitance ratio can be achieved by digital phase shifter and thus more suitable in the millimeter-wave frequency range [29].

1.1.2.2.1 Analog Phase Shifter

Analog DMTL phase shifter is defined by two varying states as shown in Fig. 1.1. For commercial applications, large phase shift with minimum loss is desired. Reliability of phase shifter plays an important role in the commercialization which is a strong function of number of MEMS bridges as well as stability of the MEMS bridge.
The DMTL analog phase shifter has demonstrated by Barker et al. [23] for W-band and U-band on a quartz substrate. The W-band DMTL phase shifter comprised of large number of MEMS bridge: 48 which are placed at a gap of 200 µm. The capacitance ratio of 1.15 was achieved at a pull-down voltage of 26 V. The measured phase shift/decibel loss, insertion, and return loss have been 70 °/dB (75 to 110 GHz), -2.5 dB, -11 dB at 94 GHz, respectively. Later various research groups developed phase shifters for phased array antenna applications. W. Palei et al. [30] have demonstrated MEMS TTD phase shifter for Ku band with 11 bridges, placed at 800 µm spacing. The measured phase shift was 150 °, return loss: -15 dB and an average insertion loss: -2 dB. W. Palei et al. [31] have presented five various designs for TTD phase shifter that have been based on unloaded line impedance of 70, 65 and 50 Ω, which have been loaded periodically with shunt capacitive switches. The TTD phase shifter has been fabricated on 675 µm high resistivity silicon substrate using surface micromachining techniques. The design has been operated up to Ku band with measured $S_{11}$ below -15 dB and average loss of -2.3 dB/phase shift of 250 ° at 20 GHz. N. Scott. Barker [32] has developed true-time delay DMTL phase shifter for phased array application on quartz substrate for 0-60 GHz under an applied voltage of 0-22 V. The measured results have been 2 dB/118 ° phase shift at 60 GHz and -1.8 dB/84 ° phase shift at 40 GHz. The MEMS bridge becomes unstable at $g_0/3$ from zero bias state as shown in Fig. 1.1. The phase shifter starts work as wide band switch at pull-down voltage of 23 V with -40 dB isolation and -2 dB
insertion loss at 60 GHz. However, instability is a major issue for commercialization.

Pull-in voltage is given by Eq. 1.1

$$V_p = \sqrt{\frac{8kg_0^3}{27\varepsilon_0 A}}$$

where $V_p$, $k$, $g_0$, $\varepsilon_0$, and $A$ are pull-down voltage, spring constant of bridge, gap between bridge and transmission line, vacuum permittivity and overlap area between bridge and transmission line, respectively.

**Paola Farinelli et al.** [33] have presented a new concept of phase shifter with wide tuning range. The measured S-parameters of MEMS varactor have been -25 dB return loss and -0.2 dB insertion loss up to 20 GHz. The novel concept of pull-out electrodes has been first introduced by **Rangra et al.** in RF MEMS toggle type switches [13]. Incorporation of outer electrodes improves the insertion loss by increasing the gap between the transmission line and suspended bridge in on state and also resolved the problem of stiction in down state. The above concept has been adopted by several other research groups to improve performance of phase shifter. **S. Dey et al.** [34] have presented 114°/dB FOM over 0-40 GHz frequency band on alumina substrate. Analog phase shifter has contributed continuous phase shift of 0°-360° over 0-40 GHz with minimum 8.1 V actuation voltage with 11 bridges. Total occupied area is of 8.5x1 mm². The aim is to accomplish large phase shift by achieving large tuning range. **Greg McFeters et al.** [35] have demonstrated phase shifter which was based on two techniques: distributed capacitance transmission line phase shifter and large tuning range RF MEMS capacitor. The phase shifter has been designed using 17 MEMS bridges which were spaced at a spacing of 300 µm. The measured results have indicated 170°/dB phase shift with insertion and return loss of -1.8 dB and -10 dB, respectively. **Amrita et al.** [36] have discussed design, fabrication and characterization of unit cell of phase shifter. The measured results of unit cell are 15° phase shift with return and insertion loss of -15 dB and -1.8 dB, respectively at 15 GHz. However, the design and fabrication of phase shifter have not been reported in this paper. **Pandey et al.** [37] have presented a novel approach
in order to resolve instability of MEMS bridge as well as increasing the phase shift by incorporating stoppers. The optimization of unit cell and design of phase shifter using 6 MEMS bridges for Ku band application has been presented in this paper. The simulated results are 88.63 ° of phase shift at 17 GHz with insertion and return loss of -1.75 dB and -20.49 dB, respectively. The simulated results have been verified with analytical modelling.

1.1.2.2.2 Digital Phase Shifter

*Figure-Of-Merit (FOM)* is defined as maximum phase shift with minimum loss. For phase shifter, FOM primarily depends upon capacitance ratio \( C_r \) as shown in Eq.1.2.

\[
\nabla \phi = \omega \sqrt{L_u C_u} \left( \sqrt{1 + \frac{L_{Lu}}{sC_u}} - \sqrt{1 + \frac{C_r C_{Lu}}{sC_u}} \right) \text{deg/ meter},
\]

where \( L_u, C_u, s, \) and \( C_{Lu} \) are the inductance and capacitance per unit length of the unloaded co-planar waveguide (CPW), spacing between bridges and loaded line up-state capacitance, respectively [28]. Another way to attain a large capacitance ratio, \( C_r \), using digital approach [28], in which fixed capacitor are placed in series combination with MEMS bridges as shown in Fig. 1.2. The fixed capacitors can be employed using:

*Metal-insulator-metal (MIM) capacitors in Co-Planar Waveguide (CPW) design*

The phase shifter is realized by two states (on and off state) of the MEMS bridge which is actuated by dc bias as shown in Fig. 1.2.
The load capacitance $C_l$ seen by the transmission line is the series combination of the suspended bridge capacitance $C_b$ and the total fixed capacitance $C_s$ and is

$$C_l = \frac{C_s C_b}{C_b + C_s} \quad \text{(1.3)}$$

Under zero bias voltage, MEMS bridge will be in upstate position, then the bridge capacitance $C_{bu}$ will be in limit and smaller than $C_s$ and the effective capacitance seen by line will be $C_{tu} \approx C_{bu}$. When bias voltage is applied, MEMS bridge comes in down state position, now the bridge downstate capacitance $C_{bd}$ becomes much larger than $C_s$, and the total capacitance will be $C_{td} = C_s$. In maximum designs, $C_{bu} \approx C_s/4$ to $C_s$ [28]. $L_t$ and $C_t$ are the inductance and capacitance per unit length of the unloaded co-planar waveguide (CPW) as shown in Fig. 1.2 (b).

For higher Q, fixed capacitor can be changed by Metal Air Metal (MAM) capacitors. However, large phase shift cannot be achieved by this approach due to small dielectric constant of air (fixed capacitor: MAM) which results in small capacitance ratio. Nevertheless, losses can be improved using MAM as fixed capacitor.

The instability of analog phase shifter can also be resolved by digital approach. Various research groups have developed multibit DMTL phase shifters. Joseph S. Hayden et al. [38] have demonstrated a novel topology for a digital distributed phase shifter implemented for 10 GHz. The 2-bit phase shifter has been composed of 18 bridges at a spacing of 884 µm. This produced maximum $S_{11}$ of -11 dB and $S_{12}$ of
1.0±0.3 dB at 10 GHz. Hung et al. [39] have discussed design and optimization of a low loss distributed 2-bit W-band DMTL MEMS phase shifter on a glass substrate. The 2-bit phase shifter has been comprised of a 90° section with 8 switches and a 180° sections with 16 switches. Phase shift of 0°, 89.3°, 180.1° and 272° have been measured at 81 GHz with return loss below -11 dB and an average insertion loss was -2.2 dB. Hung et al. [40] have presented design and fabrication of 3-bit DMTL RF MEMS phase shifter on glass substrate using MEMS switch with measured average loss of -2.7 dB at 78 GHz (-0.9 dB/bit) and figure of merit of 93 °/dB-100 °/dB at 75-110 GHz. Yu Liu et al. [41] have demonstrated 3-bit distributed phase shifter for K-band applications. Unit cells of 14 have been used with spacing of 780 µm, total length was 11 mm. The phase shifter has produced phase shift from 0° to 360° (45° phase step) with measured phase error for all switching states was less than 8.5°, an average insertion and return loss of -1.7 dB and -7 dB at 26 GHz, respectively. Joseph S. Hayden et al. [42] have described 2-bit DMTL phase shifter for Ka and X band using MEMS switch and MAM capacitors on quartz substrate. The total occupied area has been 8.4 x 2.1 mm² with 21 sections. The 2-bit Ka band phase shifter has produced return and insertion loss of -11.5 dB and -1.5 dB, respectively. The 2-bit X-band phase shifter has produced phase shifts of 0°, 94°, 176°, and 270° with return loss better than -12.5 dB, insertion loss -1.2 dB and at 13.6 GHz. S. Nagra et al. [24] have presented a 1-bit low loss K/Ka band phase shifter that employed MEMS capacitors. The phase shifter contained of a transmission line length 8.58 mm, loaded periodically with 11 MEMS capacitors at 780 µm spacing. The phase shifter showed a phase shift of 180° with an insertion loss of -1.17 dB at 25 GHz, a phase shift of 270° with an insertion loss of -1.69 dB at 35 GHz and a return loss better than -11 dB over 0-35 GHz frequency range. K. Topalli et al. [43] have demonstrated the phase array sub-system designed at 15 GHz using 3-bit DMTL phase shifter consisting 28 unit cells. The S11 of sub-system has been found better than -20 dB. The total chip size has been about 5.1x5.1 cm² and 3-bit phase shifter consists of 28 unit cells.

The enhancement in the number of MEMS bridges in phase shifter degrades its reliability. MEMtronics developed 3-bit phase shifter for various applications such as: space, low-cost military radar and communication systems. Compact low-loss
phase shifter was designed for Ka band with insertion loss $<-1.5$ dB and return loss $>-18$ dB. MEMtronics [45] also demonstrated 4-bit Ka band phase shifter with 7 MEMS bridges for phased array applications. The chip size was 1.7x5.4 mm$^2$. Smaller number of MEMS bridges leads to better fabrication yield and also consumes less area.

1.2 Objective of Research

The objective of this research work is the “Design and Fabrication of RF MEMS DMTL phase shifter for communication applications”. The analog and digital DMTL phase shifter are designed and fabricated for Ku band applications. Thin films of high-k dielectric material i.e. HfO$_2$ and Ta$_2$O$_5$ have been characterized for RF MEMS devices. The initial specifications include 0 - 90 $^\circ$ phase shift with return loss below -15 dB for working frequency of 17 GHz for analog phase shifter and design of 4-bit DMTL phase shifter. The work presented in this thesis is inspired by ongoing project at CEERI, Pilani. The work was explored under the project entitled “Advanced Microsensors and Microsystems Design Development and Application: RF MEMS switch”, sponsored by CSIR. The objective of this project is to design and develop capacitive switch, ohmic switch. The design, fabrication and characterization of phase shifter was also explored in this project. The fabrication process has been optimized with short loop iterations under the project “Innovative high-k dielectric, reduced size and high speed SPST and SPDT design and development” which was sponsored by NPMASS-ADA (Aeronautical Development Agency). The standard fabrication process of low (SiO$_2$) and high-k (HfO$_2$) dielectric capacitive switch (SPST and SPDT) for X and Ku band, based on electrostatic actuation mechanism using surface micro machining has been optimized under NPMASS project at CEERI. The simulated insertion loss and isolation is -0.08 dB and -45 dB, respectively. The measured actuation voltage is 10-15 V of SiO$_2$ based STS (symmetric toggle switch). Using HfO$_2$ high-k dielectric for capacitive switches, the capacitive area has been reduced to almost 78 % of the dimension of the SiO$_2$ devices, and actuation voltage lies between 5-15 V. The same fabrication process is carried out for RF MEMS phase shifter.
RF MEMS phase shifter has several advantages over other commercially available phase shifters. However, for developing world still it is desirable to explore persisting demerits. The major issues of RF MEMS phase shifters are actuation voltage of MEMS bridge, reliability, instability of analog phase shifter, size, number of MEMS bridges. For electrostatic actuation mechanism: actuation voltage is a function of various parameters such as size of bridge (length, width and thickness), spring constant, gap between transmission line and suspended bridge etc. In Analog DMTL phase shifters, reliability also depends up on the stability of MEMS bridges, as it snaps down at pull-in voltage. Thus, controlling the height of bridge at a particular gap from transmission line is a challenging task.

RF MEMS switches or varactors are the basic building blocks of DMTL RF MEMS Phase Shifter. Thus, the overall performance in terms of degree/dB (figure of merit (FOM)) of phase shifter depends on substrate type, unloaded CPW impedance, unit cell, number of unit cells, and the spacing between them. Hence, it’s desired to optimize single unit cell in order to accomplish maximum phase shift with minimum amount of loss.

The aim of the presented research work is the parametric extraction, optimization of unit cell, designing and fabrication of DMTL phase shifter. First, the parameters will be obtained from analytical modeling part such as unloaded CPW impedance by maintaining the return loss of -15 dB, up-state capacitance, $C_{bu}$, the capacitance ratio, $C_r$, spacing, $s$, bragg frequency, $f_B$. Further, phase shift, insertion loss ($S_{12}$), return loss ($S_{11}$) etc. of designed phase shifter will be simulated on Ansoft HFSS. Simultaneously, mechanical parameters of bridge structure such as pull-in voltage, hysteresis, mechanical resonance frequency, stress etc. will be optimized using Coventor Ware (FEM simulator).

1.2.1 Parametric Optimization

The performance of phase shifter depends upon the parameters such as type to waveguide i.e. CPW or Microstrip, the unloaded line impedance, the underlying
substrate etc. The parametric optimization is necessary in order to achieve better performance of phase shifter.

**Co-Planar Waveguide Vs. Microstrip** A conventional CPW on a dielectric substrate consists of a center conductor with semi-infinite ground planes on both side. The CPW deals numerous benefits over conventional microstrip line:

- CPW simplifies fabrication
- Assists both shunt and series surface mounting of active and passive components [45-49]
- It removes the requirement of via holes [45]
- It moderates radiation loss

Thus, CPW has been selected for designing DMTL phase shifter.

**Co-Planar Waveguide Unloaded Line Impedance and Loss** To design DMTL Phase shifter, unloaded line impedance, $Z_0$, of a CPW is determined using elliptical function, described in Eq. 1.4:

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{eff} K(k)}}$$  \hspace{1cm} 1.4

where effective dielectric constant is defined by assuming half of the fields are present in the air above the thick transmission line and the other half is in the substrate and given by Eq 1.5.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2}$$  \hspace{1cm} 1.5

The elliptical function, $K(k)$, can be given as follows:
where $W$ and $G$ are the width of central transmission line and CPW gap, respectively. Total ground to ground distance, $S=W+2G$ is an important parameter of CPW lines. Practically, the limit for $S$ is $S=\lambda_g/10$ where $\lambda_g$ is the guided wavelength. For a CPW line on Silicon substrate at 17GHz, $S = 511 \mu m$ before the line begins to radiate substantially into substrate.

There are three types of losses:

1. **Conductor loss on the CPW line**
2. **Dielectric loss**
3. **Radiation loss**

Dielectric loss is minimal in quartz substrate as $\tan \delta = 0.0009$: $\alpha_d = 2.73\frac{\tan \delta}{\lambda_0}$ (dB/m). However, it has some significant value in case of silicon substrate ($\tan \delta = 0.015$ at 10GHz). Now, $Z_0$ not only impacts on phase shift per section, but also on the total loss of the DMTL phase shifter. Thus, unloaded line impedance has been optimized in order to achieve maximum amount of phase shift with minimum amount of loss for designed frequency.
**Substrate Selection** There is a trade-off between phase shift and losses. Phase Shift is directly dependent on effective dielectric constant $\varepsilon_{\text{eff}}$ as shown in Eq. 1.9. Hence, a DMTL phase shifter on a Si substrate results in more phase shift/length than on a quartz substrate. However, the transmission line losses/length on silicon are much higher than that of quartz. In this research work, high resistive silicon wafer is preferred due to compatibility with semiconductor fabrication techniques.

\[
\varphi = \frac{\omega Z_0 \sqrt{\varepsilon_{\text{eff}}}}{c} \left[ \frac{1}{Z_{\text{ld}}} - \frac{1}{Z_{\text{lu}}} \right] \text{rad/m} \tag{1.9}
\]

where $Z_{\text{lu}}$ and $Z_{\text{ld}}$ are loaded line impedance in up and down state, respectively.

**Phase shift and loss dependency on movable gap and overlap area** Phase shift increases with large tuning range of MEMS bridge for analog phase shifter. However stability of bridge is challenging task. Large overlap area gives higher phase shift.

1.3 **Structure of Thesis**

This thesis comprises of five chapters. *Chapter 1* presents general introduction of phase shifter for space, military and communication applications. The advantages of RF MEMS technology over conventional technology is focused; addressing fabrication compatibility, RF performance, miniaturization, low-cost etc. The fundamental unit cell of phase shifter i.e. switch is also reviewed in brief for research as well as application prospective. The electrical performance of RF MEMS phase shifter is compared with commercially available phase shifters. The distributed MEMS transmission line (DMTL) is broadly studied due to outstanding performance in the millimeter-wave frequency range. The two working modes of DMTL phase shifter i.e. Analog and Digital are explored and analyzed. The objective of this research work is discussed with key emphasis on RF MEMS phase shifter.
Methodologies, technical and scientific issues are also discussed for application prospect.

Chapter 2 presents design, fabrication and measurement of Analog DMTL phase shifter for Ku band applications. The electrical optimization and selection of substrate for reliable analog phase shifter is discussed which includes substrate dielectric constant, CPW dimensions, capacitance ratio, spacing between MEMS bridges, tuning range etc. The mechanical parameters of bridge i.e. actuation voltage, switching time, resonance frequency, and the most important stability of MEMS bridge is resolved by incorporating stopper in the design. The two proposed device designs of analog phase shifter for Ku band application i.e. initial and final designs, have been presented. The initial design is focused on large phase shift while, the final design focuses more on the reliability point of view as well as low loss. The simulated results are verified with analytical modelling which are in close match. The surface-micromachining based fabrication process which is compatible with IC processing technology, is explained and the issues handled during the process have also been explored. The complete device fabrication process has 8 mask levels. The short loop iterations are performed to optimize each step such as photoresist thickness, thin film thickness and its adhesion to surface, lift off, wet etching, releasing step: sacrificial layer removal etc. The SEM micrograph, optical 3-D profile, mechanical response and RF characterization of analog phase shifter has been discussed.

Chapter 3 discusses design, fabrication and measurement of compact 4-bit DMTL phase shifter for Ku band application. The brief state-of-art and major considerations of reliable digital phase shifter has been discussed. Conventional approach for DMTL based phase shifters is to load CPW transmission line periodically with similar type of MIM capacitors at particular spacing. A novel approach is adapted to reduce the size as well as the number of MEMS bridges by optimizing different unit cells for each section (22.5°, 45°, 90°, 180°) rather than fixed MIM capacitor. Unit cells are optimized with less number of MEMS bridges. The change in mask layout i.e. incorporation of MIM capacitor for digital DMTL phase is discussed. Fabrication
process steps which are similar to analog phase shifter, is briefly discussed for unit cells and 4-bit DMTL phase shifter. The SEM micrograph, optical 3-D profile, mechanical response and RF characterization of all unit cells and 4-bit phase shifter has been discussed.

Chapter 4 discusses high-k dielectric characterization for RF MEMS device i.e. capacitive switches, phase shifters etc. The detailed information of the microstructure and morphology of HfO$_2$ and Ta$_2$O$_5$ thin films are well studied for RF MEMS devices. HfO$_2$ and Ta$_2$O$_5$ thin films, deposited by sputtering technique and further annealed separately at various temperatures (400-1000 ºC) in step of 200 ºC in O$_2$ and N$_2$ ambient for 10 min, have been characterized through X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), Energy dispersive X-ray spectroscopy (EDX), Laser Ellipsometry and Atomic force microscopy (AFM). Structural properties such as crystallite size, phase, orientation, stress were investigated using XRD. Annealing temperature as well as ambient has significant effect on stress, crystal size and thus arrangement of atoms.

Chapter 5 discusses conclusion and future work.

References have been included at the end of each chapter.
1.4 References of Chapter 1


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