LOW VOLTAGE RF MICROELECTRO-MECHANICAL SWITCH USING 0.35 µm MIMOS CMOS COMPATIBLE PROCESS

by

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LIST OF ABBREVIATIONS

MEMS	Micro Electro Mechanical System
IC	Integrated Circuit
RF	Radio Frequency
DARPA	Defense Advanced Research Projects Agency
ATE	Automated Test Equipment
IT	Information Technology
FEM	Finite Element Method
MPW	Multi-Wafer Project
CMOS	Complementary Metal-Oxide Semiconductor
FBAR	Film Bulk Acoustic-Wave Resonator
FET	Field Effect Transistor
HEMT	High Electron Mobility Transistor

GaAs	Gallium Arsenide
CPW	Coplanar Waveguide
STO	Strontium Titanium Oxide
PR	Photo resists
KOH	Potassium Hydroxide
EDP	Ethylenediamine Pyrocatechol
TMAH	Tetramethylammonium Hydroxide
MMIC	Monolithic Microwave Integrated Circuit
TEM	Transverse Electromagnetic Mode
CLR	Capacitor-Inductor-Resistor
PECVD	Plasma-Enhanced Chemical Vapor Deposition
RIE	Reactive Ion Etching
DRIE	Deep Reactive Ion Etching
MDF	Main distribution frames
EDGE	Enhanced Data Rate for GSM Evolution
3G	Third generation
3D	Three dimension
2D	Two dimension
DC	Direct Current
CPW	Coplanar Waveguide
FET	Field Effect Transistor

CLR	Capacitance, inductance & resistance
EM3DS	Electromagnetic 3D simulator
Al	Aluminum
Si	Silicon
Si_3N_4	Silicon nitrite
SiO_2	Silicon dioxide
EDX	Energy Dispersive X-Ray
FIB	Focused Ion Beam

LIST OF SYMBOLS

E	Young's modulus (Pa)
Hz	Hertz
dB	Decibels
π	Piezo-resistive coefficient (Pa)
N	Newton
C_d	Down state capacitance (F)
C_u	Up state capacitance (F)
V_p	Pull down voltage (V)
K_z	Total Spring constant on z-direction (Nm^{-1})
k_z	Spring constant on z-direction (Nm^{-1})
g_0	Initial gap displacement (m)
g	Gap displacement (m)
A	Area (m^2)

ϵ_0	Permittivity of air (C^2/Nm^2)
ϵ_r	Relative permittivity
N	Newton (N)
a	Serpentine primary meander length (m)
b	Serpentine secondary meander length (m)
t	Thickness (m)
t_d	Thickness of dielectric layer (m)
v	Poisson's ratio
G	Sheer modulus (Pa)
W	Width of center conductor (m)
w	Width of membrane (m)
I_x	x-axis moment of inertia (kgm^2)
I_z	z-axis moment of inertia (kgm^2)
I_p	Polar moment of inertia (kgm^2)
J	Torsion constant
Z_s	Switch impedance (Ω)
Z_0	Load impedance (Ω)
R_s	Resistance (Ω)
j	Imaginary number
C	Capacitance (F)
ω	Omega
L	Inductance (H)
f_0	Resonant frequency (Hz)

s	Second
μ	Micro
m	Milli
V	Voltage

SUIS RF MIKROELEKTRO-MEKANIKAL BERVOLTAN RENDAH MENGGUNAKAN PROSES SETARA MIMOS CMOS 0.35 µm

ABSTRAK

Suis RF MEMS bervoltan rendah dan boleh berintegrasi dengan litar lain sangat diperlukan di dalam produk pengguna, sektor industri dan telekomunikasi. Voltan penggerak kurang daripada 10 V dengan proses fabrikasi yang mudah sangat dikehendaki kerana kebanyakan aplikasi memerlukan sistem kuasa rendah dengan kos fabrikasi yang rendah. Sehingga kini, suis RF MEMS yang telah dikomersilkan mempunyai voltan penggerak 90 V menggunakan proses fabrikasi MEMS. Tesis ini membincangkan kerja-kerja yang dilakukan dalam menghasilkan sebuah suis RF MEMS yang bervoltan rendah (<10 V) untuk aplikasi telekomunikasi yang boleh beroperasi pada frekuensi 1 hingga 25 GHz. Simulasi menggunakan peringkat sistem dan peringkat fizikal (Kaedah Unsur Terhingga), Coventor Ware telah digunakan untuk merekabentuk dan membuat simulasi voltan penggerak, kelajuan suis, frekuensi resonan dan histeresis.

Keputusan yang diperolehi daripada kedua-dua kaedah modul perisian tersebut dibandingkan. Prestasi RF suis, kehilangan sisipan dan pemencilan juga disimulasi menggunakan penganalisis elektromagnet, EM3DS. Suis RF MEMS ini difabrikasi menggunakan proses CMOS 0.35μm MIMOS daripada Projek Berbilang-Wafer (MPW). Proses setara CMOS ini sangat mudah dan dipercayai. Pasca-proses seperti punaran basah dilaksanakan untuk membuang lapisan korban (oksida) di bawah logam melalui lubang-lubang kecil pada jambatan untuk mendapatkan struktur jambatan. Keputusannya, voltan penggerak terendah bagi suis yang telah difabrikasi dengan ukuran 2x2-meander dan 4x4-meander masing-masing sebanyak 10.4 V dan 6.0 V. Kehilangan sisipan suis 2x2-meander ialah -6 dB pada 1 GHz atau -18 dB pada 17 GHz sementara pemencilan ialah -22 dB pada 17 GHz. Suis 4x4-meander pula mempunyai kehilangan sisipan sebanyak -12 dB pada 10 GHz manakala pemencilan ialah -21 dB pada 25 GHz dan bertambah baik apabila frekuensi meningkat. Keputusan ini menunjukkan suis-suis tersebut mempunyai voltan penggerak lebih kurang 10 V dan masa penggerak 17 μs dengan prestasi RF yang baik memberi potensi yang tinggi untuk diaplikasikan ke sektor telekomunikasi yang memerlukan operasi kuasa rendah.

LOW VOLTAGE RF MICROELECTRO-MECHANICAL SWITCH USING 0.35 µm MIMOS CMOS COMPATIBLE PROCESS

ABSTRACT

Low voltage RF MEMS switch that can be integrated with other circuits is required in the consumer product, industrial and telecommunication sector. Voltage actuation less than 10 V with simple fabrication process is desirable as most of applications need low power system with low fabrication cost. As for now, commercialized RF MEMS switch has voltage actuation of 90 V using MEMS fabrication process. This thesis describes the work carried out in the development of a low voltage (<10 V) of RF MEMS switch for application of telecommunication which is able to operate at frequency of 1 to 25 GHz. System–level and physical-level (Finite Element Module) simulations, Coventor Ware were used to design and simulate the voltage actuation, switching speed, resonance frequency and hysteresis. Results obtained from the two methods of software modules were compared. The RF performances, insertion loss and isolation were also simulated using the electromagnetic analyzer, EM3DS. The RF MEMS switch is fabricated using 0.35µm MIMOS CMOS Multi-Wafer Project (MPW). This CMOS compatible process is simple and reliable. Post-process which is wet etching was implemented to etch the sacrificial layer (oxide) under the metal through the small holes on the bridge to obtain the bridge structure. As a result, fabricated switch with dimension of 2x2-meander and 4x4-meander have lowest voltage actuation of 10.4 V and 6.0 V, respectively. Insertion loss for switch 2x2-meander is about -6 dB at 1 GHz or -18 dB at 17 GHz while the isolation is -22 dB at 17 GHz. Switch 4x4-meander has insertion loss of -12 dB at 10 GHz which is quite high while the isolation -21 dB at 25 GHz and get better for higher frequencies. These results show the switches have about 10 V of voltage actuation and actuation time about 17 µs with good RF performances would have high potential to be applied in telecommunication sector which require low power operations.

CHAPTER 1

INTRODUCTION

Micro-Electro-Mechanical System (MEMS) is a current research leads to many electronics devices such as accelerometer, Radio Frequency (RF) switch, pressure sensor, gas sensor, micro pump, micro relay, micro mirror, micro nozzle, flow sensor, micro-optics, optical scanner, fluid pump and many more. MEMS are integrated micro devices or systems that integrate electrical and mechanical components together. MEMS are fabricated using MEMS fabrication process and can be fabricated using the established integrated circuit (IC) fabrication techniques. The electronics part can be fabricated using standard IC processing while the micromechanical parts can be fabricated using compatible micromachining processes. MEMS devices can be designed in range of micrometers to millimeters in size and are able to operate in its scale, may function individually or in arrays to generate effects depended on the applications.

1.1 Motivation

MEMS technology market forecast from year 2012 to 2018 is shown in Figure 1.1. The market forecast which published in 2013 (Yole Developpement, 2013), breakdown into different area of MEMS technology. It shows that high growing area of MEMS is microfludics, inertial sensors and pressure sensors. However, RF MEMS also shows significant grow from 2012 to 2018. RF MEMS devices have a great market potential and it have been stated as one of the main MEMS applications.

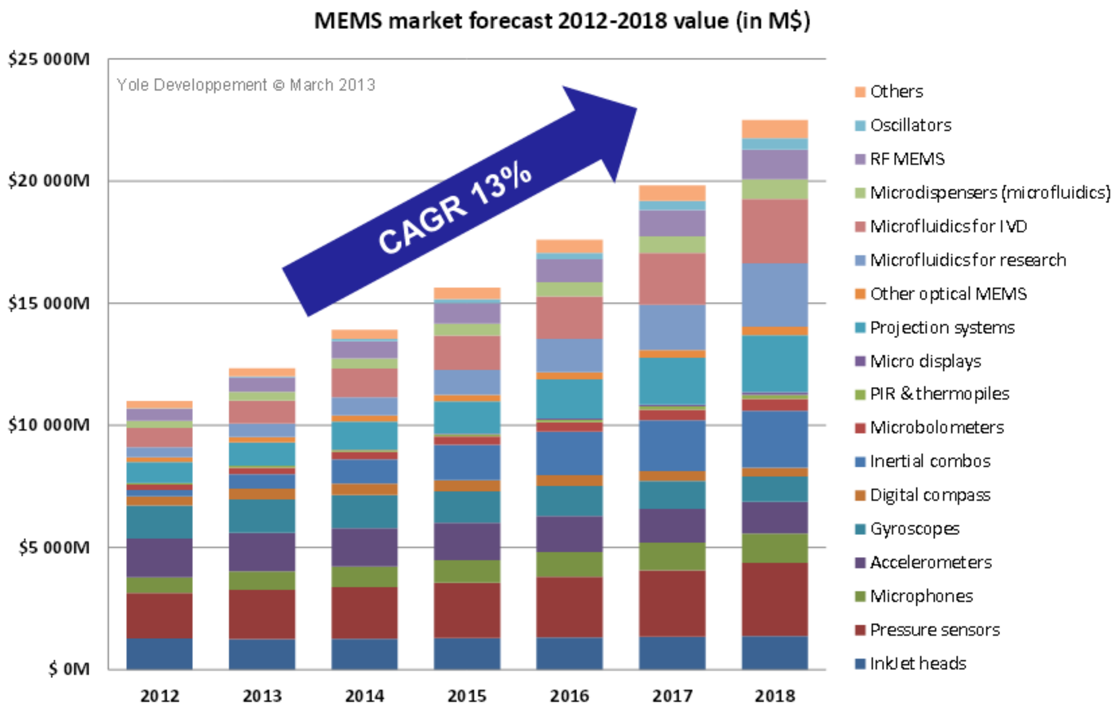

Figure 1.1 MEMS market forecast for 2012-2018 (Yole Developpement, 2013)

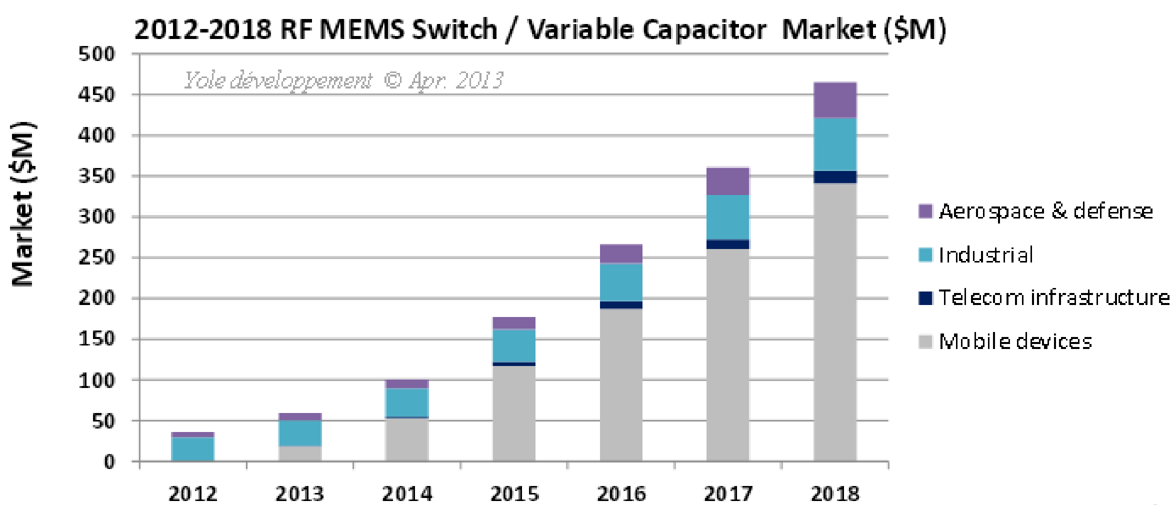

Figure 1.2 RF MEMS switch market forecast for 2012 -2018 (Yole Developpement, 2013)

Figure 1.2 shows the market value of RF MEMS switch with breakdown into different applications from 2012 to 2018 (Yole Developpement, 2013). The expected applications are mobile devices, telecom infrastructure, industrial, aerospace and defense. From the prediction, RF MEMS switches are mostly used for mobile devices purposes such as mobile and smart phones. In the area of telecom infrastructure, MEMS switches can be used in wire line telecom switching matrices even though the switches are no longer classified as RF as they operate in MHz range. In defense applications, the developments of RF MEMS switches are mainly on phase array antennas for communication and radar (Bouchaud and Knoblic, 2007). Figure 1.3 shows the market value of RF MEMS switches and varactors from 2006 to 2014 (Bouchaud, 2010).

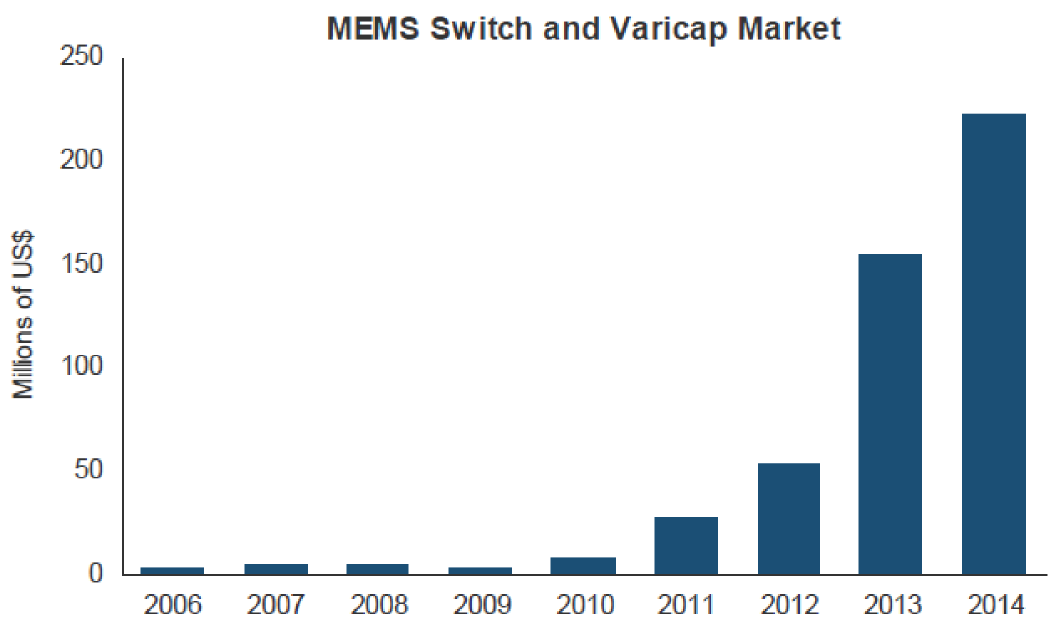

Figure 1.3 RF MEMS switches and varactors market forecast for 2006-2014 (Bouchaud, 2010)

1.2 RF MEMS Switch

Switch is one of the RF MEMS devices that been studied until present. RF MEMS switch has great potential and ability to be embedded in low and medium power applications as replacements for current switching technology, and the potential to create highly flexible RF systems. RF MEMS switches are already shipping to or poised to grow into five distinct applications types as listed and shown in Figure 1.4.

- High value applications – satellites, military tactical radio, military phased array
- Test equipment – RF instrumentation, automated test equipment (ATE)
- Telecom infrastructure – base stations, microwave communications
- Mass applications – mobile phones, consumer electronics, and IT
- Automotive – anti-collision radar, roof antenna

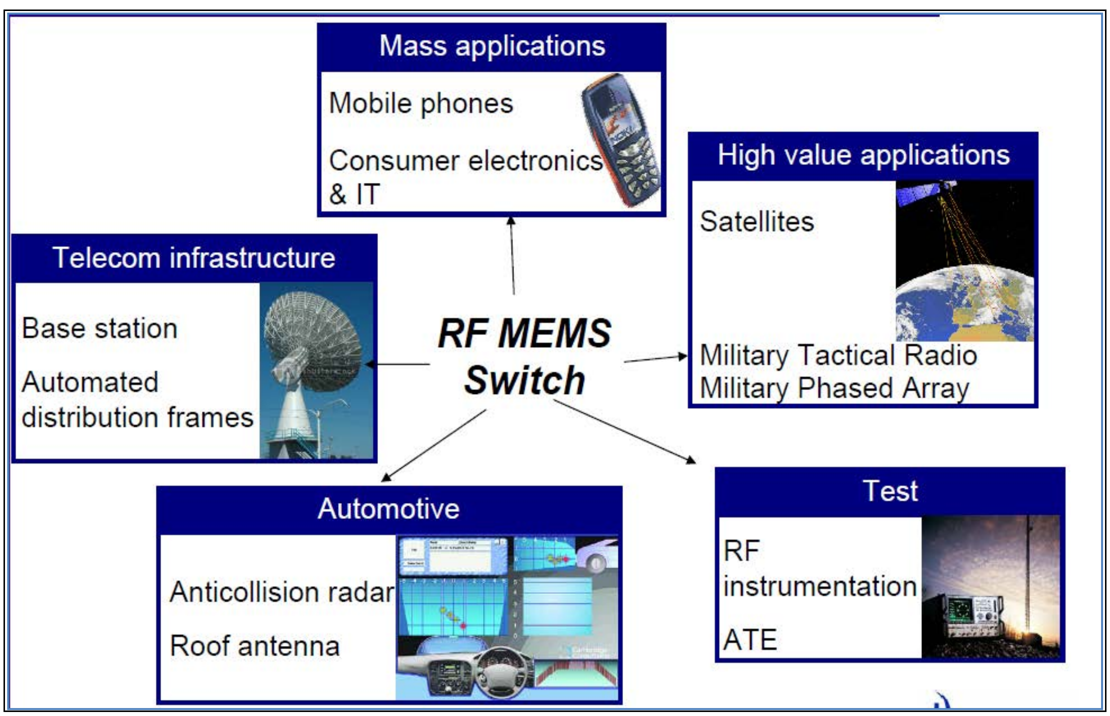

Figure 1.4 RF MEMS switch applications (Yole Developpement, 2009)

This demanding area of MEMS technology also creates devices and techniques that have great potential to improve the performance of communications circuits and systems. RF MEMS switch particularly enables the realization of micro size mechanical switches embedded in electronics devices and offers the advantages of low actuation (currently has already established 90V), low insertion loss, high isolation and large capacitance ratio. Although they have disadvantages compared to (Field Effect Transistor) FET and P-I-N diodes switch like slower switching speed, heavy and bulky, they are inferior in insertion loss, higher power consumption and power handling capabilities (Rebeiz, 2003). The potential market for RF MEMS switches is therefore very large because MEMS based switches are expected to substitute existing products and enable new applications, particularly for electronic consumer product such as microphones, accelerators, pressure sensors, gyroscopes, smart mobile phones and many more within the short term.

1.3 Problem Statement

RF MEMS switch has been explored few years back until today as the performance is still below the par while the demands are very high. Thus, improvements are necessary to achieve low voltage actuation, low loss, high isolation, high speed and low cost. All these improvement could be realized by improving the switch types, dimensions, structures, mechanisms, processes and materials. The current commercialized RF MEMS switch by Radant has actuation voltage of 90 V which is very high and not suitable for most of applications that need low power technology. The current demand voltage actuation is between 1-10 V which suits many applications especially in the area of RF communications, automated test equipment and mobile phones.

The main goal for this work is to design and implement less than 10 V of voltage actuation capacitive MEMS switches using electrostatic mechanism with relatively good RF parameters. Most recent works reported on MEMS switches achieved low actuation voltage from 3V-20V require a more complex mechanical suspension system and complex MEMS fabrication process. MEMS fabrication process is also a key to improve as the cost of MEMS surface micromachining fabrication process is very high and not fully available in Malaysia. Although many current researches have reported less than 10 V voltage actuation, commercialization is still pending due to high fabrication cost.

Thus, the proposed RF MEMS switches are fabricated using MIMOS CMOS 0.35 µm 2-Polysilicon and 3-Metal Multi Wafer Project (MPW) fabrication process. The simple structures design were fabricated using very simple CMOS process (does not follow full flow of CMOS process) and involved only one post-process, which is maskless wet etching using Silox Vapox III to realize the bridge structure in MEMS switch. This wet etching post-process is very simple compared to recent work by (Fouladi et. al, 2010). Instead of using combination of three processes, dry etching (RIE), deep dry etching (DRIE) and wet etching, the proposed post-process only employed a wet etching process and thus the process cost is lower.

1.4 Research Objectives

The main objective of this work has been mentioned in the problem statement. In order to realize the low actuation voltage of RF MEMS switch, there are few sub-objectives of this work needed along the way which are listed as follows:

(a) To design low voltage (less than 10 V) RF MEMS switches using MEMS software package, Coventor Ware by system level design which could operate in frequency range of 1-25GHz.
(b) To simulate the switch designs to predict the performances of important parameters such as voltage actuation, switching speed, resonance frequency using both system level and physical level simulation methods.
(c) To fabricate the MEMS switch using the simple MIMOS CMOS process.
(d) To characterize the fabricated MEMS switches in wafer level measurement.

In the software part, RF MEMS switches are designed in few structures and dimensions such as 2x2-meander type, 2x4-meander type and 4x4-meander type to lower the spring constant and thus to achieve the aim of less than 10 V of voltage actuation. This specification is targeted as it will be the most important parameter of a good RF MEMS switch that increase its potential to be integrated in the most of system and replace the solid state conventional switches. These RF MEMS switch structures will be designed and simulated using system level (Architect Module) and the results are then to be compared to physical level simulation (Analyzer Module).

In the hardware part, designed switches will be fabricated using MIMOS CMOS process and does not follow the full flow of standard CMOS process. This is due to RF MEMS switch only require physical layers deposited and do not require ion implantations. The arrangement of the all CMOS processes are quite challenging to suit the proposed RF MEMS switch. The very simple maskless wet etching will be the post-CMOS process to etch the sacrificial layer between the top bridge and lower conductor is the most contribution as this single process has not been used before. From three postprocesses (Fouladi et. al, 2010), the proposed process will be reduced into one process. This will greatly reduce the cost of fabrication and thus realize the commercialization of RF MEMS switch. Moreover, compared to MEMS process, CMOS process give more benefit in terms of compatibility of the switches to be integrated into other analog and digital circuits for various systems and fabricated into a single chip. This is due to the process compatibility between RF MEMS switches and other Integrated Circuits (IC). For measurement, appropriate measurement setups of the RF MEMS switch for testing with the available measurement instruments in the lab are necessary. Thus, the proposed switches should actuate less than 10 V with other acceptable specifications such as switching speed of less than 50 µs, insertion loss of less than -2dB and isolation more than -20 dB.

1.5 Thesis Outline

The structure of this thesis reflects the sequence of the development of research implementation. The organization of the thesis is as follows:

Chapter 2 reviews the research background and literature study of RF MEMS switches including the theoretical background such as MEMS fabrications and development of existing switches done by previous researchers in various aspects such as using different materials as dielectrics, using flexures beams to reduce the spring constant and using CMOS process for low fabrication cost.

Chapter 3 describes the methodology of the research including software and hardware parts. It also describes design considerations in mechanical such as spring constant, voltage actuation, capacitances while microwave consideration such as transmission line model and loss. Calculation based on equations of some important parameters such as spring constant and voltage actuations are also shown.

Chapter 4 describes the design of switches using software and the simulation result. The analytical calculation of RF MEMS switch performances are also discussed in this chapter. Mechanical simulation of RF MEMS switches such as pull-in voltage, switching, transient and frequency response using both system level simulation module and physical level simulation (Finite Element Method) for verification are also discussed in detail. Fabrication process steps for CMOS processes and the detailed post-process fabrication steps with the etching time are also described in the chapter.

Chapter 5 details out the results from simulation of both methods and results from the measurement in the characterization lab. The results and discussions include the comparison between the simulation using the two modules and comparison between calculated and measurement results. The output of MIMOS CMOS post-process and analysis such as SEM and EDX are also discussed in the chapter.

Chapter 6 draws the conclusions and results of the RF MEMS switches obtained. Recommendations of potential future works are also outlined.

CHAPTER 2

RESEARCH BACKGROUND AND LITERATURE REVIEW

This chapter presents background information and fundamental RF MEMS technology, RF semiconductor switches and MEMS switches. Also, micro fabrication process technology for MEMS and CMOS-MEMS are outlined in this chapter. Then, more detailed survey of existing MEMS switches and researches done to improve the performance follow.

2.1 RF MEMS

The growing demands for high performance RF communication systems have motivated many researchers to focus on RF MEMS technology. RF MEMS technology enables MEMS applications especially in wireless and satellite communication systems. MEMS technology enables the realization of RF passive components with low loss, small size, low power consumption, high quality factors, high tunable characteristics and high linearity compared with conventional semiconductor-based passive. RF MEMS devices include MEMS variable capacitor, MEMS tunable inductors and RF MEMS switches (Kim et al*.,* 2005). RF MEMS devices such as switch, inductor, capacitor, acoustic wave and many more are one of the most exciting and rapidly growing set of RF MEMS devices. The reason why RF MEMS is growing tremendously is due to better performance than existing non-MEMS devices in many applications. The application of

RF MEMS devices are antenna and radar, portable wireless systems, switching networks, satellite communication systems and tunable filters. However, developing RF MEMS circuits and subsystems is some kind of performance trade-off due to limited parameters such as fabrication process technology. It is much easier to deal with single-mode systems like an old-fashioned cell phone, or modern Bluetooth circuit, but this gets harder to develop as frequencies get higher, data bandwidth gets larger and also, when multiple broadband signals have to be handled in the same device. This is a defining trend in the wireless industry, and one that is taxing the limits of conventional technologies and the "old-school" radio architectures (Bouchaud & Knoblic, 2007).

The most widely used RF MEMS device that has been designed is the RF MEMS switch, consisting of an actuation electrode, dielectric layer, an air gap, movable layer or bridge that pulled down to the bottom electrode and pulled up from the transmission line during short circuit or open circuit. This structure of RF MEMS switch is shown in Figure 2.1. RF MEMS switch is a micro-scaled mechanical switch used in communication devices which comprises of a movable switching membrane, which is called top bridge or armature, is suspended over a transmission line. The top bridge or armature moves up and down during the switching operation to change the state of the circuit. The RF MEMS switch can be designed using different actuation mechanism, type of contact, position of the armature, driving and circuit configuration.

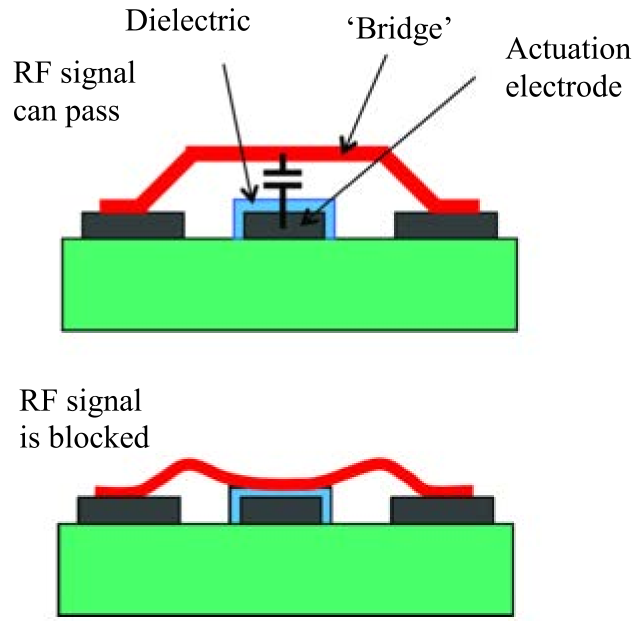

Figure 2.1 RF MEMS switch structure (Van Spengen, 2012)

2.2 Semiconductor switch

The semiconductor switch normally used electronic solid-state switches such as PIN diodes transistors and Field-Effect Transistor (FET) transistors instead of mechanical switch. PIN diodes switch allows signal to be passed through the transmission line if the PIN diode is forward biased. This state has low impedance (on) so that the signal can flow from the input to the output. However, during high impedance state, when the diode is reverse biased (off), the signal is reflected. In addition, when forward biased above the threshold voltage *Vth*, the device exhibits a low resistive impedance *Ron*. In this state the power handling capacity is set by the maximum current swing that can be sustained by the device. When reverse biased, the device is well modeled by a depletion capacitance *Cj*, and a small series resistance *Rs* which is due to the bulk (undepleted) semiconductor near the contacts (Varadan et al., 2002). The equivalent circuit of PIN diode is shown in Figure 2.2.

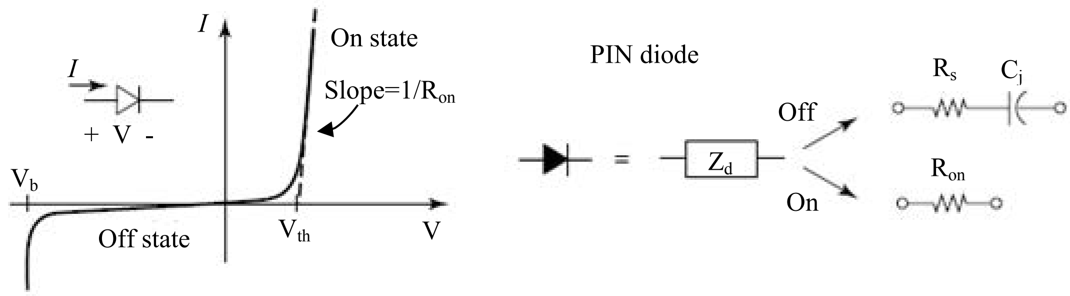

Figure 2.2 Equivalent circuit for a PIN diode in the forward bias (on) and reverse-biased (off) states (Varadan et al., 2002)

FET switch is a three terminal device as they are transistor with the gate voltage acts as control signal. The on and off states of FET can be controlled by varying the gate voltage (Varadan et al., 2002). The on and off switch states also due to the low and high impedance by setting the gate voltage of the switch to zero and greater than the pinch off voltage. The switch is close when the V_{GS} is zero, so the output is more or less equal to the input. Consequently, when the FET is open, V_{GS} is more negative than V_{GS} (off). Thus, V_{out} is zero. However, in shunt configuration, the FET is cut off and open when the V_{GS} is more negative than V_{GS} (off). Hence, the output is the same as input (Varadan et al., 2002).

Figure 2.3 shows the shunt switch equivalent circuit for a FET diode where R_d and R_{ds} are bias resistance and drain-source resistance respectively.

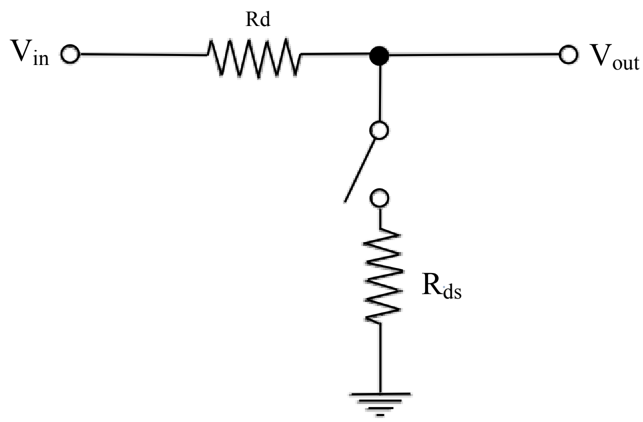

Figure 2.3 Shunt switch equivalent circuit for a FET diode (Varadan et.al, 2002)

The solid state switches exhibit a large insertion loss in the on state (typically 1 to 2 dB) and poor isolation in the off state (-20dB) for signal of frequencies that higher than 1 GHz (Varadan et al., 2002). Large insertion loss means the signal measured at the output port is lower than the input and poor isolation means the signal measured at the output port is high when it should be minimum due to the short circuit in this case. This limitation provides a MEMS switch to replace those switches in application of mobile, communication and satellite systems.

2.3 RF MEMS switch

The MEMS switch was first demonstrated by Petersen in 1979 using bulk micro machined cantilever (Petersen, 1979). This type of switch is realized on silicon substrate with an electrostatic movable cantilever bridge as the switching part. It was also small and consumed low power. Since then, various types of MEMS switches have been reported. RF MEMS switch had been developed by Dr. Larry Larson under Defense Advanced research projects Agency (DARPA) at the Hughes Research Labs in California for microwave applications (Larson, 1991). The switch had excellent performance operated up to 50 GHz but had poor yield and reliability. In 1995, metal-to-metal contact type and capacitive contact switch had been developed by the Rockwell Science Center and Texas Instruments respectively. Both kinds of switches have better performances and suitable for DC- 60GHz and 10-120 GHz (Rebeiz, 2003).

MEMS switches operate based on mechanical movement to achieve on and off states. MEMS switches for RF application operate through short and open circuit to transmitting the signal. The actuation mechanisms to obtain the required forces for mechanical movement are electrostatic, electromagnetic, piezoelectric and thermal. These mechanisms will be further explained in Section 2.3.2. The most common actuation used for MEMS switch is electrostatic actuation due to its low power consumption (Varadan et al., 2002).

MEMS switches have both mechanical and semiconductor advantages and properties. MEMS switches offer high RF performance and low DC power consumption. For RF applications, MEMS switches offer low insertion loss (0.1 dB) and high isolation (>40 dB) at 1 GHz (Varadan et.al, 2002).

MEMS switches demonstrate better performance in comparison with conventional semiconductor switches. They exhibit lower resistive loss (0.5-2Ω), low power handling capability (<1 W)and low power consumption (0.05 – 0.1mW).The excellent performance at microwave to mm-wave frequencies compared to other types of switches such as GaAs-based FET, pHEMT (High Electron Mobility Transistor) or PIN-diode switches creates much interest in research and development of MEMS switch. Nevertheless, one of major disadvantage is low switching speed (2 –40 μs) which is much slower than the solid-state switches (Rebeiz, 2003). Consequently, the moderate speed limits its capability in particular communication devices that expect much faster in switching speed.

2.3.1 Comparison of RF MEMS Switches With Conventional Switches

As explained earlier, the commercial RF switches in use are commonly PIN or FET transistor switches. RF MEMS switches however have many advantages compared to semiconductor switches of FETs and PIN diodes. Typically, semiconductor PIN and FET switches are suitable for high speed switching applications because the semiconductor switches can operate at much faster speed. They are also smaller in size and weight. However, they are poorer in insertion loss, Direct Current (DC) power consumption, power handling capabilities and also isolation compared to MEMS switches. Table 2.1 below shows a comparison between the semiconductor GaAs PIN diode, transistor and electrostatic MEMS switches (Rebeiz, 2003; Varadan et al., 2002).

Table 2.1 Performance comparison of FETs, PIN Diode and RF MEMS Switches

Parameter	RF MEMS	PIN	FET
Voltage (V)	20-80	± 3-5	3-5
Current (mA)	<10 μ	3-20	<10 μ
Power consumption (mW)	0.05 – 0.1	5-100	0.05-0.1
Switching time	1-300 μs	1-100 ns	1-100 ns
Cup (series) (fF)	1-6	40-80	70-140
Rs (series) (Ω)	0.5-2	2-4	4-6
Capacitance ratio	40-500	10	N/A
Cutoff frequency (THz)	20-80	1-4	0.5-2
Isolation (1 GHz) (dB)	>40	40	20-40
Isolation (10-40 GHz) (dB)	Very high	Medium	Low
Isolation (60-100 GHz)(dB)	High	Medium	N/A
Loss (1-100 GHz) (dB)	0.05-0.2	0.3-1.2	0.4-2.5

2.3.2 RF MEMS Switches Mechanism

RF MEMS switch has two parts of section to be considered which are the mechanical actuation and the electrical actuation. The mechanism required to realize mechanical movements includes electrostatic, electromagnetic, thermal or piezoelectric mechanisms.

Electrostatic actuation mechanism is the common approach presently used due to its low power consumption, thin layers of material, small electrode size, low switching time and achievable range of contact forces at 50-200 μN (Rebeiz, 2003).They also have a very large on-off capacitance ratio. However, it requires a higher actuation voltage, typically 5-100 V (Varadan et al., 2002).

Electromagnetic actuation requires lower voltage but with significantly higher current consumption (Varadan et al., 2002). It uses coil and ferromagnetic armature as electromagnetic actuator. The permanent magnets or semi hard magnetic materials allow addition of a self-latching mechanism in electromagnetic actuators. The electromagnetically actuated micromechanical relay is an example of MEMS device that used the mechanism. The relay can also be simplified using thermal actuator. It consists of permanent magnets, armature of a soft magnetic material and thermo sensitive magnetic materials stators (Tilmans, et al., 1999).

Piezoelectric mechanism is one of the switch mechanisms for switching which offer unique material characteristics where elastic deformation is induced by the electrical field stimulation. Piezoelectric actuator is designed and attached to the switch membrane to create the downward force to actuate on and off conditions (Hudson, 2008). The structure is as shown in

Figure 2.4. This mechanism enables the switch to have the high force so that low voltage actuation can be achieved. The high forces allow the gap to be maximized without reducing other parameter such as switching times (Hudson, 2008).

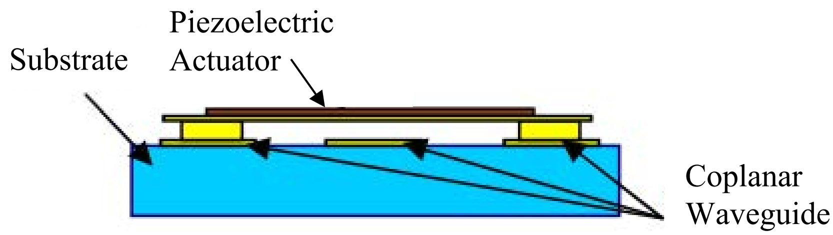

Figure 2.4 Piezoelectric RF MEMS shunt switch (Hudson, 2008)

Thermal mechanism is another mechanism that can be applied to actuate the switch. This mechanism generally used thermal micro actuators connected to a thin metal to actuate the switch. For example, two thermal actuators are connected to two thin metal arms which serve as signal lines of coplanar transmission lines and the switch can be actuated on and off by using short voltage or current pulses as shown in

Figure 2.5 (Daneshmand et al., 2009). Some other researches that use thermal actuated RF MEMS switches (Streeter et al., 2001 and Wang et al., 2004) can be designed with high spring constants and large contact forces to obtain low contact resistance and thus improve the switch power handling capability and increase the switch reliability. Even though this mechanism has some advantages, it is not commonly used to actuate the switch due to its higher dc power consumption compared to the electrostatic mechanism.

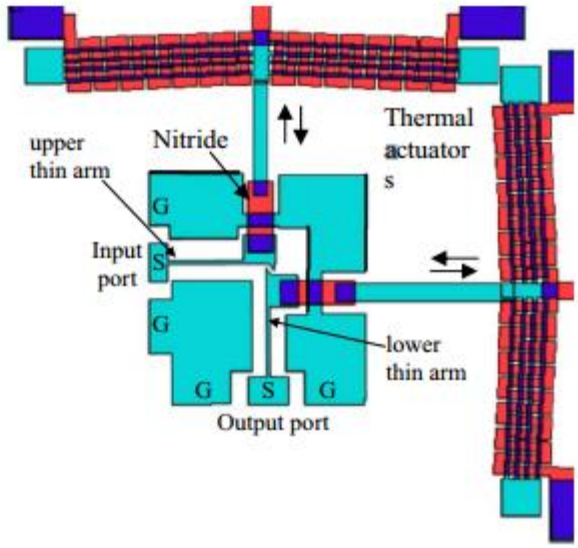

Figure 2.5 Thermal actuation RF MEMS switch (Daneshmand et al., 2009)

2.3.3 RF MEMS Switch Configurations

Two common types of these switches are resistive (metal-to-metal) contact to achieve ohmic contact and capacitive (metal-insulator-metal) contact which gives capacitance ratio between on and off states. For both types, the actuation voltage will pull down the strip to close gap in transmission line and make a conducting path. There are two configurations of MEMS switches that can be developed which are the series switch and shunt switch. The switches are connected in series and parallel respectively with the transmission line as shown in Figure 2.6.

Generally, the shunt switch is designed for higher frequency applications, at 10-100 GHz while series switch is designed with a low ohmic contact for the lower Gigahertz range (Sattler et al., 2002).

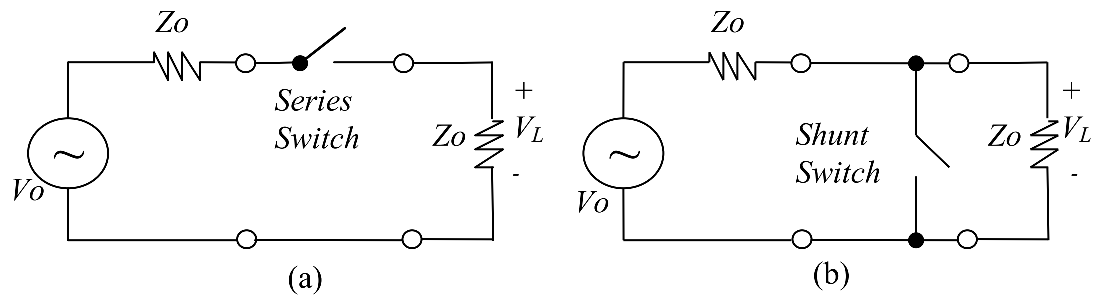

Figure 2.6 RF MEMS switch configurations (a) series switch (b) shunt switch

2.3.4 RF MEMS Series Switch

Series switch commonly used cantilever structure which basically consists of a thin strip of metal fixed at one end and is suspended over the transmission line with a gap height. The cantilever is connected in series with the transmission line or the metallic contact can be on top of the transmission line. Metallic electrode is lying in between the transmission line and the fixed end of cantilever that serves as pull-down electrode (Varadan et al., 2002). This switch performs a 'make and break' operation in an electrical path which shows good insertion loss and exhibit excellent linearity (Varadan et al., 2002). Figure 2.7 shows the schematic illustration for the RF MEMS series switch. Series switch can also be designed with capacitive contact which requires electrostatic force to create the contact. Series cantilever switch with capacitive contact is shown in Figure 2.8. The switch is anchored at one end and has a suspended cantilever structure over the dielectric pad on the RF transmission line. During off state, there is no voltage applied to the electrode, therefore the beam stays up with small switch capacitance. As a result, no RF signal flows through the lines due to there is no connection between input and output ports. Oppositely, whenever a DC bias applied to the electrode, the beam is pulled down onto the dielectric and the switch capacitance becomes high so that the RF signal can flow through the lines due to the connection between RF input and RF output. This is called on state.

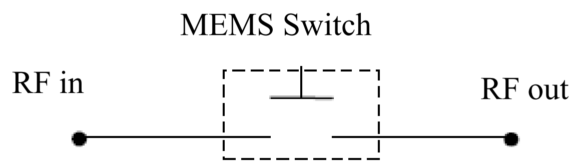

Figure 2.7 Equivalent circuits for the RF MEMS series switch (Kiang, 2011)

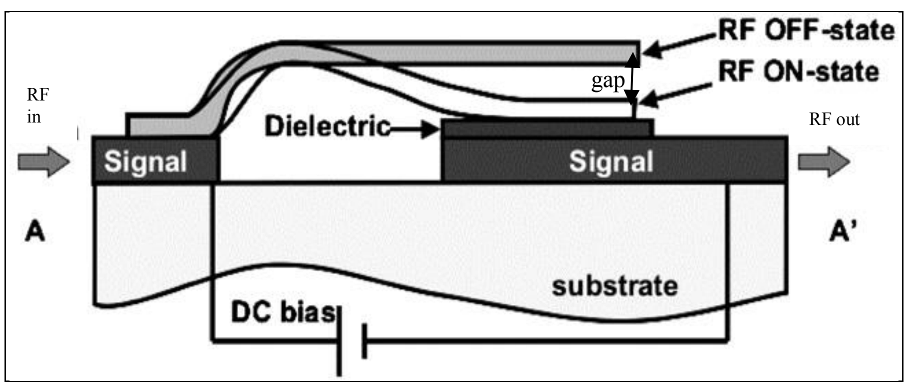

Figure 2.8 RF MEMS capacitive series switch operation (Rottenberg et al., 2005)

2.3.5 RF MEMS Shunt Switch

RF MEMS shunt switch consists of a suspended movable thin metal bridge over the center conductor, fixed at both ends and anchored to the ground line of transmission line. In on state, a Direct Current (DC) bias voltage applied to the signal line is 0 V, the bridge remains up and the signal freely passes through the transmission line due to low capacitance as the distance is high. However, during off state, when the DC voltage is applied and increasing, the center electrode provides electrostatic force and evenly distributed across the bridge and causes the beam membrane to deflect downward and decreasing the gap thus creates high RF capacitance between the transmission line and the ground. The capacitance between switch membrane and signal line increases significantly after contact, due to higher relative permittivity of the dielectric film and lower distance between the bridge and center electrode. When the bridge is pulled down onto the dielectric layer placed on top of the signal line, RF signal is shorted to the ground. Figure 2.9 and Figure 2.10 show the schematic illustration and typical MEMS shunt switch in on state and off state conditions.

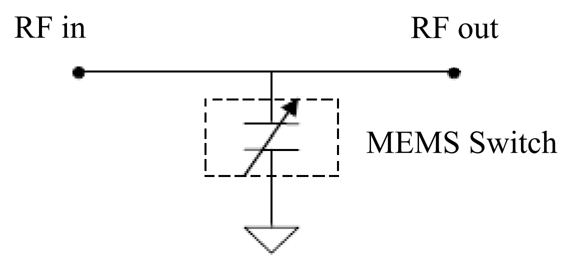

Figure 2.9. Schematic illustration for RF MEMS shunt switch (Kiang, 2011)

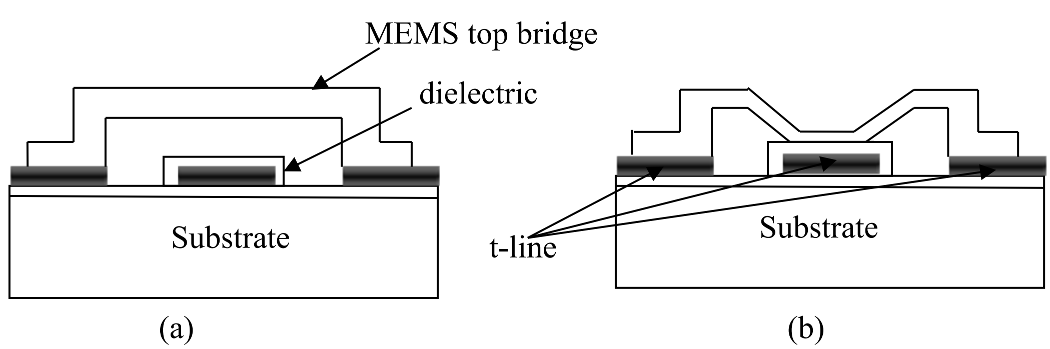

Figure 2.10. RF MEMS shunt switch on CPW transmission line
(a) on state (b) off state

The shunt switch can be integrated in a coplanar waveguide (CPW) or in a microstrip transmission line. In a CPW transmission line, the anchors of the switch are normally connected to the CPW ground planes while in the microstrip configuration, one anchor is connected to quarter-wave open stub that makes the short circuit at the bridge and the second anchor is left unconnected or connected to the bias resistor (Rebeiz, 2003).

2.4 RF parameters

The RF behavior of the switch is determined by its insertion loss, return loss and isolation with the range of frequency. The insertion loss and isolation are obtained from s parameters when the switches transmit the signal while in the up-state and the signal is grounded when the beam is in the down-state. S_{11} and S_{21} of the RF parameters determine the return loss and insertion loss of the switch respectively. Basically, it is desirable to have a low insertion loss, high return loss and high isolation.

The MEMS shunt switch is modeled by two short sections of transmission line and a lumped capacitor-inductor-resistor (CLR) model of the bridge with capacitance having in the up-state and down-state conditions as in Figure 2.11 .