DESIGN AND DEVELOPMENT SYMMETRICAL ABSORPTIVE MODE SINGLE POLE DOUBLE THROW (SPDT) SWITCH DESIGN FOR WiMAX APPLICATION

By

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ACK	acknowledgement
ADS	Advance System Design
ARB	arbitrary waveform generator
BER	bit error ratio
BPL	Broadband over Power line
BS	base station
BWA	broadband wireless access
CAD	Computer aided design
CATV	cable TV
CDMA	code division multiple access
CQICH	channel-quality indicated channel
CW	continuous wave
DECT	digital-enhanced cordless telephony
DL	downlink
DPDT	double poles double throws
DSL	Digital Subscriber Line
DUT	device under test
Epi	epitaxial
ESD	Electrostatic Discharge
EVM	Error vector magnitude
FCC	Federal Communications Commission
FCH	frame control header
FDD	frequency division duplexing

FDMA Frequency Division Multiple Access

FFT Fast Fourier Transform

FTTH fiber-to-the-home

GaAs Gallium arsenide

GPIB general purpose interface bus

HDTV high-definition TV

H-FDD half-duplex FDD

H-PIN horizontal PIN Diode

HSOPA high speed OFDM Packet Access

I Intrinsic

IEEE Electrical and Electronics Engineers

IFFT Inverse Fast Fourier Transform

IIP3 third-order intercepts point

IL insertion loss

IM intermodulation

ISP Internet Service Provider

LAN local area network

LMDS local multipoint distribution system*s*

LNA low noise amplifier

LOS line of sight

LRM line – reflection – match

LTE long-term evolution

MAC media access control

MCMC Malaysian Communications and Multimedia Commission

MMDS multichannel multipoint distribution service*s*

MMIC Monolithic Microwave Integrated Circuits

MS mobile stations

NLOS non line of sight

OFDM orthogonal frequency division multiple

OFDMA orthogonal frequency division multiple access

PA power amplifier

PCI Peripheral Component Interconnect

PMP point to multi-point

PS physical slot

PXI PCI extensions for Instrumentation

QFI Quantum Focus Instrument

RCE relative constellation error

RMS root-mean-square

RTG receiver-transmit transition gap

SFDR spurious free dynamic range

SINR Signal to Interference plus Noise Ratio

SNR signal to noise ratio

SPDT Single Pole, Double Throw

SPST Single pole, single throw

SP4T single pole 4 throws

SOLT short – open – load – thru

TOI Third-order intercepts point

TDD time division duplexing

TDM time division multiplexing

TRL thru – reflection – line

TTG transmit-receive transition gap

TX/RX transmits and receives

UMTS universal mobile telecommunications system

UL uplink

VNAs Modern vector network analyzers

VBR Breakdown Voltage

VDSL very high data rate digital subscriber loop

V-PIN vertical PIN Diode

VoD video on demand

VoIP Voice over Internet Protocol

VXI VME extensions for Instrumentation

WLL wireless local-loop

WISP wireless Internet service provider

Rekabentuk dan Pembangunan Suis MOD Kutub Tunggal Dua Lonjar Berkeserapan Simetri untuk Aplikasi WiMAX

ABSTRAK

Dalam beberapa tahun yang lepas, pasaran komunikasi tanpa wayar telah melalui satu condongan dan perpindahan yang besar. Teknologi jalur lebar melalui WiMAX telah cepatnya menjadi satu global komoditi yang diperlukan oleh peratusan penduduk yang tinggi. Pertumbuhan teguh di WiMAX applikasi telah melancarkan cabaran yang besar kepada perindustrial component untuk mempercepatkan pengeluaran product baru dalam masa yang tersingkat untuk dipasarkan. Oleh sebab itu, ada peningkatan tuntutan untuk PIN Diod suis kuasa tinggi dengan insertion loss yang rendah, isolation yang tinggi untuk WiMAX jalur lebar basestation applikasi. Thesis ini mempersembahkan pencapaian Rekabentuk dan Pembangunan Suis MOD Kutub Tunggal Dua Lonjar Berkeserapan Simetri untuk Aplikasi WiMAX dengan mengunakan Silicon PIN Diode. Satu struktur yang novel dimana LC matching seksyen ditambah supaya membekalkan characteristics jalur lebar boleh dilaras. Demi mencapai insertion loss yang rendah dengan mengunakan PIN Diod, fokus utama semasa rekabentuk adalah mengurangkan penentangan maju ke hadapan PIN Diod.Disebabkan oleh kemudahan PIN Diod sebagai teknologi, saiz yang kecil dan kos yang rendah, reliabiliti, power handling dan switching pertunjukan yang sangat bagus di frekuensi gelombang mikro, oleh itu PIN Diod banyak digunakan dalam pelaksanaan front-end RF suis applikasi dalam modem, multi-system bergerak dan rekabentuk tanpa wayar .Semasa rekabentuk, ADS telah digunakan untuk simulasi signal kecil dan bahan Roger’s 4003C telah digunakan semasa fabrication. SPDT suis telah mencapai maksimum insertion loss 0.75dB di TX and RX lengan dan minimum isolation 30dB meliputi WiMAX frequensi 2.3GHz -2.7GHz. Absorptive

SPDT suis jalur lebar yang mengunakan series shunt PIN Diod topology telah direka untuk mencapai return loss lebih daripada 15dB menyeberangi 3 ports. SPDT suis kuasa tinggi yang direka dapat mencapai EVM kurang daripada 0.8% dengan input kuasa 30dBm dengan mengunakan modulasi skim 802.16e. HSMP-386x PIN Diod daripada Avago Technologies memang tidak dapat ditawani, dan ia memang sesuai untuk mereka suis yang perlu mencapai IIP3 (lebih dari 70dBm) dan t-rise switching masa yang bagus (360ns).

DESIGN AND DEVELOPMENT
SYMMETRICAL ABSORPTIVE MODE
SINGLE POLE DOUBLE THROW (SPDT) SWITCH DESIGN
FOR WiMAX APPLICATION

ABSTRACT

The wireless communications market has gone through a tremendous incline of paradigm shift in the last several years. Broadband technology via WiMAX has rapidly become an established, global commodity required by a high percentage of the population. The persistent growth in WiMAX applications introduces tremendous challenges on component manufacturing to speed up new product release in shorter time to market. As a result**,** there is an increasing demand for high power with low insertion loss, high isolation and broadband PIN Diode switches for WiMAX basestation application. This thesis presents the design and realization of Symmetrical Absorptive Mode of Single Pole Double Throw Switch Design for WiMAX Basestation Application based on Silicon (Si) PIN Diode structure. A novel structure with LC matching sections is added to provide tunable broadband characteristics. To achieve the low insertion loss PIN Diode design, the main focus is to reduce the PIN Diode's forward bias resistance. PIN Diodes are used broadly in the implementation of front-end RF switches in many of the modem, multi-system mobile and wireless designs due to its simplicity as a technology, small size and low cost, reliability, and not in the least, excellent power handling and switching performances at microwave frequencies. ADS have been used in the design process for small signal analysis and fabricated using Rogers's 4003C material. The SPDT switch achieved maximum insertion loss of 0.75dB at TX and RX arm and minimum isolation of 30dB over 2.3GHz – 2.7 GHz covering WiMAX frequency band. The broadband absorptive SPDT switch using series shunt PIN Diodes topology with good match return loss more than 15dB across 3 ports is presented. The high power SPDT switch is able to achieve for EVM less than 0.8% with input power at 30dBm using 802.16e modulation scheme. Avago Technologies HSMP-386x is unbeatable PIN Diode selection to attained excellent result on both IIP3 (above 70dBm) and t-rise switching time around 360ns.

CHAPTER 1

INTRODUCTION

1.1 Wireless Communication

In today's hyper connected world, consumers and businesses are increasingly becoming more connected and require quality communication experiences — anywhere, anytime, on any device. At the same time, service providers are looking for ways to unlock new revenue opportunities, de-risk technology investments and accelerate time to market.

The forthcoming communication systems are expected to provide a wide variety of services, from high-quality voice to high-definition videos, through high-data-rate wireless channels anywhere in the world. The high data rate requires broad frequency bands, and sufficient broadband can be achieved in higher frequency bands such as microwave, Ka-band, and millimeter- wave. Broadband wireless channels have to be connected to broadband fixed networks such as the Internet and local area networks (LAN). The future generation systems will include not only cellular phones, but also many new types of communication systems such as broadband wireless access systems, millimeter-wave LAN, intelligent transport systems, and high altitude stratospheric platform station systems. Key to the future generations of mobile communications are multimedia communications, wireless access to broadband fixed networks, and seamless roaming among different systems [1].

1.2 WiMAX Base Station

Demands for broadband wireless communication has been growing fast recently with the advent of new technologies such as WiMAX. WiMAX is a broadband wireless access (BWA) technology based on the IEEE 802.16 standard, which supports point to multi-point (PMP) broadband wireless access. With this growing demand, RF transceiver manufacturers are constantly challenged with requirements to provide compact and wideband RF components. These components essentially are integrated versions of a discrete front end RF design, composed of a power Amplifier (PA), a transmit/receive (TX/RX) or single pole double throw (SPDT) switch, low noise amplifier (LNA), filter and matching components. SPDT switches have become importance components in broadband WiMAX base station. With the new development of WiMAX communications, there is steady increase in the demand for low-cost, miniaturized RF and microwave devices and components. One problem that occurs in the front end of a radio transceiver is how to switch antenna's modes of operation [2] .This function is achieved by the use of a SPDT switch as shown in Figure 1.0 [3]. SPDT switch becomes a strong demand for Tx/Rx antenna switches with low loss and high isolation. The switch can operates in either the transmit mode with power transmitted from the PA to the antenna, or the receive mode with the power delivered from the antenna to the Low Noise Amplifier [4]. The semiconductor devices that constitute the SPDT switch should approximate no insertion loss in the ON state and nearly infinite isolation in the OFF state.

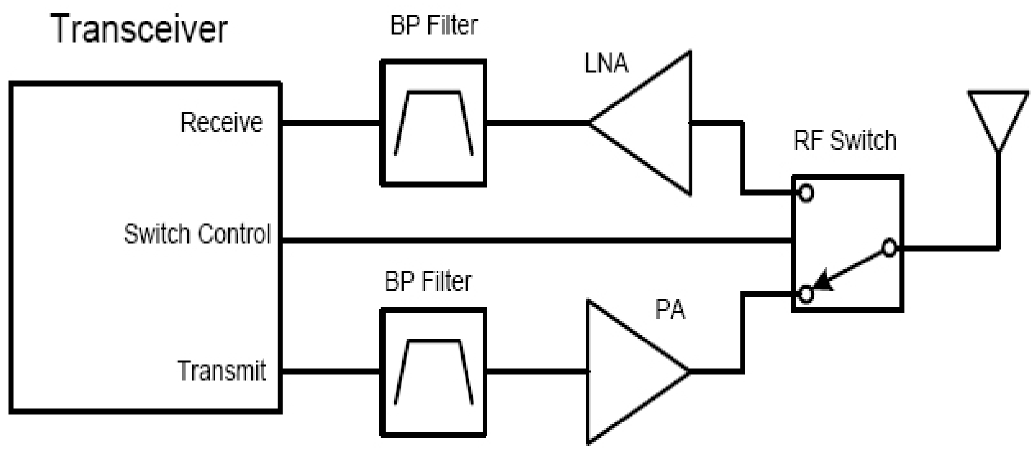


Figure 1.1: WiMAX Base Station Transceiver [3]

1.3 Problem Statement

In general conventional SPDT switch has had problem such as high insertion loss, low isolation between ports, narrow operating frequency band, and high current consumption [5]. A simple, low insertion loss, high isolation, broadband frequency range and high power handling SPDT switch is necessary to improve the overall system performance [6]. There are 4 major challenges that need to resolve by switch designer to come out with comprehensive SPDT module for WiMAX base station application:

- **High Power Handling**

The ever increasing linearity and peak-to-average power requirements of the modulation schemes employed by EDGE, 4G, TD-SCDMA, and the most challenging to date, WiMAX systems in base station, CPE, and even femtocell applications, have led designers to employ SPDT switch with high power handling switch at leas 20 watt

[7]. WiMAX Orthogonal Frequency-Division Multiplexed (OFDM) and Orthogonal Frequency-Division Multiple Access (OFDMA) signals typically have peak-to-average envelope excursions of 8-10dB or more [8].

- **Absorptive Mode Switch**

In a reflective SPDT switch design, the impedance of the port that is OFF will not be 50 ohms and will have a very high VSWR. This has caused the base station PA high potentially damaged by reflect signal from the TX port during RX mode operation. Reflective mode switch has caused system design to be more complicated. On the other hand; an absorptive switch will have a good VSWR on each port regardless of the switch mode.

- **High Linearity**

In recent years, WiMAX has become a well know term mainly because of its potential to compete with cellular and WiFi Technologies. Many companies have started to develop and introduce RF power devices specifically targeted fir this application [9]. The SPDT Switch used in WiMAX systems are based on OFDM modulation technology, which can offer high data rate and robustness in multi-path fading environments. But the OFDM signals can cause inter-modulation between orthogonal carriers when subjected to non-linearity, which severely degrade signal to noise performance. Therefore, the development of high linearity RF components, such as an antenna switch is indispensable for meeting the strict, linearity requirements for

OFDM signals [10]. This complex WiMAX signal presents a very tough challenge to the circuit designers [11]. The SPDT switch has to have high linearity to realize error-free data transmission.

- **Low Insertion Loss**

SPDT switch with insertion loss>1dB is not suitable used in WiMAX application. In order to have a power efficient transceiver without degrading its sensitivity, the losses in the switch must be low [12]. Main characteristic of an RF switch are insertion loss and P1dB [13]. At TX arm, low insertion loss is requiring to ensure the 20 watt high power signal after the PA is able to transmit from the base station with the minimum loss at SPDT switch. At 20watt high power handling, 0.75dB loss brings momentous impact to the base station and is equivalent to 3.2watt loss. Therefore this is a first and foremost parameter needs to meet during the design stage especially for high power base station application. Normally, the RF signal received at ANT is always low and feeble. As a result it is essential for RX path to have low insertion loss as well so that the weak RF signal will not become weaker after pass through the WiMAX switch.

1.4 Research Objectives

In order to address the issues as stated in problem statement, below are objectives of this research project:

- To design, develop, simulate, fabricate and measure a Symmetrical Absorptive Mode SPDT Switch design for WiMAX Base station applications cover WiMAX bandwidth 2.3GHz to 2.7GHz.

- To design the switch which is very low insertion loss, symmetrical design, high isolation, excellent return loss, high power handling, outstanding linearity and fast switching time for WiMAX application.
- Study and investigation of methods to improve the power handling, isolation, insertion loss of the absorptive mode SPDT switch. In addition, investigations and research will also be carried out to improve the bandwidth of the SPDT by researching on the broadband matching circuit methods.

1.5 Research Scopes

This project is to design and fabricate the WiMAX SPDT Switch at 2.3GHz – 2.7GHz. The research scopes for the research work are outlined as follows:

- To simulate the symmetric WiMAX SPDT switch design using ADS software.
- To fabricate the PCB for data comparison between simulation and measurement.
- To analyze and compare S-parameter performance between simulation and measurement.
- To perform WiMAX EVM, IIP3, Switching and P0.1dB measurement.
- To performance thermal heat study.

For EVM measurement, it is using OFDMA modulation signal (802.16e).

1.6 Research Contribution

The research work has the following contributions:

1. The schematic design and the data display become the template or reference for future switch research improvements project. In future, the researchers who design the single pole double throw (SPDT) switch for 3G, LTE and WLAN systems can use this template to simulate and verify the design. This will speed up the whole development process time.
2. This research can provide the materials for the training purpose regarding the WiMAX SPDT, SP2T, SP3T and etc studies. The results obtained from the simulation and measurement can become the references for other application designs.
3. The outputs of this research showed that the PIN Diode WiMAX SPDT switch can use in WiMAX application circuitry using OFDMA modulation signal with EVM less than 2.5% with power handling of 20 watt.

From the results obtained, it showed that the HSMP 386-x PIN Diode is suitable for WiMAX SPDT design due to it low insertion loss and high power handling

1.7 Thesis Organization

This thesis is organized into 6 chapters to completely cover the research work related WiMAX SPDT switch. The literature reviews of the PIN Diode, SPDT Switch, and different technique for isolation and power handling are provided in Chapter 2. Some researches that had been done by other researchers are briefly presented.

Besides, it also introduces the concept and principle for the SPDT switch.

Chapter 3 contains of the design procedure and simulation result for SPDT switch using ADS. Measurement test setup and test methodology for measure the fabricated SPDT switch is briefed in Chapter 4. Then there will be discussion between simulated and measured SPDT result in chapter 5.

Lastly, the final chapter provides an overall conclusion of work conducted in this research project. It also provides recommendations on future works of this project.

CHAPTER 2

LITERATURE SURVEY

2.1 Basic Theory of Switches

The basic theory of a switch can be described briefly by considering a switch of SPST type as shown in Figure 2.1 and the summary of formulas for SPST switches is provided in Table 2.1 as reported in [14].

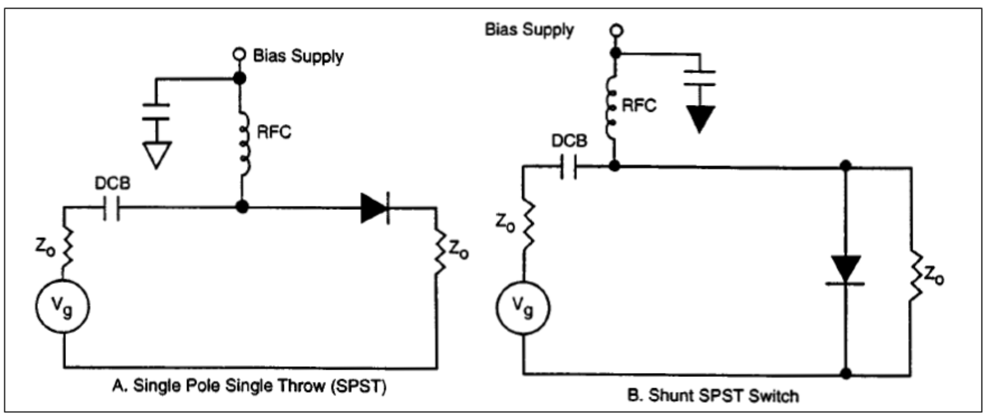


Figure 2.1: SPST switches [14]

Table 2.1: Summary of formulas for SPST switches

Type	Isolation	Insertion Loss (dB)
Series	$10\log_{10}\left[1+\left(\frac{X_C}{2Z_O}\right)^2\right]$	$20\log_{10}\left[1+\frac{R_S}{2Z_O}\right]$
Shunt	$20\log_{10}\left[1+\frac{Z_O}{2R_S}\right]$	$10\log_{10}\left[1+\left(\frac{Z_O}{2X_C}\right)^2\right]$
Series-Shunt	$10\log_{10}\left[\left(1+\frac{Z_O}{2R_S}\right)^2 + \left(\frac{X_C}{2Z_O}\right)^2 \left(1+\frac{Z_O}{R_S}\right)^2\right]$	$10\log_{10}\left[\left(1+\frac{R_S}{2Z_O}\right)^2 + \left(\frac{Z_O+R_S}{2X_C}\right)^2\right]$

2.2 SPDT Switch Configuration

N diodes are often used to design a switch that controls the path of RF signals. There are three basic configurations that may be used for a simple switch designed to control the flow of microwave signals between various ports. There are shown in Figure 2.2 for a SPDT switch, which consists of series, shunt and series shunt configurations.

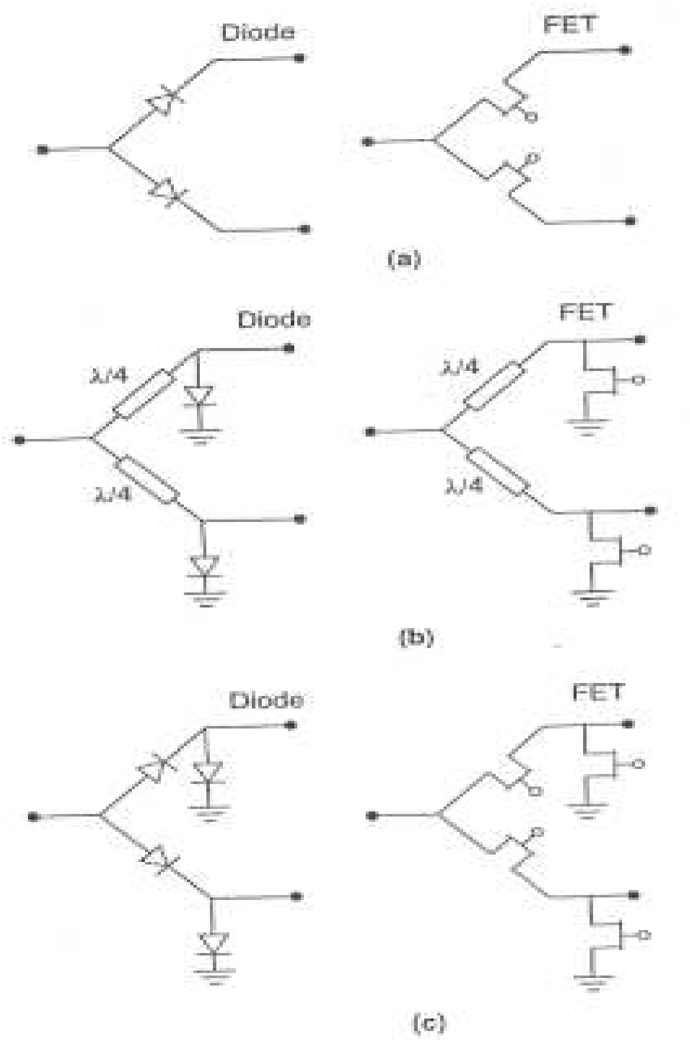


Figure 2.2: Series, shunt and series shunt configurations for SPDT switch [14]

2.2.1 SPDT - Series Configuration

The switch is "ON" when the PIN Diode is forward biased as shown in Figure 2.3. The diode resistance is lowered but is not zero. This resistance absorbs and reflects some power. Low insertion loss requires low resistance.

The switch is "OFF" when the PIN Diode is reversed biased. The diode is not an open circuit so the input is not completely isolated from the output. High isolation requires low capacitance.

The series diode switch of Figure 2.3 is capable of very large (multi-octave) bandwidth, limited only by the bias inductors L and capacitors C, and the length of any transmission line between the diodes and the common junction.

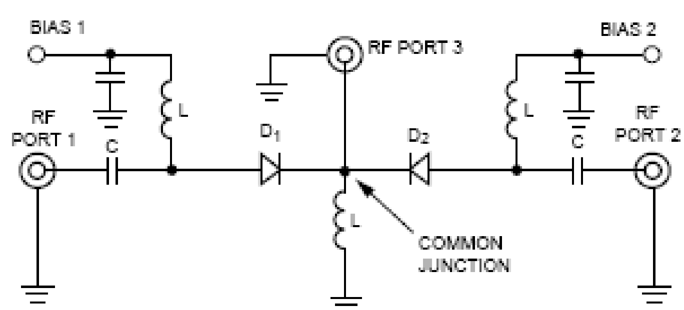


Figure 2.3: Series PIN SPDT switch [15]

2.2.2 SPDT - Shunt Configuration

The switch is "ON" when the PIN is reversed biased as shown in Figure 2.4. Low insertion loss requires low capacitance. The switch is "OFF" when the PIN is forward biased. High isolation requires low resistance.

The shunt configuration requires λ/4 line in each arm. In a shunt configuration, when a device is in high impedance state in one arm, the device in the second arm is in low impedance state. With a 50 ohm λ/4 line, the low impedance is transformed to high impedance at the input, while the parallel combination of device's high impedance and 50 ohm terminal impedance not affect the input impedance. Thus a λ/4 line reduces the effect of device's low impedance of the switch and keeps the switch circuit matched to 50 ohm at the input under both the ON and OFF states.

The shunt diode switch, shown in Figure 2.4, features high isolation, relatively independent of frequency. It is an easy structure to design and fabricate. The main drawback of this type of switch is the bandwidth restriction arising from the use of quarter wavelength transmission lines between the common junction and each shunt diode. However, as the frequency is changed from fo, the transmission lines will change in electrical length, creating a mismatch at the common junction.

For a shunt-mounted switch, the variation of the insertion loss with frequency limits the operating bandwidth. At lower frequencies the circuit size becomes larger due to the λ/4 lines.

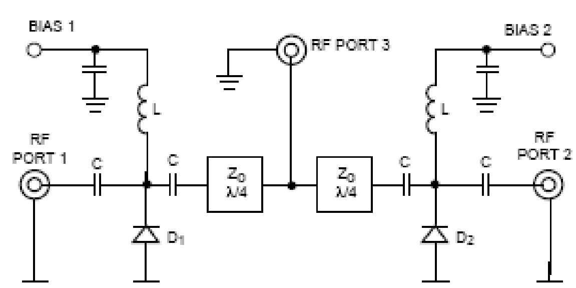


Figure 2.4: Shunt PIN SPDT switch [15]

2.2.3 SPDT - Series Shunt Configuration

To improve bandwidth without sacrificing isolation, a designer will often resort to the series shunt circuit of Figure 2.5. The series shunt configuration is the most popular. When positive bias is applied to bias Port 1 and negative bias is applied to bias Port 2, Diodes D3 and D2 are forward biased into a low resistance state, while Diodes D1 and D4 are reverse biased into a high resistance state RF power flows from RF Port 3 to RF Port 1. Diode D4 acts as an open circuit to isolate the short at D2 from the common junction. This switch, however, is complicated, and consumes twice the bias power of the shunt switch shown in Figure 2.4 [15].

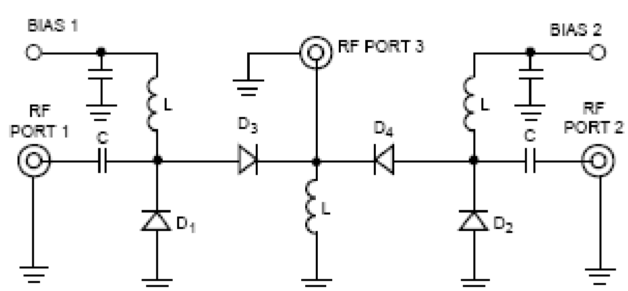


Figure 2.5: Series/Shunt PIN switch [15]

The insertion loss for the series shunt configuration is worse than that for a shunt switch but better than that for a series switch. It looks surprising that a switch using two diodes can have an insertion loss smaller than that with a single diode. However, a detailed analysis shows that use of a series shunt switch reduces the reflection loss compare with series switch and thereby improves the insertion loss. Using a combination of series shunt diode eliminates the λ/4 lines and thus improves the bandwidth characteristic of the switch circuit.

2.3 Previous Work

In general, conventional single pole double throw (SPDT) switch has had problem such as high insertion loss, low isolation between ports, narrow operating frequency band, high current consumption, low power handling and poor linearity caused the current SPDT switch is not suitable for WiMAX base station application.

Besides $\lambda/4$, below are few previous works done to improve port to port isolation:

- 3 PIN Diodes in series (series –series-series) as shown in Figure 2.6 [16] is able to enhance the port to port isolation >25dB especially at high transmit power but the main drawback is poor insertion loss. During the forward bias, the TX insertion loss is sum of the RF resistances (D1, D3 and D5) and directly caused terrible insertion loss >1.5dB.
- Experimental result of a series connected SPDT switch in a novel punched holes structure (PHS) also presented in [16] to improve the isolation of the port. In the PHS, the dielectric and ground layers are punched out in a specific size from the microstrip line and PIN Diodes are placed over the punched holes to connect the microstrip line.

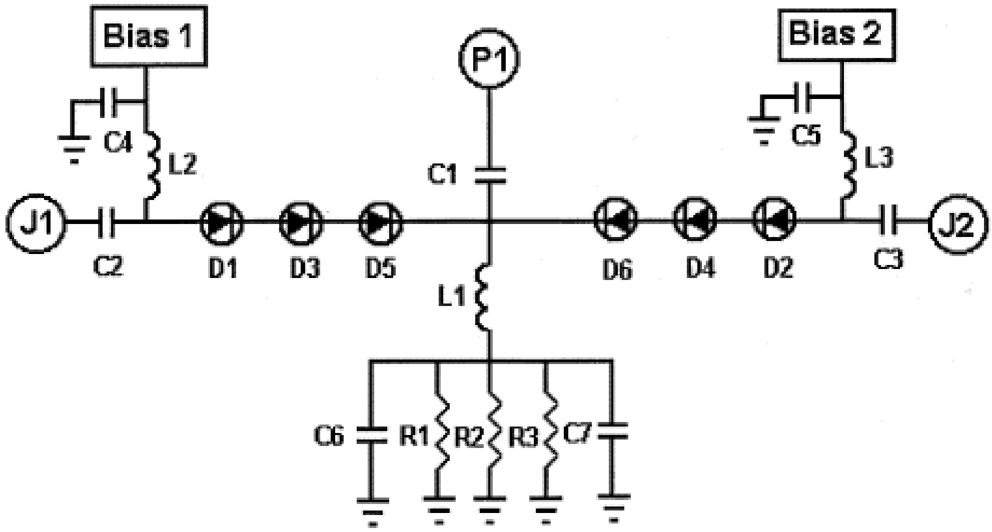


Figure 2.6: Series-series-series SPDT switch [16]

- In order to achieve high isolation, series-shunt-shunt switch arm configuration has been used as shown in Figure 2.7 [17]. Compared with the conventional series-shunt switch architecture [18], one more shunt PIN Diode is added to increase the isolation [19]. Also, two different PIN diodes with different areas are used in the switch design, each tailored for optimum performance. During the OFF stage, the 2 shunt PIN Diodes together with the transmission line will act as good Quarter Wave Length $(\lambda/4)$ between the ports and directly improve the isolation of the ports.

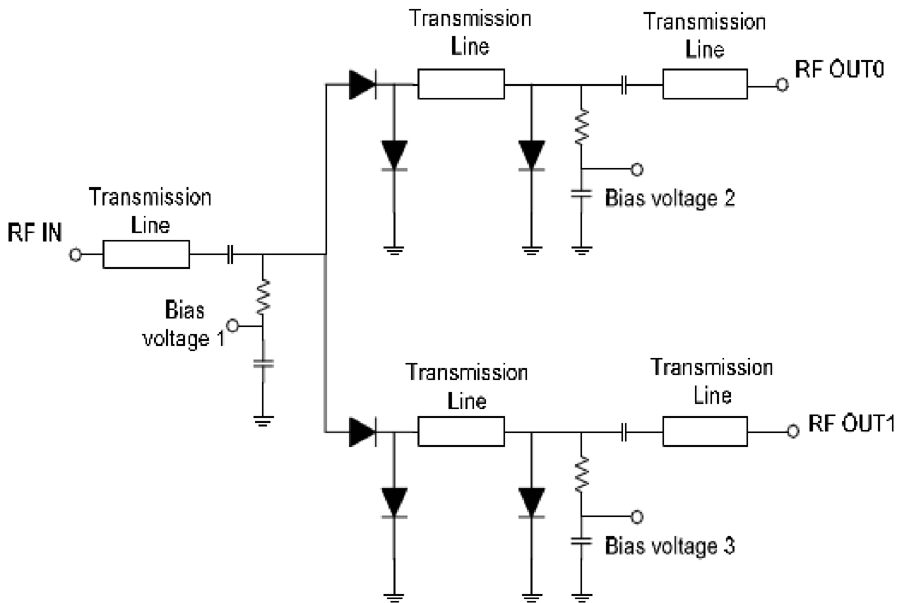


Figure 2.7: Series-shunt-shunt switch [17]

A novel CMOS high power RF switch using multi-gate structure in a 0.18-um triple-well CMOS process is designed as shown in Figure 2.8 [20]. Multi-gate devices have been introduced in many RF circuit implementations using GaAs MESFET and p-HEMT devices [71, 72]. Experimental data show that the SPDT switch exhibits 26dBm of P1dB with triple gate structure. The Rx switch utilizes the triple gate transistor to maximize voltage swing. As the number of gates in the transistor increases, the power handling capability of the Rx switch also increases. However, an increased number of gates of the Rx switch can result in higher insertion loss. Insertion loss can be improved by reducing gate length, by increasing gate width, and by increasing the control voltage. However, increasing gate width causes the lowering of OFF state impedance, which, in turn, lowers the P1dB compression point due to increased leakage current toward the OFF device.

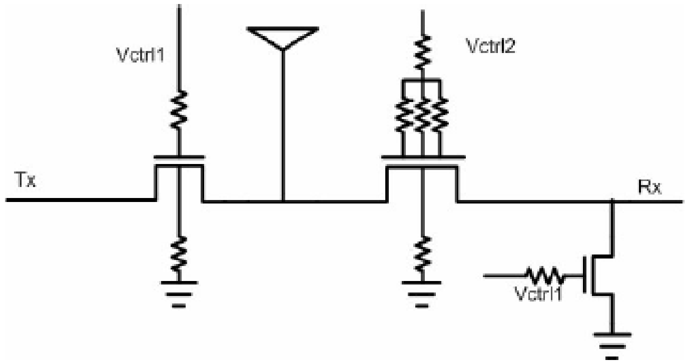
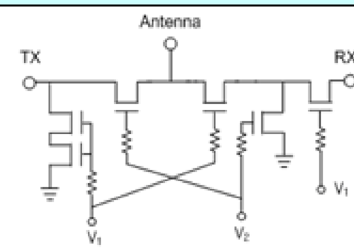
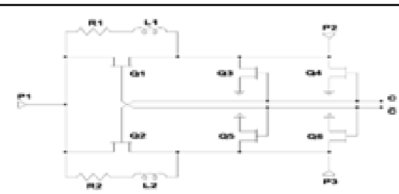
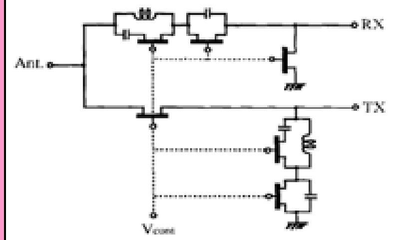


Figure 2.8: Schematic of SPDT switch using triple gate [20]

Table 2.2 shows the recently reported performance using different process for high linearity SPDT switches.

Table 2.2: Recently Reported Performance of SPDT Switches

Comparison	Process	Method	Figure
High Linearity SPDT Switch for Dual Band Wireless LAN Applications [73]	**GaAs pHEMT 0.25um**	**Using stacked FETs to replace single FET. Need to optimum gate width and number of stacked FETs to avoid degradation of Insertion Loss**	 **Figure 2.9 : Circuit diagram of the asymmetric SPDT switch using stacked FETs**
High Power Microstrip GaN-HEMT Switches for Microwave Applications [74]	**GaN HEMTs**	**Using one series and three shunt transistors. An inductive (L1) compensation has been implemented (Q1, Q2), as proposed in [75] to increase isolation performance.**	 **Figure 2.10 : Circuit topology of the X-band AlGaN/GaN SPDT power switch.**

Comparison	Process	Method	Figure
LOW VOLTAGE, HIGH POWER T/R SWITCH MMIC USING LC RESONATORS [76]		FET-switchable LC resonator composed of spiral inductors, MIM capacitors, and switching FET's, that is incorporated in the TX and RX arms	 Figure 2.11 : Circuit scheme of a T/R swith incorporating FET switcable LC resonant circuits
Design of a Microstrip SPDT PIN diode switch [77]	Heterojunction AlGaAdGaAs PIN Diode	Series-shunt topology	

2.4 SPDT Switches Technology

The semiconductor devices that constitute the diversity switch should approximate the open- and short-circuit conditions of an ideal switch – nearly no insertion loss in the ON state and nearly infinite isolation in the OFF state. PIN Diodes and MESETs or other transistor are used extensively in MICs and Monolithic Microwave Integrated Circuits (MMIC) respectively for microwave control circuits such as switches, limiters, attenuator.

2.4.1 PIN Diode Switch Vs MESET Switch

PIN Diode is a unique type of semiconductor device and is a current controlled resistance. It can be used to construct an electronic switching element, as it is easily integrated with planar circuitry and capable of high speed operation [21]. This is due to PIN Diode relative simplicity as a technology, miniature size and low cost, reliability, and not in the least, excellent power handling and switching performances at microwave frequencies. PIN Diode is a semiconductor diode in which a high resistively intrinsic I-region is sandwiched between a P and an N-type region. When no bias is applied, the PIN Diode behaves like a capacitance, when a biased is applied; the PIN Diode behaves like an inductor [22]. Furthermore, with the latest generations of surface mount PIN Diodes, it is becoming possible to achieve a satisfactory OFF condition and performances at OV bias, which is an obvious significant advantage in many applications

On the other hand, a Gallium Arsenide (GaAs) IC switch is an integrated circuit using field-effect transistor (FET) to achieve switching between multiple paths. It acts essentially as a voltage controlled resistor. Si PIN Diodes and GaAs Metal Epitaxial Semiconductor Field Effect Transistor (MESFET) have different characteristics that must be considered when designing a SPDT switch. Fundamental system operating conditions governing the switch design are [23]:

- Single or Dual DC bias voltage control and amount of DC bias current for each polarity.
- Total of RF power handling.
- Require linearity to satisfy the BER specification

Basically, Si PIN Diode is selected for the design work due to MESFET have advantages of power consumption and layout area while Si PIN Diode presumably has the advantages of high power handling capability and very good linearity. Switching powers of GaAs switches are limited by relatively low peak currents in the ON state (typically, in the range of 100–300 mA/mm) and by low Breakdown Voltages in the OFF state (typically below 15–20 V) [24]. Further, Si PIN Diode has higher Breakdown Voltage of 50V and large junction's area to handle for high power level that fulfills the WiMAX base station power handling requirement of 20 Watt. Besides Si PIN Diode is less susceptible to Electrostatic Discharge (ESD) damage compare with GaAs PIN Diode or MESFET. In Additional, PIN Diode is more robust than a MESFET switch. It is able to tolerate switching in the presence of RF power which is also known as "hot-switching". On the contrary, the MESFET switch can be damaged by the transition through a resistance region where significant power is dissipated [25]. Thus for base station application, Si PIN Diode still the best selection compare with GaAS switch which is more suitable used in battery application like mobile devices that required very low power consumption and low RF power. For above 5 to 30MHz, the silicon PIN Diode switch generates less distortion and consequently achieves a high third order intercept point than FET base switch [26, 27]. So if better distortion performance is required in base station application, then the Si PIN Diode is superior.

A summary of the differences between PIN diodes and FETs used as switching an element is shown Table 2.3 [28]. The comparisons are between "generic" PIN Diodes (both Si and GaAs) and FETs (MESFETS and PHEMTs) from no particular foundry.

Table 2.3: The differences between PIN Diodes and FETs [28]

	1 micron MESFET	0.25 micron PHEMT	Silicon PIN diode	GaAs PIN diode
Number of terminals	3	3	2	2
Typical on-resistance	1.5 ohm-mm	1.2 ohm-mm	1.7 ohms	1.7 ohms
Typical off capacitance	0.40 pF/mm	0.32 pF/mm	0.05 pF	0.05pF
Figure of merit	265 GHz	414 GHz	1872 GHz	1872 GHz
Breakdown voltage	15 volts	8 volts	50 volts	30 volts
Lower frequency limit	DC	DC	10 MHz	10 MHz
Driver circuit complexity	low	low	high	high
Driver requirements	0 volts on -5 volts off	+0.5 volts on -5 volts off	5 to 10 mA on 0 to -30 V off	5 to 10 ma on 0 to -30 V off

2.5 PIN Diode General Description

The PIN Diode is a current controlled resistor at radio and microwave frequencies. It is a silicon semiconductor diode in which a high-resistivity intrinsic I region is sandwiched between a P-type and N-type region as shown in Figure 2.12. It is a diode with a wide, lightly doped 'near' intrinsic semiconductor region between a p-type semiconductor and n-type semiconductor regions. The p-type and n-type regions are typically heavily doped because they are used for ohmic.

In the PIN Diode, the P contact is the anode, and the N contact is the cathode as shown in Figure 2.13. The convention is that the side that DC current is injected into (under forward bias) is always called the anode. In the schematic symbol the anode is the side with the arrow, the cathode is the side with the "plate". PIN diodes can be made both on Gallium Arsenide (GaAs) or silicon.

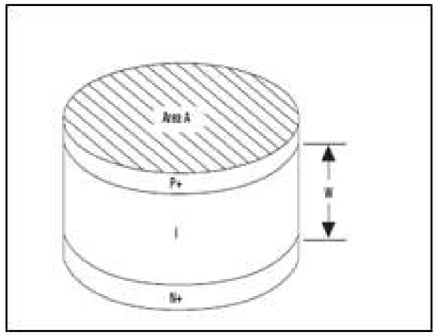


Figure 2.12: PIN Diode [29]

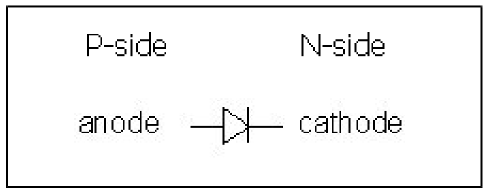


Figure 2.13: PIN Diode anode and cathode [29]

The most important feature of the PIN Diode is its basic property of being an almost pure resistor at RF frequencies, whose resistance value can be varied from approximately 10,000 W to less than 1 W by the control current flowing through it. The resistance value of the PIN Diode is determined only by the forward biased dc current. In switch and attenuator applications, the PIN diode should ideally control the RF signal level without introducing distortion which might change the shape of the RF signal. An important additional feature of the PIN Diode is its ability to control large RF signals while using much smaller levels of dc excitation. The performance of the PIN Diode primarily depends on chip geometry and the nature of the semiconductor material in the finished diode, particularly in the I-region [29].

Characteristics of PIN Diode is controlled thickness I regions having long carrier lifetimes and very high resistivity. These characteristics enhance the ability to control RF signals with a minimum of distortion while requiring low dc supply.

2.6 Types of PIN Diode

Basically, there are 3 different types of PIN Diodes for different applications which are [30]:

i) H-PIN

ii) V-PIN

iii) NIP diode

Figure 2.14 shown a horizontal PIN Diode, called H-PIN when the P and N layers are formed on top of I layer.

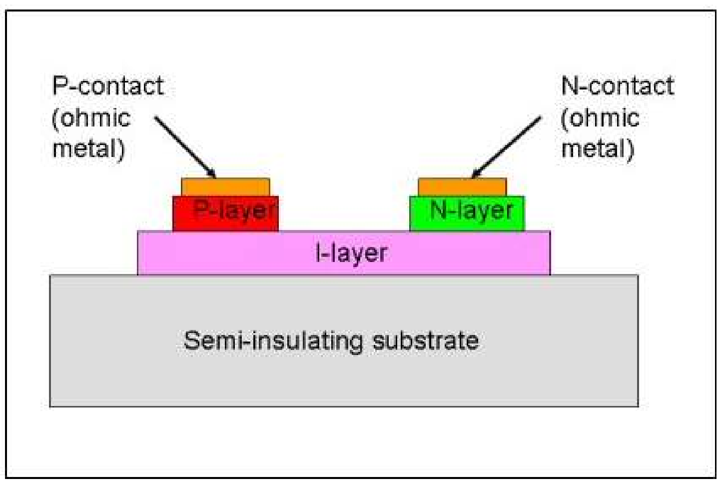


Figure 2.14: Horizontal PIN Diode [30]

For vertical PIN Diode or V-PIN, it is formed of a stack of the three materials, from top to bottom, P, I, N as shown in Figure 2.15.

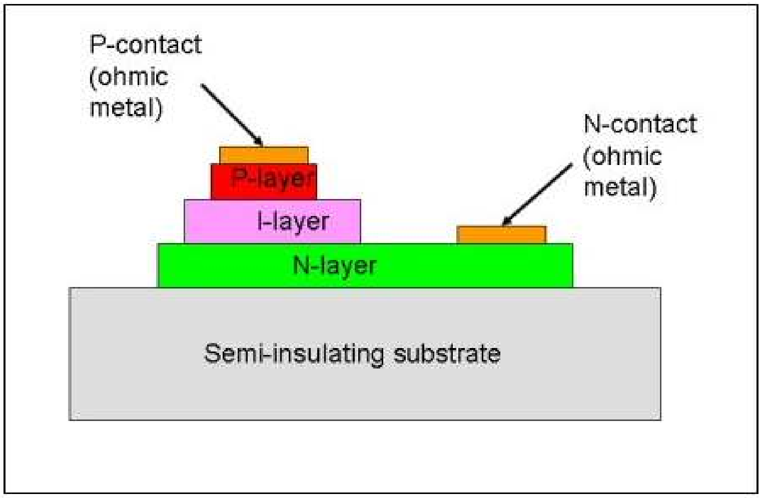


Figure 2.15: Vertical PIN Diode [30]

The structure in Figure 2.16 knows as NIP diode. It's just a PIN diode, upside down.

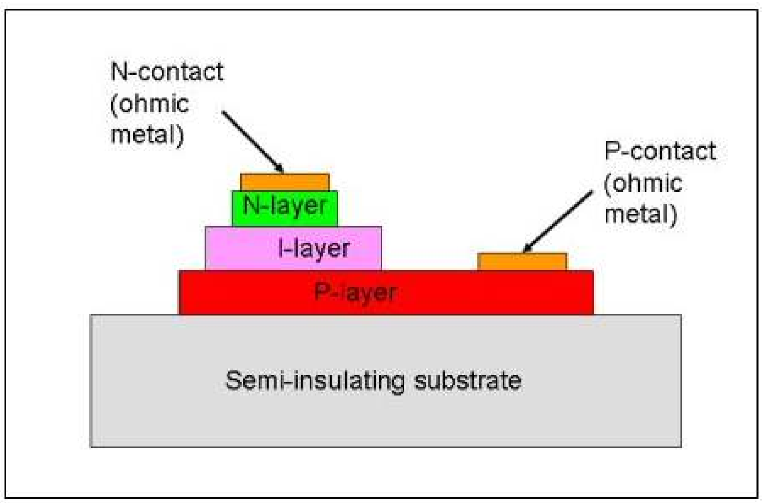


Figure 2.16: NIP Diode [30]

2.7 Forward Biased PIN Diode

Forward bias reduces I layer resistance by injecting carriers as shown in Figure 2.17. Now RF current flows through the circuit. By proper control of bias, the PIN

Diode acts as a switch, attenuator, or modulator. When the PIN Diode is forward biased, positive charges from the P region and negative charges from the N region are injected into the I layer. These charges do not recombine immediately. Instead, a finite quantity of charges always remains stored and results in a lowering of the I-region resistance [31].

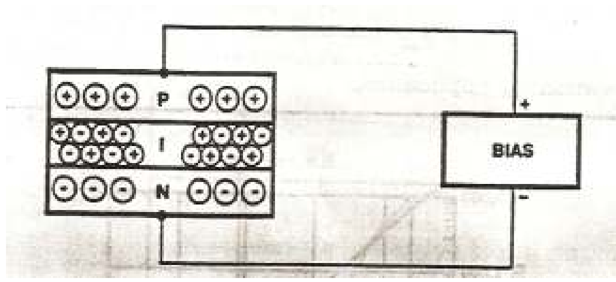


Figure 2.17: Forward bias reduces I layer resistance [31].

The equivalent circuit for the forward biased PIN Diode, Figure 2.18, consists of a series combination of the series resistance (R_s) and a small Inductance (L). The resistance of the PIN Diode under forward bias as show in Figure 2.19 is inversely proportional to the total forward bias current (I_f), making the PIN Diode perfect for achieving excellent isolation at high frequency for Avago Technologies HSMP 386x PIN Diode. L depends on the geometrical properties of the package such as metal pin length and diameter [32]. The lowest impedance will be affected by the parasitic inductance, L, which is generally less than 1nH.