CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

High Power 16-Way Compact Power Divider / Combiner and Power Amplifiers Design for S-Band Radar Transmitter Application

by

Ammad Ahmed

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Electrical Engineering

2018

This work is dedicated to my parents, wife, daughters, brother, sister, and Dr. Ali Imran for guiding me with love and patience.

CAPITAL UNIVERSITY OF SCIENCE & TECHNOLOGY
ISLAMABAD

CERTIFICATE OF APPROVAL

High Power 16-Way Compact Power Divider / Combiner and Power Amplifiers Design for S-Band Radar Transmitter Application

by

Ammad Ahmed

MEE 143019

THESIS EXAMINING COMMITTEE

S. No.	Examiner	Name	Organization
(a)	External Examiner	Dr. Junaid Mughal	CIIT, Islamabad
(b)	Internal Examiner	Dr. Noor Muhammad Khan	CUST, Islamabad
(c)	Supervisor	Dr. Ali Imran Najam	CUST, Islamabad

Supervisor Name
Dr. Ali Imran Najam
May 2018

Dr. Noor Muhammad Khan
Head
Dept. of Electrical Engineering
May 2018

Dr. Imtiaz Ahmed Taj
Dean
Faculty of Engineering
May 2018

Author's Declaration

It is declared that this is an original piece of my own work, except where otherwise acknowledged in text and references. This work has not been submitted in any form for another degree or diploma at any university or other institution for tertiary education and shall not be submitted by me in future for obtaining any degree from this or any other University or Institution.

(Ammad Ahmed)

Registration No: MEE 143019

Plagiarism Undertaking

I solemnly declare that research work presented in this thesis titled "*High Power 16-Way Compact Power Divider / Combiner and Power Amplifiers Design for S-Band Radar Transmitter Application*" is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been dully acknowledged and that complete thesis has been written by me.

I understand the zero tolerance policy of the HEC and Capital University of Science and Technology towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS Degree, the University reserves the right to withdraw/revoke my MS degree and that HEC and the University have the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized work.

(Ammad Ahmed)

Registration No: MEE 143019

Acknowledgements

I humbly praise and grateful to ALMIGHTY ALLAH, Who permits me to live and accomplish tasks including the research work being presented in this thesis.
Dr. Ali Imran Najam, my Supervisor is the person who was always there to help me during my entire graduate program. I would have been no where without him. I am very proud to have work under his supervision. I offer my sincerest thanks to him for his many years of patience, guidance, illustrious advices, useful suggestions, kind and dynamic supervision throughout the research work. His personal interest, valuable suggestions, most co-operative, constructive and thoughtful affectionate behavior resulted in completion of this thesis.
I must also thank the CUST administration for providing me an excellent environment, perfect for conducting research for MS Studies.
I am also thankful to Dr. Aamir Iqbal Bhatti , Dr. Noor Muhammad, Dr. Amir Qayyum, Dr. Sajad, all teachers and other staff members of CUST for their cooperation, help and valuable suggestions. I am also using this opportunity to thank all my friends who prayed for me and encouraged me through their love and sincerity.
May ALLAH bless all these wonderful people

Abstract

In radar transmitter systems, high power amplifier design along with the high power divider/combiner for parallel amplification is one the most critical area. To design the high power divider/combiner, high power handling capability with low insertion loss and high isolation are necessarily required. In addition, impedance matching design of power amplifiers throughout the operating frequency band is also a great challenge in radar transmitter design. This research aims at designing and implementation of an equal split 16-way Wilkinson power divider/combiner at a frequency range of 2700 to 3000 MHz. Furthermore, transistor input and output impedance matching networks are designed and simulated using Advance Design System (ADS) software.

The circuitry hardware is implemented on Rogers RT/Duroid 5870 substrate and simulated in ADS 2016. With simulations, 16-way divider/combiner exhibits insertion loss between -12.181 dB to -12.50 dB, Return loss better than -18.656 dB and Isolation more than -25 dB over the entire frequency band of 2700 MHz to 3000 MHz is achieved.

In the next phase, 75W PH2731-75L is selected as RF transistor whose impedance matching networks are designed and simulated in ADS. In simulations, Return Loss better than -18dB for input matching and better than -16dB for output matching network is achieved in simulations. After achieving the desired results in simulations, layout is designed for fabrication. After fabrication, module is tested and the measured results are compared with the simulated results.

Contents

List of Figures

Abbreviations

PSR	Primary Surveillance Radar
SSR	Secondary Surveillance Radar
IFF	Identification Friends and Foe
RF	Radio Frequency
PRF	Pulse Repetition Frequency
T/R	Transmitter Receiver
DS	Diversity Selective
EM	Electro-mechanical
FET	Field Effect Transistors
RL	Return Loss
VSWR	Voltage Standing Wave Ratio
SPST	Single Pole Single Throw
SPDT	Single Pole Double Throw
ADS	Advanced Design system
VNA	Vector Network Analyzer
IL	Insertion Loss
WPD	Wilkinson Power Divider
DUT	Device Under Test

Symbols

τ	Carrier lifetime
P_D	Maximum average power dissipation
C_T	Total capacitance in reverse bias condition
R_p	Parallel resistance when PIN diode is reverse bias
R_s	Series resistance of a PIN diode when it is forward bias
V_r	Reverse breakdown voltage
ϵ	Dielectric constant
ϵ_r	Dielectric constant of medium
A	Area of diode junction
V^+	Incident voltage wave amplitude
V^-	Reflected voltage wave amplitude
Γ	Voltage reflection coefficient
Z_O	Characteristic impedance
Z_L	Load impedance
T_{FR}	Forward bias to reverse bias transition time
T_{RF}	Reverse bias to forward bias transition time
P_{av}	Maximum available power
V_g	Generator voltage
Z_{in}	Input impedance
$Z_{microstrip}$	Microstrip line impedance
w	Conductor width
h	Substrate thickness
t	Conductor thickness

Chapter 1

INTRODUCTION

1.1 Background of Radar

Radar is an acronym of radio detecting and ranging. Radars basic principle of operation is similar to the principle of sound wave reflection. Time required for an echo is representative of target range, i.e. the distance from person to target [1]. Distance may be calculated by basic formula, distance = velocity × time. Radar uses electromagnetic (radio frequency) energy pulses as shown in Figure 1.1. Radio frequency energy is emitted by transmitter and object in path reflects back the pulse to radar antenna. Returned energy is also known as echo, and direction and distance is calculated by radar using echo coming from reflecting object [1].

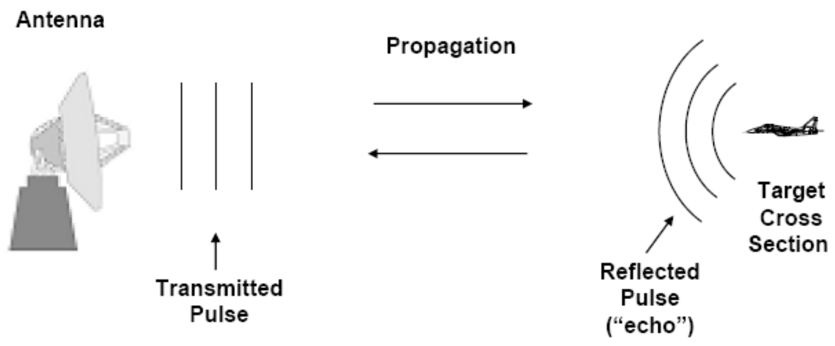


Figure 1.1: Radar Principle [1]

1.2 Main subsystems of Radar:

The main subsystems of Radar are classified as follow:

1.3 Antenna:

RF energy from the transmitter is radiated through antenna subsystem. Antenna subsystem radiates RF energy in a directional beam and collects the returning echoes. Returned echos are transferred to the receiver with a minimum loss. Antenna subsystem includes the antenna, waveguide and transmission lines from the transmitter to radiating antenna, and the transmission line and waveguide from the antenna to the receiver. Sometimes the duplexer is also considered as a component of the antenna subsystem.

1.4 Receiver

Weak echo signals from the antenna system are fed to the receiver that amplifies, detects the pulse envelope, amplifies the pulses, and then routes the signal to the indicator. Primary feature of the radar receiver is to convert high frequency signal received back to a lower frequency that are easy to amplify. This is because radar frequencies are very high and are difficult to amplify. Lower frequency is called IF (Intermediate Frequency). Type of receivers, which performs frequency conversion, are called super heterodyne receivers. Utilization of Super heterodyne receivers in radar systems must ensure best stability and extremely high sensitivity. Stability is confirmed by carefully designing the overall sensitivity, which is greatly increased by the use of multiple IF stages

1.5 Transmitter

The transmitter of radar generates high power electromagnetic pulses at a specific time intervals. Said high power is achieved by using a high power microwave oscillator, such as a klystron, magnetron or a microwave solid-state amplifier. The most important parameter of any radar transmitter is its power amplifier portion.

1.6 Power Amplifier

RF power amplifiers are a type of electronic amplifier that converts a low power RF signal into a higher power RF signal. RF power amplifiers drivers are the main component of radar transmitter. Designing goals are often, power output , high bandwidth, power efficiency high gain, , linearity, heat dissipation and input / output impedance matching, and. The main portion of any radar transmitter is its power amplifier stage. To achieve the desired power which is normally in kilowatts, multiple RF power amplifiers are used in parallel topology. When multiple RF amplifiers are implemented in parallel topology, the use of high power divider/combiner becomes critical. Therefore the two things which are the most critical in high power radar transmitter are:

(a) RF amplifier Designing

(b) High Power Divider Combiners

The important parameter in designing RF amplifier is its input and output impedance matching. RF amplifier key parameters like maximum power transfer, return loss are related to impedance matching. Amplifier optimum power rating can be achieved if its input and output impedance matching is done properly. Better the impedance matching better will be the performance of amplifier and it can be used in its optimum power rating. If impedance matching is not properly implemented it may result in producing standing waves and amplifier optimum rated cannot be achieved. The power divider and combiner plays a vital role in RF circuitry of present day solid state transmitters. Power Dividers and combiners can directly influence the RF amplification and output power of the transmitter. The role of high power divider/combiner becomes very critical when large number of power amplifiers implemented in parallel topology. Parameters like Insertion loss, Return Loss, Isolation, Power handling is very important while designing high power divider/combiner.

1.7 Problem Statement

When designing RF power amplifier, transistor input and output impedance matching becomes very critical. To achieve the optimum input & output Return Loss across the complete frequency band is very challenging. Size of matching networks is also needs to be considered due to the constraint of limited available space. Power divider / combiner is a critical part of a solid state transmitters. To achieve linearity between all the output ports of divider/combiner is very challenging along with other parameters like Return Loss, Isolation between the ports & Power handling. Size limitation is also the constraint.

1.8 Objective

The objective of this research is to design, simulate, fabricate and analyze the 16 way power divider/combiner in power amplification stage of S-band radar. The operating frequency band is from 2700MHz to 3000MHz. For 16way divider combiner, amplitude linearity better than 0.75 dB is of prime interest. Furthermore in implementation of input and output impedance matching networks of RF power transistor, input and output Return Loss better than -10dB is also desired.

1.9 Summary

In this chapter, the research background, problem statement and objective is stated clearly so that the reader could have a clear understanding about this research.

Chapter 2

RF POWER DIVIDERS / COMBINERS AND POWER AMPLIFIERS

2.1 Introduction to Power Dividers / Combiners

Power couplers/dividers are microwave components, passive in nature and are used for power combining or power division. In power division, an input signal is divided into two or more signals of lesser power. There are several types of microwave power dividers on the basis of the functions they perform such as Wilkinson power divider, T-junctions, ring coupler & hybrid junctions.

2.2 Types of Power Dividers / Combiners

Some of the existing techniques for power divider and combiner are studied and mentioned below:

2.3 Wilkinsons Power Divider (WPD)

Wilkinsons Power Divider (WPD) is a three-port microwave passive device and has the advantage of being matched at all ports and lossless. Wilkinson PCDs established $\lambda/4$ wave transformers to match the split ports to the common port. This is a popular power divider / combiner technique since it is convenient to implement therefore it has few extremely useful properties such as, it provides large isolation and matched at all ports, it provides reciprocity and it is lossless when all output ports are matched. A 2-way Wilkinson power divider uses $\lambda/4$ impedance

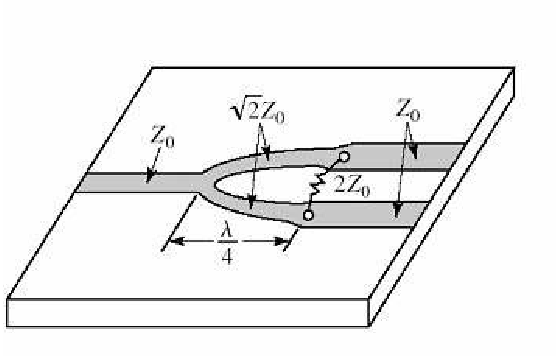


FIGURE 2.1: Basic Wilkinson Power Divider (Microstrip form) [2]

transformation with characteristic impedance of $\sqrt{2}Z_o$ and a lumped isolation resistor of $2Z_o$ with three ports matched, high isolation between all the output ports is achieved [2]. The design of a 3 dB equal split Wilkinson power divider is often made in stripline and microstrip technologies, depending on requirements. The designs considered in the present research is microstrip based, as depicted above in Figure 2.1. The equivalent transmission line network is given in Figure 2.2.

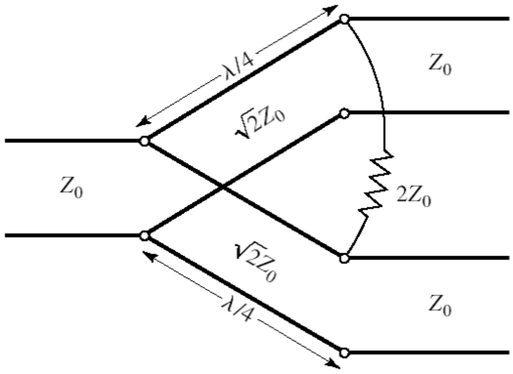


FIGURE 2.2: Equivalent Transmission Line Circuit [3]

2.4 Hybrid Couplers

Hybrid coupler is a 4 port, 90 degree device which can be utilized in both equally split networks were an input signal is required to be split in two paths with phase shift of 90 degree in-between them, or it can be used to combine two signals by keeping high isolation between them. 90-degree Hybrid couplers gives benefits of low insertion loss, less VSWR and comparatively high power rating in a small dimensions as per requirements. The basic type of a hybrid coupler is given in

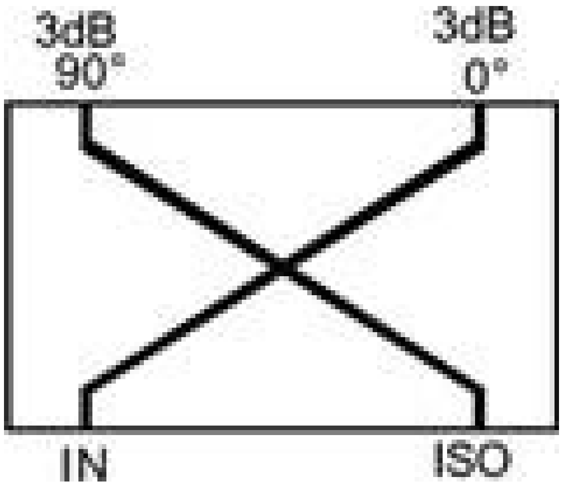


FIGURE 2.3: Basic Type of Hybrid Coupler [3]

Figure 2.3, which depicts two crossed lines of transmission having a length of $\lambda/4$ wavelength, with center frequency of operations. While power is given at the input port, the 3dB (half power) flows to the first 0^o port and the remaining half power goes to the 90^o port (in the opposite direction). Reflections from mismatched network goes back at the output ports and further goes directly to the ISO port or get cancelled at the input port. That is the reason why hybrid couplers are widely used for splitting high power signals in many applications where requirements exists of rejecting unwanted reflections that can easily damage the driver devices.[3]

2.5 Limitation of Hybrid Couplers

Hybrid couplers cost, size, interferences and limited bandwidth are most of the time biggest drawbacks/ limitations in their implementation. Keeping in view these limitations, developers are required to provide a vast set of designs to satisfy multiple frequency bands. It must be noted that 90^o hybrid couplers if used as an improved design have to be tuned at some specific frequency, as per the system requirements. [3]

2.6 Hybrid Ring Couplers

Hybrid Ring Couplers (3 dB) with 0^o and 180^o splitted ports are also known as 'rat-race coupler', it is designed and capable for high power applications, hybrid ring like four port devices are generally optimized to sum up two inphase signals with no loss or used to equally split an input signal with less difference in phase between inputs and outputs and fourth port is terminated. It is also possible that the hybrid ring coupler may be configured as 180^o phase shifted, dividers output or otherwise to sum two 180^o phase shifted signals combined with no or very less loss. Fourth port is thus terminated [3].

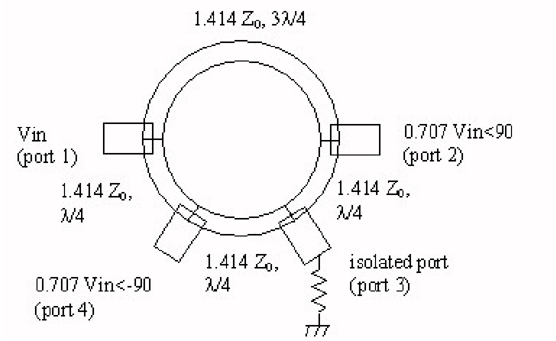


FIGURE 2.4: Rat-Race or Hybrid Ring or Coupler (with equal power split) [4]

2.7 Limitation of Hybrid Ring Couplers

The main limitation of the hybrid ring couplers is that it is not symmetric on all its ports, by selecting different ports as an input it is not mandatory that it will give same results.[3]

2.8 Comparison of Different Power Dividers/ Combiners

Dividers and combiners have a wide variety available. They come in waveguides and strip line which may have in phase or out of phase output, can have equal power division or unequal. So the requirement of application where it is to be used decides the specification. In this research, different designs of a power divider/-combiner which can meet the specifications given in Table 2.1. Multiple designs were studied to implement a power splitter/ combiner which can full fill given requirements, following pros and cons table was made to choose the most feasible design among them:

Design Name	**Pros and Cons**
Lossless T-Junction **(POZAR 2011)**[4]	**Pros:** Lossless, matched from input, can be used to make equal split 16-Port power divider, can be matched looking into input port **Cons:** No isolation in between the output. ports, mismatch looking into output. ports, susceptance at junction makes it narrow band Resistive
(POZAR 2011)[4]	**Pros:** Lossless, can be matched from input and output, can be used to make equal split 16-Port power divider **Cons:** Lossy, no isolation between output ports
Wilkinson Power Divider As a Proposed design	**Pros:** Lossless*, matched, perfect isolation, easy implementation of equal split 16-Port power divider **Cons:** Uses lumped resistor for isolation
Gysel (S.Banu 2012)[5]	**Pros:** High isolation between output ports, Low insertion loss, Matched conditions at all ports, high power-handling capability, monitoring capabilities. for imbalances at the input .ports **Cons:** Low bandwidth, multiple resistors(resistive losses), relatively larger in size than WPD
Wilkinson Power Divider (DIN APRIL 2007)[6]	**Pros:** High isolation between. output ports, Low insertion loss, matched conditions at all ports, High bandwidth **Cons:** Three cascaded sections of WPD for 2x1 port splitter with a lumped inductor and capacitor in last section,
Coupled with Open Stub Line (S. C. Siva Prakash MAY 2015)[7]	**Pros:** High isolation between. output ports Low insertion loss**, , matched conditions at all ports, High bandwidth **Cons:** A 2x1 port splitter requires four quarter wavelength coupled lines and two resistors, much larger in size than simple WPD, more insertion loss in comparison to WPD
WPD using Stepped Impedance and Shunt Open Stubs (Soman n.d.)[8]	**Pros:** Low insertion loss, high isolation between output ports, High bandwidth, compact **Cons:** A 2x1 port splitter requires two open stubs and one resistor

Table 2.1: Pros and Cons of different Power Divider Design

* When the signals at port 2 and 3 are in phase and have equal magnitude

** In comparison to majority high bandwidth power dividers

First two designs of Table 2.1 does not provide isolation between the output ports, along with this T-junction has mismatches while looking into output ports and resistive divider is matched from all the ports but it has losses, therefore these two designs were rejected in preliminary examination. Literature suggests that rest of the five designs full fill all the desired specifications so there was a tough competition between them. The last four designs are the Wilkinson Power Divider. Gysel (S.Banu 2012)[5] power divider has been designed for high power applications, it uses two additional shunt resistors for power dissipation which makes it more difficult to fabricate in strip line, and it is also relatively larger in size than Wilkinson Power Divider. Moreover, the given specifications does not include high power requirement, therefore this design was rejected. Another modification of Wilkinson Power Divider, modified power splitter (DIN APRIL 2007)[6] was originally designed for Radar and electronic intelligence system where wide bandwidth is required for frequency hopping and frequency sweeping. It has high bandwidth, excellent isolation between output ports and low insertion loss but for 2x1 port splitter it has three cascaded sections of Wilkinson Power Divider and an inductor and a capacitor in the last section. For 16x1 port transmission their size will be much larger than the simple Wilkinson Power Divider. Similarly, last two dividers of Table 1 are modified to increase the operational bandwidth which make them either difficult to implement or larger in size with increased insertion loss than original Wilkinson Power Divider.

To keep the design simple which full fills our requirement, simple to understand mathematically and intuitively, and easy to extend to 16x1 port design while fulfilling the given requirements, Wilkinson Power Divider was selected to design and simulate in ADS. It also has excellent characteristics of matched impedance at all ports, lossless (for equal and same phase power), good isolation, compact, and can easily be fabricated using cost effective readily available materials.

2.9 Wilkinson Power Dividers/ Combiners as a Selected and most Feasible Design

Wilkinson Power Divider is the most feasible design because it is the simplest and easiest power divider which satisfactorily meets all the specifications given in Table2.1. The Wilkinson power divider may be considered the best, because of its optimizable characteristics over defined band. This design also demonstrated a higher port to port return loss, a higher isolation value and the straight quarter-wavelength transmission lines, which is easy to design. In any case, each of this design provides improved performance over the hand-made design, especially considering equal-split power division as the main goal. Basic design parameters of Wilkinson power divider and figures of merit are analyzed, calculated for the design and fabrication as given in chapter 4 of this research.

2.10 Power Divider/Combiner Figure of merits

The performance of the Wilkinson divider/coupler is commonly evaluated by the following figures of merits:

2.10.1 Return Loss

Return loss of a device is defined as the ratio of reflected power to incident power at its input. Since the power is proportional to the square of the voltage at that point, it may be found as shown below. Generally, it is expressed in dB as shown in Equation 2-1.

$$RL_{12}[dB] = -20log|S_{11}| \tag{2.1}$$

Return loss at port 1 and 2

2.10.2 Insertion Loss

The term Insertion Loss is defined as the ratio of output transmitted power i.e power available at the output ports to the incident power at the input port. Transmitted power is equal to the difference of incident and reflected powers for a netwrk considered lossless. The insertion loss can be calculated by using Equation 2-2.

$$IL_{23}[dB] = -20log|S_{23}| \tag{2.2}$$

Isolation between port 2 and 3

2.10.3 Isolation

The term isolation is given as the ratio of a signal entering output port number 1 that is measured at output port number 2, with the assumption that all other ports are impedance matched usually matched on 50. Generally value of isolation better than 15 dB are taken as good, however Wilkinson power dividers, can give isolations better than 20 dB. Equation 2-3 for isolation is given below:

$$CP_{12}[dB] = -20log|S_{12}| \tag{2.3}$$

Isolation or Coupling between ports1 and 2

2.11 RF Power Amplifiers

RF power amplifier is a one of the types of amplifiers used in electronics that functions by converting less power RF signal into a signal of relatively higher power. Generally, in radar engineering Radio Frequency power amplifiers are used in transmitters to drive the RF energy from antenna. Goals to design RF power amplifiers are often gain, bandwidth, output power, linearity (low. signal. compression. at rated output), power efficiency at input and impedance matching at output and heat dissipation. Requirement of designing the RF amplifiers in radar transmitters can be to produce thousands of kilowatts of output power, to achieve maximum coverage range of radar system. [9]

2.12 Radar Power Amplifier Technology Overview

At the end of the 20th century, the dominance or the rise in the use of semiconductor devices in electronics applications was made possible. Similar is the case with application of radar power amplifiers. Initially the Vacuum Electron Devices known as VEDs or electronic tubes were used as a Power Amplifiers devices. VEDs can output power in megawatts even at very high frequencies i.e. from 1 GHz to 100 GHz. The most common applications of VEDs in radar technology are Klystrons, TWTs (Traveling Wave Tubes), Gysrotrons and Magnetrons. TWT tubes when used as amplifiers in radar transmitters can provide amplification in multiple kilowatt peak output power with high bandwidth and can support of high frequencies, Moreover TWTs can be rugged and have high reliability factor in terms of usage. Furthermore as compared to TWT amplifiers, Klystron based power amplifiers (KPA) are even better, as they provide better. efficiency. About two decades ago usage of semiconductor based power amplifiers also known as solid state power amplifiers or SSPAs has started to replace the tubular design of amplifier especially in radar transmitter applications due to their better efficiency in design and cost effects. [9]

2.12.1 Solid State BJTs vs TWT Technology Differences

Traveling wave tube amplifiers also known as TWTAs is relatively older technology however these kind of amplifiers are still in use in some radar application and considered as a beneficial solution. On the other hand solid state amplifiers comes in many sizes and shapes , and can achieve high output power levels in small packages such as BJTs. The clear differences between the solid-state amplifiers such as BJTs and TWTAs are in terms of power output, power supplies, overall size and packaging. With the understanding of the differences between the two amplifier technologies one can choose amplifier for a required application. Size and weight are the most prominent difference between TWT and solid-state amplifiers. Moreover, power supplies in BJTs have become considerably more compact as compared to TWTAs power supplies [10].

2.13 Impedance Matching

Impedance matching is the technique of designing the input and output impedance of an. electrical load and source in such a way to maximize the power output and to minimize. reflections. Impedance matching is not only used in electronics but also used in photonics where impedance is equivalent to refractive.indices, acoustics as well as in.mechanics [11].

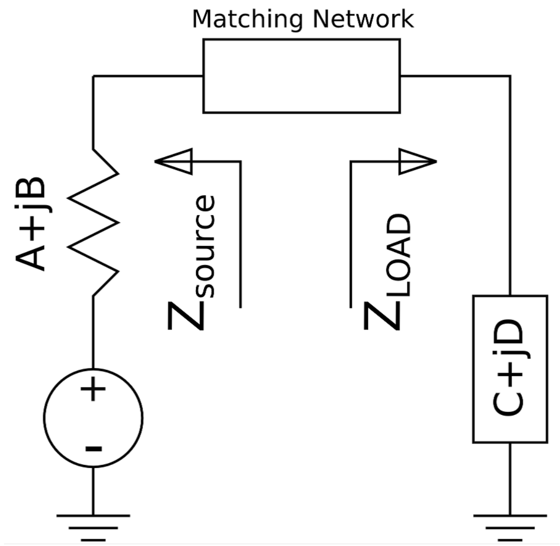


FIGURE 2.5: 4 Basic Diagram of Impedance. Matching

2.14 Impedance Matching Using Smith Chart

Smith chart consists of impedance (Z) or admittance (Y) circles with constant resistances, and curved lines also known as a persistent reactance segments. The numbers on the chart are normalized to the goal impedance i.e. 50 Ohm [12]. The admittance chart and resistive chart are given in Figure 2.6.

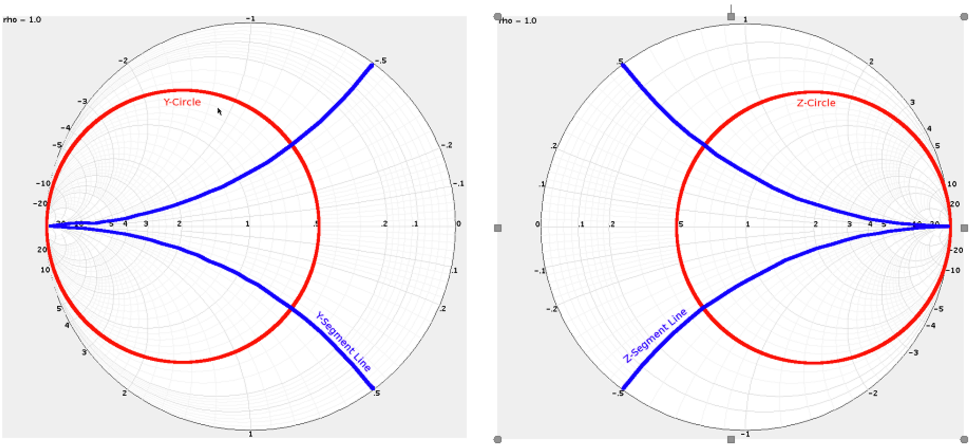


FIGURE 2.6: Admittance Chart (Y Smith) and Resistance Chart (Z Smith)

2.15 Micro-Strip Technology Overview

Since we are using microstrip technology in our proposed design, therefore brief introduction on microstrip technology is explained. A microstrip transmission line is a 'high grade' printed circuit structure, which consists of conductor or other track of copper on an insulating substrate. On the other side of this insulated structure, lies the 'backplane'. This plane is formed from the similar conductor employed to make transmission line [13]. The microstrip line width can be calculated as follow in equation 2.4:

$$Z_{microstrip} = \frac{Z_o}{2\pi\sqrt{2(1+\epsilon_r)}} ln \left(1 + \frac{4h}{\omega_{eff}} \left(\frac{14+\frac{8}{\epsilon_r}}{11} \frac{4h}{\omega_{eff}} + \sqrt{\left(\frac{14+\frac{8}{\epsilon_r}}{11} \frac{4h}{\omega_{eff}} \right)^2 + \pi^2 \frac{1+\frac{1}{\epsilon_r}}{2}} \right) \right) \tag{2.4}$$

Where, ω_{eff} is the effective width, which is actual width of the strip, moreover a correction to account for the non zero thickness of the conductor. The effective width is given by-

$$\omega_e ff = \omega + t\frac{1+\frac{1}{\epsilon_r}}{2\pi} ln\left(\frac{4\epsilon_r}{\sqrt{\left(\frac{t}{h}\right)^2 + \left(\frac{1}{\pi}\frac{1}{\frac{W}{t}+\frac{11}{10}}\right)^2}}\right) \tag{2.5}$$

The characteristic impedance Z_0 is also a function of the ratio of the height to the width w/h (and ratio of width to heighth/w) of the transmission line. According to Bahl and Trivedi I. [17], the characteristic impedance Z_0 of microstrip is calculated by:

when= $(\frac{w}{h}) < 1$

$$Z_0 = \frac{60}{\sqrt{\omega_{eff}}} ln\left(8\frac{h}{w} + 0.25\frac{w}{h}\right)(ohms) \tag{2.6}$$

when= $(\frac{w}{h}) \geq 1$

$$Z_0 = \frac{120\pi}{\sqrt{\omega_{eff} \times \left[\frac{w}{h} + 1.393 + \frac{2}{3} ln\left(\frac{w}{h} + 1.44\right)\right]}}(ohms) \tag{2.7}$$

This equation is helpful in order to roughly calculate the width of microstrip line matched to the port.

2.16 Summary

In this chapter, different RF Power Divider/Combiner techniques have been discussed briefly. Advantages, features and applications of Wilkinson based power divider/ combiner circuits make it very versatile and excellent choice for a designer to use in the development of efficient, high power Final stage Power Amplifier for radar transmitter applications. RF power amplifier design and its impedance matching through smith chart are also explained at the end so the reader can understand the theory behind implementation of 16:1 Wilkinson power divider/-combiner and amplifier design using smith chart for its impedance matching.

Chapter 3

LITERATURE REVIEW

This chapter gives an overview of 1:16 power divider/ combiner with amplifier design to transmitter output RF power of 1kW and its technological trends are presented in literature.

3.1 Compact Dual Band Wilkinson Power Divider

Said paper presents the design of a Wilkinson power divider compact in size and for two applications. The compact dual band Wilkinson power divider uses transformation section of the quarter wavelength for power divider with no short circuit stubs via holes. EM simulators are used to analyze said dual band power divider and then its is fabricated at frequency range of 1.8 and 4.5 GHz. The designed compact dual band Wilkinson power divider is designed on RT/Duroid 5870 substrate. The measurements of the designed compact dual band Wilkinson power divider shows that it is comparable to simulated results .Achieved coupling is -3 dB with a little variation. less than 0.65 dB[14]. The results for simulated and measured values of return loss S11 are given in Figure 3.2. The simulated and measured results of insertion loss (S21, S31) are given below in Figure 3.3.

FIGURE 3.1: The Realized Dual Band Wilkinson Power Divider [14].

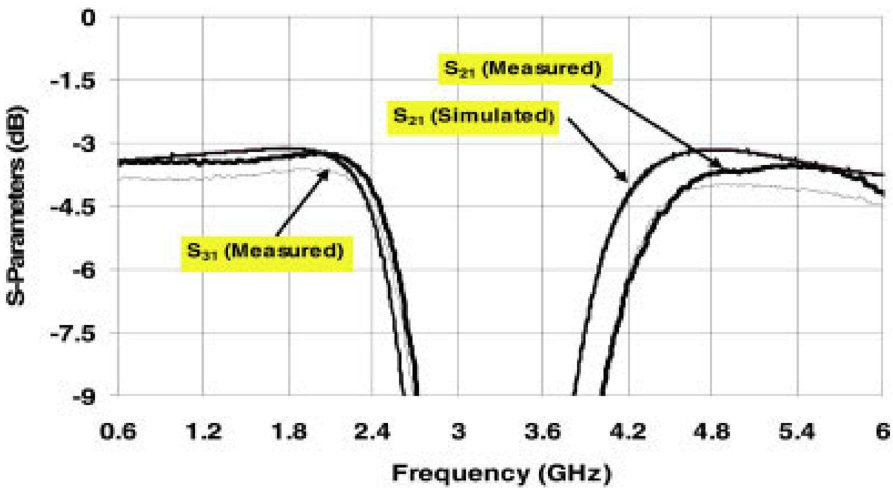


FIGURE 3.2: Simulated and measured return loss (S11) [14]

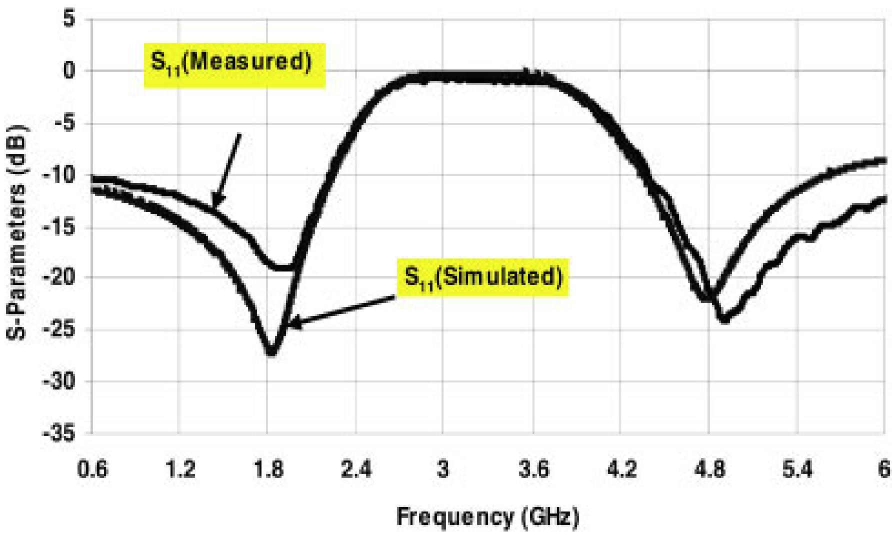


FIGURE 3.3: Simulated and measured insertion loss (S21, S31) [14].

3.2 Modified Wilkinson Power Divider 1 to 4 at S-Band as the Part of Smart Antenna for Satellite Tracking, Telemetry, and Command Subsystem

In this research paper the smart antenna system for the purpose of satellite tracking, telemetry, and command subsystem is proposed. Designed Wilkinson Power Divider has 3 ports and 5 ports. In 5 ports design it gives 4 output ports and same can operate on a frequency range of 2.3 2.45 GHz with the insertion loss of each port less than -8 dB. The theoretical maximum value is calculated to be -6 dB as the proposed power divider works by dividing power in ratio of 1:4. The Figure 3.4 given below depict the fabricated version of proposed power divider [15]. Figure

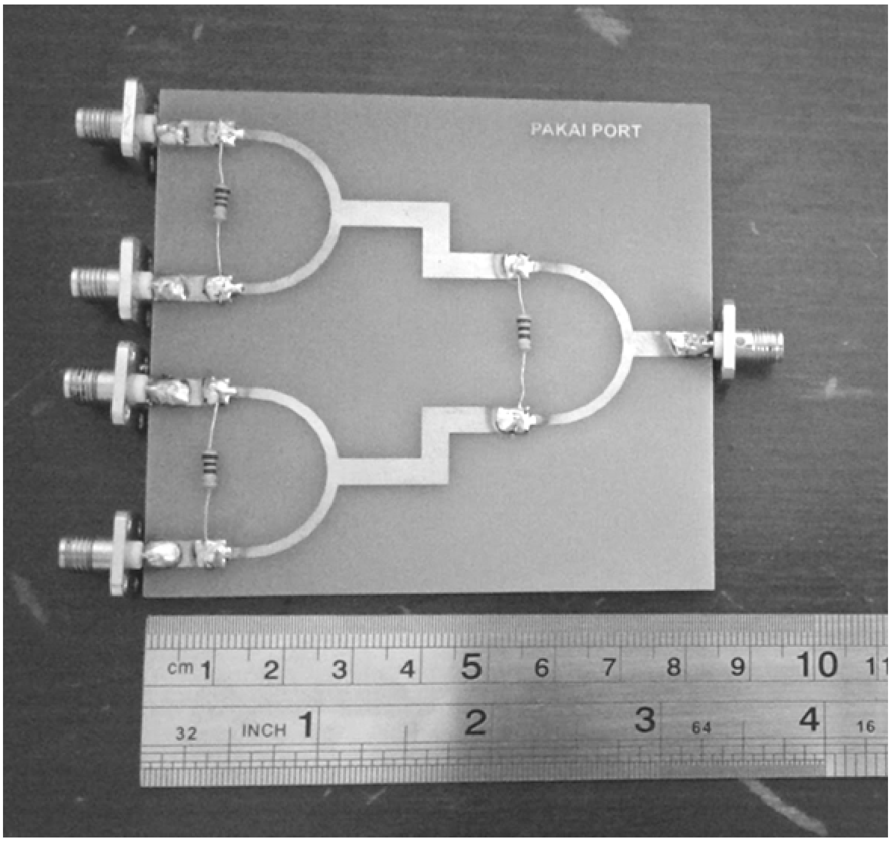


FIGURE 3.4: Fabricated Power Divider 1:4

3.5 gives Return Loss S11 in dBs and Figure 3.6 below depicts insertion lossS31 in dBs of the proposed design. Comparison of Measured and simulated results

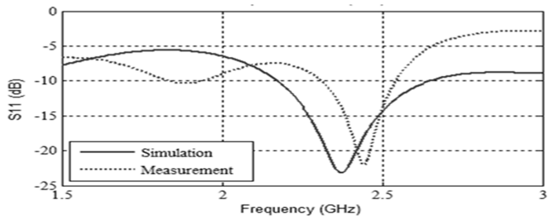


FIGURE 3.5: Return Loss (S11) dB [15]

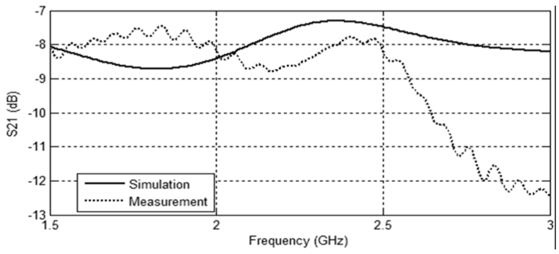


FIGURE 3.6: Insertion Loss (S31) dB [15]

are given below in Figure 3.7.

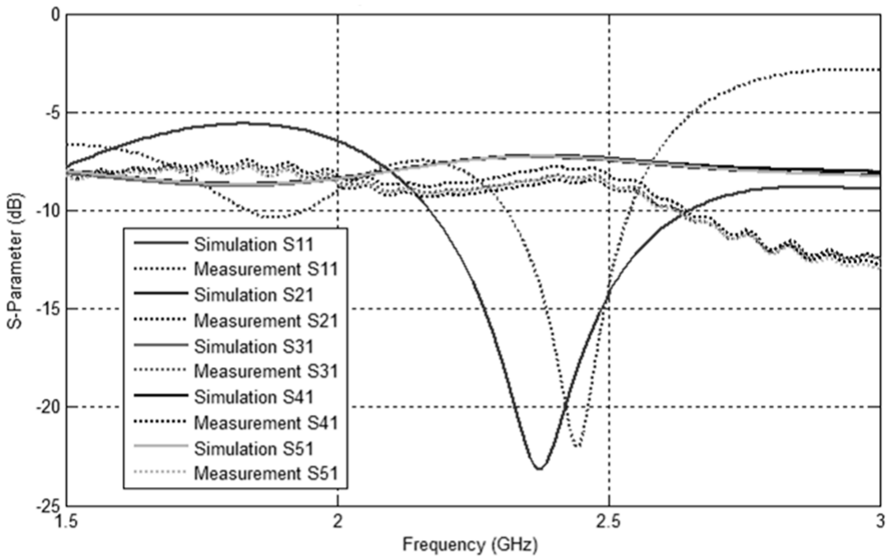


FIGURE 3.7: Measured and Simulated Results of Return Loss and Insertion Loss [15]

3.3 A New N-Way Power Divider/ Combiner Suitable For High-Power Applications

The N way Divider and Combiner technique is an extension of Wilkinson type power divider/ combiner. In this paper the difficulties realized in implementation of the original Wilkinson power divider/ combiner are improved upon by addition of an high power resistive isolation loads. It gives conveniently designable geometry and monitoring capabilities of differences at the output ports. A proposed 1:8 way power divider/ combiner has been built with center frequency of 1.15 GHz. Measured results in comparison with the simulated results shows a good coherence. However measured results depicts higher VSWR, insertion loss and isolation between the ports, therefore said design cannot be implemented for the present research. The figures below shows the N-port and 4-port network as described in this paper. The Figure 3.8 depicts proposed High power N way divider / combiner and Figure 3.9 shows equivalent circuit of four port divider/ combiner [16].

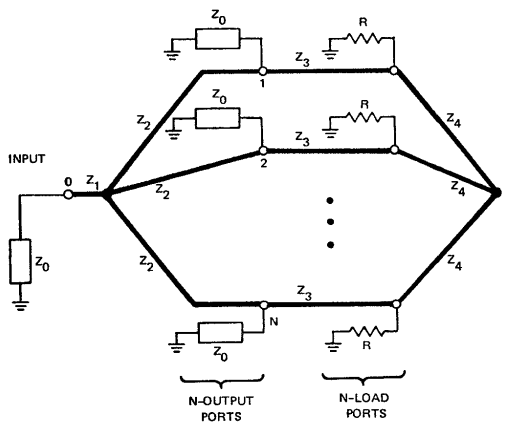


FIGURE 3.8: High-Power N-Way Combiner [16]

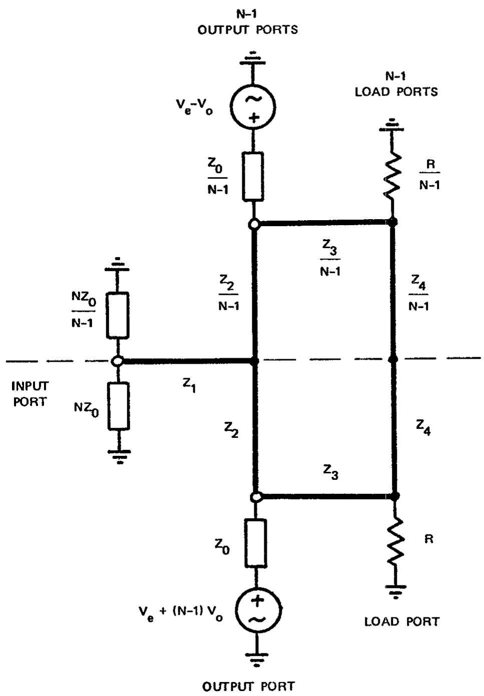


FIGURE 3.9: Equivalent Circuit of Four-Port for the Divider /Divider/ Combiner[16]

3.4 Design and Analysis of Various Wilkinson Power Divider Networks for L Band Applications

In this paper different Wilkinson Power Divider Networks by using stepped multiple sections of the conventional Wilkinson Divider designs are presented. The chosen range of operating frequency is 1.25 GHz to 1.45 GHz. Since the selected frequency range lies in the L band, these power dividers can be used as antenna arrays feeding networks in the L band. The proposed design for 2:1, 4:1, 8:1 and 16:1 Wilkinson Power Divider Networks are simulated, fabricated and verified. Figure 3.10 shows fabricated version of 8:1 Wilkinson power divider[17]. Designed Wilkinson power divider/ combiners for 2:1, 4:1, 8:1 and 16:1 as presented in the present paper shows that all output ports have almost equal power division and it gives very good isolation between the output ports at the required frequency range i.e.1.25-1.45 GHz[17].

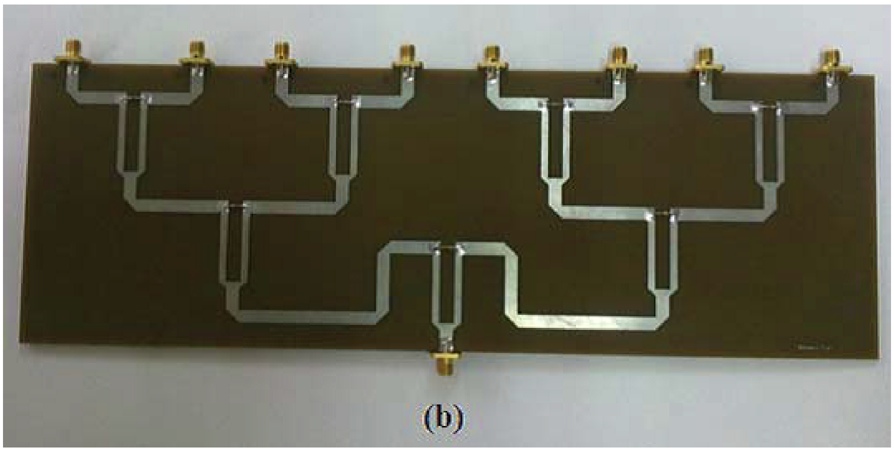


FIGURE 3.10: Fabricated 8:1 Wilkinson Power Divider [17]

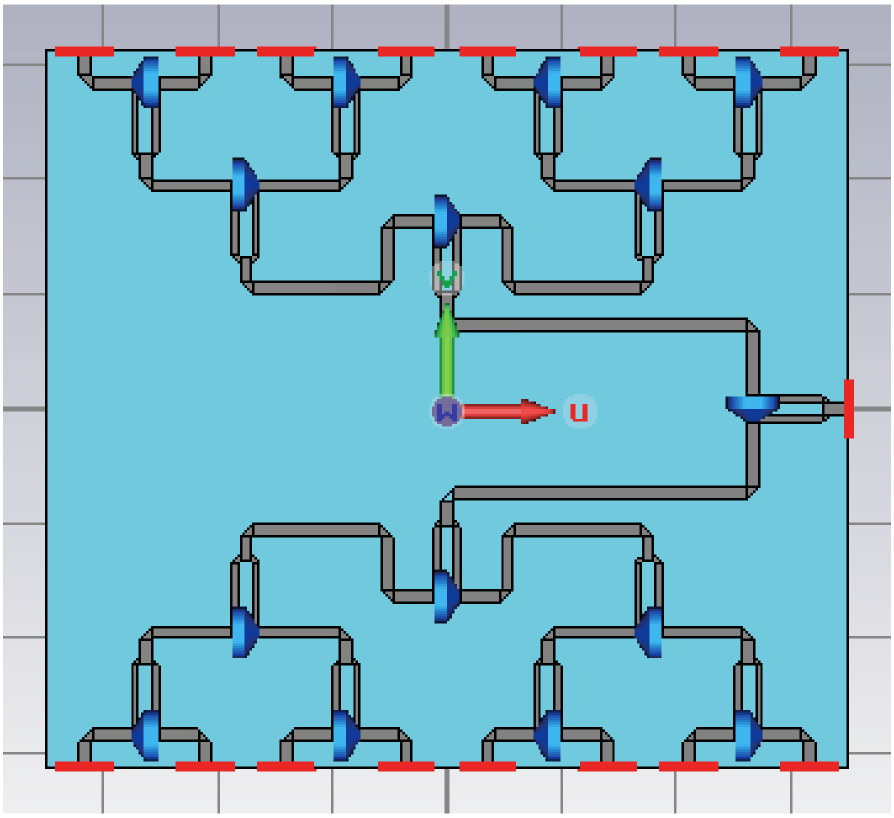


FIGURE 3.11: Shows Simulated Version of 16:1 Wilkinson Power Divider

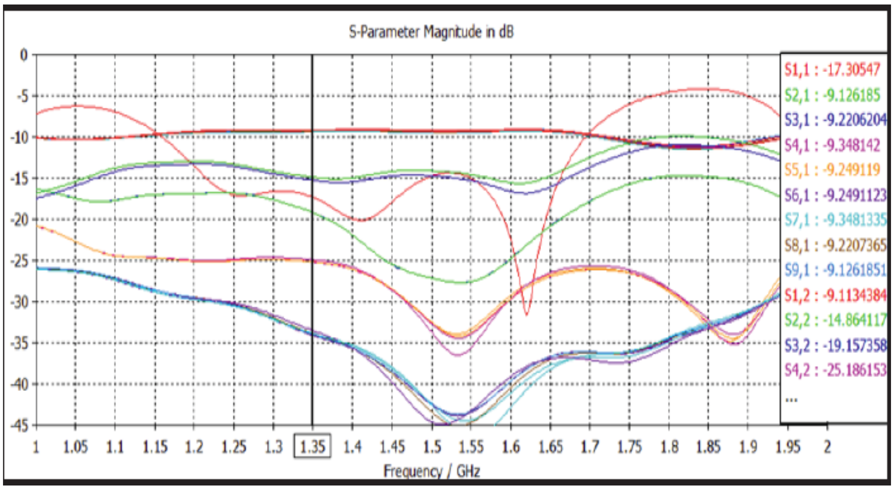


FIGURE 3.12: Simulated 8:1 Wilkinson Power Return Loss Plot [17]

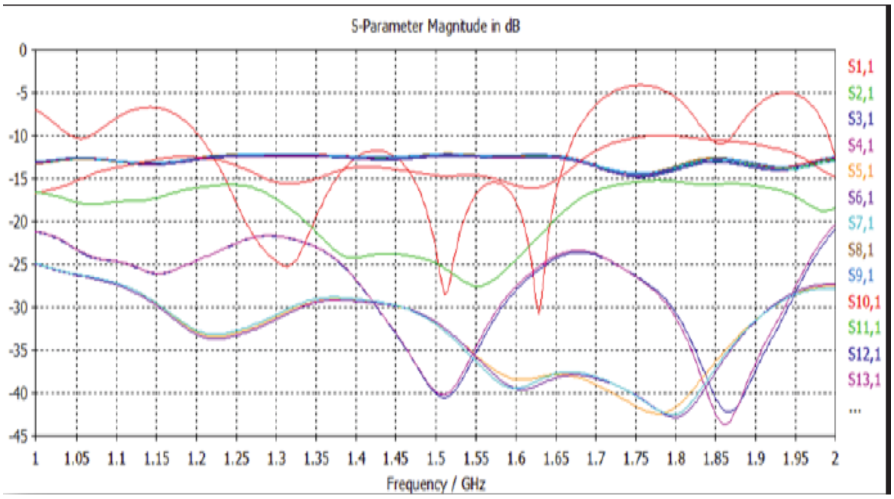


FIGURE 3.13: Simulated 16:1 Divider Return Loss Plot [17]

3.5 Design of A Dual Band Power Divider using Meander Line Technique Frequency 4928 MHz and 9856 MHz for Radar Application

In this paper design of Wilkinson power divider for dual band application by using dual impedance transmission line with stubs is presented. Meander pattern design is selected and implemented to reduce the overall size of the device. Simulated of the proposed design was done by using ADS 2011.10 software and then it is fabricated on Roger Duroid 5880 substrate. The simulated results depicts the insertion loss (S12 and S13) of -3.17 dB at frequency spot of 4928 MHz and -4.1 dB at frequency spot of 9856 MHz. At frequency of 4928 MHz the isolation S32 is better than -21 dB input return loss (S11) is less than -16 dB and output return loss (S22 and S33) where less than -17 dB and at frequency of 9856 MHz isolation is less than -27 dB isolation is less than -15 dB and output return loss is -22 dB. Figure 3.14 depicts the simulated design of proposed wilkinson power divider[18]. On both frequencies of 4928 MHz and of 9856 MHz the proposed dual

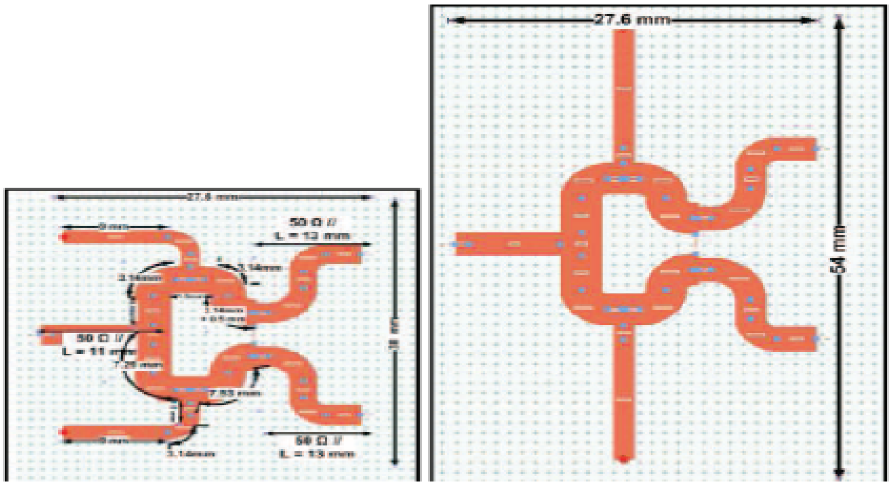


FIGURE 3.14: Simulated Design of Two-Way Dual Band Power Divider [18]

band Wilkinson Power Divider have an acceptable isolation and insertion loss, and also produce a better return loss of input and output ports. Proposed dual band power divider can further be improved in terms of isolation. The proposed design is the initial step using simulation software and it can be fabricated and utilized in many customized applications such as Low Probability of Intercept (LPI) Radars. Figure 3.15 show reflection S11of input and output ports and Figure 3.16 shows simulated results of insertion loss and isolation [18].

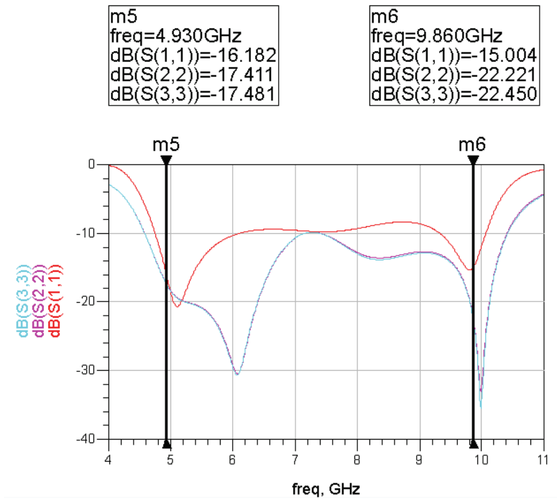


FIGURE 3.15: Simulation results of input and output ports [18]

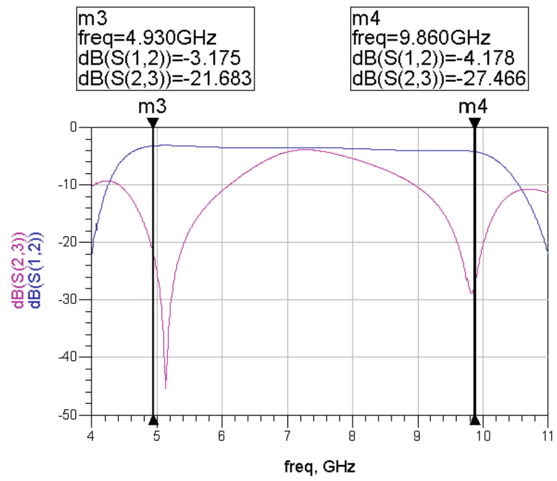


FIGURE 3.16: Simulation results of insertion loss and isolation[18]

3.6 Summary

Research on power dividers/ combiners and amplifier circuit design reveals that insertion loss is a critical parameter. While designing power dividers and combiners improvement of insertion loss is of paramount importance keeping gain, flatness over the complete frequency band. The size of the circuit required for the specific application and designing it to optimize intersection loss and other performance parameters including gain linearity, phase and amplitude balance over the required frequency band are critically important.

Chapter 4

DESIGN, SIMULATIONS AND MEASUREMENTS

4.1 Introduction

In the first part of the chapter, design approach and its utilization in the development of high power 16 way Divider / Combiner is discussed in detail. ADS-2016 is used for simulations and layout designing. In the final part of the chapter, transistor impedance matching is implemented using smith chart utility tool available in ADS-2016 [19]. Advanced Design system (ADS) 2016 from Agilent is used to validate the working principle. With the help of simulation results, it is proved that the proposed design of 1:16 power divider/ combiner provides insertion loss of -12dB with amplitude variation better than 0.75dB. After fabrication scattering parameters of proposed design are measured with the help of Agilent vector network analyzer part number E5071C.

4.2 Working Principle

The main objective of proposed research is to amplify 250 W power into greater than 1KW through 16 RF transistors in parallel topology[20]. Transistor selected in this design is PH2731-75L [21] since it has a capability to provide output power of 75W in 2700 MHz to 3000 MHz band. Input to the individual amplifier is around 15W. Input available from preamplifier is around 250 W which is divided in the ratio of 16 to drive each amplifier.

Output from each amplifier is combined through high power 16-way combiner. Combined output power is greater than 1KW. The power divider / combiner used in the proposed design is based on Wilkinson theory as discussed in chapter 2. Working principle is illustrated in Figure 4.1. The proposed design can be divided

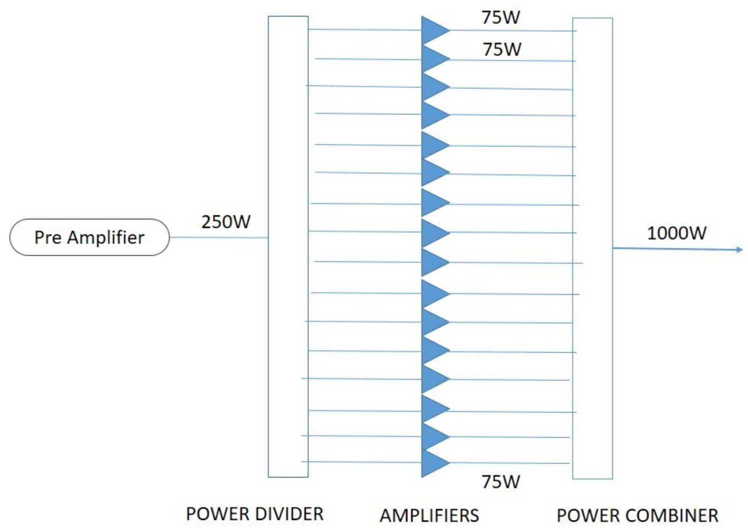


FIGURE 4.1: Working Principle of Proposed Transmitter Design

into two main parts:

(a) 16 Way power divider/ combiner.

(b) Transistor Input and Output Impedance Matching design.

At first the 16-Way Power Divider/ Combiner Design is discussed

4.3 Design Considerations

4.3.1 Substrate Selection

Roger RT/duroid 5870[22] substrate is used in the design as it offers low loss for high power amplification and its cost effectiveness. Main specifications of substrate is available in table 4.1.

Material	Roger RT/duroid 5870
Dielectric constant	2.33
Substrate Thickness	0.787 mm
Loss Tangent	0.0012
Copper Thickness	35um
Thermal Conductivity	0.22 W/K*m

Table 4.1: Substrate Specifications

4.3.2 Transmission Line Power Handling

Transmission line power handling is computed using Rogers microwave impedance calculation tool[23]. Since proposed amplifier is providing peak output power of 1 KW with 10 percent duty cycle so the average power is around 100W. From the figure 4.2, it can be seen that micro strip transmission line can handle power levels up to 500W average power.

4.3.3 Power Handling Capability of Microstrip Line

A detailed analysis for calculating the power handling capability of micro strip lines is discussed in this paper. It describes that the power handling capability of microstrip lines is limited due to the factors including heating caused by ohmic and dielectric losses. The average power handling capability is limited due to increase in temperature in conductor and its dielectric losses. Where-as the peak power handling capability is limited due to breakdown between the strip conductor and

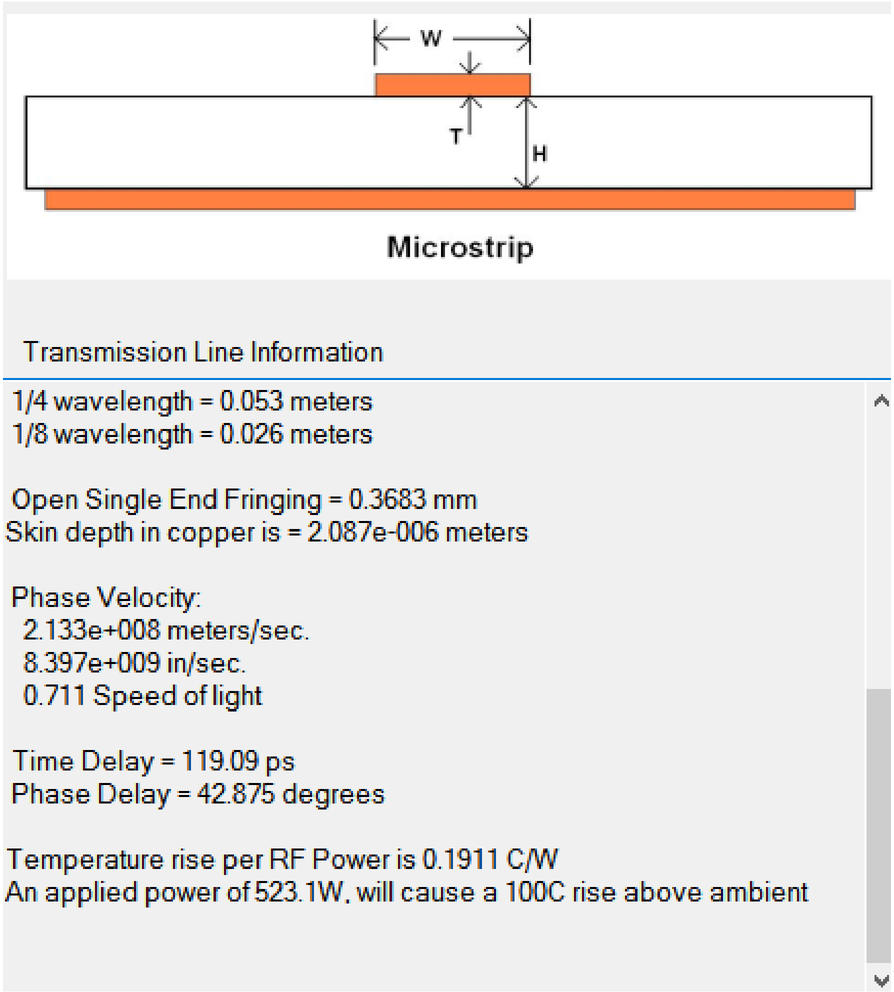


FIGURE 4.2: Transmission Line Power Handling Using Line Calc. Tool

ground plane. The parameters which affect the average power handling capabilities of microstrip line includes :

(a) Transmission line losses

(b) Thermal conductivity of the substrate material

(c) Surface area of the conductor strip

(d) Ambient temperature of the surroundings

A typical microstrip line is shown in the figure 4.3 in which,

h = Substrate thickness

t = Strip Conductor Thickness

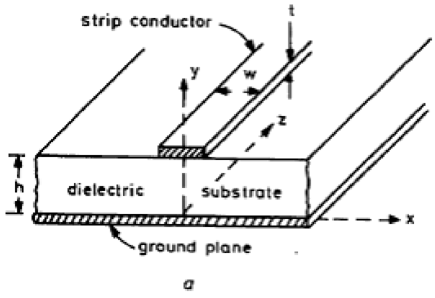


FIGURE 4.3: Microstrip Substrate[24]

W = Strip Conductor Width

The following relation can calculate the average power handling capability

$$P_{avg} = (T_{max} - T_{amb})/\Delta T \tag{4.1}$$

ΔT= Rise in Temperature per Watt

T_{max}=Maximum Operating Temperature

T_{amb}=Ambient Temperature The rise in temperature is given by the following relation

$$\Delta T = \frac{h}{K}\left(\frac{\Delta P_e}{W_e} + \frac{\Delta P_d}{2W_{eff}}\right) \tag{4.2}$$

Where K = Thermal Conductivity of Substrate

h = Thickness of strip conductor

$$\Delta P_e = 1 - e^{(-0.2303\alpha_c)} \tag{4.3}$$

Where $\alpha_c\left(\frac{dB}{m}\right)$ is the attenuation coefficient due to loss in the conductor strip

Calculation of attenuation coefficient due to conductor strip given by the relation

$$\alpha_c\left(\frac{dB}{m}\right) = \frac{8.686R_s}{Z_oW} \tag{4.4}$$

$$R_s = \sqrt{\frac{\pi f \mu_o}{\sigma}} \tag{4.5}$$

$$\Delta P_d = 1 - e^{(-0.2303\alpha_d)} \tag{4.6}$$

$\alpha_d \left(\frac{dB}{m}\right)$ is the attenuation coefficient due to dielectric loss

The relation gives calculation of attenuation coefficient due to dielectric loss

$$\alpha_d \left(\frac{dB}{m}\right) = \frac{27.3\sqrt{\epsilon_r} tan\delta}{\lambda_o} \tag{4.7}$$

$$W_e = \frac{120\pi h}{Z\sqrt{\epsilon}} \tag{4.8}$$

Where ϵ =effective relative permittivity

$$W_{eff} = W + \frac{W_{eff}(0) - W}{1 + (f/f_p)} \tag{4.9}$$

where

$$f_p = \frac{Z}{2\mu h} \tag{4.10}$$

$$W_{eff}(0) = \frac{377h}{Z\sqrt{\epsilon}} \tag{4.11}$$

4.3.4 Power Handling Capability of Rogers 5870 LM

The properties of rogers 5870 substrate are given as following :

Thermal conductivity $K = 0.2W/m.C$

Characteristic Impedance $Z = 50\Omega$

Operating frequency $f = 2800MHz$

Thickness of sheet $h = 0.000787meters$

Dielectric Constant $\epsilon_r = 2.33$

Width for 50Ω transmission line $W = 0.00322m$

Loss tangent for FR4 $\tan\delta = 0.0012$

Relative permittivity $\mu_o = 4\pi * 10^{-7}$

The average power handling capability of roger can be calculated by the using equations 4.1, 4.2, 4.3 as per the following details:

Calculation of attenuation coefficient due to conductor strip given by the relation.

$$\alpha_c\left(\frac{dB}{m}\right) = \frac{8.686R_s}{Z_oW} \tag{4.12}$$

$$R_s = \sqrt{\frac{\pi f \mu_o}{\sigma}} \tag{4.13}$$

Putting the values in the above equations results $R_s = 0.0136$

Putting the value in equation above

$$\alpha_c\left(\frac{dB}{m}\right) = 0.733 \tag{4.14}$$

The relation gives calculation of attenuation coefficient due to dielectric loss

$$\alpha_d\left(\frac{dB}{m}\right) = \frac{2.73\sqrt{\epsilon_r}\tan\delta}{\lambda_o} \tag{4.15}$$

$$\alpha_d\left(\frac{dB}{m}\right) = 0.46 \tag{4.16}$$

Since rise in temperature in degree Celsius per unit watt is given by the following relation

$$\Delta T = \frac{h}{K}\left(\frac{\Delta P_e}{W_e} + \frac{\Delta P_d}{2W_{eff}}\right)\frac{C^o}{Watt} \tag{4.17}$$

Where

$$\Delta P_c = 1 - e^{(-0.2303\alpha_c)} \tag{4.18}$$

$$\Delta P_c = 0.154 \tag{4.19}$$

And

$$\Delta P_d = 1 - e^{(-0.2303\alpha_d)} \tag{4.20}$$

$$\Delta P_d = 0.10 \tag{4.21}$$

Where

$$W_e = \frac{120\pi h}{Z\sqrt{\epsilon}} \tag{4.22}$$

and

$$W_{eff} = W + \frac{W_{eff}(0) - W}{1 + (f/f_p)^2} \tag{4.23}$$

where

$$W_{eff}(0) = \frac{377h}{Z\sqrt{\epsilon}} = 0.00039 \tag{4.24}$$

$$W_{eff} = W + \frac{W_{eff}(0) - W}{1 + (f/f_p)^2} \tag{4.25}$$

$$W_{eff} = 0.00325m \tag{4.26}$$

Putting values in main equation to calculate change in temperature per unit watt

$$\Delta T = 0.2296 \frac{C^o}{Watt} \tag{4.27}$$

If the maximum operating temperature is 100 C^o and ambient temperature is 25 C^o Then the average power handling is

$P_{av} = (T_{max} - T_{amb})/\Delta T$

$$P_{av} = 331 Watts \tag{4.28}$$

Since proposed amplifier is providing peak output power of 1 KW with 10 percent duty cycle, so the average power is around 100W. From above results, it can be seen that micro strip transmission line can handle power levels up to 331W average power

4.4 Designing in ADS-2016

Initially 2 way Wilkinson power divider/ combiner using ideal transmission lines is implemented in ADS for proof of concept given in chapter 2. Schematic was designed in ADS and its S-parameters simulations were performed. Figure 4.4 depicts schematic design in ADS. In S parameter simulations it was observed that

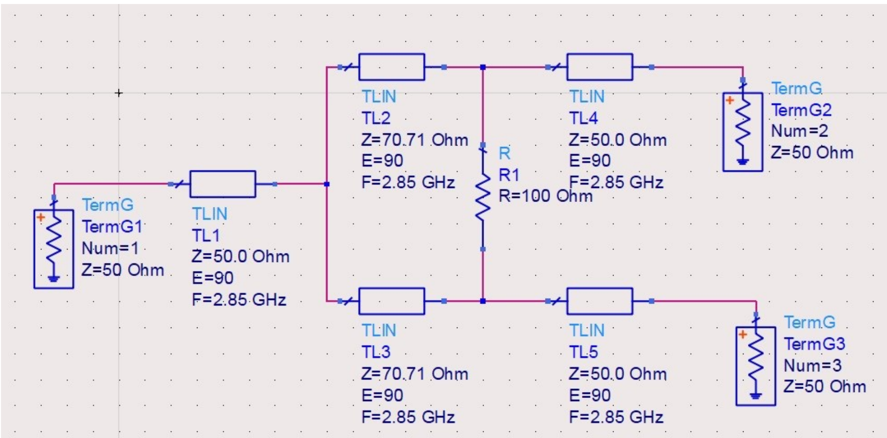


FIGURE 4.4: 2 Way Wilkinson Ideal Transmission Line Simulation in ADS

return loss better than -25dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.5. In S parameter simulations it was observed that insertion loss

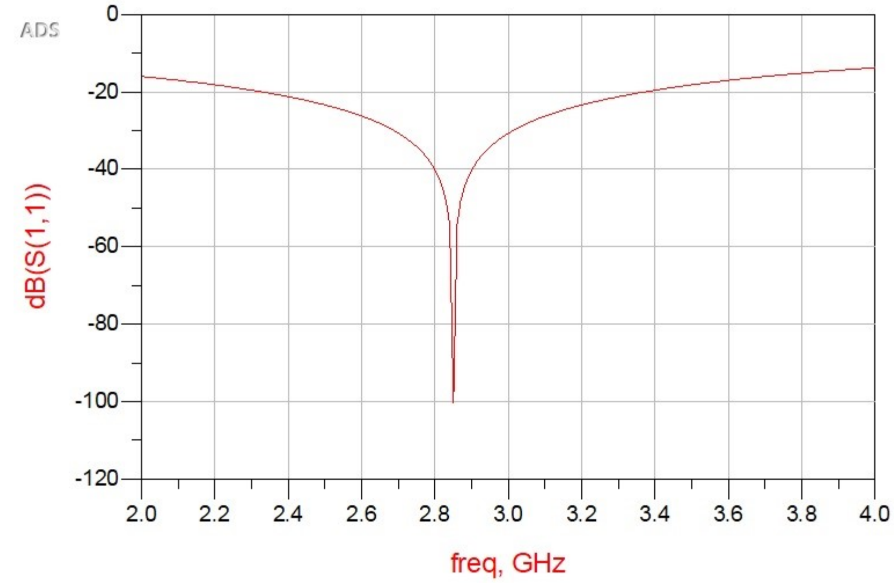


Figure 4.5: Return Loss of simulated 2-Way Wilkinson PCD

of around -3 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Figure 4.6. In S-parameter simulations it was observed that isolation better than

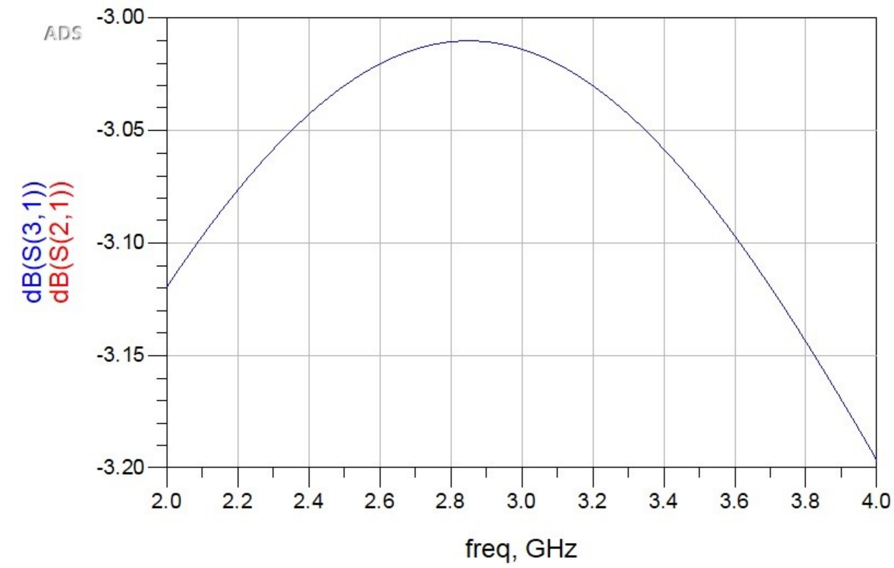


Figure 4.6: Insertion Loss of simulated 2 Way Wilkinson PCD

-30 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Figure 4.7. After proof of concept the design needs to be implemented in hardware. For that, the design is implemented on Rogers 5870 substrate.

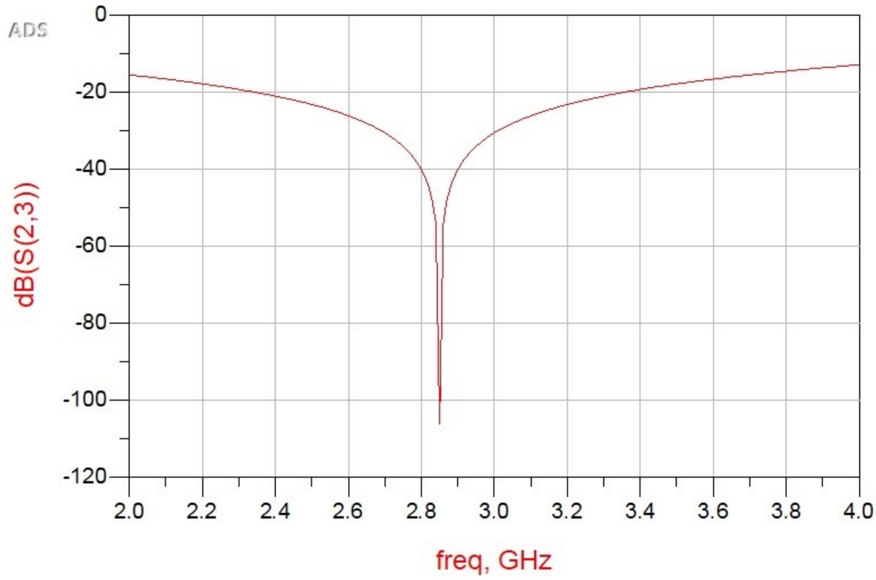


FIGURE 4.7: Isolation of simulated 2 Way Wilkinson PCD

4.4.1 2-way Divider / Combiner Layout

2-Way divider/ combiner layout is designed using microstrip transmission lines. MLIN available in ADS component library was utilized to design microstrip. Impedance and angle of each individual transmission line was calculated using linecalc tool available in ADS. Values determine using Table 4.2, the layout was

Impedance(Z)	Angle (deg)	Length (mm)	Width(mm)
50 Ω	90^o	18.78	2.27
70.71 Ω	90^o	19.14	1.27

TABLE 4.2: Impedance and Angle of each Transmission line

designed. Same is given in Figure 4.8. Since lumped component (resistor) is used in a design so momentum Cosimulation is required to investigate the performance of 2-way Divider / Combiner. Co-simulation Design is shown in Fig 4.9.

4.4.2 2-way Divider / Combiner Results

1. **Insertion Loss**

   In Momentum Cosimulation it was observed that insertion loss of around -3 dB is achieved across the frequency band 2.7 to 3.0 MHz as shown in Figure 4.10.

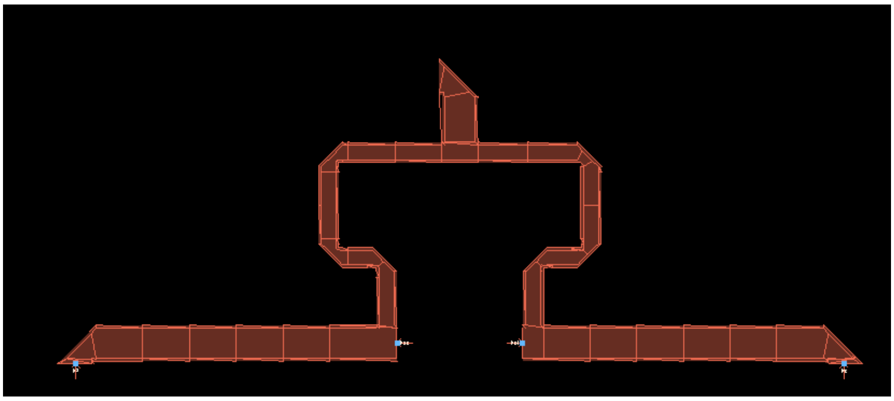


FIGURE 4.8: 2-way Wilkinson Divider/ Combiner Layout

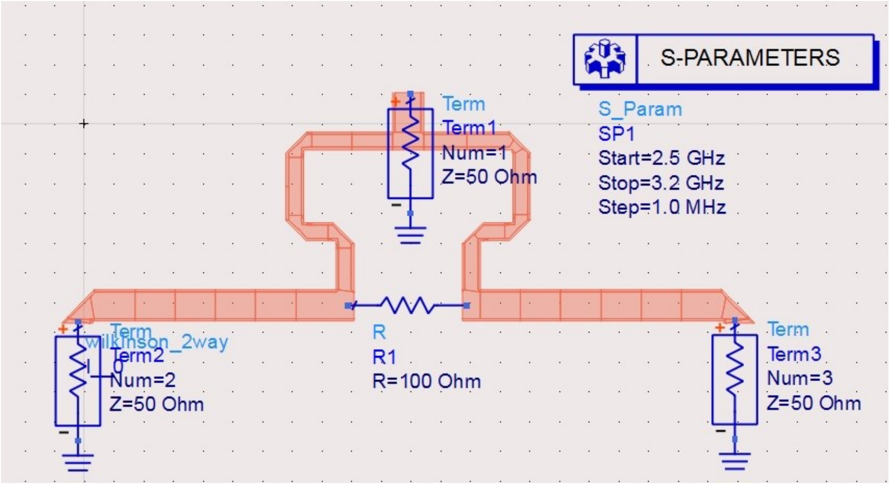


FIGURE 4.9: 2-way Wilkinson Divider/ Combiner Co-Simulation Design

2. **Return Loss**

   In Momentum Cosimulation it was observed that return loss better than -20.9 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.11.

3. **Isolation**

   In Momentum Cosimulation it was observed that isolation better than -18 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.12.

4.4.3 4-way Divider / Combiner Layout

4-Way divider/ combiner layout is designed using microstrip transmission lines. MLIN available in ADS component library was utilized to design microstrip. Since

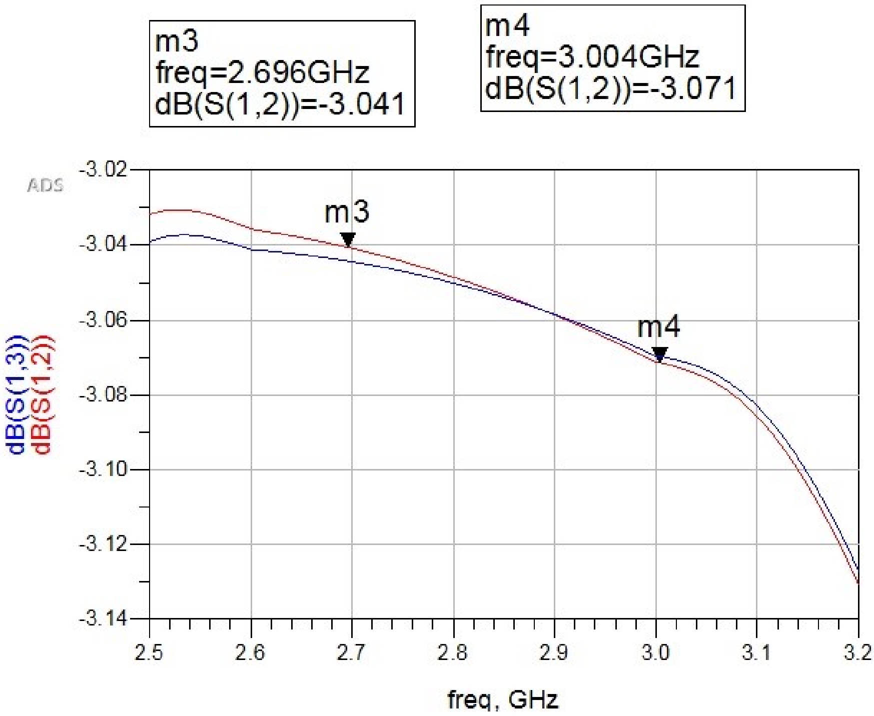


FIGURE 4.10: Insertion Loss Cosimulation of 2 way Wilkinson PCD

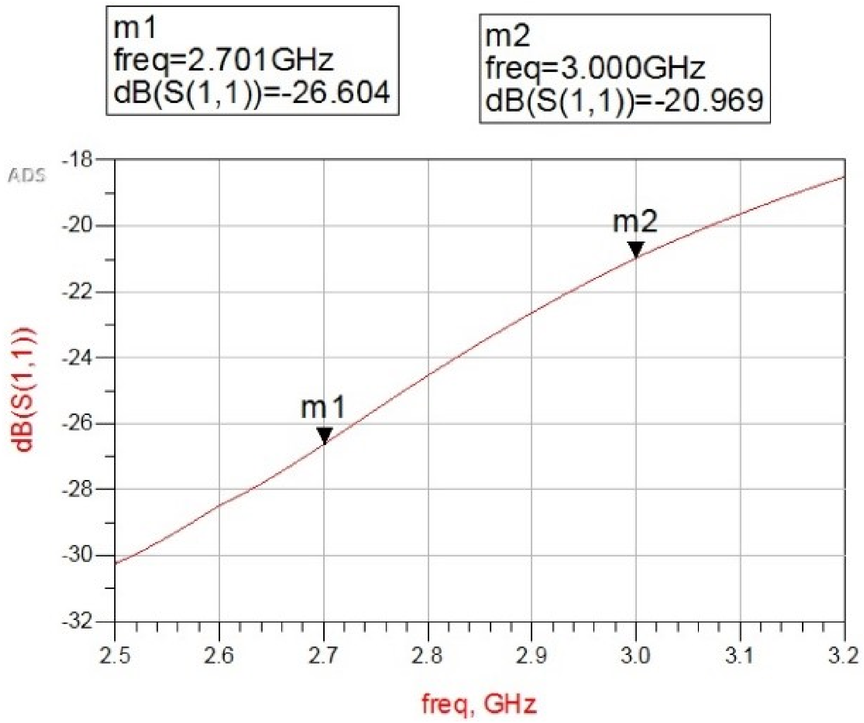


FIGURE 4.11: Return Loss Cosimulation of 2 way Wilkinson PCD

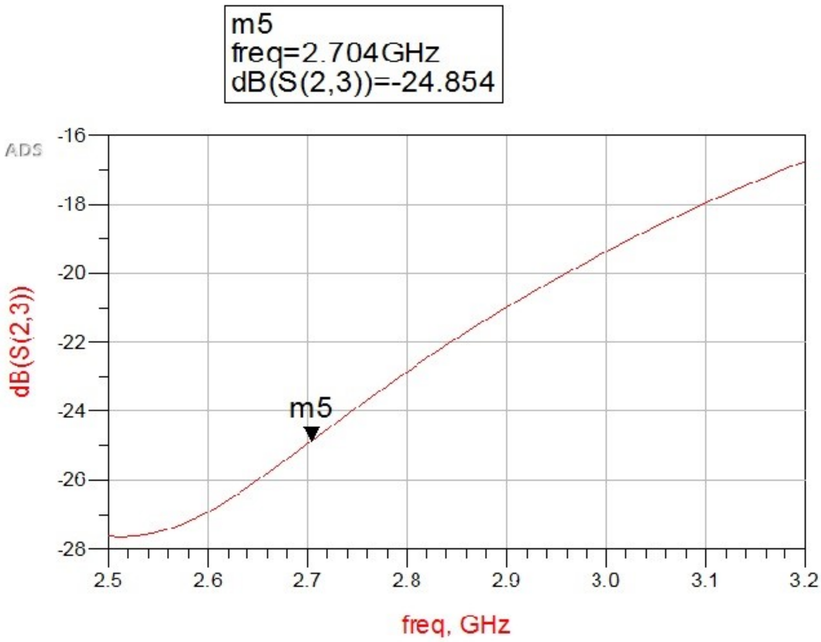


FIGURE 4.12: Isolation Cosimulation of 2 way Wilkinson PCD

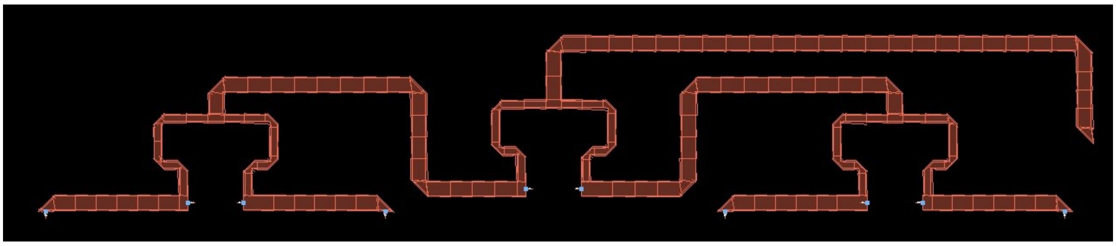


FIGURE 4.13: 4-way Wilkinson Divider/ Combiner Layout

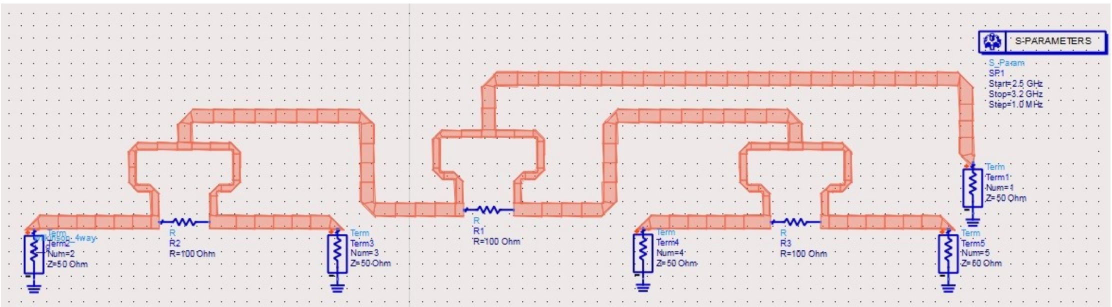


FIGURE 4.14: 4-way Divider / Combiner. Co-simulation Design

lumped component (resistor) is used in a design so momentum Cosimulation is required to investigate the performance of 4-way Divider / Combiner. Co-simulation Design is shown in Fig 4.14.

4.4.4 4-way Divider / Combiner Results

1. **Insertion Loss**

   In Momentum Cosimulation it was observed that insertion loss of better than -6.28 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.17.

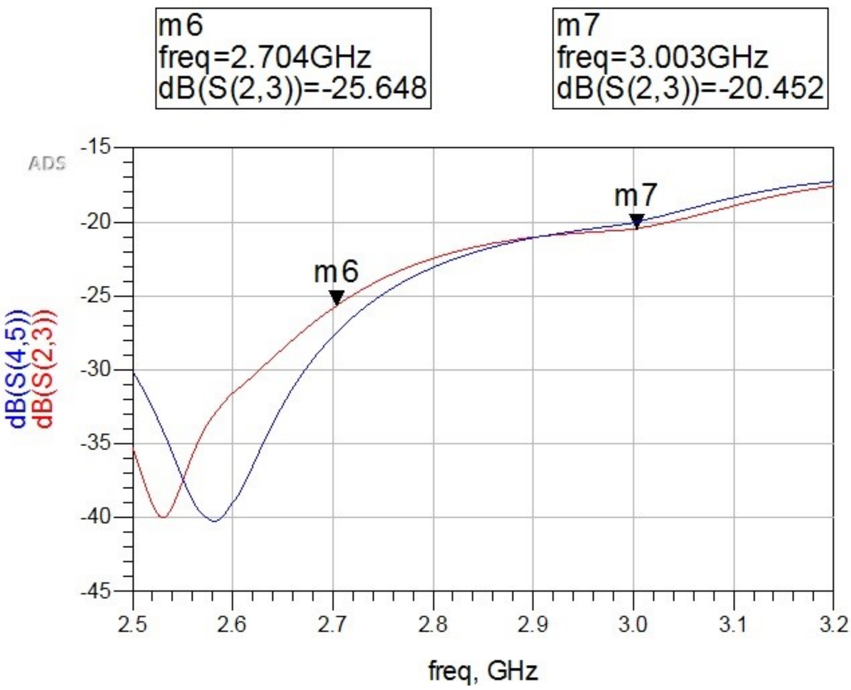


FIGURE 4.15: Insertion Loss Cosimulation of 4 way Wilkinson PCD

2. **Return Loss**

   In Momentum Cosimulation it was observed that return loss better than -17.7 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.16.

3. **Isolation**

   In Momentum Cosimulation it was observed that isolation better than -20.45 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.17.

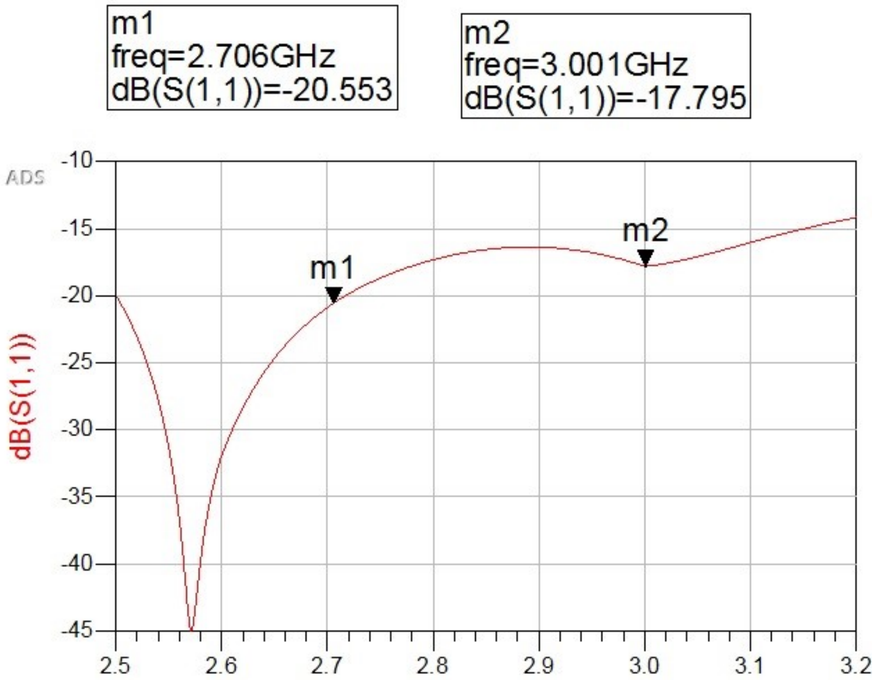


Figure 4.16: Return Loss Cosimulation of 4 way Wilkinson PCD

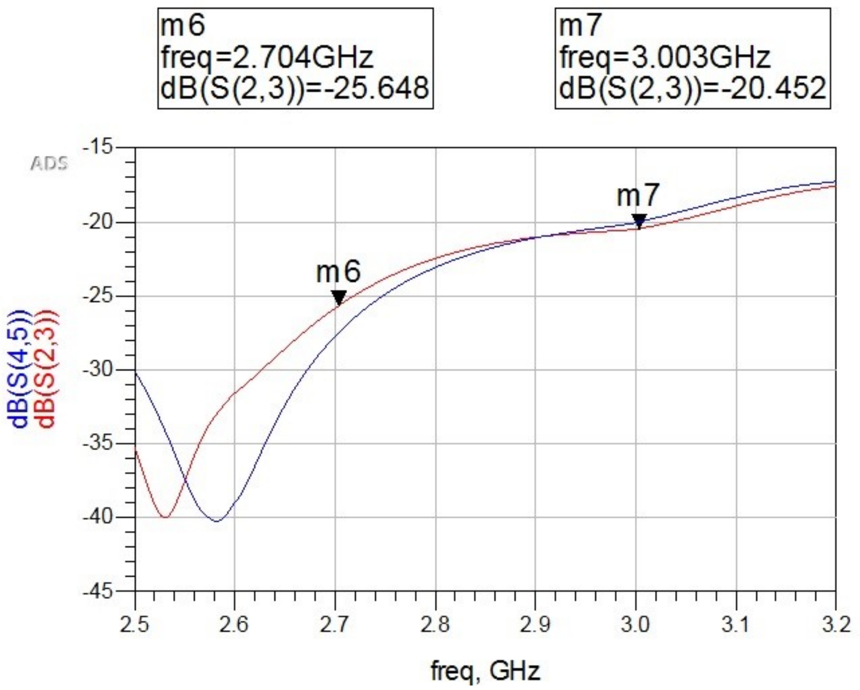


Figure 4.17: Insertion loss Cosimulation of 4 way Wilkinson PCD

4.4.5 8-way Divider / Combiner Layout

8-Way divider/ combiner layout is designed using microstrip transmission lines. MLIN available in ADS component library was utilized to design microstrip. Since

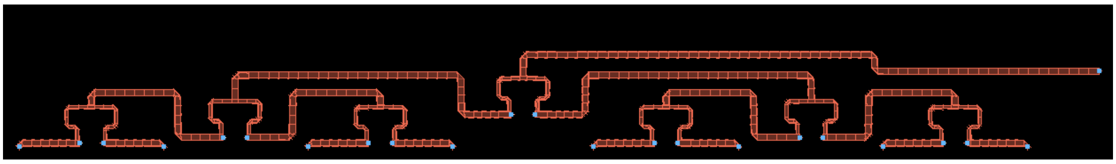


FIGURE 4.18: 8-way Wilkinson Divider/ Combiner Layout

lumped component (resistor) is used in a design so momentum Cosimulation is required to investigate the performance of 8-way Divider / Combiner. Co-simulation Design is shown in Fig 4.19.

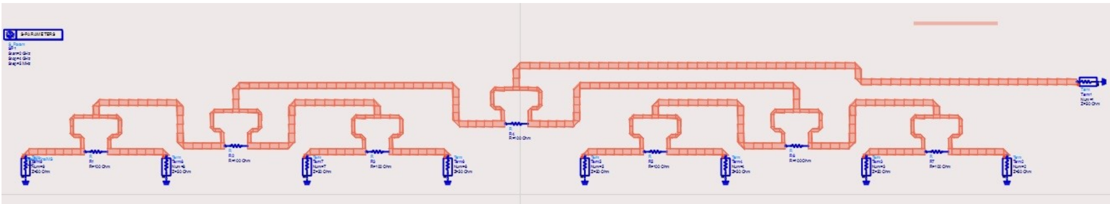


FIGURE 4.19: 8-way Divider / Combiner Layout

4.4.6 8-way Divider / Combiner Results

1. **Insertion Loss**

   In Momentum Cosimulation it was observed that insertion loss of better than -9.25 dB is achieved across the frequency band 2.7 to 3.0 MHz as shown in Fig 4.20.

2. **Return Loss**

   In Momentum Cosimulation it was observed that return loss better than -11.9 dB is achieved across the frequency band 2.7 to 3.0 MHz as shown in Fig 4.21.

3. **Isolation**

   In Momentum Cosimulation it was observed that isolation better than -20.45

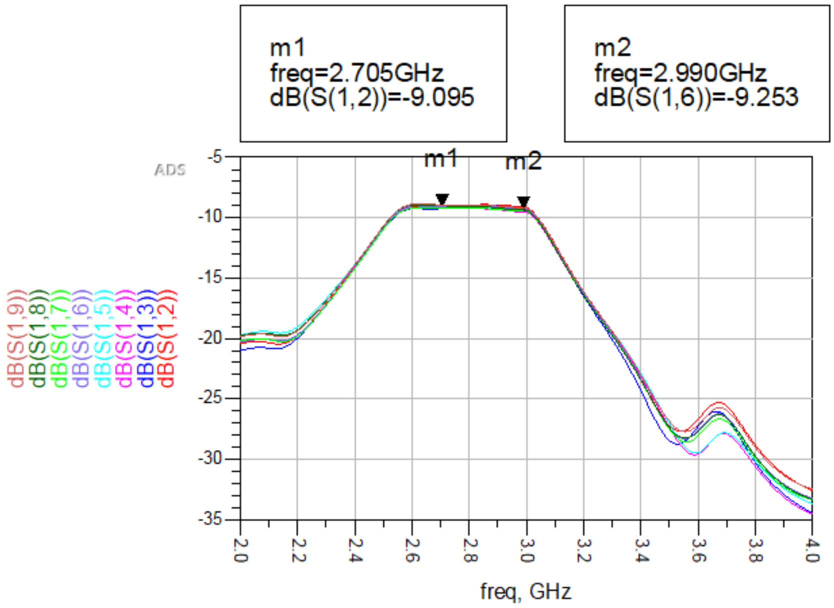


FIGURE 4.20: Insertion loss Cosimulation of 8 way Wilkinson PCD

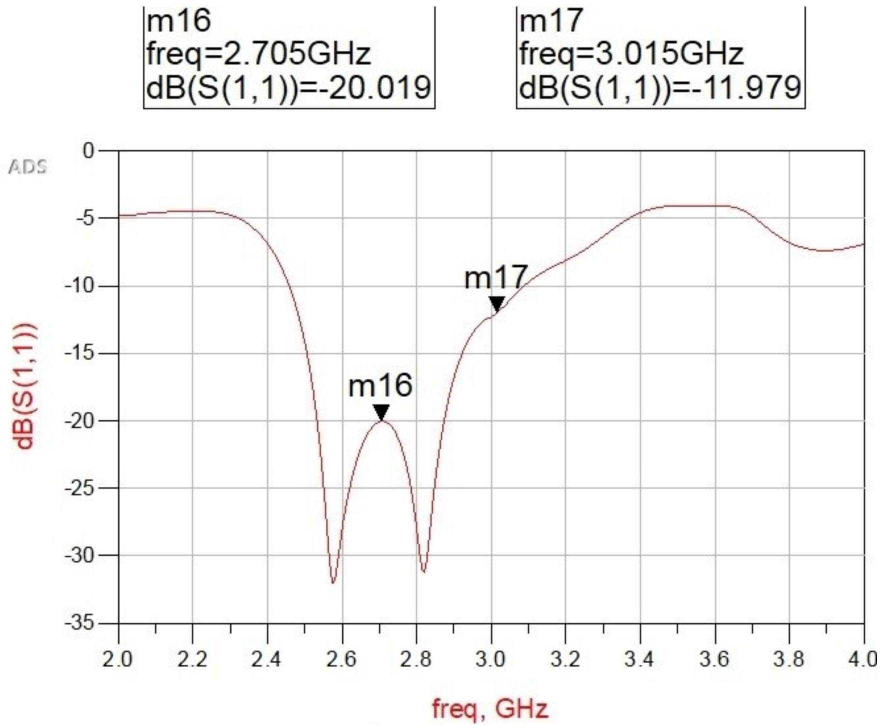


FIGURE 4.21: Return loss Cosimulation of 8 way Wilkinson PCD

dB is achieved across the frequency band 2.7 to 3.0 MHz as shown in Fig 4.22.

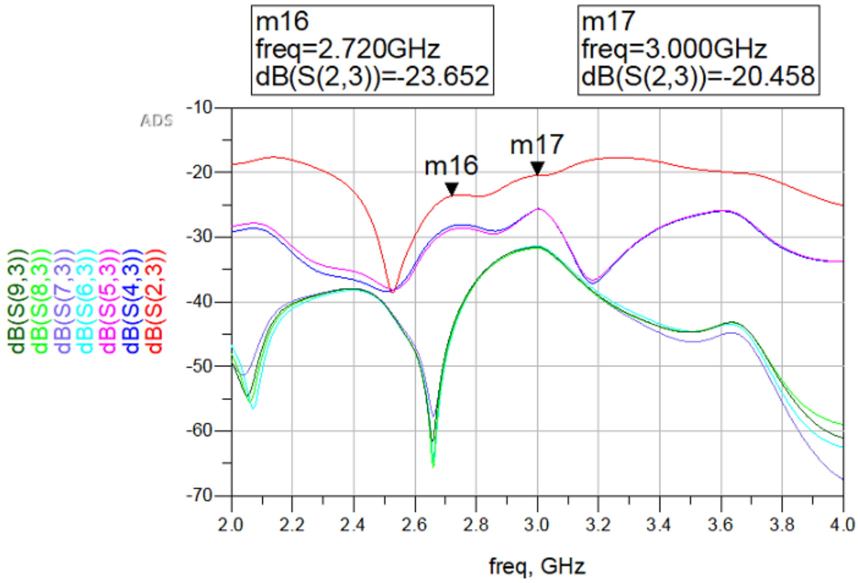


FIGURE 4.22: Isolation Cosimulation of 8 way Wilkinson PCD

4.4.7 16-way Divider / Combiner Layout

16-Way divider/ combiner layout is designed using microstrip transmission lines. MLIN available in ADS component library was utilized to design microstrip. Since lumped component (resistor) is used in a design so mo-

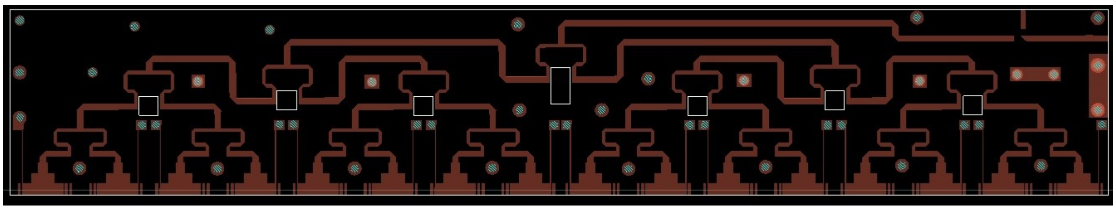


FIGURE 4.23: 16-way Wilkinson Divider/ Combiner Layout

mentum Cosimulation is required to investigate the performance of 8-way Divider / Combiner. Co-simulation Design is shown in Fig 4.24.

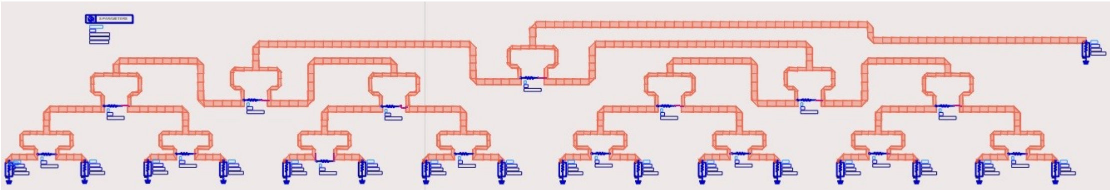


FIGURE 4.24: 16-way Divider / Combiner Layout

4.4.8 16-way Divider / Combiner Results

1. **Insertion Loss**

   In Momentum Cosimulation it was observed that insertion loss of better than -12.50 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.25.

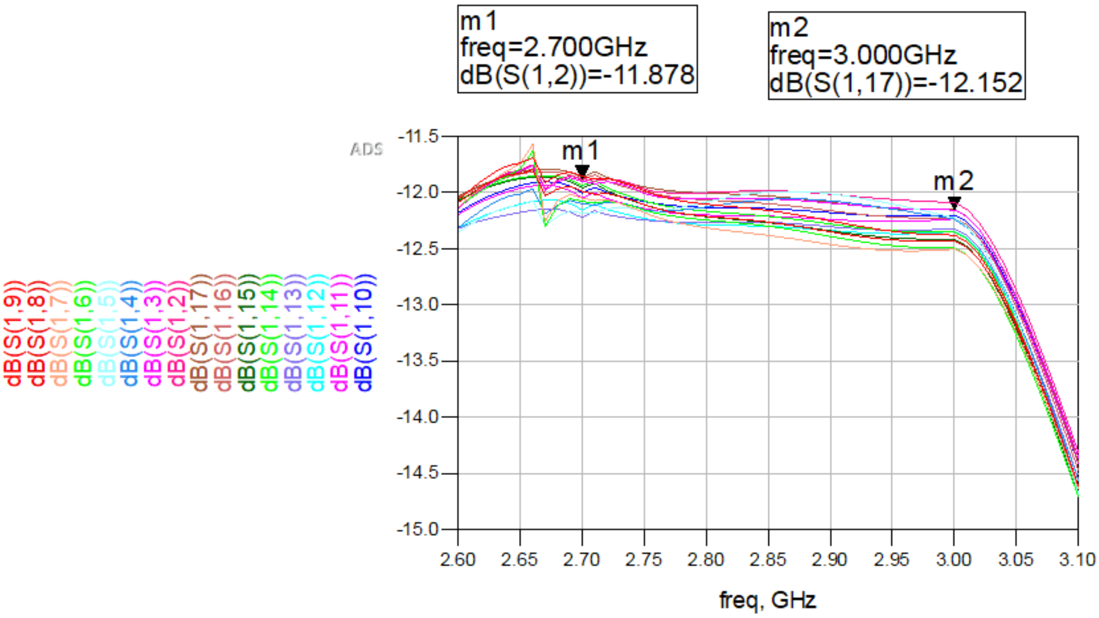


FIGURE 4.25: Insertion loss of Cosimulation of 16 way Wilkinson PCD

2. **Return Loss**

   In Momentum Cosimulation it was observed that return loss better than -14.6 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.26.

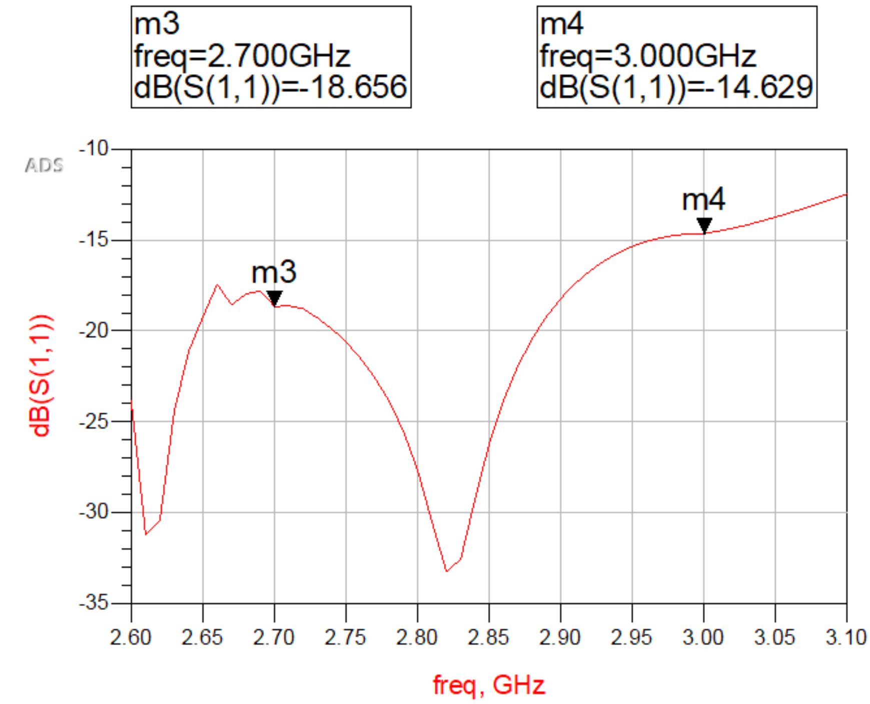


FIGURE 4.26: Return Loss Cosimulation of 16 way Wilkinson PCD

3. **Isolation**

   In Momentum Cosimulation it was observed that isolation better than -27.16 dB is achieved across the frequncy band 2.7 to 3.0 MHz as shown in Fig 4.27.

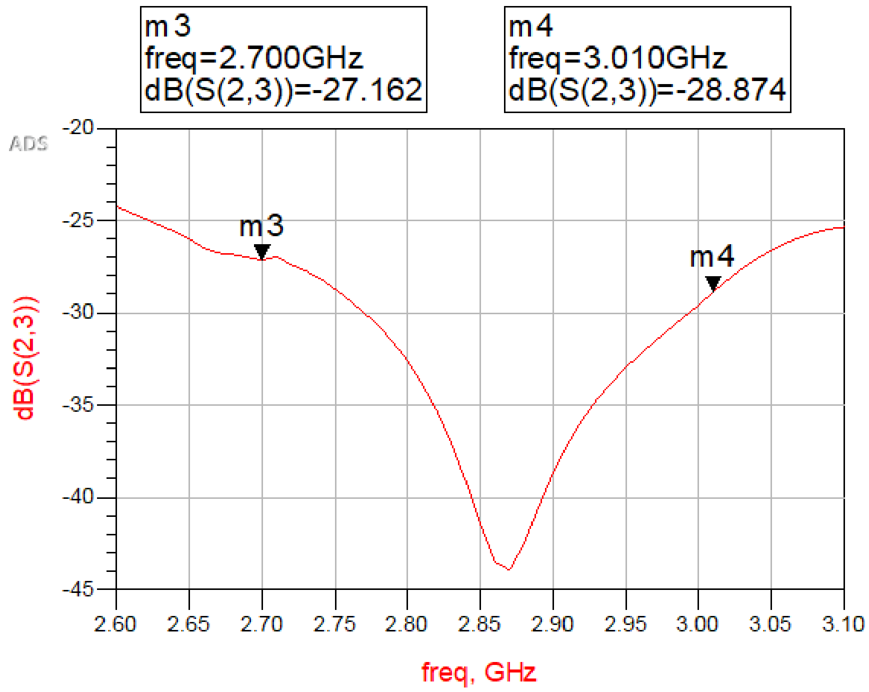


FIGURE 4.27: Isolation Cosimulation of 16 way Wilkinson PCD

4.4.9 16-Way Power Divider combiner Results Summary

1. **Insertion Loss**

   Insertion loss came out to -12.181 dB to -12.50 dB over the entire frequency band of 2700 MHz to 3000 MHz

2. **Return Loss**

   Return loss is better than -18.656 dB over the entire frequency band of 2700 MHz to 3000 MHz

3. **Isolation**

   Isolation is better than -25 dB over the entire frequency band of 2700 MHz to 3000 MHz

4.5 Designing RF Amplifier

As discussed in chapter 2 RF transistor is used to amplify the incoming RF signal. To amplify the signal up to the power level of 75W in 2700 to 3000 MHz frequency band, MACOM PH-2731-75L RF Transistor is selected. Specification of the Transistor in tabulated in Table 4.3. Its data sheet is attached in appendix. The objective of the research is to design transistor optimum input and output impedance matching network. Impedance matching is being done by using smith chart utility tool available in ADS.

F(GHz)	Z IN (Ω)
2.7	6.9-j12.2
2.9	6.0-j11.7
3.1	5.2-j10.0

TABLE 4.3: Input Impedance

4.5.1 Input impedance matching

The transistor input impedances available in data sheet are listed in Table 4.3. The objective is to match these impedances to the impedance of incoming RF signal which is 50 for maximum power transfer from source to the input terminal of transistor.

4.5.2 Transistor Input Impedance Matching Using Smith Chart

Transistor input impedance matching is done by using smith chart utility tool available in ADS[25] as shown in Fig 4.28.

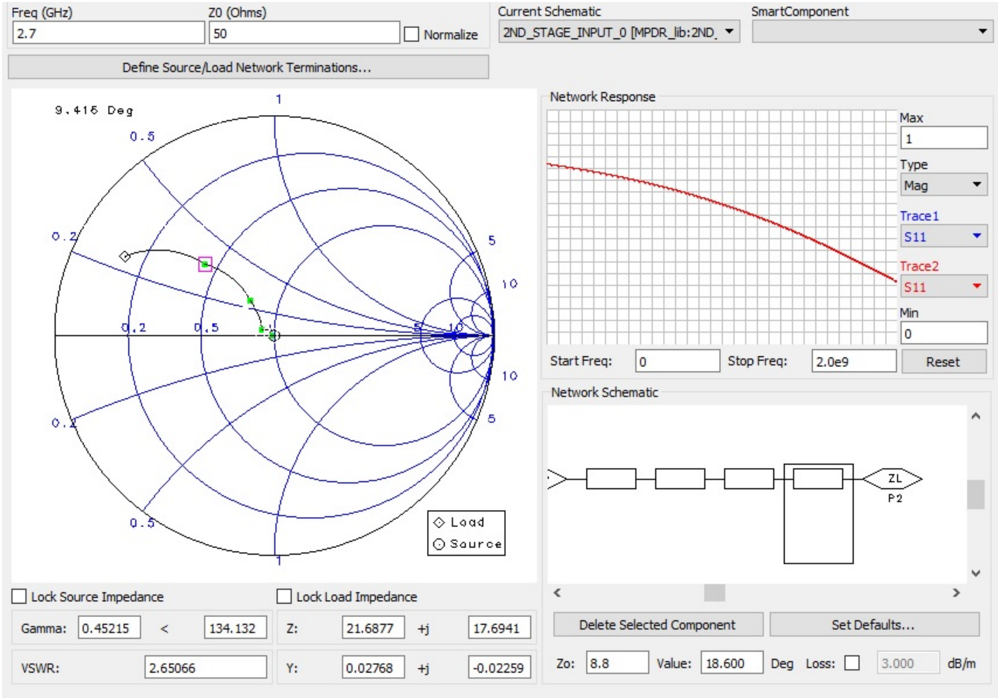


FIGURE 4.28: Transistor Input Impedance Matching Using Smith Chart

Four-microstrip transmission lines are used whose impedances and angles are tabulated in table 4.7: After that, transistor input impedance matching network is

	Impedance, Z(Ω)	**Angle (Deg)**
TLIN 1	46	57
TLIN 2	25	14
TLIN 3	18.1	17.466
TLIN 4	8.8	18.6

TABLE 4.4: Impedance and Angle

designed and simulated using ideal transmission lines shown in figure 4.29. In

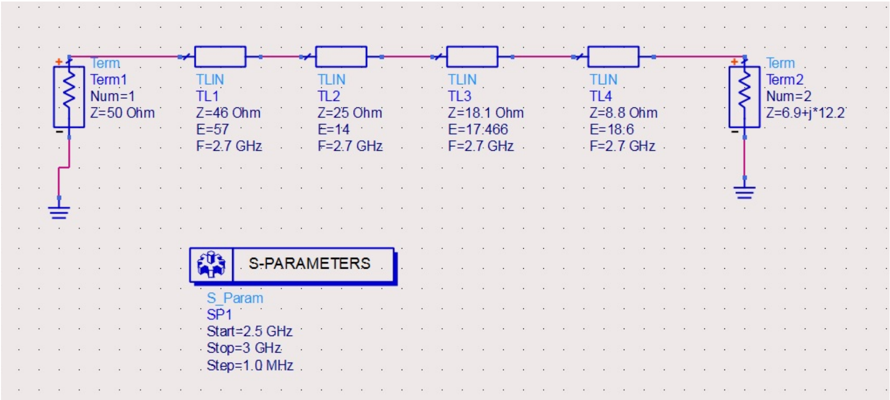


FIGURE 4.29: Designed and Simulated Using Ideal Transmission Lines

simulations it is observed that Return loss had better than -18.3 dB in 2700 to 3000 MHz frequency band is achieved successfully. The result implies that input matching network is designed perfectly. Return Loss of simulated impedance matching network is shown in figure 4.30.

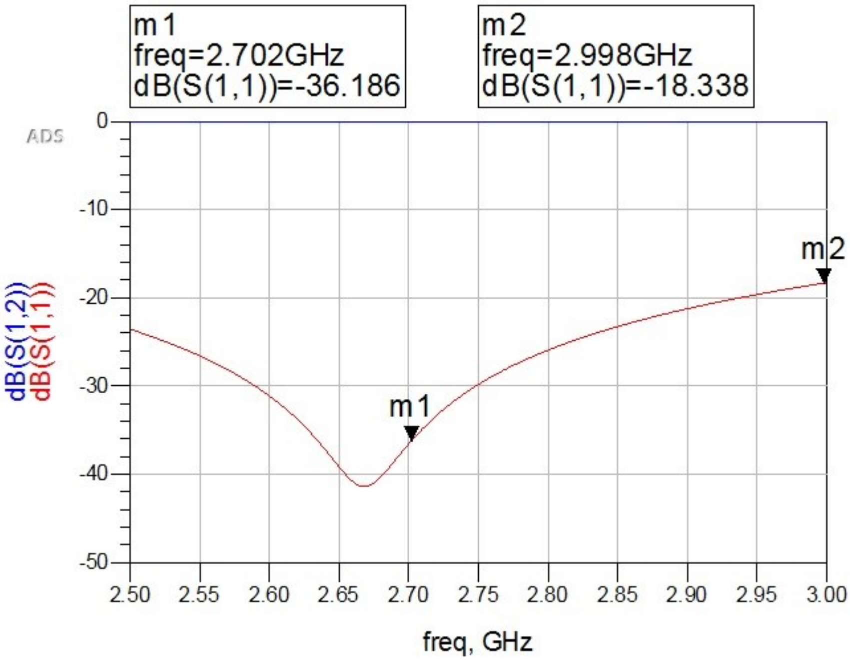


FIGURE 4.30: Return Loss of Simulated Impedance Matching Network

After achieving the required results using ideal transmission lines the next step is to implement matching network in hardware. For this purpose design is implemented in Rogerss 5870 substrate. The dimensions of microstrip lines computed using linecalc tool are tabulated in table 4.5.

Transmission line sections	Trace Width(mm)	Trace Length(mm)
TLIN 1	2.58	12.50
TLIN 2	5.85	2.988
TLIN 3	8.643	3.681
TLIN 4	18.14	3.856

Table 4.5: Trace Width and Trace Length

The schematic is designed in ADS using MLIN component available in ADS library as shown in figure 4.31. Afterwards design layout is implemented in ADS using

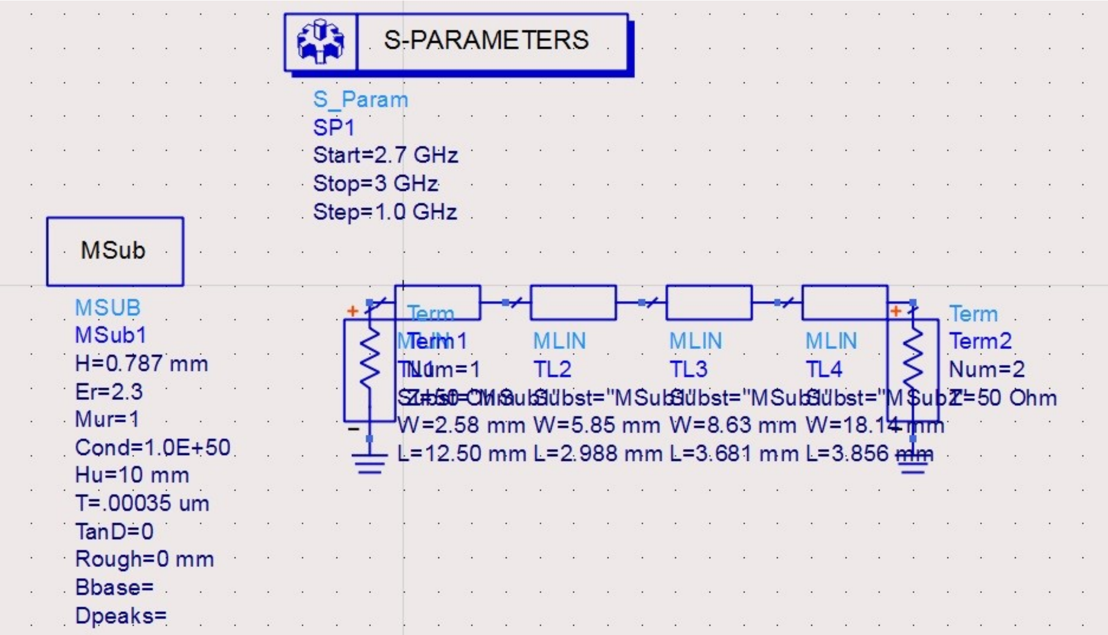


Figure 4.31: MLIN Component Available in ADS Library

MLIN microstrip transmission lines available in ADS as shown in figure 4.32. Next step is to implement momentum Cosimulation to compute the results of input matching network. Design is shown in figure 4.33.

4.5.3 Results

In momentum co-simulation results, it was observed that return loss better than -16.8dB in 2700 to 3000MHz frequency band is achieved which implies that input matching network is designed successfully. Result of return loss is shown in figure 4.34.

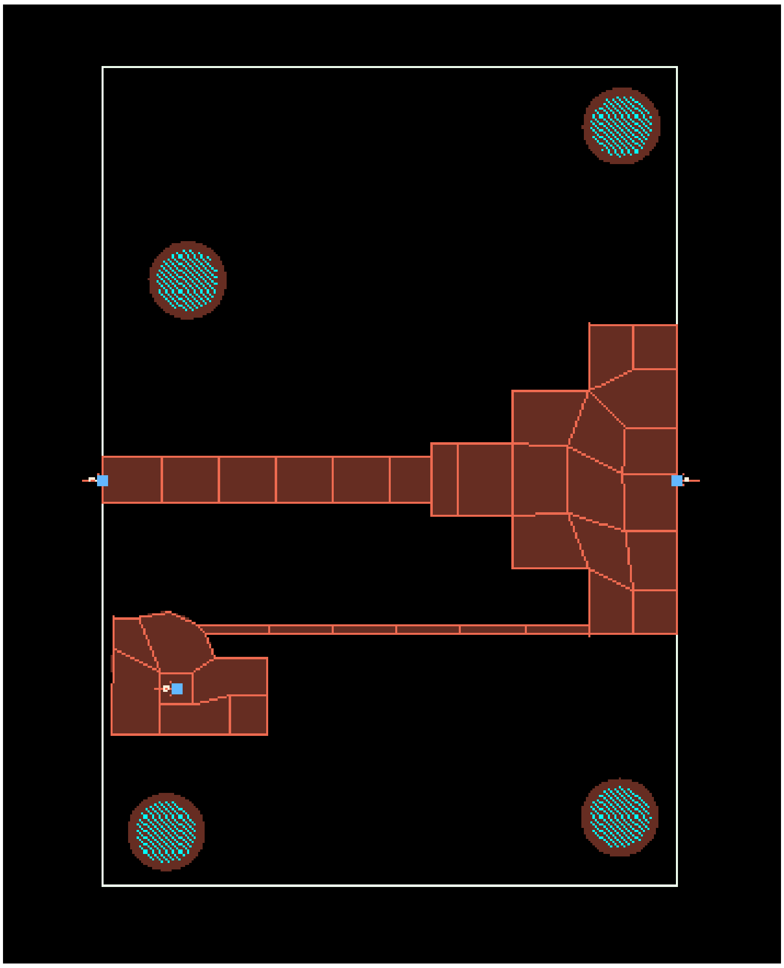


FIGURE 4.32: Microstrip Transmission Lines Available In ADS

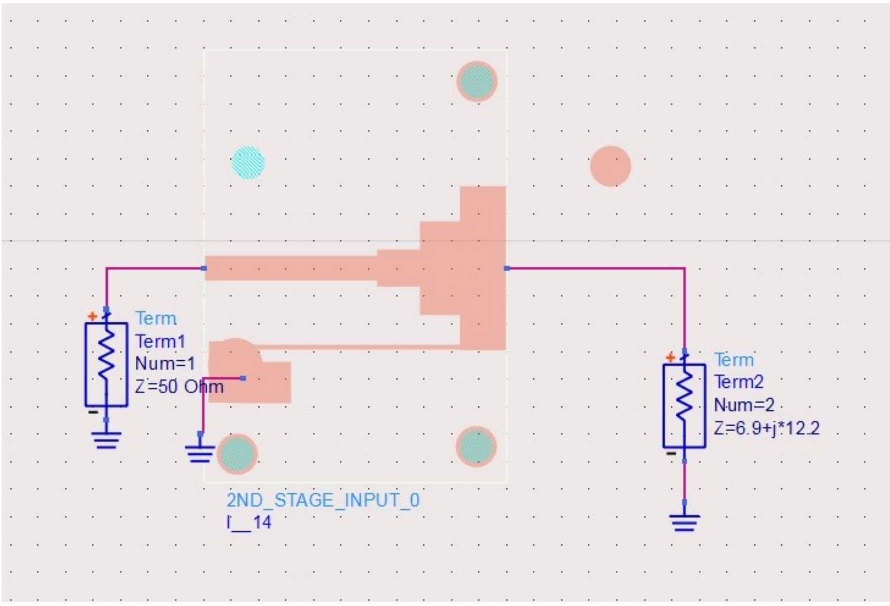


FIGURE 4.33: Results of Input Matching Network

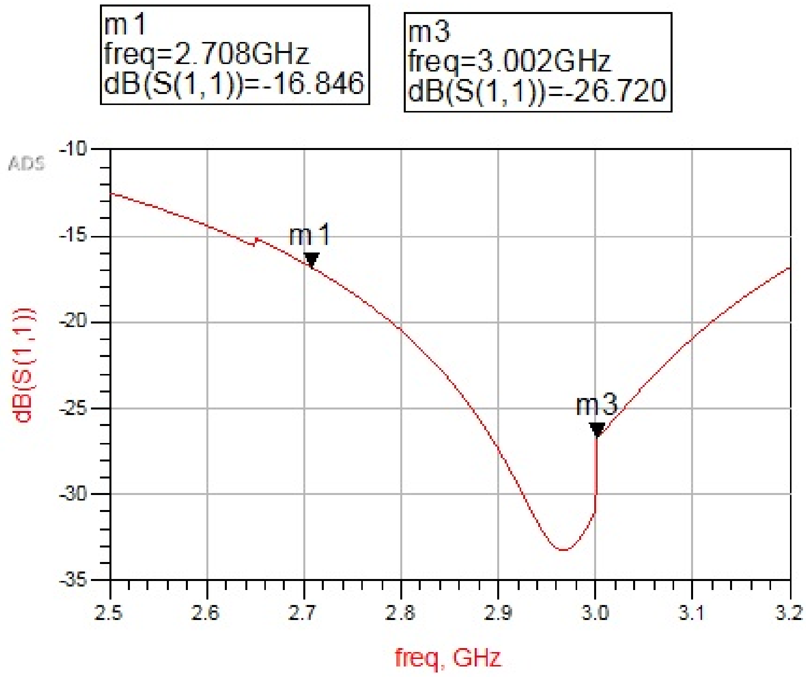


FIGURE 4.34: Return Loss of input matching network

4.5.4 Transistor output Impedance matching

The transistor output impedances available in data sheet are listed in Table 4.6. The objective is to match these impedances to the impedance of RF signal which is 50 Ω for maximum power transfer from output terminal of transistor to the load.

F(GHz)	Z OUT (Ω)
2.7	4.5-j6.8
2.9	3.9-j6.1
3.1	3.4-j4.8

TABLE 4.6: Output Impedance

4.5.5 Transistor Output Impedance Matching Using Smith Chart

Transistor output impedance matching is done by using smith chart utility tool available in ADS as shown in Fig 4.35. Eight micro strip transmission lines are used whose impedances and angles are tabulated in table 4.7.

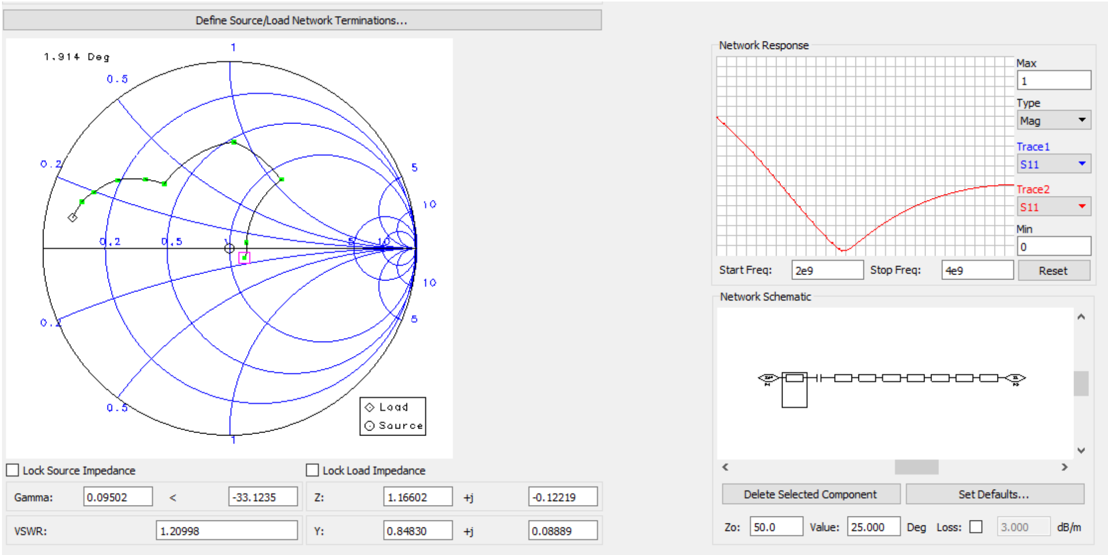


FIGURE 4.35: Smith Chart Utility Tool Available in ADS

	Impedance, Z(Ω)	Angle (Deg)
TLIN 1	46	57
TLIN 2	25	14
TLIN 3	18.1	17.4
TLIN 4	8.8	18.6
TLIN 5	5.1	15
TLIN 6	4.3	16.4
TLIN 7	3.1	17.2
TLIN 8	2.6	13

TABLE 4.7: Impedance and Angle

After that, transistor input impedance matching network is designed and simulated using ideal transmission lines shown in figure 4.36. In simulations it is observed

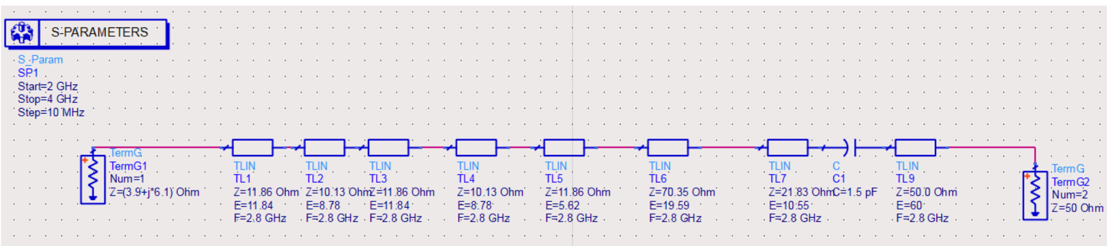


FIGURE 4.36: Designed and Simulated Using Ideal Transmission Lines

that Return loss better than -11.3 dB in 2700 to 3000 MHz frequency band is achieved successfully. The result implies that output matching network is designed perfectly. Return Loss of simulated impedance matching network is shown in figure 4.37. After achieving the required results using ideal transmission lines

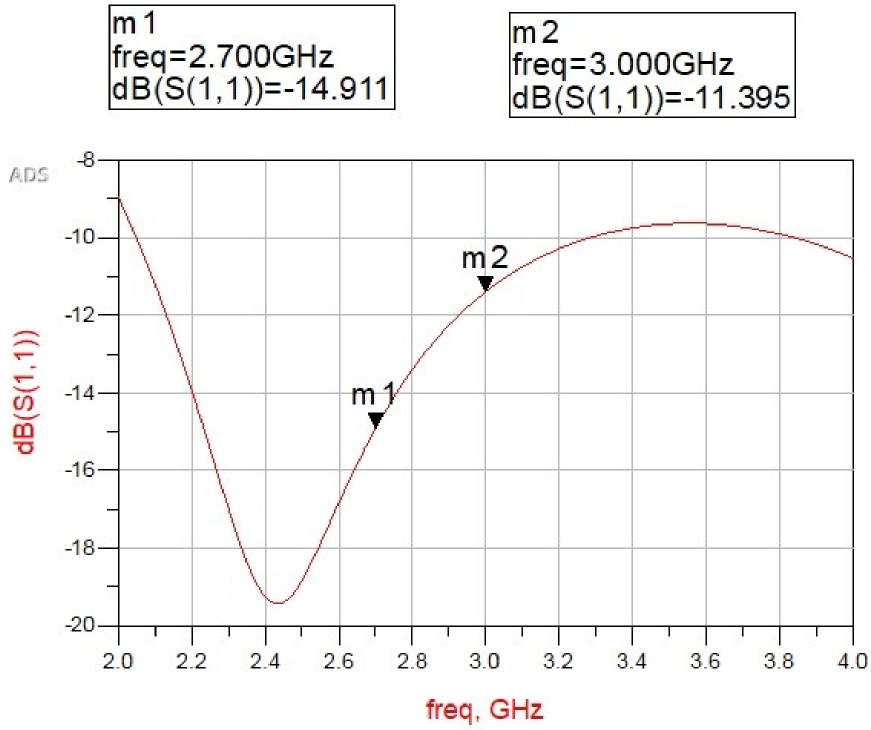


FIGURE 4.37: Return Loss of Simulated Impedance Matching Network

the next step is to implement matching network in hardware. For this purpose design is implemented in Rogerss 5870 substrate. The dimensions of microstrip lines computed using line calc tool are tabulated in table 4.8. The schematic

Transmission line sections	Trace Width(mm)	Trace Length(mm)
TLIN 1	2.58	12.502
TLIN 2	5.85	2.988
TLIN 3	8.643	3.681
TLIN 4	18.14	3.856
TLIN 5	20.32	3.581
TLIN 6	23	2.856
TLIN 7	26.76	10.507
TLIN 8	29.10	4.988

TABLE 4.8: Trace Width and Trace Length for Eight Tranmission lines

is designed in ADS using MLIN component available in ADS library as shown in figure 4.38. Afterwards design layout is implemented in ADS using MLIN microstrip transmission lines available in ADS as shown in figure 4.39. Next step is to implement momentum Cosimulation to compute the results of input matching network. Design is shown in figure 4.40.

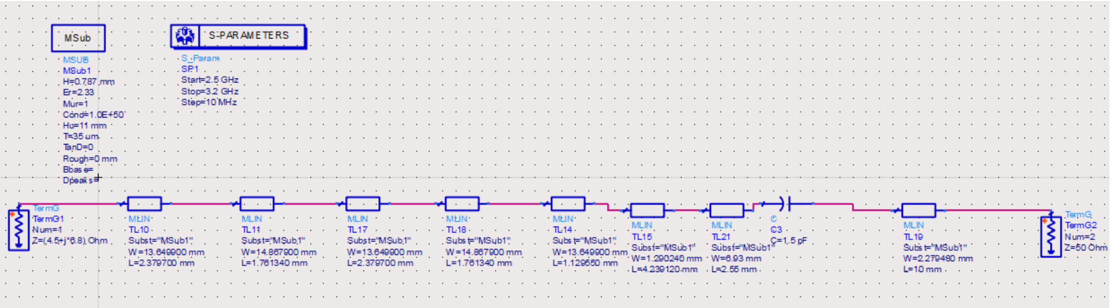


FIGURE 4.38: MLIN Component Available In ADS Library

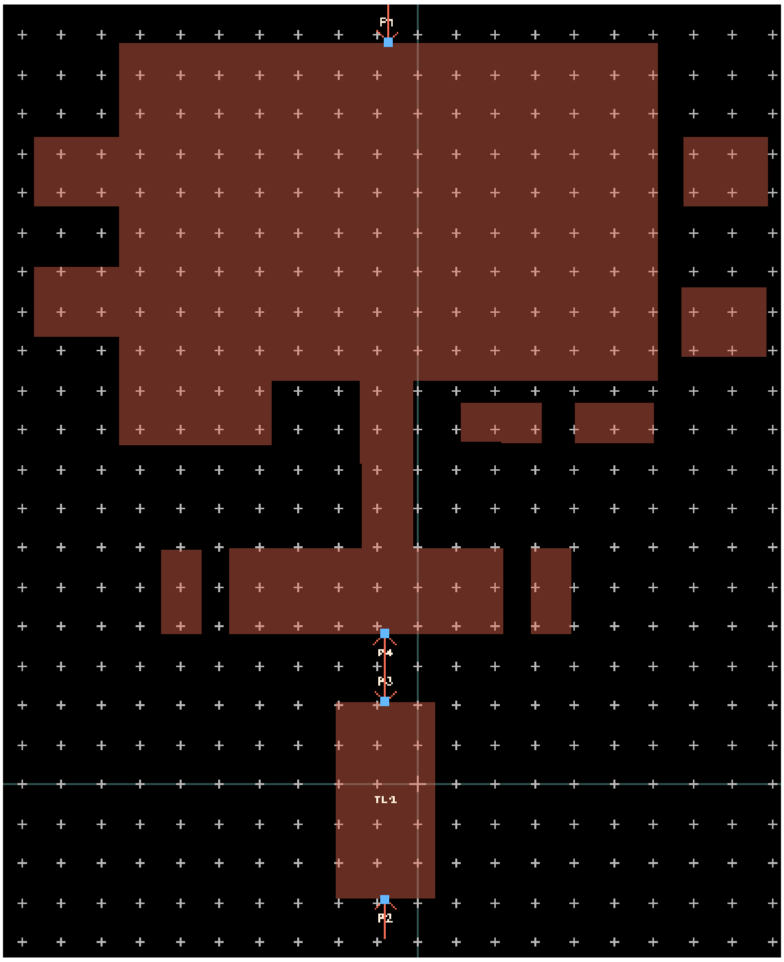


FIGURE 4.39: MLIN Microstrip Transmission Lines Available In ADS

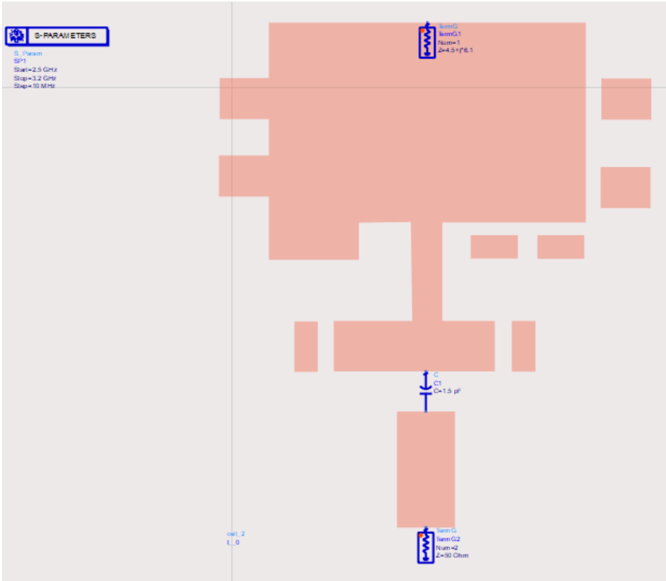


FIGURE 4.40: Results Of Input Matching Network

4.5.6 Result

In momentum co-simulation results, it was observed that return loss better than -8.9dB in 2700 to 3000MHz frequency band is achieved which implies that output matching network is designed successfully. Result of return loss is shown in figure 4.41.

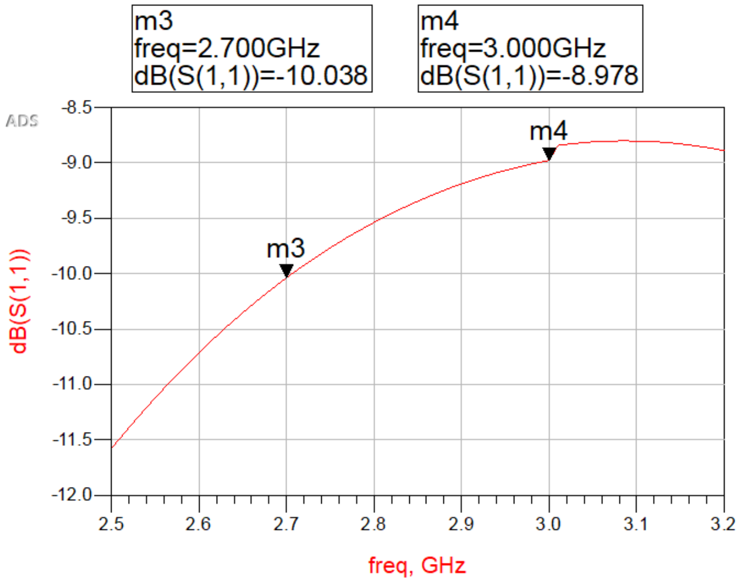


FIGURE 4.41: Result of Return Loss

Chapter 5

MEASUREMENT RESULTS AND DISCUSSION

5.1 Introduction

The measurement for the current thesis can be divided into two main parts, results of 16 way divider/ combiner measured using vector network analyzer part number E5071C[26]. After that testing of complete amplifier design along with 16 way divider / combiner was implemented.

5.2 Test setup of 16-way Power Divider/ Combiner

To evaluate performance of 16 way Divider / Combiner prototype is physically tested with Agilent vector network analyzer part number E5071C[27]. S parameters are recorded to validate the performance. Input from VNA is feed to port 1 while the output is taken from port 2 to port 17. Since VNA is a two port device therefore 15 remaining port were terminated with 50 load [28]. Test setup diagram is shown in Figure 5.1.

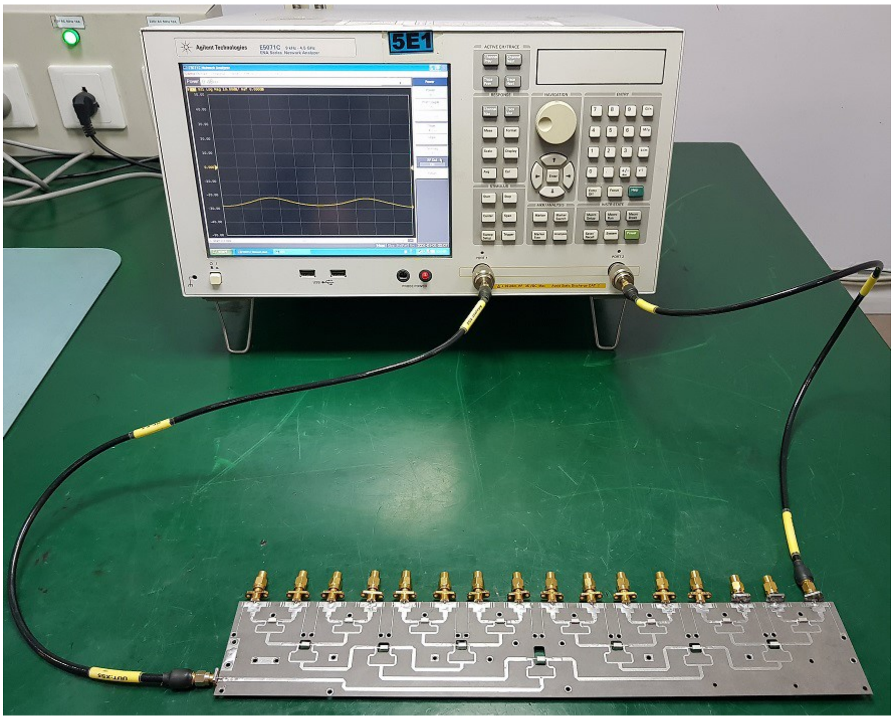


FIGURE 5.1: Testing of 16:1 Power Divider/ Combiner with Vector Network Analyzer

5.2.1 16-way Power Divider/ Combiner Measured Results

Scattering parameters are measured to estimate Insertion loss. Insertion loss measured at port 2 is displayed in Figure 5.2. The data collected from port2 to port17 is tabulated in the Table 5.1.

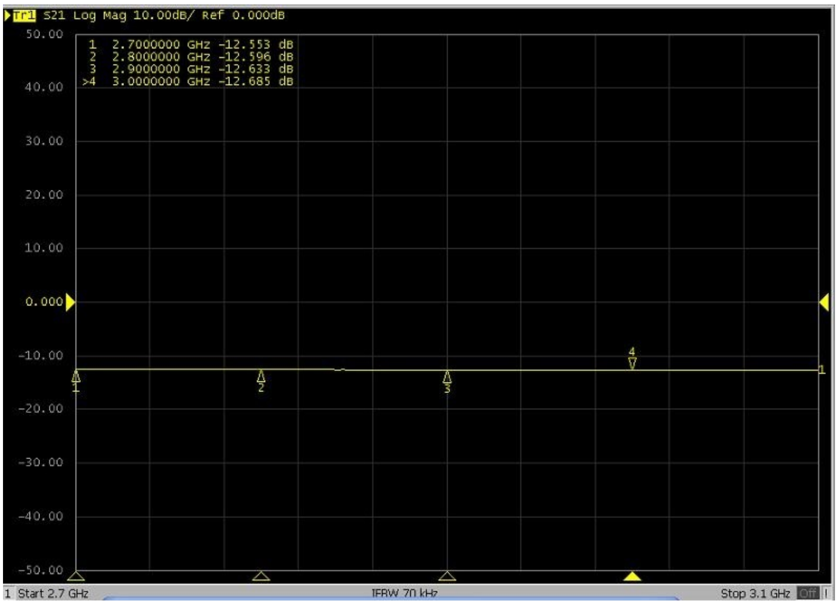


FIGURE 5.2: Measured Results of 16:1 Power Divider / Combiner

Insertion Loss(dB)	2.7GHz	2.8GHz	2.9 GHz	3.0 GHz
S21	-12.553	-12.596	-12.633	-12.685
S31	-12.412	-12.466	-12.621	-12.688
S41	-12.544	-12.506	-12.590	-12.576
S51	-12.325	-12.588	-12.644	-12.544
S61	-12.466	-12.612	-12.690	-12.566
S71	-12.621	-12.624	-12.498	-12.671
S81	-12.783	-12.429	-12.689	-12.689
S91	-12.590	-12.661	-12.577	-12.694
S101	-12.541	-12.577	-12.611	-12.734
S111	-12.447	-12.499	-12.476	-12.722
S121	-12.544	-12.510	-12.492	-12.667
S131	-12.559	-12.568	-12.621	-12.632
S141	-12.355	-12.598	-12.587	-12.651
S151	-12.422	-12.499	-12.729	-12.597
S161	-12.509	-12.523	-12.677	-12.584
S171	-12.412	-12.589	-12.680	-12.624

TABLE 5.1: Insertion Loss in dB

5.3 Comparison of Simulated and Measured Results

The data collected from measurements and simulations is plotted on the graph in MATLAB as shown in Figure 5.3.

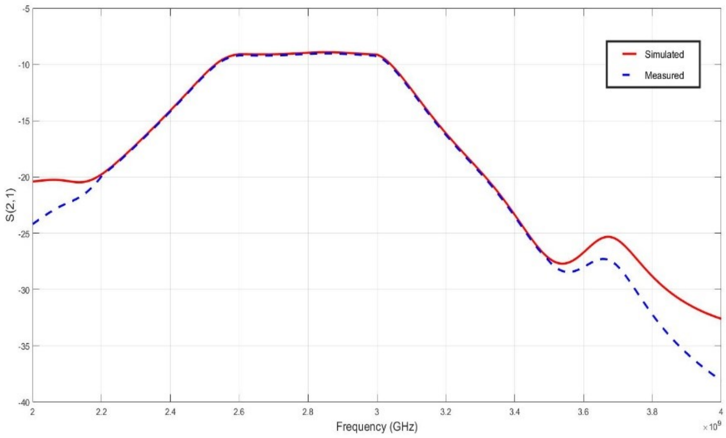


FIGURE 5.3: Measurements and Simulations Results

Comparison of simulated and measured results are tabulated in Table 5.2.

Insertion Loss at output ports	**Simulated Results at 2.7 GHz**	**Measured Results at 2.7 GHz**	**Simulated Results at 3.0 GHz**	**Measured Results at 3.0 GHz**
Insertion Loss at Port 2	-11.872	-12.553	-12.143	-12.685
Insertion Loss at Port 3	-12.112	-12.412	-12.353	-12.688
Insertion Loss at Port 4	-12.324	-12.544	-12.656	-12.576
Insertion Loss at Port 5	-12.184	-12.325	-12.487	-12.544
Insertion Loss at Port 6	-11.982	-12.466	-12.543	-12.566
Insertion Loss at Port 6	-12.429	-12.621	-12.633	-12.671
Insertion Loss at Port 7	-12.564	-12.783	-12.766	-12.689
Insertion Loss at Port 8	-12.185	-12.590	-12.872	-12.694
Insertion Loss at Port 9	-11.655	-12.541	-12.674	-12.734
Insertion Loss at Port 10	-12.336	-12.447	-12.432	-12.722
Insertion Loss at Port 11	-12.324	-12.544	-12.766	-12.667
Insertion Loss at Port 12	-12.244	-12.559	-12.566	-12.632
Insertion Loss at Port 13	-11.776	-12.355	-12.764	-12.651
Insertion Loss at Port 14	-12.673	-12.422	-12.893	-12.597
Insertion Loss at Port 15	-12.877	-12.509	-12.236	-12.584
Insertion Loss at Port 16	-12.335	-12.412	-12.187	-12.624

Table 5.2: Comparison of Simulated and Measured Results

5.4 Test setup for Amplifier Testing

RF Signal Generator Part Number E4428C Agilent is used to generate RF signal in 2.7 GHz to 3.0 GHz frequency band with the pulse modulation [29]. Duty cycle of amplifier is 10 %. RF signal level taken from device is +30 dBm. Low loss RF cable is used to feed pre-amplifier, cable loss is around 0.2 dB in 2.7 GHz to 3.0 GHz band. Pre-Amplifier is used to drive power amplifier which has an O/P power of around 54dBm.

High power amplifier O/P cannot feed directly to Spectrum Analyzer Part number E4440A Agilent. Since it has maximum limit to measure power of +30 dBm, so high power Attenuator DTS-500 of 50 dB (500W) is used to protect signal analyzer test setup[30].

In the first part of testing, 16-way divider/ combiner was tested using VNA as discussed above. In measurements, it was seen that there was a slight variation of around 0.5 dB in insertion loss results as compared to the simulated results. This may be because of insertion of RF connectors and RF cables [31].
In the next part, RF amplifier was tested. RF amplifier was producing output power of more than 1 KW in the operating band, implies that the matching networks designed for RF power transistors are working fine.

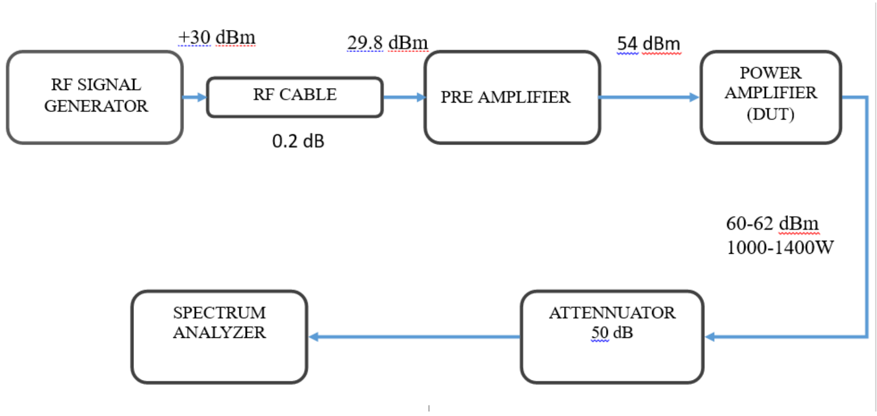


FIGURE 5.4: Block diagram of Test Setup

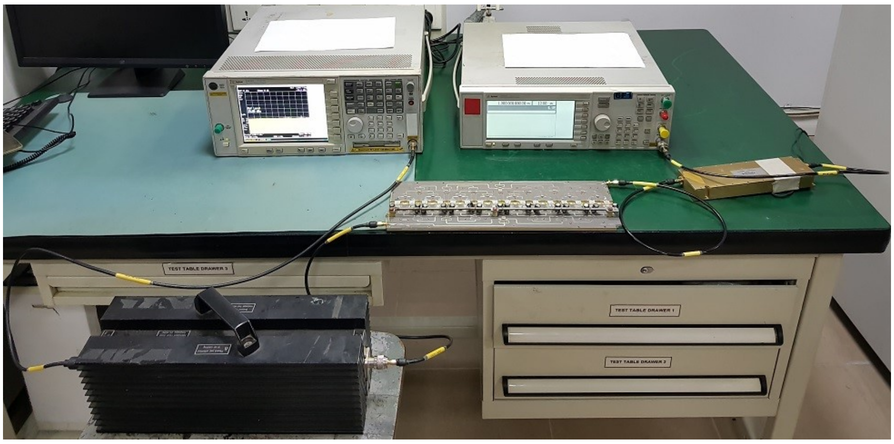


FIGURE 5.5: DUT Test Setup

5.5 Results

The results of the designed and fabricated device under test in test setup as shown in the figure 5.5 depicts that average amplification of 60dB with in the frequency band of 2.7Ghz to 3.0 Ghz is achieved as per requirements. The output powers viz-a-viz transmitted frequencies are shown in the table 5.3.

Frequency	**Output Power**
2.7	60.84
2.8	60.26
2.9	61.24
3.0	59.97

Table 5.3: Frequency Output Power

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusion

Efficient and functional form 1:16 Wilkinson Based power divider and combiner along with amplifier impedance matching has been successfully designed, simulated, fabricated and tested. The behaviors and properties of said Power divider/-combiner have been studied when designing 1:16 way power divider/ combiner and amplifier circuit. First, the design methodology is implemented using ideal transmission lines on ADS 2016 for proof of concept. After that, the design is implemented in hardware on Rogers RT/Duroid 5870 substrate and simulated. Simulation results showed that insertion loss of -12.5 dB with return loss of -18.565 dB and isolation of -25dB was achieved in case of power divider/ combiner. After achieving these results, PCB was designed for fabrication. After fabrication, module was tested for measurements from Agilent vector network analyzer part number E5071C. Measured results showed that isolation of around -25.5 dB and insertion loss of -12.14dB was achieved successfully. Furthermore the amplifier design was successfully matched with designed power divider/combiner to achieve the output power of 1000 W with the custom size and design. The output power was checked at Agilent Spectrum Analyzer Part number E4440A with the setup as mentioned in previous chapter. Things that learned are that practical work needs patience and special skills: linking theoretical design parameters with the simulated and measured ones, and producing RF layout PCB and taking measurements using test equipment, such as signal generator, spectrum analyzer and VNA related skills.

6.2 Future Work

Although a lot of development has been done in the field of power divider/ combiners and amplifier designs of radar RF power transmitters, still room for improvement for custom based requirement is available. With the advancement in radar technology, there is a need of miniaturization and cost effective solution. The insertion loss can be further be improved in case of power divider/ combiners.

Appendix A

Bill of Materials

Sr.No.	Description	Part No.	QTY
1	Power Transistor-MACOM	PH 2731-75L	16
2	Load 50Ω	909F	15
3	SMA-Connector	SMA-50KKF	02
4	Resistor	RFP-30- 100R	24
5	SMD Capacitors	SMTC 1206	16
6	Electrolytic Capacitor	63V100UF	16

Appendix B

Radar Pulsed Power Transistor PH 2731-75L Datasheet

PH2731-75L

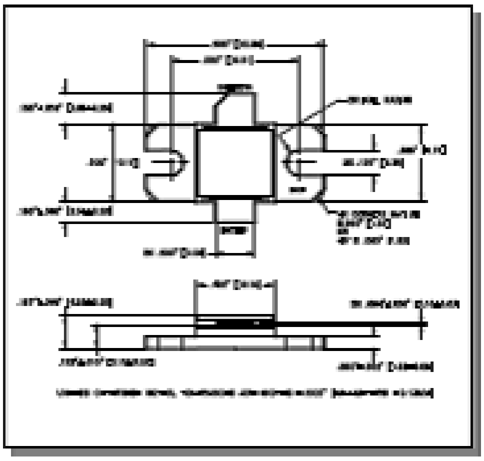
MACOM

Radar Pulsed Power Transistor
75 W, 2.7 - 3.1 GHz, 300 µs Pulse, 10% Duty Rev. V1

Features

- NPN silicon microwave power transistors
- Common base configuration
- Broadband Class C operation
- High efficiency inter-digitized geometry
- Diffused emitter ballasting resistors
- Gold metallization system
- Internal input and output impedance matching
- Hermetic metal/ceramic package
- RoHS compliant

Outline Drawing



Absolute Maximum Ratings at 25°C

Parameter	Symbol	Rating	Units
Collector-Emitter Voltage	V_{CES}	65	V
Emitter-Base Voltage	V_{EBO}	3.0	V
Collector Current (Peak)	I_C	7.0	A
Power Dissipation @ +25°C	P_{TOT}	220	W
Storage Temperature	T_{STG}	-65 to +200	°C
Junction Temperature	T_J	200	°C

Electrical Specifications: $T_C = 25 \pm 5°C$ (Room Ambient)

Parameter	Test Conditions	Frequency	Symbol	Min	Max	Units
Collector-Emitter Breakdown Voltage	I_C = 50mA		BV_{CES}	65	-	V
Collector-Emitter Leakage Current	V_{CE} = 36V		I_{CES}	-	7.5	mA
Thermal Resistance	Vcc = 36V, Pout =75W	F = 2.7, 2.9, 3.1 GHz	$R_{\theta(JC)}$	-	0.8	°C/W
Output Power	Vcc = 36V, Pout =75W	F = 2.7, 2.9, 3.1 GHz	P_{IN}	-	13.5	W
Power Gain	Vcc = 36V, Pout =75W	F = 2.7, 2.9, 3.1 GHz	G_P	7.45	-	dB
Collector Efficiency	Vcc = 36V, Pout =75W	F = 2.7, 2.9, 3.1 GHz	η_C	38	-	%
Input Return Loss	Vcc = 36V, Pout =75W	F = 2.7, 2.9, 3.1 GHz	RL	-	-8	dB
Load Mismatch Tolerance	Vcc = 36V, Pout =75W	F = 2.7, 2.9, 3.1 GHz	VSWR-T	-	3:1	-
Load Mismatch Stability	Vcc = 36V, Pout =75W	F = 2.7, 2.9, 3.1 GHz	VSWR-S	-	1.5:1	-

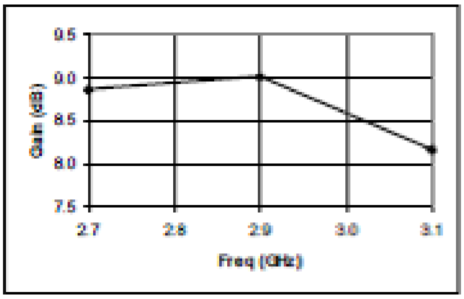
PH2731-75L

Radar Pulsed Power Transistor
75 W, 2.7 - 3.1 GHz, 300 µs Pulse, 10% Duty Rev. V1

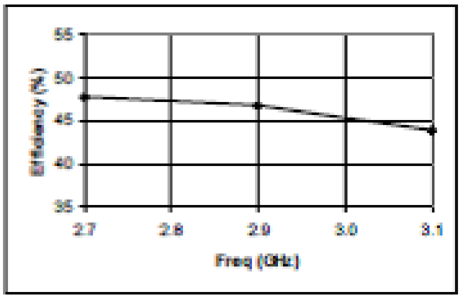
Typical RF Performance

Freq. (GHz)	Pin (W)	Pout (W)	Gain (dB)	Ic (A)	Eff (%)	RL (dB)	VSWR-S (1.5:1)	VSWR-T (3:1)
2.7	9.8	75	8.86	4.40	47.8	-11.0	S	P
2.9	9.4	75	9.01	4.50	46.7	-18.5	S	P
3.1	11.5	75	8.16	4.80	43.8	-17.7	S	P

Gain vs. Frequency

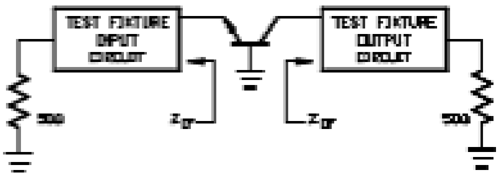


Collector Efficiency vs. Frequency



RF Test Fixture Impedance

F (GHz)	Z_{IF} (Ω)	Z_{OF} (Ω)
2.7	6.9 - j12.2	4.5 - j6.8
2.9	6.0 - j11.7	3.9 - j6.1
3.1	5.2 - j10.0	3.4 - j4.8

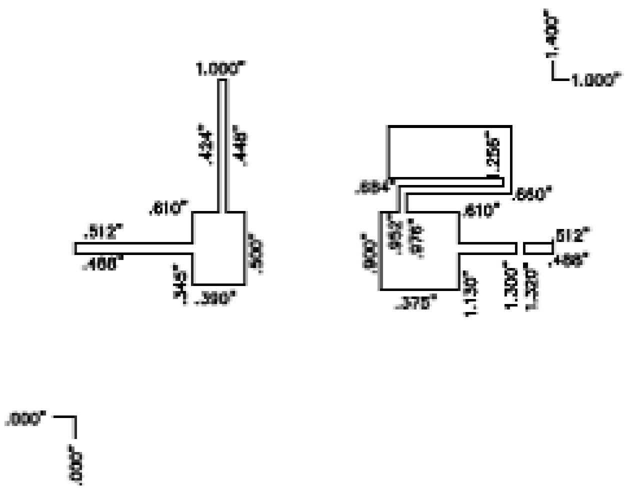


PH2731-75L

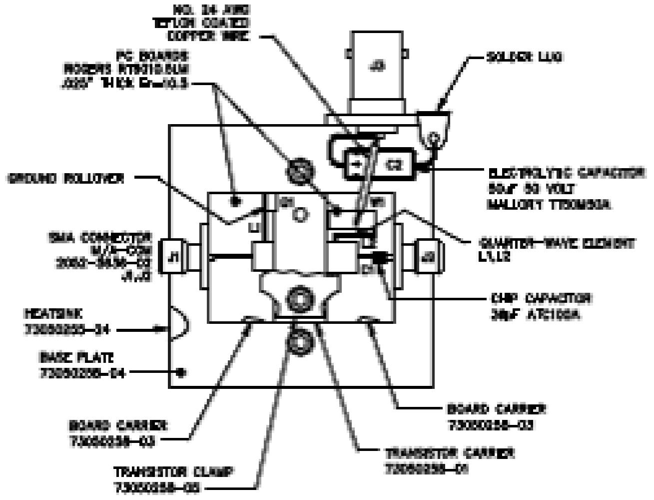
Radar Pulsed Power Transistor
75 W, 2.7 - 3.1 GHz, 300 µs Pulse, 10% Duty

Rev. V1

Test Fixture Circuit Dimensions



Test Fixture Assembly



Bibliography

[1] Skolnik,M. *Radar Handbook*, New York : McGraw-Hill (2009)

[2] Wilkinson,E. *An N-way hybrid power divider, IRE Trans Microwave Theory* NewYork:Tech MTT-8 (1960), p.116118.

[3] Thomas Koryu Ishii. *Handbook of Microwave Technology* : Academic Press (1995), p. 94-98

[4] Pozar, D. M., *Microwave engineering*, Hoboken,NJ : John Wiley & Sons, Inc.(2005), pp. 318- 324

[5] S.Banu, A.Vishwapriya, R.Yogamathi,A.V.Meenakshi, SPK.Babu. *Comparison of Wilkinson Power Divider and Gysel Power Divider* CoNeCo,WiMo, NLP, CRYPSIS, ICAIT, ICDIP, ITCSE, CS & IT. India, 2012.

[6] DIN, AMIR RUDIN BIN MAT. *DESIGN OF MODIFIED MICROWAVE POWER DIVIDER FOR RADAR* University Teknologi Malaysia, APRIL 2007.

[7] S. C. Siva Prakash, M. Pavithra M. E., A. Sivanantharaja. "DESIGN OF COMPACT COUPLED LINE WIDE BAND POWER DIVIDER WITH OPEN STUB" *ARPN Journal of Engineering and Applied Sciences*, MAY 2015.

[8] P.Deng, J.Guo and W.Kuo, "New Wilkinson Power Divider Based on Compact Stepped-Impedance Transmission Lines and Shunt Open Stubs." *Progress In Electromagnetics Research*, vol.123, pp.407-426, 2012.

[9] L. N. Ridenour, *Radar System Engineering*, New York: McGraw-Hill, vol 1, 1947.

[10] P.N.Joseph, *Naval Air Warfare Center, Electronic Warfare and Radar System Engineering Handbook*, Patuxent River, Md: The Division (1998)

[11] Misra, Devendra, *Radio Frequency and Microwave Communication Circuits*, New York : Wily (2012)

[12] Laverghetta, Thomas S. *Microwaves and Wireless Simplified*, London: Artech House (2005).

[13] "Microwave Theory", *madmadscientist.com* 2017. [Online]. Available:http://www.madmadscientist.com/html/Theory.htm. [Accessed: 09-May 2017].

[14] A. S. S. Mohra, "Compact dual band Wilkinson power divider," *2008 National Radio Science Conference*, Tanta, 2008, pp. 1-7

[15] C. Mahardika, B. S. Nugroho, B. Syihabuddin, A. D. Prasetyo and D. A. Nurmantris, "Modified Wilkinson Power Divider 1 to 4 at S-band as the part of smart antenna for satellite tracking, telemetry, and command subsystem", *International Conference on Control, Electronics, Renewable Energy and Communications (ICCEREC)*, Bandung, 2016, pp. 70-73.

[16] M. Park, "Comments on planar wideband in-phase power divider / combiner using modified gysel structure", *IET Microwaves, Antennas and Propagation*, vol 8, no 14, pp 1259-1260, (2014)

[17] Debajit De, Anand Prakash "Design and Analysis of Various Wilkinson Power Divider Networks for L Band Applications", *IEEE Conference on Signal Processing and integrated Networks*, pp. 67-72, (2016)

[18] A. B. Santiko and F. Darwis, "Design of a dual band power divider using meander line technique frequency 4928 MHz and 9856 MHz for radar application",*International Seminar on Intelligent Technology and Its Applications (ISITIA)*, Lombok, 2016, pp. 295-298.

[19] W.John*ADS Example Book: Focused on RF & Microwave Design*, New York:Keysight Technologies (2016)

[20] Ali A. Behagi, *RF and Microwave Circuit Design,A Design Approach Using (ADS).* California :Ladera Ranch, (2015)

[21] “MACOM Power Amplifiers”, *Macom.com* [Online]. Available: https://www.macom.com/products/amplifiers/power-amplifiers. [Accessed: 09- June- 2017].

[22] “Rogers Cooperation RT/duroid 5870 /5880 High Frequency Laminates data sheet”, *Rogerscorp.com* [Online]. Available : https://www.rogerscorp.com/acm/RT-duroid-5870-5880-Data-Sheet.pdf [Accessed: 15-July-2017]

[23] “Rogers Coporation, MWI-2017 Transmission Line modeling Software revision 3”, *Rogerscorp.com* [Online]. Available : https://www.rogerscorp.com/documents/8939/acs/2017-Microwave-Instruction-Manual.pdf [Accessed: 15-August-2017]

[24] Bahl, I.J., Gupta K. C., “Average Power Handling Capability of Microstrip Lines”, *IEE proceedings on H Microwaves, Optics and Antennas*, vol.127, no.1, p.40,1980.

[25] “Usage of Smith Chart in ADS”, *keysight.com*. [Online] Available http://edadocs.software.keysight.com/display/ads2009/Introducing+theSmith+Chart+Uti [Accessed: 09- June- 2017]

[26] “Principles of measuring high frequency networks with network analyzer by Keysight Technologies”, *keysight.com* [Online] Available : https//www.keysight.com/en/pcx-x2015001 [Accessed: 15 August 2017]

[27] “Technical manual of E5071C ENA Vector Network Analyzer by Keysight Technologies” *keysight.com* [Online] Available : https/l/iterature.cdn.keysight.com/litweb/pdf/5989-5478EN.pdf [Accessed: 15 August 2017]

[28] "Impedence matching of Electronic Circuits", *electronicdesign.com*[Online] Available :http://www.electronicdesign.com/datasheet/back-basics-impedance-matching-part-1-pdf [Accessed: 30 August 2017]

[29] "Getting Started Guide: Agilent E4440A Spectrum Analyzer", *keysight.com* [Online] Available : https//literature.cdn.keysight.com/litweb/pdf/E4440-90607.pdf [Accessed: 30 August 2017]

[30] "Product catalogue coaxial fixed attenuators Model DTS250 DC-4GHz 500 Watts", *weinschel-catalog.apitech.com* [Online] Available : https//http://weinschel-catalog.apitech.com/category/er-fixed-coaxial-attenuators-100-1000-w-dc-18-ghz [Accessed: 30 August 2017]