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B. ENG. (HONS) ELECTRICAL & ELECTRONICS ENGINEERING

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DESIGN OF MICROWAVE IM3 FREE TRANSMITTER

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**ELECTRICAL & ELECTRONICS ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
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**Design of 3rd Order Intermodulation (IM3) Free
Microwave Transmitter**

by

Tan Et Chian

18055

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics)

JANUARY 2017

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirements for the
BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL & ELECTRONICS)

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JANUARY 2017

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(TAN ET CHIAN)

ABSTRACT

This research is designed to develop a microwave transmitter that able to eliminate third order intermodulation distortion (IM3) for microwave input signals of 1.90 GHz and 1.95 GHz.

Microwave transmitter is a collection of electronic devices or circuits that have function in transmitting microwave data signal from the source or signal generator to the atmosphere. Typically, microwave has the frequency range from 0.3 GHz to 3 GHz in electromagnetic spectrum and signal wavelength from 1 mm to 1 m. Intermodulation distortion (IM) products are formed when numerous signals are combined in a nonlinear system. This nonlinearity response can be occurred due to component malfunction or over-burden of excessive signal strength. As those IM pulses are undesirable and located very near to the fundamental frequency pulses, adjacent of channel due to signal crosstalk problem can be occurred. Thus, a narrowband interdigital bandpass filter is needed to isolate IM pulses especially IM3 which located very close to the fundamental data pulses and exponentially power increment of IM pulses due to power increment of input signal. A high gain microwave transistor amplifier is designed to boost up the amplitude of the signal pulses to match the pulses power with the power level that required by the device for the signal transmission. A small patch antenna is also produced to convert the filtered signal to electromagnetic (EM) waveform and radiate the data signal out to the open spaces.

The study scope for this project is separated into three respective phases which are theoretical modelling, design stimulation and prototype development of microwave IM3 free transmitter. The methodology used for the generation of IM3 free transmitter is started with determine the required design specification and get the design parameters for the transistor amplifier, bandpass filter and antenna. Ideal stimulation and prototype layout generation is done by using Advanced Design System (ADS) software with the parameters calculated based on the specific requirements for each device. After verifying the stimulation response of the system, development of hardware prototype is done. Then, testing and measurement of the hardware prototype is done by using the Anritsu Network Analyzer. Finally, the integration process of the prototypes into one system is done by using SMA male-male connector.

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ABBREVIATIONS AND NOMENCLATURES

FYP	Final Year Project
IM	Intermodulation
IM3	3 rd Order Intermodulation Distortion
DUT	Device Under Test
BPF	Bandpass Filter
Q-Factor	Quality Factor
S-Parameter	Scattering Parameter
MHz	Mega Hertz
GHz	Giga Hertz
dB	Decibel
IL	Insertion Loss
RL	Return Loss
EM	Electromagnetic Wave
ADS	Advanced Design System
EMDS	Electromagnetic Design System
VNA	Visual Network Analyzer

CHAPTER 1

INTRODUCTION

1.1 Background Study

Microwave signal is a type of electromagnetic wave with frequencies range from 300 MHz to 300 GHz and wavelength from 1 millimeter to 1 meter [1]. It has an enormous impact on present day society. Its applications are various, from entertainment via satellite television, to civil and military radar system. Today's, it has wide application in wireless networking and communication system due to its features in easier focus into narrower beams compared to radio waves and allowing frequency to be reused [1, 2].

Signal combination is the process of adding two amplitude varying signals together in frequency spectrum [1, 3]. Combination of data signals in a linear system will generate an exact same output frequency as the input signal. While for the injection of two data signals in a non-linear device under test (DUT), it will generate multiple additional frequency signals corresponded to the sinusoidal inputs [1]. Besides harmonic signals from multiplication of each input signals, the system will also generate infinity order of unwanted cross product of the frequency of the input signals which also known as intermodulation (IM) distortion due to the interferences uncorrelated of signal between desired data and previous order signal pulses [3-5]. The generation of IM signal pulses will interface with the information signal in the circuit and cause crosstalk and problem of properties changes in the data signal due to interruption as well as the adjacent channel interference [3].

1.2 Problem Statement

Combination of two or more data signals in a non-linear system will generate numbers of despicable harmonics signal pulses and mixer products of the input signal pulses called intermodulation (IM) distortion pulse. Third order IM process will generate IM3 signals due to the summation between fundamental signal pulses and IM2. FIGURE 1 shows the output power response of IM signals with the power manipulation in input signal. The power increment of input signal will cause exponentially power increment of IM3. When the input signal increased by 1 dB, the power of the IM3 pulses will increased by 3 dB and cause crosstalk issue when the power level of the IM pulse reaches 3rd order intercept point [6]. As the IM3 located very close to the fundamental signal pulse, those pulses will cause the issue of conversion loss of the devices and signal distortions as well as adjacent channel distortion to the output spectrum.

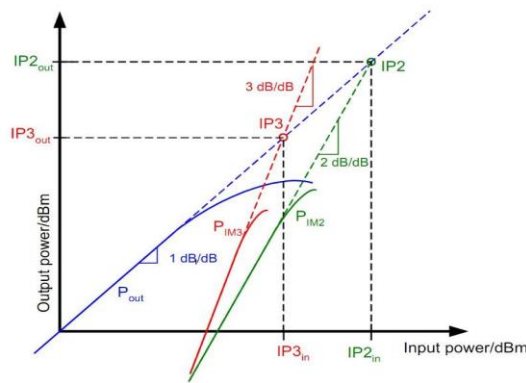


FIGURE 1: Third Order Intercept Point [6]

1.3 Objectives

This research is done to fulfill below objectives:

- To design a high efficiency microwave bandpass filter in filtering IM3 pulses out from output frequency spectrum.
- To design an amplifier and antenna at its resonant frequency.
- To fabricate designs and measure the prototypes generated.
- To integrate the fabricated prototypes for signal transmission.

1.4 Scope of Study

This research is about design and generate a microwave transmitter that can eliminates all the intermodulation disturbances (IM) produced by combination of fundamental data signals and cross products of the fundamental data signals. This IM elimination process can be done by employing a narrowband bandpass filter with high selectivity. Besides filter, a microwave amplifier with high power gain factor transistor is also designed to boost up the power of the output signal produced by the device. A patch antenna is also designed to convert the electrical signal to the electromagnetic (EM) wave for signal transmission to the atmosphere.

1.5 Relevancy of Project

This project is relevant because it provides a solution to eliminate the 3rd order intermodulation distortion (IM3) from the frequency spectrum. Typically, IM3 will interface with the fundamental frequencies and affect the quality of the data signal to be transmitted. The formation of IM3 exceeding 3rd order intercept point due to exponential increment of the amplitude of the IM3 pulse than fundamental pulses will cause the problem of adjacent signal channel and crosstalk issue. Hence, the development of IM3 free transmitter with high roll-off filter is needed to optimally eliminate the IM3 pulses and improve the quality of output data signal.

1.6 Chapter Organization

This research paper consists of FIVE chapters. Chapter 1 introduces about the background, description about problems to be solved, objectives and study scope of this project as well as project relevancy. Chapter 2 is the literature review and relevant research on the problem addressed by this project. Chapter 3 presents the methodology and procedure taken in generating the prototype as well as tools for output data collection. Chapter 4 presents and discusses the results and data analysis of the project outputs. Chapter 5 is the summary and future works of the project.

CHAPTER 2

LITERATURE REVIEW

In telecommunication, transmitter plays an important role in processing and transmitting data signal from sources to destination. It is the collection of several transmission components like signal generator, modulator, power amplifier, filter and transmission antenna [3].

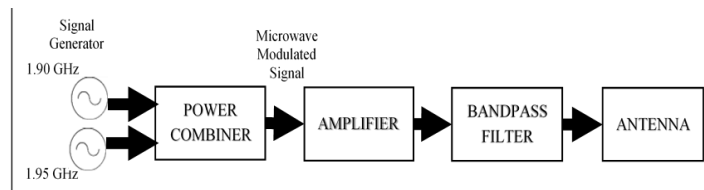


FIGURE 2: Transmitter Block Diagram

Signal generator is also known as oscillator which has the function in generating the information signal with a synchronized radio frequency. Signal combiner acts in combining the input signal in frequency spectrum. While power amplifier acts in matching the power level at output port to the input port with larger amplitude by converting the low frequency signal to certain output power level. Next filter acts in controlling the frequency range of the transmitted signal and blocking the unwanted signal pulses from the system. Lastly, transmission antenna will convert the filtered microwave signal to electromagnetic (EM) signal wave [3].

2.1 Intermodulation Distortion in Transmitter

Ideally, the components in the transmitter will behave as a linear system whereby the output is a constant multiplication of input with the frequency same as the input signal. However, in real phenomena, the output of the system is a complex function of

the input [7]. This nonlinear condition can be due to the component malfunction or excessive load from high signal strength [8]. As the physical device only have ideal characteristic over a limited range of input amplitude, the output amplitude is limited. If the input amplitude is such that output of ideal system exceed physical system limit, the output of the system will be saturated. Modulation of a non-linear network will include a lot of other terms output frequency pulse called spectral regrowth, beyond the linear components generated in a linear system [5, 6, 9].

Below is the N-order intermodulation response of a non-linear network [6].

$$\begin{aligned}
 y_{NL} = & a_1 A(t - \tau_1) \cos[\omega_c t + \theta(t - \tau_1) - \phi_1] \\
 & + a_2 A(t - \tau_2)^2 \cos[\omega_c t + \theta(t - \tau_2) - \phi_2]^2 \\
 & + a_3 A(t - \tau_3)^3 \cos[\omega_c t + \theta(t - \tau_3) - \phi_3]^3 \\
 & + \dots \\
 & + a_n A(t - \tau_n)^n \cos[\omega_c t + \theta(t - \tau_n) - \phi_n]^n
 \end{aligned} \tag{2.1}$$

where $\phi_n = \omega_c \tau_n$

FIGURE 3 is the output frequency spectrum of two frequency varying input signals in a non-linear system. The formation of IM3 frequency pulses will cause the problem of signal crosstalk and channel adjacent issue when the amplitude of IM pulse attains input signal and reaches intercept point due to the location of IM3 which very close to the input frequency and amplitude increment of input signal that causes the exponentially increment in power amplitude of IM pulse. Thus, all IM products resulted should be removed from the device to prevent performance degradation of the device and optimize the quality of the signal transmitted [6, 9].

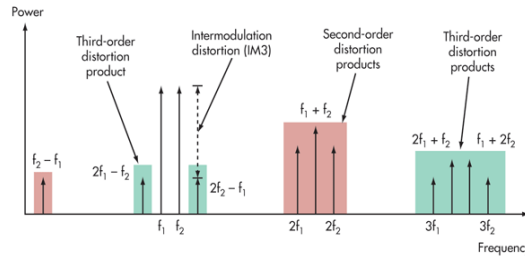


FIGURE 3: Output Spectrum of Nonlinear 2-Port Network [4]

2.2 Bandpass Filter

Microwave filter is a 2-port network electronic device that isolates and controls passband frequency in only allowing specific frequency to pass through the system and attenuating those frequencies that outside of the passband frequency range [1, 2].

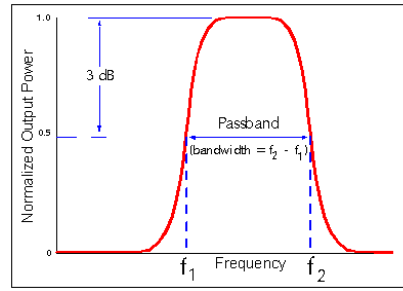


FIGURE 4: Bandpass Filter Response [3]

FIGURE 4 shows the response of a bandpass filter. As described in [1], the passband of a filter is located in frequency range whereby the filter has at least half of the peak power gain [1]. Theoretically bandpass filter is designed by mixing a low-pass filter with a high-pass filter or using conventional technique in performing passband frequencies shifting of a low pass filter to a bandpass filter. Ideally a bandpass filter will produce exactly flat boundary at both side of passband frequency with no gain and attenuation at all stopband frequencies [1, 2]. Practically, this condition cannot be achieved due to the impulse response of filter over time and its causality characteristics. The phenomena of attenuation at stopband is known as roll off and calculated in decibel (dB). The insertion loss resulted in devices determines how does power changed when a signal passes through a device while return loss determines power loss of the signal due to discontinuity in the transmission line [1, 2].

Any circuit that has resonant elements can act as a filter [1, 2]. In designing a bandpass filter, fractional bandwidth (FBW) or Q-factor is one of the most important parameters in obtaining the ratio between the bandwidth and centre frequency. There are many types of filters be researched such as capacitive gap filter, parallel coupled lines filter and interdigital filter. Capacitive gap filter is filter that consists of multiple of 180° series lines ($\frac{\lambda}{2}$ in length) that act as resonators and each line is separated by varies gap sizes. It is easily implemented in PCB and spaces saver than plain transmission line. However, the insertion loss of system increases with increment in FBW causing low in Q factor. Furthermore, the design is hard for low Q-factor filter due to small gap width needed in design. Parallel coupled line is a filter that consists of multiple row of parallel resonators with $\frac{\lambda}{2}$ in length and coupled only $\frac{\lambda}{4}$ portion with the next row of line, forming stair-like pattern. In this design, wider bandwidth is allowed compared to capacitive gap filter but still will facing gap width problem where tighter gap between each line is needed as Q-factor decreases and thus limits the

accuracy of printing process. While for interdigital filter, it is a couple line filter which is $\frac{\lambda}{4}$ in length and short-circuited at the alternative end of each line segment. One of the advantages in this design is that no insulators is needed in eliminating the dielectric losses between lines. It is compact in line structures whereby each line is same in length and spaced by certain gap. Besides, the gap spacing between lines is more flexible compared with parallel coupled line as it is applicable in system with higher FBW and lower Q-value requirements [1]. With that, a higher Q-factor and system with low energy loss can be achieved. In the addition, the spurious response of this filter is not possible to occur as its 2nd passband is appeared at three times the center frequency of the first passband is located. Unlike the other filter with line length of half wavelength, parallel-coupled resonators will result in narrow spurious passband at twice the center frequency of the first passband is [10].

2.3 Transistor Amplifier

A microwave transistor amplifier is a device that transform input power into an effective output power level in running certain device with the presence of transistors. It has the benefits of low cost, reliable and ease in installing in microwave integrated circuits. Various of microwave transistor are available nowadays such as gallium arsenide field effect transistors (GaAs FETs), silicon bipolar transistors, heterojunction bipolar transistors (HBTs) and high electron mobility transistors (HEMTs). Among all, silicon bipolar transistors and GaAs FETs are the most commonly used transistor. GaAs FET has better noise figures and capable to operate at higher frequencies compared to bipolar transistor [1, 11]. Since the electronic properties for every equipment is varies from one another, thus an amplifier circuit is important to standardize and increase signal power to the desired output power [11]. The utilization of microwave transistor amplifier will increase the waveform of the output spectrum proportionally[12]. In designing a microwave transistor amplifier, the selection of a gain transistor plays a significant functionality in determine the performance of the device as well as the output waveform. Besides that, the stability of the transistor in an amplifier also very critical. The condition whereby reflection coefficient less than unity at the input and output port will causing instability in the system[13]

2.4 Microwave Antenna

There are multiple types of antenna can be designed and fabricated. As defined in Webster's dictionary, antenna is a metallic device for signal wave transmission and reception. The choice of antenna is highly depending on the location, centre frequency and applications that a user needed. The return loss of an antenna is highly depending on its resonant frequency[14, 15]. The microstrip patch antenna is one of the easiest and cheapest fundamental antenna that can be fabricated. Its light weight, low cost, small size and flat profile characteristics[16] make it famous be applied in mass-produced wireless products like handset, GPS receiver and communication devices [14, 17-19]. It mainly consists of three major parts (patch, feed line and ground). The dielectric substrates plane highly determined by the efficiency of the patch antenna, ϵ_r . A copper layer on the substance functions in radiating the data and determines both return loss and gain value of the antenna. In fabricating a patch antenna, parameters like resonant frequency, return loss, gain, bandwidth (working frequency range), directivity and radiation pattern play an important role in optimizing the performance and transmission bandwidth of antenna [20].

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

Research methodology is a systematic way which describes how a research is conducted. Essentially, it is the procedures taken by researches in going through their work of descriptions, explanations and predictions. With the proper planning of the procedure, the targets of this research can be achieved within certain period and indirectly improve the time effectiveness of this project. FIGURE 5 shows the general flow of the research methodology of this project.

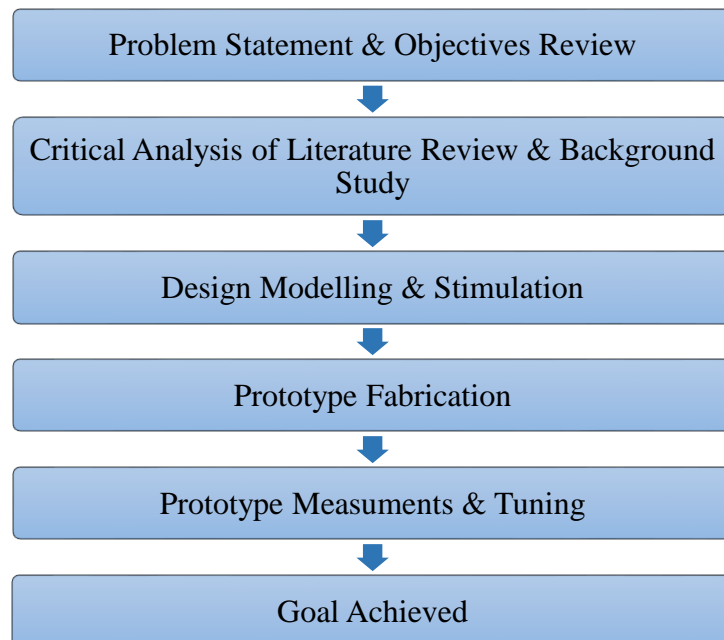


FIGURE 5: General Research Methodology Flow

3.2 Prototype Design Flow

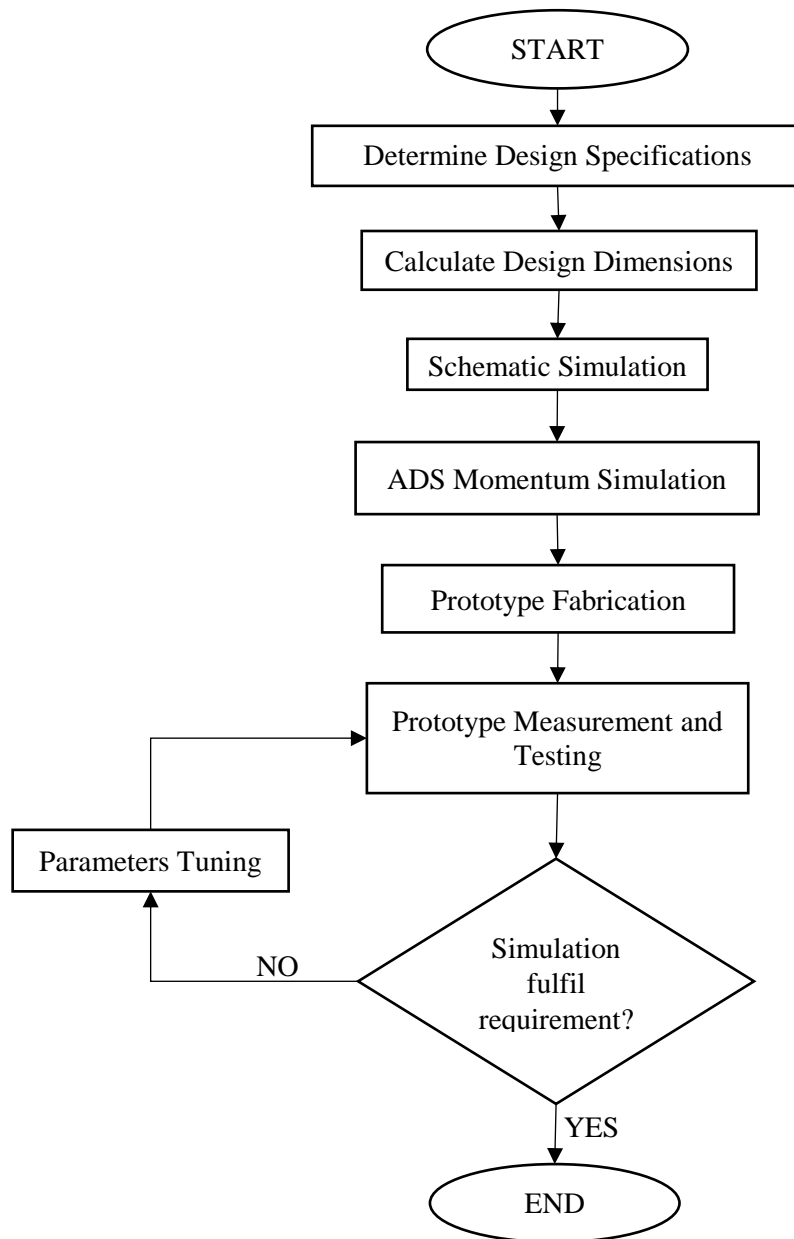


FIGURE 6: General Flow Chart of Design Flow

FIGURE 6 is the general design flow chart for three components in transmitter which are amplifier, bandpass filter and antenna. The first step in prototype design process is design specifications determination. The filter design specifications like centre frequency, passband frequency, bandwidth range, insertion loss and return loss are figured out. Then, the dimensions of the design parameters are calculated and then inserted in the designs schematic and layout in Advanced Design System (ADS) software for stimulation. The S-parameter method is selected in running the stimulation and the generated response of the circuit is observed and analyzed. The

design parameters are tuned to obtain the signal response that fulfill the design requirements. Next, the layout of the design is sent for prototype fabrication. Prototype measurement with Aritsu Network Analyzer and tuning process is done after fabrication to fulfill the design specifications.

3.3 Project Activities

In this research, the design of the prototype is based on some specific design requirements as stated below. All the parameters for the components in the prototype are calculated. For the amplifier, a high gain transistor is selected to power up the signal pulse. For the filter, a narrowband interdigital bandpass filter is selected to achieve filter output as close as possible to the ideal response. A patch antenna is designed in converting the signal to waveform and radiating it to the receiver due to its convenience in design and fabrication. The layout of prototype is simulated by using ADS stimulation software to determine and analyze the circuit response.

TABLE 1: Prototype Design Specifications

Requirements	Amplifier	Filter	Antenna
Centre Frequency, f_0	1.925 GHz	1.925 GHz	1.925 GHz
Passband Frequency, f_p	-	1.875 – 1.975 GHz	-
Bandwidth, BW	-	100 MHz	-
Narrowband wavelength	10% BW	-	-
In-Band Gain / Insertion Loss, S_{21}	10 dB (min)	-4 dB (Typical)	-
Return Loss (S_{11} , S_{22})	< -7 dB	-10 dB	-15 dB
Insertion Loss at IM3	-	-15 dB	-
Port Impedances	50 Ω		

3.4 Simulation and Measurement Response

The design of the system for each device is done based on the specific requirements by using ADS software and the stimulation of prototype layout is done by using ADS momentum and EMDS simulator. Testing and measurement of the fabricated prototype is done by using the Anritsu Network Analyzer.

3.4.1 ADS Momentum Simulation

Momentum is one of the ADS design simulation tools in analyzing and predicting the design performance of the modern communication system by computing S-parameter of the circuits. Momentum optimization extends the momentum capability to a true design automation tool by process varies geometry parameters automatically to achieve the optimal structure that meets the circuit or device performance goals [21, 22].

3.4.2 EMDS (Electromagnetic Design System) Simulation

Electromagnetic Design System (EMDS) for Advanced Design System (ADS) is a complete solution for electromagnetic simulation of arbitrarily-shaped, passive three-dimensional (3D) structures which enable the high accuracy and speed designs be made. It provides the best price/performance of 3D EM simulator, with a full 3D electromagnetic field solver, a modern solid modeling front-end and fully automated meshing and convergence capabilities for modeling arbitrary 3D shapes [23].

3.4.3 Anritsu Network Analyzer Response

The signal response of the fabricated prototype is tested and measured with Anritsu Network Analyzer MS2034B as shown in FIGURE 7. It is a device that can act as a Vector Network Analyzer (VNA) in measuring prototype for frequency range of 500 kHz to 4 GHz and as a Spectrum Analyzer in measuring prototype for frequency range of 100 kHz to 4 GHz. There are two steps involved in prototype testing and measurement process to get the precise response, which are equipment calibration process and prototype testing and measurement process [24, 25].



FIGURE 7: Anritsu Network Analyzer MS2034B [24]

I. Equipment Calibration Procedure

Equipment calibration with calibration tools as shown in FIGURE 8 is always be done prior to the prototype measurement to ensure the getting response is accurate under the operating condition. Various factors such as change in environment, physical length of external and internal cables as well as conditional of the test port connectors will affect the validation of the VNA as well as accuracy and repeatability of the measurement obtained. Thus, Anritsu endorses warming up of the instrument to typical operation temperature before calibrating. A repetition calibration of the VNA is needed if the internal instrument temperature changes more than 15 °C after calibration [24]. The calibration of the network analyzer is done under four conditions: short-circuit, open-circuit, fixed load condition and through connection.



FIGURE 8: Anritsu Calibration Kit[24]

- Short-circuit

Defined by an S-parameter file or a model consisting of a transmission line length and a frequency-dependent inductance. The inductance is defined as

$$L = L_0 + L_1 \cdot f + L_2 \cdot f^2 + L_3 \cdot f^3$$

- Open-circuit

Defined by an S-parameter file or a model consisting of a transmission line length and a frequency-dependent capacitance. The capacitance is defined as

$$C = C_0 + C_1 \cdot f + C_2 \cdot f^2 + C_3 \cdot f^3$$

- Fixed Load condition

Defined by an S-parameter file or a model consisting of a transmission line length, a shunt capacitance, a resistance, and a series inductance as shown.

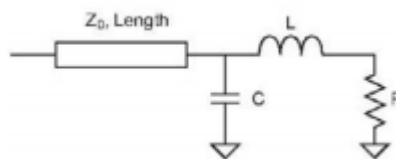


FIGURE 9: General Representation of Load Model

- Through Connection

Modeled as a transmission line length with some frequency dependent loss. A root-f frequency dependence of that loss is assumed. If 0 is entered for f_0 (the reference frequency), the loss is assumed to be constant with frequency.

$$Loss(f) = Loss(f_0) \cdot \sqrt{\frac{f}{f_0}}$$

II. Measurement Procedure

The prototype is measured with frequency range from 1.5 GHz to 2.5 GHz by using VNA MS2034B. A label marker function is selected to mark the frequency response at 1.925 GHz and the measured values for both S_{11} and S_{21} as shown on the screen. The results are recorded and saved in s2p file format.

3.5 Key Milestones and Deliverables

Week 3 - 6	Critical Literature Review
Week 7 - 9	Interdigital Bandpass Filter Design Modelling and Stimulation with ADS
Week 10 - 12	Patch Antenna Design Modelling and Stimulation with ADS
Week 13 - 15	Transistor Amplifier Design Modelling and Stimulation with ADS
Week 16 - 18	Design Layout Generation with ADS
Week 19 -23	Prototype Fabrication
Week 24 -27	Prototype Measurement and Testing with VNA
Week 28	Prototype Integration

FIGURE 10: Key Milestones and Deliverables

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Microstrip Interdigital Bandpass Filter

A N-order microstrip interdigital filter is constructed as shown in Figure 4. The design parameters are calculated using following equations [2, 26]:

$$N \geq \frac{L_A + L_R + 6}{20 \cdot \log_{10} \left(S + (S^2 - 1)^{\frac{1}{2}} \right)} \quad (4.1)$$

$$\theta = 90 \cdot \frac{f_p}{f_0} \quad (4.2)$$

$$\alpha = \frac{1}{\tan \left(\theta \cdot \frac{\pi}{180} \right)} \quad (4.3)$$

$$1 + \varepsilon^2 = \frac{1}{|S_{12}|^2} \quad (4.4)$$

$$\eta = \sinh \left(\frac{1}{N} \cdot \operatorname{arcsinh} \left(\frac{1}{\varepsilon} \right) \right) \quad (4.5)$$

$$C_i = \frac{2}{\eta} \cdot \sin \frac{(2 \cdot i - 1) \cdot \pi}{2 \cdot N} \quad (4.6)$$

$$K_{i,i+1} = \frac{\left(\eta^2 + \sin^2 \left(\frac{i \cdot \pi}{N} \right) \right)^{\frac{1}{2}}}{\eta} \quad (4.7)$$

$$n_1 = \frac{1}{\left(1 + \frac{C_1}{\alpha} \right)^{\frac{1}{2}}} \quad (4.8)$$

$$n_i = \left(\frac{\alpha}{C_i} \right)^{\frac{1}{2}} \quad (4.9)$$

$$Y_{i,i+1} = n_i \cdot n_{i+1} \cdot K_{i,i+1} \quad (4.10)$$

$$Y_i = 1 - n_{i-1} \cdot n_i \cdot K_{i-1,i} - n_i \cdot n_{i+1} \cdot K_{i,i+1} \quad (4.11)$$

$$Z_i = \frac{1}{Y_i} * Z_{in} \quad (4.12)$$

$$Z_{i,i+1} = \frac{1}{Y_{i,i+1}} * Z_{in} \quad (4.13)$$

$$B = \frac{377 \cdot \pi}{2 \cdot Z_0 \cdot \sqrt{\epsilon}} \quad (4.14)$$

$$W = \frac{2}{\pi} \cdot d \cdot \left(B - 1 - \ln(2 \cdot B - 1) + \frac{\epsilon - 1}{2 \cdot \epsilon} \cdot \ln(B - 1) + 0.39 - \frac{0.61}{\epsilon} \right) \quad (4.15)$$

$$L = \frac{1}{4} \cdot \frac{c}{f_0} \quad (4.16)$$

TABLE 2 shows the design parameters calculated by using the equations (4.1) to (4.16) and parameters values after tuning with ADS software with the filter order of 5. The type of substrate that be used in this research is Rogers RT/duroid 5880 substrate. TABLE 3 shows the substrate properties of RT/duroid 5880 substrate.

TABLE 2: Filter Design Parameters Calculated and After Tuning with ADS

Design Parameters	Calculated (μm)	After Tuning (μm)
L	58507.20	26950.91
W ₀	1783.45	1535.04
W ₁	1674.02	2343.62
W ₂	2224.66	1801.97
W ₃	2248.53	2023.68
W ₄	2224.66	1801.97
W ₅	1674.02	2343.62
W ₆	1783.45	1535.04
S ₀₁	250.00	385.00
S ₁₂	649.75	2794.62
S ₂₃	846.23	3695.02
S ₃₄	846.23	3695.02
S ₄₅	649.75	2794.62
S ₅₆	250.00	385.00

TABLE 3: Rogers RT/duroid 5880 Substrate Properties

Substrate Properties	Value
Substrate Name:	Rogers RT/duroid 5880
Substrate Height, h:	787 μm
Relative Dielectric Constant:	2.2
Conductivity:	5.88×10^7
Dielectric Loss Tangent:	0.0009

With all the design parameters calculated, the design schematic diagram is stimulated with Advanced Design Stimulation (ADS) software as shown in FIGURE 11.

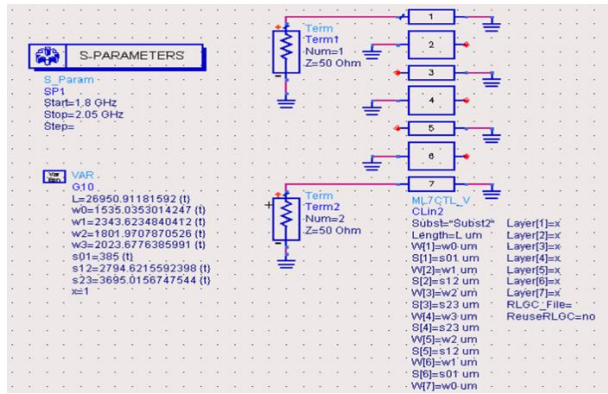


FIGURE 11: Interdigital BP Filter Design Schematic Diagram (5th Order Filter)

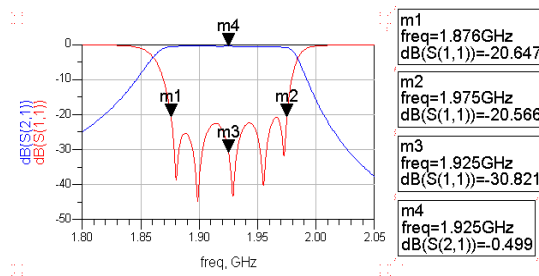


FIGURE 12: Interdigital Filter S-Parameter Response

FIGURE 12 shows the ideal S-parameter response of the interdigital bandpass filter with the design stimulation tuning parameters as shown in TABLE 2. The passband region of the filter is located from 1.876 GHz to 1.975 GHz with the filter bandwidth of 100 MHz and centre frequency of 1.925 GHz. The filter return loss is around -20 dB at the passband and -30 dB at 1.925 GHz with passband attenuation of -0.5 dB.

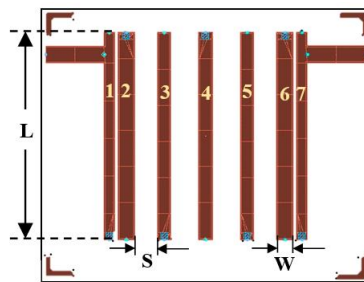


FIGURE 13: Interdigital Filter Design Layout

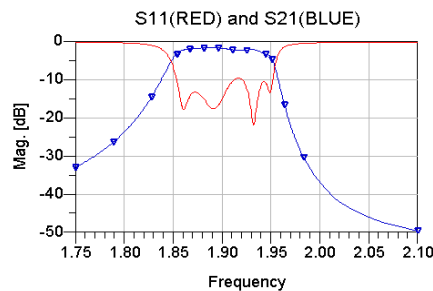


FIGURE 14: Interdigital Filter ADS Momentum Response

FIGURE 13 is the layout diagram of the filter design. The accuracy of the filter is optimized with momentum which uses frequency-domain Method of Moments (MoM) technology in accurately simulating complex EM effects. FIGURE 14 shows the filter momentum response of the designed bandpass interdigital filter. The passband region of the filter is located from 1.871 GHz to 1.978 GHz with the filter bandwidth of 107 MHz and centre frequency of 1.925 GHz. The filter return loss is around -23 dB and passband attenuation of 1.5 dB at 1.925 GHz. The insertion loss of -22 dB are recorded at IM3 frequency of 1.85 GHz and 2 GHz.

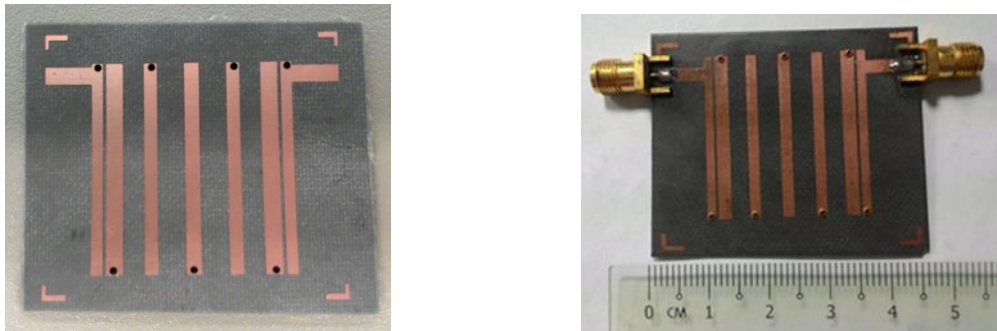


FIGURE 15: Interdigital Filter Prototype

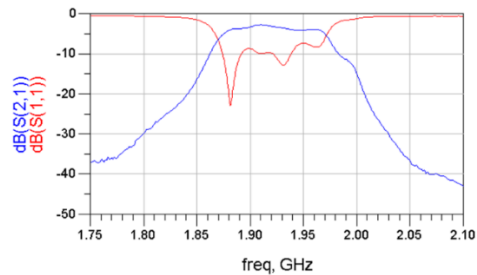


FIGURE 16: Interdigital Filter Measured Response with Anritsu Network Analyzer

FIGURE 15 is the fabricated prototype diagram of the interdigital filter design. The prototype measured response is captured by using Anritsu Network Analyzer and shown in FIGURE 16. The insertion loss of the filter design is -3.3 dB with return loss of -11 dB at the centre frequency of 1.925 GHz. As observed, the insertion loss and return loss of the filter are higher in measurement compared to the stimulation response. It might due to the fabrication tolerance of the prototype as well as imprecise dimensions in length and width of the transmission line during the fabrication. The insertion loss of -16.45 dB and -14.97 dB are recorded at IM3 frequencies of 1.85 GHz and 2 GHz.

4.2 Microstrip Transistor Amplifier

The design of amplifier falls into two categories: low noise and power. In a low noise amplifier, the transistor's input is matched for optimum noise figure and the transistor's output is conjugately matched to 50-ohm system impedance for maximum gain and return loss (RL). In a power amplifier, the 50-ohm system impedance is matched to a required load at the transistor's output for maximum power and the transistor's input is conjugately matched for gain and RL. The most important characteristics in designing an amplifier are frequency range or bandwidth, power gain, noise figure, power output, 1-dB gain compression point, input and output VSWR, power added efficiency (PAE), intermodulation distortion, adjacent channel power ratio (ACPR), dynamic range, phase noise, stability and reliability[13]. The design parameters are calculated using following equations [1, 13, 27, 28]. The accuracy of the calculated variables is verified and plotted by using ADS software as shown in Appendix 4.

$$\Delta = S_{11} \cdot S_{22} - S_{12} \cdot S_{21} \quad (4.17)$$

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2 \cdot |S_{12} \cdot S_{21}|} \quad (4.18)$$

$$C_L = \frac{(S_{22} - \Delta \cdot S_{11}^*)^*}{|S_{22}|^2 - |\Delta|^2} \quad (4.19)$$

$$R_L = \frac{S_{12} \cdot S_{21}}{|S_{22}|^2 - |\Delta|^2} \quad (4.20)$$

$$C_S = \frac{(S_{11} - \Delta \cdot S_{22}^*)^*}{|S_{11}|^2 - |\Delta|^2} \quad (4.21)$$

$$R_L = \frac{S_{12} \cdot S_{21}}{|S_{11}|^2 - |\Delta|^2} \quad (4.22)$$

$$G = \frac{P_L}{P_{in}} = \frac{|S_{21}|^2(1 - |\Gamma_L|^2)}{(1 - |\Gamma_{in}|^2)|1 - S_{22} \cdot \Gamma_L|^2} \quad (4.23)$$

$$G_A = \frac{P_{avn}}{P_{avs}} = \frac{|S_{21}|^2(1 - |\Gamma_S|^2)}{|1 - S_{11} \cdot \Gamma_S|^2(1 - |\Gamma_{out}|^2)} \quad (4.24)$$

$$G_T = \frac{P_L}{P_{avs}} = \frac{|S_{21}|^2(1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)}{|1 - \Gamma_S \cdot \Gamma_{in}|^2|1 - S_{22} \cdot \Gamma_L|^2} \quad (4.25)$$

$$G_{TU} = \frac{|S_{21}|^2(1 - |\Gamma_S|^2)(1 - |\Gamma_L|^2)}{|1 - S_{11} \cdot \Gamma_S|^2|1 - S_{22} \cdot \Gamma_L|^2} \quad (4.26)$$

TABLE 4 shows the design parameters calculated using the equations (4.17) to (4.26). With all the design parameters calculated, the design schematic diagram and

layout of the prototype are generated with Advanced Design Stimulation (ADS) software as shown in FIGURE 17 and FIGURE 18.

TABLE 4: Amplifier Design Calculated Parameters

Parameters (μm)	S_{in}	L_{in}	L_{out}	S_{out}	Z_0	$\lambda/4$
L	17678.7	6313.8	30971.1	10698.7	5000	31962.5
W	2397.83					500

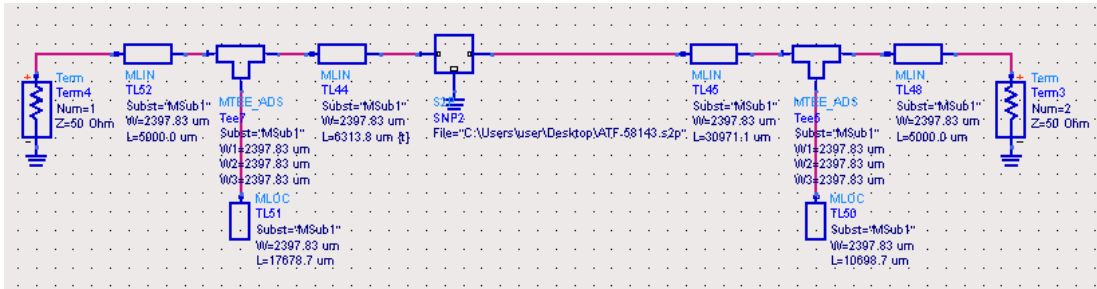


FIGURE 17: Amplifier Design Schematics Diagram

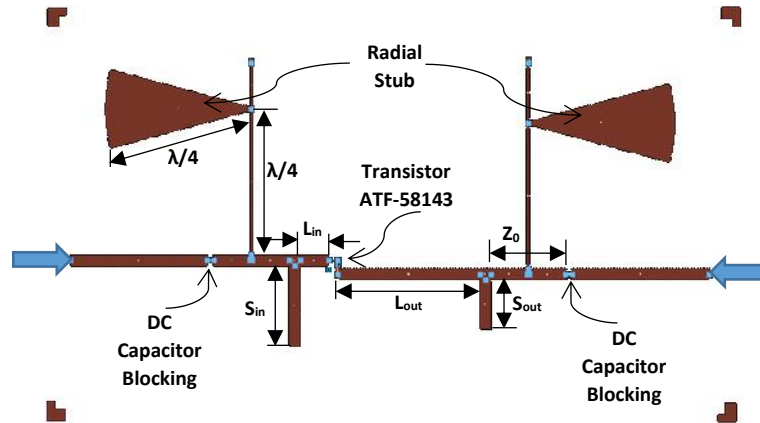


FIGURE 18: Transistor Amplifier Design Layout

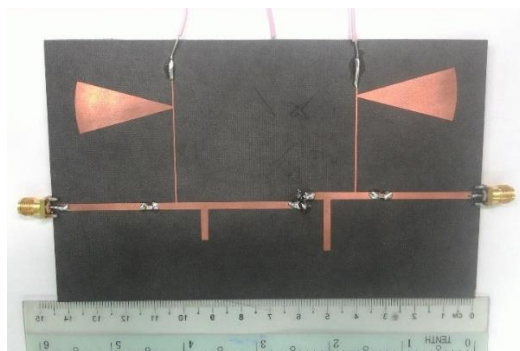


FIGURE 19: Transistor Amplifier Prototype

A radial stub and line which are $\lambda/4$ in length are installed at each side of the amplifier design to act as the network biasing circuit to the design and enable the circuit to rotate 180° about the centre of the Smith chart and perform switching between open-circuit and short-circuit. FIGURE 19 is the fabricated prototype of the transistor

amplifier with a unit of ATF-58143 transistor and two units of capacitors which act as DC current blocking components to prevent DC current from gate and drain port to flow toward input and output signal ports.

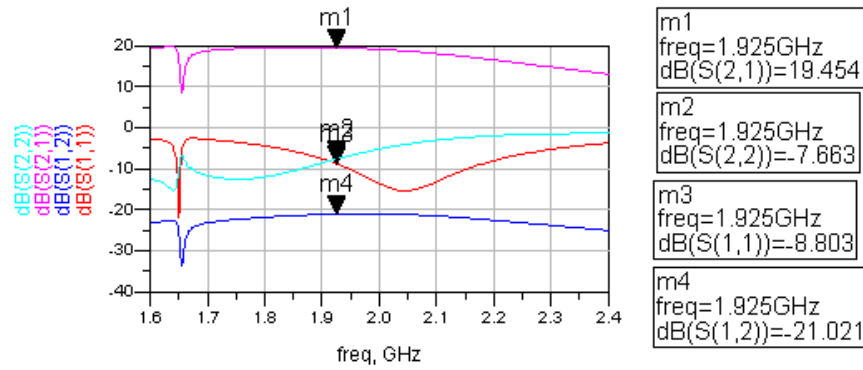


FIGURE 20: Stimulation Response of ATF-54143 Transistor Amplifier

The ideal stimulation response of the amplifier is captured as FIGURE 20. The amplifier in-band gain of 19.45 dB is obtained at the output port. The input and output impedance matching of the design are -8.8 dB and -7.67 dB are measured which mean only 13% and 17% of signal power reflected from the load. The output to input power ratio of -21.02 dB or only 0.8% of signal power transmitted from port 2 to port 1.

4.3 Microstrip Patch Antenna

Microstrip patch antenna is an antenna that constructed by placing a very thin metallic strip with a small fraction of wavelength above the ground plane [14]. The resonant input resistance can be modified by using an inset feed which inserted a distance y_0 into the patch [29]. Below are the equations to identify the design parameters of a patch antenna [14, 15, 19].

$$W = \frac{c}{2 \cdot f} \cdot \sqrt{\left(\frac{2}{E_r + 1}\right)} \quad (4.27)$$

$$E_{reff} = \left(\frac{E_r + 1}{2}\right) + \left(\frac{E_r - 1}{2}\right) \cdot \left(1 + 12 \cdot \frac{h}{W}\right)^{-\frac{1}{2}} \quad (4.28)$$

$$L_{eff} = \frac{c}{2 \cdot f \cdot \sqrt{E_{reff}}} \quad (4.29)$$

$$\frac{\Delta L}{h} = 0.412 \cdot \left(\frac{(E_{reff} + 0.3) \cdot \left(\frac{W}{h} + 0.264\right)}{(E_{reff} - 0.258) \cdot \left(\frac{W}{h} + .8\right)}\right) \quad (4.30)$$

$$L = L_{eff} - 2 \cdot \Delta L \quad (4.31)$$

$$k_0 = \frac{2 \cdot \pi}{\lambda} \quad (4.32)$$

$$G_1 = \frac{W}{120 \cdot \lambda} \cdot \left(1 - \left(\frac{1}{24}\right) \cdot (k_0 \cdot h)^2\right) \quad (4.33)$$

$$B_1 = \frac{W}{120 \cdot \lambda} \cdot (1 - 0.636 \cdot \ln(k_0 \cdot h)) \quad (4.34)$$

$$Y_{in} = 2 \cdot G_1 \quad (4.35)$$

$$Z_{in} = \frac{1}{Y_{in}} \quad (4.36)$$

$$R_{in(y=y_0)} = \frac{1}{2 \cdot G_1} \cdot \cos^2\left(\frac{\pi}{L} \cdot y_0\right) \quad (4.37)$$

TABLE 5 shows the design parameters calculated using the equations (4.27) to (4.37) and parameters after tuning with ADS software.

TABLE 5: Antenna Design Parameters Calculated and After Tuning with ADS

Design Parameters	Calculated (μm)	After Tuning (μm)
W	61602.81	61602.81
L	52202.03	50652.03
y_0	15943.54	10943.54
gap	4588.67	1000.00
w_0	2425.48	2425.48

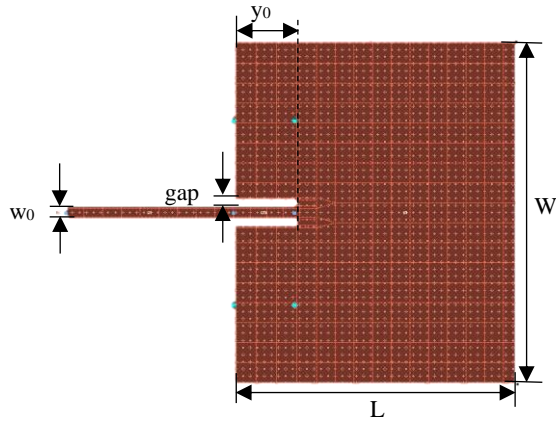


FIGURE 21: Patch Antenna Design Layout

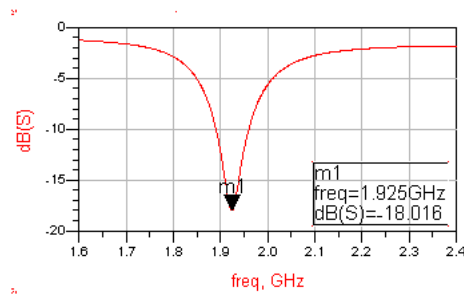


FIGURE 22: ADS EMDS Response of Antenna

FIGURE 21 is the design layout of the patch antenna. The EMDS simulation response of the designed microstrip patch antenna is shown in FIGURE 22. From the graph, the maximum reflection coefficient of the antenna is -18 dB and located at 1.925 GHz. As the radiation efficiency of an antenna is a ratio of the power delivered to the antenna relative to the power radiated from the antenna, the designed antenna has the ideal radiation efficiency of 98.4%.

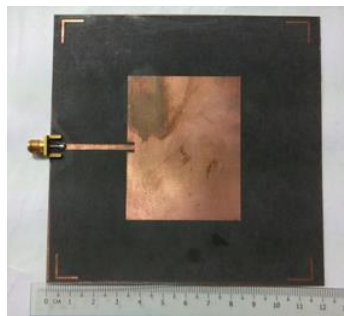


FIGURE 23: Patch Antenna Fabricated Prototype

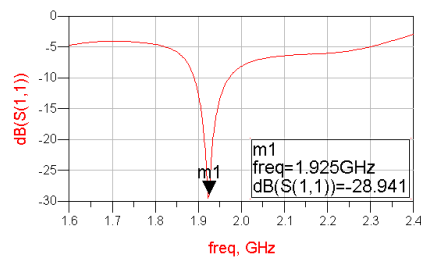


FIGURE 24: Measured Response with VNA

FIGURE 23 is the fabricated prototype of the microstrip patch antenna. The measured response of the designed patch antenna with Anritsu Network Analyzer is shown in FIGURE 24. It can be observed that the maximum reflection coefficient of the fabricated antenna is -28 dB with antenna radiation efficiency of 99.8 % at 1.925 GHz.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Intermodulation distortion (IM) pulses occurred when multiple of signal is mixed through a non-linear device. Those IM pulses increase proportional to the intermodulation order number. Besides increase the bandwidth of the frequency spectrum in the system, IM pulses will also cause the problem of adjacent channel interference whereby carried information signal will be compressed from one transmission line to another. Therefore, an effective filter transmitter must be designed to remove all IM pulses from spectrum.

In this research, the author has designing a narrowband bandpass filter that has high roll off frequency. The insertion loss of the fabricated interdigital bandpass filter is measured as -3.3 dB (47% of input power transmits to output port) with the return loss of -11 dB (8% of power returns to input port) at the centre frequency of 1.925 GHz. The insertion loss of -16.45 dB (2.26%) and -14.97 dB (3.18%) are transmitted between input and output port at IM3 frequencies of 1.85 GHz and 2 GHz.

Before filter the IM pulse from the spectrum, the input signal is flow through a microwave transistor amplifier to boost the power level to the desirable rate. The designed microstrip transistor amplifier has in-band gain of 19.45 dB at the output port. The input and output impedance matching of the design are -8.8 dB and -7.67 dB are measured which mean only 13% and 17% of signal power reflected from the transistor itself with less than 1% of signal power transmitted from output to input port.

A patch antenna is fabricated for to convert the filtered signal to EM waveform for signal transmission. The maximum signal radiation of the fabricated patch antenna is -28 dB with antenna radiation efficiency of 99.8 % at 1.925 GHz.

5.2 Recommendation

The integration of microstrip transistor amplifier, interdigital bandpass filter and patch antenna into a transmitter unit will be done by using SMA Male-to-Male Connector. In future, a higher order of filter should be designed to achieve higher selectivity and closer response curve to the ideal filter. With that, better telecommunication services can be provided by the mobile operators for better utilization experiences. As each designed component is flexible and portable in connection, it is very useful especially for education and training purpose in studying the output response of each device.

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APPENDICES

Appendix 1: Mathematical Modeling of Interdigital Bandpass Filter

Appendix 2: Transistor ATF-58143 Touchstone (S2P) File

Appendix 3: Mathematical Modeling of Transistor Amplifier (ATF-58143)

Appendix 4: S-Parameter, Noise Figure, Gain and Stability Circle of Transistor

Appendix 5: Mathematical Modeling of Patch Antenna

Appendix 6: Project Gantt Chart

Appendix 1: Mathematical Modeling of Interdigital Bandpass Filter

$$h := 787 \cdot 10^{-6}$$

$$\frac{787}{1000000} \quad (1)$$

$$\epsilon_r := 2.2$$

$$2.2 \quad (2)$$

$$Z_{in} := 50$$

$$50 \quad (3)$$

$$f_{p1} := 1.9 - 0.025$$

$$1.875 \quad (4)$$

$$f_{p2} := 1.95 + 0.025$$

$$1.975 \quad (5)$$

$$BW := f_{p2} - f_{p1}$$

$$0.100 \quad (6)$$

$$f_{s1} := f_{p1} - 0.025$$

$$1.850 \quad (7)$$

$$f_{s2} := f_{p2} + 0.025$$

$$2.000 \quad (8)$$

$$f_0 := f_{p1} + \frac{BW}{2}$$

$$1.925000000 \quad (9)$$

$$N := 5$$

$$5 \quad (10)$$

$$L_R := 20$$

$$20 \quad (11)$$

$$\theta_1 := 90 \cdot \frac{f_{p1}}{f_0}$$

$$87.66233766 \quad (12)$$

$$\alpha := \frac{1}{\tan\left(\frac{\theta_1 \cdot \pi}{180}\right)}$$

$$0.04082255882 \quad (13)$$

$$|S_{11}|^2 = 10^{-\left(\frac{L_R}{10}\right)}$$

$$|S_{11}|^2 = \frac{1}{100} \quad (14)$$

$$\# |S_{12}|^2 = 1 - |S_{11}|^2$$

$$|S_{12}|^2 = 1 - \frac{1}{100}$$

$$|S_{12}|^2 = \frac{99}{100} \quad (15)$$

$$\# \text{ Insertion Loss, } L_A = 10 \cdot \log_{10}(1 + \epsilon^2) = 10 \cdot \log_{10}\left(\frac{1}{|S_{12}|^2}\right) \Rightarrow 1 + \epsilon^2 = \frac{1}{|S_{12}|^2}$$

$$1 + \epsilon^2 = \frac{1}{\frac{99}{100}} \xrightarrow{\text{solve}} -0.1005037815, 0.1005037815$$

$$\epsilon := 0.1005$$

$$0.1005 \quad (16)$$

$$\eta := \sinh\left(\frac{1}{N} \cdot \sinh^{-1}\left(\frac{1}{\epsilon}\right)\right)$$

$$0.6350562203 \quad (17)$$

$$C_1 := \frac{2}{\eta} \cdot \sin\left(\frac{(2 \cdot 1 - 1) \cdot \pi}{2 \cdot N}\right)$$

$$3.149327470 \sin\left(\frac{1}{10} \pi\right) \quad (18)$$

$$\xrightarrow{\text{simplify } 3.149327470 \cdot \sin(1/10 \cdot \pi)}$$

$$0.9731957092 \quad (19)$$

$$C_2 := \frac{2}{\eta} \cdot \sin\left(\frac{(2 \cdot 2 - 1) \cdot \pi}{2 \cdot N}\right)$$

$$3.149327470 \sin\left(\frac{3}{10} \pi\right) \quad (20)$$

$$\xrightarrow{\text{simplify } 3.149327470 \cdot \sin(3/10 \cdot \pi)}$$

$$2.547859444 \quad (21)$$

$$C_3 := \frac{2}{\eta} \cdot \sin\left(\frac{(2 \cdot 3 - 1) \cdot \pi}{2 \cdot N}\right)$$

$$3.149327470 \quad (22)$$

$$C_4 := \frac{2}{\eta} \cdot \sin\left(\frac{(2 \cdot 4 - 1) \cdot \pi}{2 \cdot N}\right)$$

$$3.149327470 \sin\left(\frac{3}{10} \pi\right) \quad (23)$$

$$\xrightarrow{\text{simplify } 3.149327470 \cdot \sin(3/10 \cdot \pi)}$$

$$2.547859444 \quad (24)$$

$$C_5 := \frac{2}{\eta} \cdot \sin\left(\frac{(2 \cdot 5 - 1) \cdot \pi}{2 \cdot N}\right)$$

$$3.149327470 \sin\left(\frac{1}{10} \pi\right) \quad (25)$$

$$\xrightarrow{\text{simplify } 3.149327470 \cdot \sin(1/10 \cdot \pi)}$$

$$0.9731957092 \quad (26)$$

$$K_{1,2} := \frac{\left(\eta^2 + \sin^2 \left(\frac{1 \cdot \pi}{N} \right) \right)^{\frac{1}{2}}}{\eta}$$

$$1.574663735 \sqrt{0.4032964029 + \sin \left(\frac{1}{5} \pi \right)^2} \quad (27)$$

simplify K[1,2] →

$$1.362596397 = 1.362596397 \quad (28)$$

$$K_{2,3} := \frac{\left(\eta^2 + \sin^2 \left(\frac{2 \cdot \pi}{N} \right) \right)^{\frac{1}{2}}}{\eta}$$

$$1.574663735 \sqrt{0.4032964029 + \sin \left(\frac{2}{5} \pi \right)^2} \quad (29)$$

simplify K[2,3] = 1.574663735*(.4032964029+sin(2/5*Pi)^2)^(1/2)

$$1.800774390 = 1.800774390 \quad (30)$$

$$K_{3,4} := \frac{\left(\eta^2 + \sin^2 \left(\frac{3 \cdot \pi}{N} \right) \right)^{\frac{1}{2}}}{\eta}$$

$$1.574663735 \sqrt{0.4032964029 + \sin \left(\frac{2}{5} \pi \right)^2} \quad (31)$$

simplify K[3,4] →

$$1.800774390 = 1.800774390 \quad (32)$$

$$K_{4,5} := \frac{\left(\eta^2 + \sin^2 \left(\frac{4 \cdot \pi}{N} \right) \right)^{\frac{1}{2}}}{\eta}$$

$$1.574663735 \sqrt{0.4032964029 + \sin \left(\frac{1}{5} \pi \right)^2} \quad (33)$$

simplify K[4,5] →

$$1.362596397 = 1.362596397 \quad (34)$$

$$n_1 := \frac{1}{\left(1 + \frac{C_1}{\alpha} \right)^{\frac{1}{2}}}$$

$$\frac{1}{\sqrt{1 + 77.14674339 \sin \left(\frac{1}{10} \pi \right)}} \quad (35)$$

simplify $1/(1+77.14674339*\sin(1/10*\pi))^{(1/2)}$

$$0.2006444828 \quad (36)$$

$$n_5 := n_1$$

$$\frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} \quad (37)$$

simplify $1/(1+77.14674339*\sin(1/10*\pi))^{(1/2)}$

$$0.2006444828 \quad (38)$$

$$n_2 := \left(\frac{\alpha}{C_2}\right)^{\frac{1}{2}}$$

$$0.1138521408 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \quad (39)$$

simplify $.1138521408*(1/\sin(3/10*\pi))^{(1/2)}$

$$0.1265792094 \quad (40)$$

$$n_3 := \left(\frac{\alpha}{C_3}\right)^{\frac{1}{2}}$$

$$0.1138521408 \quad (41)$$

$$n_4 := \left(\frac{\alpha}{C_4}\right)^{\frac{1}{2}}$$

$$0.1138521408 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \quad (42)$$

simplify $.1138521408*(1/\sin(3/10*\pi))^{(1/2)}$

$$0.1265792094 \quad (43)$$

$$Y_{1,2} := n_1 \cdot n_2 \cdot K_{1,2}$$

$$\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} \quad (44)$$

simplify $.1792788373/(1+77.14674339*\sin(1/10*\pi))^{(1/2)}*(1/\sin(3/10*\pi))^{(1/2)}*(.4032964029+\sin(1/5*\pi)^2)^{(1/2)}$

$$0.03460643300 \quad (45)$$

$$Y_{2,3} := n_2 \cdot n_3 \cdot K_{2,3}$$

$$0.02041127942 \frac{\sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2}}{\text{simplify } .2041127942e-1*(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(2/5*\text{Pi})^2)^{(1/2)}} \quad (46)$$

$$\frac{\text{simplify } .2041127942e-1*(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(2/5*\text{Pi})^2)^{(1/2)}}{0.02595152512} \quad (47)$$

$$Y_{3,4} := n_3 \cdot n_4 \cdot K_{3,4}$$

$$0.02041127942 \frac{\sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2}}{\text{simplify } .2041127942e-1*(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(2/5*\text{Pi})^2)^{(1/2)}} \quad (48)$$

$$\frac{\text{simplify } .2041127942e-1*(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(2/5*\text{Pi})^2)^{(1/2)}}{0.02595152512} \quad (49)$$

$$Y_{4,5} := n_4 \cdot n_5 \cdot K_{4,5}$$

$$0.1792788373 \frac{\sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5}\pi\right)^2}}{\text{simplify } .1792788373/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)*}(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(1/5*\text{Pi})^2)^{(1/2)}} \quad (50)$$

$$\frac{\text{simplify } .1792788373/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)*}(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(1/5*\text{Pi})^2)^{(1/2)}}{0.03460643300} \quad (51)$$

$$Y_0 := 1 - n_1$$

$$1 - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} \quad (52)$$

$$\frac{\text{factor } 1-1/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)}}{0.7993555172} \quad (53)$$

$$Y_{0,1} := n_1$$

$$\frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} \quad (54)$$

$$\frac{\text{simplify } 1/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)}}{0.2006444828} \quad (55)$$

$$Y_1 := 1 - n_1 - n_1 \cdot n_2 \cdot K_{1,2}$$

$$0.1792788373 \frac{\sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5}\pi\right)^2}}{\text{simplify } .1792788373/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)*}(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(1/5*\text{Pi})^2)^{(1/2)}} \quad (56)$$

$$\frac{\text{simplify } .1792788373/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)*}(1/\sin(3/10*\text{Pi}))^{(1/2)*}(.4032964029+\sin(1/5*\text{Pi})^2)^{(1/2)}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}}$$

$$\frac{-\frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} + 1}{\text{factor } -.1792788373/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)}*(1/\sin(3/10*\text{Pi}))^{(1/2)}*(.4032964029+\sin(1/5*\text{Pi})^2)^{(1/2)}-1/(1+77.14674339*\sin(1/10*\text{Pi}))}$$

$$0.7647490842 \quad (57)$$

$$Y_5 := Y_1$$

$$\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}}$$

$$\frac{-\frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} + 1}{\text{factor } -.1792788373/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)}*(1/\sin(3/10*\text{Pi}))^{(1/2)}*(.4032964029+\sin(1/5*\text{Pi})^2)^{(1/2)}-1/(1+77.14674339*\sin(1/10*\text{Pi}))}$$

$$0.7647490842 \quad (59)$$

$$Y_2 := 1 - n_1 \cdot n_2 \cdot K_{1,2} - n_2 \cdot n_3 \cdot K_{2,3}$$

$$\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}}$$

$$-0.02041127943 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5} \pi\right)^2} + 1$$

$$\frac{\text{factor } -.1792788373/(1+77.14674339*\sin(1/10*\text{Pi}))^{(1/2)}*(1/\sin(3/10*\text{Pi}))^{(1/2)}*(.4032964029+\sin(1/5*\text{Pi})^2)^{(1/2)}-.2041127943e-1*(1/\sin(3/10*\text{Pi}))}{0.9394420419}$$

$$(61)$$

$$Y_3 := 1 - n_2 \cdot n_3 \cdot K_{2,3} - n_3 \cdot n_4 \cdot K_{3,4}$$

$$-0.04082255886 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5} \pi\right)^2} + 1$$

$$\frac{\text{factor } -.4082255886e-1*(1/\sin(3/10*\text{Pi}))^{(1/2)}*(.4032964029+\sin(2/5*\text{Pi})^2)^{(1/2)}+1}{0.9480969497}$$

$$(62)$$

$$(63)$$

$$Y_4 := 1 - n_3 \cdot n_4 \cdot K_{3,4} - n_4 \cdot n_5 \cdot K_{4,5}$$

$$\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}}$$

$$(64)$$

$$\begin{aligned}
 & -0.02041127943 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2} + 1 \\
 & \text{factor } -0.1792788373 / (1 + 77.14674339 \sin(1/10 \cdot \pi))^{1/2} \cdot (1/\sin(3/10 \cdot \pi))^{1/2} \cdot (0.4032964029 + \sin(1/5 \cdot \pi)^2)^{1/2} - 0.02041127943 \cdot (1/\sin(3/10 \cdot \pi))^{1/2} \\
 & \hline
 & 0.9394420419 \tag{65}
 \end{aligned}$$

$$Z_0 := \frac{1}{Y_0} \cdot Z_{\text{in}}$$

$$\frac{50}{1 - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}}} \tag{66}$$

simplify

$$62.55039081 \tag{67}$$

$$Z_6 := Z_0$$

$$\frac{50}{1 - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}}} \tag{68}$$

simplify $50 / (1 - 1 / (1 + 77.14674340 \sin(1/10 \cdot \pi))^{1/2})$

$$62.55039081 \tag{69}$$

$$Z_1 := \frac{1}{Y_1} \cdot Z_{\text{in}}$$

$$\left. \begin{aligned}
 & 50 \left(\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5}\pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} \right. \\
 & \left. - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} + 1 \right) \tag{70}
 \end{aligned} \right\}$$

simplify

$$65.38092175 \tag{71}$$

$$Z_5 := Z_1$$

$$50 \left(\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5}\pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} \right) \quad (72)$$

$$\left. \begin{aligned} & - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} + 1 \end{aligned} \right) \quad (73)$$

65.38092175

$$Z_2 := \frac{1}{Y_2} \cdot Z_{\text{in}}$$

$$50 \left(\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5}\pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} \right) \quad (74)$$

$$\left. \begin{aligned} & - 0.02041127943 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2} + 1 \end{aligned} \right) \quad (75)$$

53.22308110

$$Z_4 := Z_2$$

$$50 \left(\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5}\pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} \right) \quad (76)$$

$$\left. \begin{aligned} & - 0.02041127943 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2} + 1 \end{aligned} \right) \quad (77)$$

53.22308110

$$Z_3 := \frac{1}{Y_3} \cdot Z_{\text{in}}$$

$$\frac{50}{-0.04082255886 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5} \pi\right)^2} + 1}$$

simplify

$$52.73722270 \quad (79)$$

$$Z_{0,1} := \frac{1}{Y_{0,1}} \cdot Z_{\text{in}}$$

$$50 \sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}$$

simplify $50 \cdot (1 + 77.14674340 \cdot \sin(1/10 \cdot \pi))^{1/2}$

$$249.1969842 \quad (81)$$

$$Z_{5,6} := Z_{0,1}$$

$$50 \sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}$$

simplify $50 \cdot (1 + 77.14674340 \cdot \sin(1/10 \cdot \pi))^{1/2}$

$$249.1969842 \quad (83)$$

$$Z_{1,2} := \frac{1}{Y_{1,2}} \cdot Z_{\text{in}}$$

$$\frac{278.8951599 \sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}}{\sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}$$

simplify $278.8951599 \cdot (1 + 77.14674340 \cdot \sin(1/10 \cdot \pi))^{1/2} / (\sin(3/10 \cdot \pi))^{1/2} / (.4032964029 + \sin(1/5 \cdot \pi)^2)^{1/2}$

$$1444.818077 \quad (85)$$

$$Z_{4,5} := Z_{1,2}$$

$$\frac{278.8951599 \sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}}{\sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}$$

simplify $278.8951599 \cdot (1 + 77.14674340 \cdot \sin(1/10 \cdot \pi))^{1/2} / (\sin(3/10 \cdot \pi))^{1/2} / (.4032964029 + \sin(1/5 \cdot \pi)^2)^{1/2}$

$$1444.818077 \quad (87)$$

$$Z_{2,3} := \frac{1}{Y_{2,3}} \cdot Z_{\text{in}}$$

$$\frac{2449.625962}{\sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}\sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2}}}$$

simplify 2449.625962/(1/sin(3/10*Pi))^(1/2)/(.4032964029+sin(2/5*Pi)^2)^(1/2)

$$1926.669039 \quad (89)$$

$$Z_{3,4} := \frac{1}{Y_{3,4}} \cdot Z_{\text{in}}$$

$$\frac{2449.625962}{\sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}\sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2}}}$$

simplify 2449.625962/(1/sin(3/10*Pi))^(1/2)/(.4032964029+sin(2/5*Pi)^2)^(1/2)

$$1926.669039 \quad (90)$$

$$C_0'' := \frac{377}{Z_0 \cdot (\epsilon_r)^{\frac{1}{2}}}$$

$$\frac{377}{50} \frac{1 - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}}}{\sqrt{0.1005_r}}$$

$$(92)$$

simplify

$$\frac{6.027140600}{\sqrt{0.1005_r}}$$

$$(93)$$

$$C_6'' := C_0''$$

$$\frac{377}{50} \frac{1 - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}}}{\sqrt{0.1005_r}}$$

$$(94)$$

simplify

$$\frac{6.027140600}{\sqrt{0.1005_r}}$$

$$(95)$$

$$C_1'' := \frac{377}{Z_1 \cdot (\epsilon_r)^{\frac{1}{2}}}$$

$$\frac{377}{50} \frac{1}{\sqrt{0.1005_r}} \left(- \frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} \right) \quad (96)$$

$$\left. - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} + 1 \right) \quad \text{simplify}$$

$$\frac{5.766208095}{\sqrt{0.1005_r}} \quad (97)$$

$$C_5'' := C_1''$$

$$\frac{377}{50} \frac{1}{\sqrt{0.1005_r}} \left(- \frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} \right) \quad (98)$$

$$\left. - \frac{1}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} + 1 \right) \quad \text{simplify}$$

$$\frac{5.766208095}{\sqrt{0.1005_r}} \quad (99)$$

$$C_2'' := \frac{377}{Z_2 \cdot (\epsilon_r)^{\frac{1}{2}}}$$

$$\frac{377}{50} \frac{1}{\sqrt{0.1005_r}} \left(- \frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)}} \right) \quad (100)$$

$$-0.02041127943 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2 + 1}$$

simplify

$$\frac{7.083392996}{\sqrt{0.1005_r}}$$

(101)

$$C_4'' := C_2''$$

$$\frac{377}{50} \frac{1}{\sqrt{0.1005_r}} \left(\frac{0.1792788373 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5}\pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10}\pi\right)}} \right)$$

(102)

$$-0.02041127943 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2 + 1}$$

simplify

$$\frac{7.083392996}{\sqrt{0.1005_r}}$$

(103)

$$C_3'' := \frac{377}{Z_3 \cdot (\epsilon_r)^{\frac{1}{2}}}$$

$$\frac{377}{50} \frac{-0.04082255886 \sqrt{\frac{1}{\sin\left(\frac{3}{10}\pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5}\pi\right)^2 + 1}}{\sqrt{0.1005_r}}$$

(104)

simplify

$$\frac{7.148651001}{\sqrt{0.1005_r}}$$

(105)

$$C_{0,1}'' := \frac{377}{Z_{0,1} \cdot (\epsilon_r)^{\frac{1}{2}}}$$

$$\frac{377}{50 \sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)} \sqrt{0.1005_r}} \quad (106)$$

simplify

$$\frac{1.512859400}{\sqrt{0.1005_r}} \quad (107)$$

$$C''_{5,6} := C''_{0,1}$$

$$\frac{377}{50 \sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)} \sqrt{0.1005_r}} \quad (108)$$

simplify

$$\frac{1.512859400}{\sqrt{0.1005_r}} \quad (109)$$

$$C''_{1,2} := \frac{377}{Z_{1,2} \cdot (\epsilon_r)^{\frac{1}{2}}}$$

$$\frac{1.351762433 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)} \sqrt{0.1005_r}} \quad (110)$$

simplify .9113580470/(1+77.14674340*sin(1/10*Pi))^(1/2)*(1/sin(3/10*Pi))^(1/2)*(0.4032964029+sin(1/5*Pi)^2)^(1/2)

$$0.1759206590 \quad (111)$$

$$C''_{4,5} := C''_{1,2}$$

$$\frac{1.351762433 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{1}{5} \pi\right)^2}}{\sqrt{1 + 77.14674339 \sin\left(\frac{1}{10} \pi\right)} \sqrt{0.1005_r}} \quad (112)$$

simplify .9113580470/(1+77.14674340*sin(1/10*Pi))^(1/2)*(1/sin(3/10*Pi))^(1/2)*(0.4032964029+sin(1/5*Pi)^2)^(1/2)

$$0.1759206590 \quad (113)$$

$$C''_{2,3} := \frac{377}{Z_{2,3} \cdot (\epsilon_r)^{\frac{1}{2}}}$$

$$\frac{0.1539010469 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5} \pi\right)^2}}{\sqrt{0.1005_r}} \quad (114)$$

$$\text{simplify } .1037600647 \cdot (1/\sin(3/10 \cdot \pi))^{1/2} \cdot (.4032964029 + \sin(2/5 \cdot \pi)^2)^{1/2}$$

$$0.1319237207$$

(115)

$$C''_{3,4} := C''_{2,3}$$

$$\frac{0.1539010469 \sqrt{\frac{1}{\sin\left(\frac{3}{10} \pi\right)}} \sqrt{0.4032964029 + \sin\left(\frac{2}{5} \pi\right)^2}}{\sqrt{0.1005_r}}$$

(116)

$$\text{simplify } .1037600647 \cdot (1/\sin(3/10 \cdot \pi))^{1/2} \cdot (.4032964029 + \sin(2/5 \cdot \pi)^2)^{1/2}$$

$$0.1319237207$$

(117)

$$B := \frac{377 \cdot \pi}{2 \cdot Z_{in} \cdot \sqrt{\epsilon_r}}$$

$$2.541733482 \pi$$

(118)

$$B := \text{eval}(B, \pi = 3.142)$$

$$7.986126600$$

(119)

$$R := \frac{2}{\pi} \cdot \left(B - 1 - \ln(2 \cdot B - 1) + \frac{\epsilon_r - 1}{2 \cdot \epsilon_r} \cdot \left(\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right) \right)$$

$$\frac{9.681666820}{\pi}$$

(120)

$$R := \text{eval}(R, \pi = 3.142)$$

$$3.081370726$$

(121)

$$W := R \cdot h$$

$$0.002425038761$$

(122)

$$L := \frac{1}{4} \cdot \frac{3 \cdot 10^8}{f_0 \cdot 10^9}$$

$$0.03896103896$$

(123)

Appendix 2: Transistor ATF-58143 Touchstone (S2P) File

ATF-58143 Typical Scattering Parameters, $V_{DS} = 3V$, $I_{DS} = 30\text{ mA}$

Freq. GHz	S_{11}			S_{21}			S_{12}		S_{22}		MSG/MAG dB
	Mag.	Ang.	dB	Mag.	Ang.	dB	Mag.	Ang.	Mag.	Ang.	
0.1	0.98	-17.1	27.29	23.14	168.7	-40.10	0.010	80.8	0.67	-12.1	33.69
0.5	0.81	-92.0	25.25	18.31	123.7	-28.10	0.039	45.7	0.42	-46.6	26.68
0.9	0.75	-126.4	21.87	12.40	103.4	-26.12	0.049	34.8	0.32	-66.7	23.99
1.0	0.73	-132.2	21.18	11.46	99.8	-25.87	0.051	33.4	0.31	-72.3	23.52
1.5	0.69	-153.2	18.38	8.31	85.1	-24.70	0.058	29.4	0.25	-90.8	21.54
1.9	0.66	-165.9	16.74	6.88	75.4	-23.86	0.064	27.4	0.23	-103.6	20.30
2.0	0.65	-169.3	16.40	6.61	73.1	-23.65	0.066	26.9	0.22	-106.0	20.03
2.5	0.63	-176.3	14.83	5.51	61.9	-22.71	0.073	24.4	0.19	-118.1	18.77
3.0	0.61	-160.7	13.51	4.74	50.9	-21.87	0.081	21.1	0.17	-133.3	17.69
3.5	0.61	-147.4	12.35	4.15	40.4	-21.10	0.088	17.7	0.15	-145.4	16.73
4.0	0.62	-133.8	11.28	3.66	30.2	-20.45	0.095	13.5	0.13	-155.7	15.86
4.5	0.64	-123.7	10.32	3.28	20.5	-19.86	0.102	9.3	0.13	-175.4	15.09
5.0	0.66	-112.5	9.41	2.96	11.1	-19.39	0.107	4.9	0.13	-166.2	14.40
5.5	0.68	-103.7	8.61	2.70	2.1	-18.87	0.114	0.7	0.14	-152.8	13.74
6.0	0.69	-93.0	7.84	2.47	-7.3	-18.44	0.120	-4.4	0.14	-140.7	13.14
7.0	0.71	-77.2	6.47	2.11	-24.8	-17.63	0.131	-14.6	0.17	-120.7	12.06
8.0	0.74	-58.3	5.14	1.81	-43.1	-17.13	0.139	-26.1	0.19	-95.4	11.14
9.0	0.78	-39.7	3.77	1.54	-60.7	-16.67	0.147	-37.0	0.24	-70.1	10.22
10.0	0.84	-25.1	2.55	1.34	-78.8	-16.21	0.155	-50.2	0.34	-52.4	9.39
11.0	0.87	-10.2	1.25	1.16	-97.1	-16.04	0.158	-64.2	0.41	-37.3	8.65
12.0	0.89	-3.9	0.19	1.02	-114.0	-15.72	0.164	-78.3	0.46	-21.5	7.96
13.0	0.90	-20.0	-1.09	0.88	-132.2	-15.86	0.161	-93.6	0.52	-2.5	7.39
14.0	0.93	-31.4	-2.53	0.75	-148.3	-16.22	0.154	-106.5	0.58	-14.1	6.85
15.0	0.96	-43.9	-4.00	0.63	-162.8	-16.73	0.146	-118.2	0.66	-26.0	6.36
16.0	0.94	-54.2	-5.46	0.53	-176.5	-17.15	0.139	-128.6	0.72	-36.3	5.85
17.0	0.96	-65.1	-7.14	0.44	-168.6	-17.68	0.131	-142.4	0.74	-49.0	5.27
18.0	0.93	-79.8	-8.81	0.36	-153.8	-18.36	0.121	-155.6	0.77	-64.8	4.77

Typical Noise Parameters, $V_{DS} = 3V$, $I_{DS} = 30\text{ mA}$

Freq GHz	F_{min} dB	Γ_{opt} Mag.	Γ_{opt} Ang.	R_{noise}	G_{min} dB
0.5	0.12	0.39	17.775	0.04	25.33
0.9	0.18	0.37	46.9	0.04	22.26
1.0	0.20	0.36	53.525	0.04	21.54
1.5	0.32	0.32	80	0.04	19.16
1.9	0.43	0.30	101	0.04	17.65
2.0	0.45	0.30	107.7	0.04	17.33
2.4	0.51	0.29	125.2	0.04	16.23
3.0	0.58	0.31	154.475	0.05	14.77
3.9	0.75	0.35	-156.95	0.06	13.39
5.0	0.87	0.42	-120.93	0.09	11.92
5.8	1.01	0.50	-100.83	0.15	11.07
6.0	1.04	0.53	-97.15	0.18	10.93

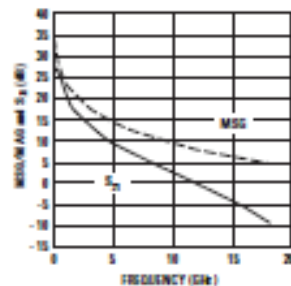


Figure 18. MSG/MAG and S_{21} vs. Frequency at 3V, 30 mA.

Notes:

- F_{min} values at 2 GHz and higher are based on measurements while the F_{min} below 2 GHz have been extrapolated. The F_{min} values are based on a set of 16 noise figure measurements made at 16 different impedances using an ATN NPS test system. From these measurements F_{min} is calculated. Refer to the noise parameter application section for more information.
- S and noise parameters are measured on a microstrip line made on 0.025 inch thick alumina carrier. The input reference plane is at the end of the gate lead. The output reference plane is at the end of the drain lead. The parameters include the effect of four plated through via holes connecting source landing pads on top of the test carrier to the microstrip ground plane on the bottom side of the carrier. Two 0.020 inch diameter via holes are placed within 0.010 inch from each source lead contact point, one via on each side of that point.

Appendix 3: Mathematical Modeling of Transistor Amplifier (ATF-58143)

$$S_{11} := \text{evalf}\left(0.657 \cdot e^{i \cdot \frac{-166.75 \cdot \pi}{180}}\right)$$

$$-0.6395101728 - 0.1505846566 I \quad (1)$$

$$S_{21} := \text{evalf}\left(6.813 \cdot e^{i \cdot \frac{74.825 \cdot \pi}{180}}\right)$$

$$1.783425967 + 6.575436170 I \quad (2)$$

$$S_{12} := \text{evalf}\left(0.065 \cdot e^{i \cdot \frac{27.275 \cdot \pi}{180}}\right)$$

$$0.05777312265 + 0.02978701560 I \quad (3)$$

$$S_{22} := \text{evalf}\left(0.228 \cdot e^{i \cdot \frac{-104.2 \cdot \pi}{180}}\right)$$

$$-0.05593008408 - 0.2210335398 I \quad (4)$$

$$dB_{11} := 10 \cdot \log_{10}\left(\left|S_{11}\right|^2\right)$$

$$-3.648692610 \quad (5)$$

$$dB_{21} := 10 \cdot \log_{10}\left(\left|S_{21}\right|^2\right)$$

$$16.66676778 \quad (6)$$

$$dB_{12} := 10 \cdot \log_{10}\left(\left|S_{12}\right|^2\right)$$

$$-23.74173287 \quad (7)$$

$$dB_{22} := 10 \cdot \log_{10}\left(\left|S_{22}\right|^2\right)$$

$$-12.84130306 \quad (8)$$

$$\Delta := S_{11} \cdot S_{22} - S_{12} \cdot S_{21}$$

$$0.09531213069 - 0.2832310077 I \quad (9)$$

$$\xrightarrow{\text{to polar}}$$

$$\text{polar}(0.2988380933, -1.246182955) \quad (10)$$

$$K := \frac{1 - \left|S_{11}\right|^2 - \left|S_{22}\right|^2 + \left|\Delta\right|^2}{2 \cdot \left|S_{12}S_{21}\right|}$$

$$0.6838410800 \quad (11)$$

$$C_L := \frac{\text{conjugate}(S_{22} - \Delta \cdot \text{conjugate}(S_{11}))}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}$$

$$1.008227311 - 11.16058134 I \quad (12)$$

$$\xrightarrow{\text{to polar}}$$

$$\text{polar}(11.20602954, -1.480702637) \quad (13)$$

$$\text{evalf}\left(\frac{-1.480702637 \cdot 180}{\pi}\right)$$

$$-84.83801180 \quad (14)$$

$$r_L := \left| \frac{S_{12} \cdot S_{21}}{|S_{22}|^2 - |\Delta|^2} \right|$$

11.86609205 (15)

$$C_S := \frac{\text{conjugate}(S_{11} - \Delta \cdot \text{conjugate}(S_{22}))}{|S_{11}|^2 - |\Delta|^2}$$

-2.035324976 + 0.5476729066 I (16)

to polar
→

polar(2.107722318, 2.878734996) (17)

$$\text{evalf}\left(\frac{2.878734996 \cdot 180}{\pi}\right)$$

164.9393656 (18)

$$r_S := \left| \frac{S_{12} \cdot S_{21}}{|S_{11}|^2 - |\Delta|^2} \right|$$

1.293564290 (19)

$$B_1 := 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2$$

1.290360794 (20)

$$B_2 := 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2$$

0.5310307941 (21)

$$C_1 := S_{11} - \Delta \cdot \text{conjugate}(S_{22})$$

-0.6967829095 - 0.1874929683 I (22)

$$C_2 := S_{22} - \Delta \cdot \text{conjugate}(S_{11})$$

-0.03762725095 - 0.4165151949 I (23)

$$\Gamma_{in} := S_{11}$$

-0.6395101728 - 0.1505846566 I (24)

$$\Gamma_{out} := S_{22}$$

-0.05593008408 - 0.2210335398 I (25)

$$\Gamma_S := \text{conjugate}(\Gamma_{in})$$

-0.6395101728 + 0.1505846566 I (26)

to polar
→

polar(0.6569999999, 2.910336528) (27)

$$\Gamma_L := \text{conjugate}(\Gamma_{out})$$

-0.05593008408 + 0.2210335398 I (28)

to polar
→

polar(0.2280000000, 1.818633081) (29)

$$G_T := 10 \cdot \log_{10}\left(|S_{21}|^2\right)$$

$$G_{S(max)} := 10 \cdot \log_{10} \left(\frac{1}{1 - |S_{11}|^2} \right) \quad 16.66676778 \quad (30)$$

$$G_{L(max)} := 10 \cdot \log_{10} \left(\frac{1}{1 - |S_{22}|^2} \right) \quad 2.453833714 \quad (31)$$

$$G_S := 10 \cdot \log_{10} \left(\frac{1 - |\Gamma_S|^2}{|1 - S_{11} \cdot \Gamma_S|^2} \right) \quad 0.2318433304 \quad (32)$$

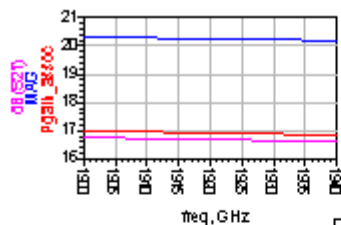
$$G_L := 10 \cdot \log_{10} \left(\frac{1 - |\Gamma_L|^2}{|1 - S_{22} \cdot \Gamma_L|^2} \right) \quad 2.453833714 \quad (33)$$

$$G_{total} := G_T + G_S + G_L \quad 0.2318433304 \quad (34)$$

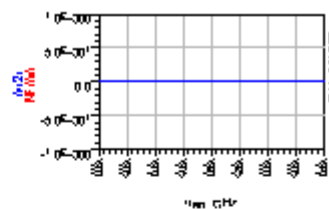
$$19.35244482 \quad (35)$$

Appendix 4: S-Parameter, Noise Figure, Gain and Stability Circle of Transistor

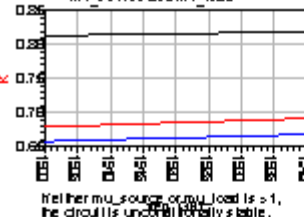
Maximum Available Gain, Associated Power Gain (opt matched for NF min, output is conjugately matched), and dB (S21)



Minimum Noise Figure, dB, and Noise Figure with Z0 Optim terminations



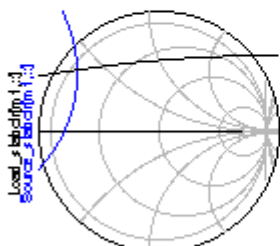
Stability Factor, K, Geometric stability factors in source and in load



Equations are on the "Equations" page.

See also the "Gain, Noise, and Stability Circles" page, and the "S Parameters, Group Delay" page.

Source and Load Stability Circles; Optimal Source Reflection Coefficients for Minimum NF (Sopt), Simultaneous Conjugate Matching, and Load Reflection Coefficient for Simultaneous Conjugate Matching, and with source matched for NFmin



Indep(Source_s_bdc(m 1, :)) (0.0000 to \$1.0000)
Indep(Load_s_bdc(m 1, :)) (0.0000 to \$1.0000)

Note: If the device (or circuit) is unstable at the freq point, the simultaneous conjugate matching impedances are undefined and Gamma_ML_freq_p1 and Gamma_MS_freq_p1 default to 0. Also, MAG is set equal to the maximum stable gain, |S21|/|S12|.

Mouse marker m1 to select freq point. All listings and impedances on Smith Chart will be updated.

RF Frequency: 1.925 GHz

dB(S11): -3.642 dB(S12): -23.809 dB(S21): 16.666 dB(S22): -12.860

Matching For Gain

Maximum Available Power Gain, dB: 20.231

Simultaneous Match: Zsource = 50.000, Zload = 50.000

Stability Factor: 0.6871

System Impedance: 50.000

Matching For Noise Figure

NFmin, dB: 0.000 Zopt for NFmin: 50.0 + j0.000

Conjugate Match Load Impedance If Source Reflection Coefficient is Sopt for Minimum NF: 40.8 + j19.0

Power Gain with these Source and Load Reflection Coefficients: 16.897

Source Reflection Coefficient for Minimum NF: 0.00070000

Conjugate match Zload if source impedance is Zopt

OUT: Device Under Test (simulated circuit or device)

Appendix 5: Mathematical Modeling of Interdigital Bandpass Filter

$$h := 787 \cdot 10^{-6}$$

$$\frac{787}{1000000} \quad (1)$$

$$\epsilon_r := 2.2$$

$$2.2 \quad (2)$$

$$Z_0 := 50$$

$$50 \quad (3)$$

$$c := 3 \cdot 10^8$$

$$300000000 \quad (4)$$

$$f := 1.925 \cdot 10^9$$

$$1.925000000 \cdot 10^9 \quad (5)$$

$$W := \frac{c}{2 \cdot f} \cdot \text{sqrt} \left(\frac{2}{\epsilon_r + 1} \right)$$

$$0.06160281155 \quad (6)$$

$$E_{eff} := \frac{(\epsilon_r + 1)}{2} + \frac{(\epsilon_r - 1)}{2} \cdot \left(1 + \frac{12 \cdot h}{W} \right)^{-\frac{1}{2}}$$

$$2.158700708 \quad (7)$$

$$L_{eff} := \frac{c}{2 \cdot f \cdot \text{sqrt}(E_{eff})}$$

$$0.05303521185 \quad (8)$$

$$\Delta L := \frac{0.412 \cdot (E_{eff} + 0.3) \cdot \left(\frac{W}{h} + 0.264 \right)}{(E_{eff} - 0.258) \cdot \left(\frac{W}{h} + 0.8 \right)} \cdot h$$

$$0.0004165911727 \quad (9)$$

$$L := \frac{c}{2 \cdot f \cdot \text{sqrt}(E_{eff})} - 2 \cdot \Delta L$$

$$0.05220202950 \quad (10)$$

$$\frac{W}{L}$$

$$1.180084609 \quad (11)$$

$$B := \frac{377 \cdot \text{pi}}{2 \cdot Z_0 \cdot \text{sqrt}(\epsilon_r)}$$

$$2.541733482 \pi \quad (12)$$

$$B := \text{eval}(B, \text{pi} = 3.142)$$

$$7.986126600 \quad (13)$$

$$R := \frac{2}{\text{pi}} \cdot \left(B - 1 - \ln(2 \cdot B - 1) + \frac{\epsilon_r - 1}{2 \cdot \epsilon_r} \cdot \left(\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right) \right)$$

$$\frac{9.681666820}{\pi} \quad (14)$$

$$R := \text{eval}(R, \text{pi} = 3.142)$$

$$3.081370726 \quad (15)$$

$$w_0 := R \cdot h$$

$$0.002425038761 \quad (16)$$

$$W_s = W + 6 h$$

$$W_s = 0.06632481155 \quad (17)$$

$$L_s = L + 6 h$$

$$L_s = 0.05692402950 \quad (18)$$

