DIELECTRIC RESONATOR MATCHING MODEL FOR STABILITY PERFORMANCES OF MICROWAVE AMPLIFIER

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DIELECTRIC RESONATOR MATCHING MODEL FOR STABILITY PERFORMANCES OF MICROWAVE AMPLIFIER

by

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In the name of ALLAH S.W.T., the Most Gracious and the Most Merciful.

"There is no power nor strength except through ALLAH SWT."

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TABLES OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

ADS	Agilent's Advance Design System
ANG	Angle of *S*-parameters
BW	Bandwidth
CDR	Cylindrical Dielectric Resonator
CST	Computer Simulation Studio
CST-MW	Computer Simulation Studio-Microwave
CTO	Cobalt Titanium Oxide
DC	Direct Current
DR	Dielectric Resonator
DRO	Dielectric Resonator Oscillator
EDA	Electronic Design Automation
EM	Electromagnetics
GaAS	Gallium Arsenide
HE	Hybrid
HF	High Frequency
IL	Insertion Loss
JFET	Junction field-effect transistor
LNA	Low Noise Amplifier
MAG	Magnitude of *S*-parameters
MMICs	Monolithic Microwave Integrated Circuits
MPCDR	Multi-permittivity Cylindrical Dielectric Resonator
MPDR	Multi-Permittivity Dielectric Resonator
MTO	Magnesium Titanium Oxide

NF	Noise Figure
PA	Power Amplifier
pHEMT	Pseudomorphic high electron mobility transistor
RL	Return Losses
TE	Transverse Electric
TM	Transverse Magnetic
VSWR	Voltage Standing Wave Ratio

LIST OF SYMBOLS

C	Capacitance
C_L	Center of the output stability circle
C_s	Center of the input stability circle
d	Diameter of dielectric resonator
dB	Decibel
f_1	Lower frequency
f_2	Higher frequency
f_o	Resonant/Operating frequency
GHz	GigaHertz
G_{MAX}	Maximum available gain/Maximum stable gain
G_P	Available power gain
G_T	Transducer power gain
h	Height of substrate
h_r	Height of DR
h_v	Height of vacuum
I_{in}	Input current
IL	Insertion losses
I_{out}	Output current
K	Rollet’s stability factor
kHz	KiloHertz
L	Inductance
l	Length of substrate
MHz	MegaHertz

NF_{min}	Minimum NF
N_o	Available noise power at output
P_{in}	Input power
P_{out}	Output power
Q	Quality factor
Q_c	Conduction losses quality factor
Q_d	Dielectric losses quality factor
Q_{ext}	External quality factor
Q_L	Loaded quality factor
Q_r	Radiation losses quality factor
Q_u	Unloaded quality factor
r	Radius of dielectric resonator
R	Resistance
R_L	Radius of the output stability circle
R_s	Radius of the input stability circle
S_{nm}	Scattering parameter
t	Thickness of substrate
T	Operating temperature
V_{in}	Input voltage
V_{out}	Output voltage
w	Width of substrate
w_m	Width of microstrip line
Z_L	Load impedances
Z_o	Output impedances
Z_s	Source impedances

β	Coupling spacing
ε_{eff}	Effective dielectric constant of the substrate
ε_r	Relative dielectric constant of the material used
λ	Wavelength in waveguide
Γ_{in}	Input reflection coefficient
Γ_L	Load reflection coefficient
Γ_{opt}	Optimum reflection coefficient
Γ_{out}	Output reflection coefficient
Γ_s	Source reflection coefficient

MODEL PADANAN PENGAYUN DIELEKTRIK UNTUK PRESTASI KESTABILAN BAGI PENGUAT GELOMBANG MIKRO

ABSTRAK

Faktor kestabilan dan teknik sepadan bagi penguat gelombang mikro merupakan perbincangan penting untuk mengekalkan prestasi yang diperlukan, seperti kuasa tinggi bagi penguat kuasa tinggi dan bunyi hingar yang rendah bagi penguat hingar rendah. Pada masa yang sama, isu-isu kestabilan juga memerlukan perhatian yang utama untuk mengelakkan kehadiran ayunan dan menjadikan ianya berjaya berfungsi sebagai penguat. Biasanya, faktor kestabilan dan teknik padanan penguat bergantung terhadap frekuensi. Oleh itu, satu mekanisma pembolehubah frekuensi diperlukan untuk memastikan frekuensi bagi penguat tersebut berada di dalam kawasan yang stabil. Pengayun dielektrik dijadikan sebagai mekanisma pembolehubah frekuensi untuk mengatasi masalah tersebut yang dinilai pada parameter fizikal dan bahannya dengan topologi berlainan bagi mikrostrip selari. Konfigurasi terbaik pengayun dielektrik yang diperolehi diwakili oleh konfigurasi lengkungan 155° dengan jarak mikrostrip selari 19 mm untuk kedudukan liang pandu gelombang yang sama. Konfigurasi pengayun dielektrik ini dipadankan sebagai model padanan pengayun dielektrik untuk prestasi kestabilan penguat gelombang mikro. Penyiasatan ini dinilai untuk penguat yang berkeadaan stabil bersyarat dan tidak bersyarat pada 5 GHz. Disamping itu, kepelbagaian ketelusan dielektrik baru dibangunkan oleh tindak balas parameter sebaran yang merujuk kepada penyiasatan transistor sebelumnya, terutama pada aplikasi penyalun pengayun dielektrik. Perolehan ketelusan dielektrik baru yang merujuk kepada operasi frekuensi stabil bagi transistor terdahulu yang digunakan diadaptasikan ke dalam konfigurasi terbaik pengayun dielektrik yang dicadangkan

sebagai pengayun dielektrik homogen. Sebagai keputusannya, model padanan pengayun dielektrik boleh digunakan untuk kedua-dua transistor yang berkeadaan stabil bersyarat dan tidak bersyarat untuk mengekalkan prestasi kestabilannya. Tambahan pula, model padanan pengayun dielektrik yang dicadangkan berpotensi untuk bertindak sebagai mekanisma pembolehubah frekuensi dengan menggunakan ketelusan dielektrik yang berlainan. Prestasi kestabilan lebih besar daripada 1 yang mana menunjukkan penguat gelombang mikro beroperasi di kawasan yang stabil dan berjaya meminimumkan kejadian ayunan. Pada masa yang sama, model padanan pengayun dielektrik adalah lebih mudah untuk melakukan penyelarasan selepas fabrikasi berbanding kaedah padanan konvensional bagi gelombang mikro.

DIELECTRIC RESONATOR MATCHING MODEL FOR STABILITY PERFORMANCES OF MICROWAVE AMPLIFIER

ABSTRACT

The stability factor and matching techniques on microwave amplifier have been an important consideration in order to maintain the required performances, such as high power for the high power amplifier and low noise for low noise amplifier. Simultaneously, the issues of stability need more attention to avoid the presence of the oscillations and make it performs as the amplifier without failed. Typically, the stability factor and matching techniques of the amplifier are frequency dependent. Thus, a variable frequency mechanism is required in order to ascertain the amplifier to be operated resides within the stable region. The dielectric resonator is incorporated as the variable frequency mechanism purposely to tackle this issue. The characteristics of the dielectric resonator are evaluated on their physical parameter and material with different topologies of the parallel microstrip line. The obtained best configuration of the dielectric resonator is represented by the 155 ° curves configuration with 19 mm parallel microstrip line spacing for same waveguide port position. This configuration of the dielectric resonator is incorporated as the dielectric resonator matching model for stability performances of microwave amplifier. This investigation is evaluated for conditional stable and unconditional stable transistors at 5 GHz. In addition, the new dielectric permittivity is developed through their scattering parameters responses that referred to the previous transistor used investigation, especially dielectric resonator oscillator applications. The obtained of new dielectric permittivity that refers to the stable operating frequency of previous transistor used investigation is adopted into the best configuration of the proposed dielectric resonator as the homogenous dielectric

resonator. As results, the dielectric resonator matching model can be used for both conditional stable and unconditional stable transistors in maintaining their stability performances. The stability performances are greater than 1 which shown the microwave amplifier is operated in a stable region and successfully minimize the oscillation occurrences. Furthermore, the proposed dielectric resonator matching model has the potential to act as a variable frequency mechanism by the adopted different dielectric permittivity. Concurrently, the dielectric resonator matching model is easier to do adjustment after fabrication compared to the conventional matching method of microwave amplifier.

CHAPTER 1

INTRODUCTION

1.1 Background

One of the most important functions of microwave circuits is signal amplification. The amplification of microwave signals was first introduced by the radar during World War II. During the last two decades, amplifier technology has made tremendous progress in terms of devices for low noise and power, computer-aided design, *CAD* tools; fabrication, packaging, and applications (Inder, 2009). Nowadays, the low noise amplifier and power amplifier has drawn the attention to being studied and investigated for the Internet of Things, *IoT* applications (Rajeswari, 2018; Godfrey et al., 2017; Hamed et al, 2017; Ruochen et al., 2016). IoT is an emerging and promising technology which contributes to revolutionize the global world through connected physical objects that deals with low power consumption (Rajeswari, 2018; Godfrey et al., 2017; Ruochen et al., 2016) or low noise (Hamed et al, 2017) devices that interact with each other through the Internet. In IoT applications, the 5 GHz frequency band has attracted to use compared to 2.4 GHz due to their advantages of high in speed, wider bandwidth and lower interferences (Coextro, 2017; Hamed et al, 2017; Phorus, 2014). Thus, the 5 GHz frequency band is being a consideration to use in this research. In addition, the microwave amplifier are important circuit components used in every systems including cordless and cellular telephones, base station equipment, ground-based for fixed or mobile satellite communications, wireless local area networks, *WLAN*; terrestrial broadcast and telecommunications, point-to-point radio, *PPR*; and also global positioning systems, *GPS* (Pozar, 2005; Inder, 2009).

Besides that, the vital consideration in order to maintain the power efficiency at the output with the higher quality factor, *Q*-factor and low loss is the stability element and matching component on microwave amplifier. As well known, the identical stability factor and matching technique condition of the amplifier is still a crucial (Le et al., 2013) and critical step since the adjustment after fabrication is an impossible (Dellier et al., 2012). In addition, their input and output matching networks generally depend on frequency. Thus, it is possible for the amplifier to stable at its design frequency, but unstable at other frequencies (Pozar, 2005). Thus, the frequency variable element is needed in order to control the operating frequency to sustain in the stable region and avoid the presence of the oscillations. Therefore, the dielectric resonator, *DR* is hit this criterion as a variable element. This is due to their advantages and attractive features, such as high-quality factor, good temperature stability, compact size, ease of excitation and also relatively low cost. The DR also has attracted attention in bringing forward some application, such as antenna (Ullah et al, 2017; Ullah, 2016; Ullah et al., 2015; 2014; Patel, 2015; Ain et al., 2014), oscillator (Olokede et al., 2017; Kizilbey et. al, 2013; Kejia et al., 2013; Ugurlu, 2011; Yan, 2008; Yom et. al, 2007; Mahyuddin, 2006; Mahyuddin et al., 2006a; 2006b; Yom et. al, 2005;), filter (Sirikphon, 2013; Ain et al., 2010; Iveland, 2007) and power divider (Jain et al, 2014).

Commonly, numerous researches have been carried out that involves the DR only focused on homogeneous or single permittivity, where it can only serve one purpose at one time. Recently, the ideas of using the multi-permittivity DR are introduced in (Ullah, 2016; Ullah et al., 2015; 2014) which is focused on antenna application. The uses of the multi-permittivity DR gives this application a tendency to operate in wider bandwidth and also helped in achieving a strong coupling to the feeding structure due to the high *Q*-factors. The multi-permittivity DR are used in modeling DR to explore the best configuration of the DR in improving the stability and matching performances of microwave amplifier at 5 GHz. In addition, a homogeneous dielectric resonator also included in the analysis to analyze the dielectric resonator matching model for stability performances of microwave amplifier.

1.2 Problem Statements and Motivation

One of the essential factors for improving the accuracy and optimum performances of microwaves amplifier is the proper stability factor and matching techniques. Various techniques and approach of the stability elements and matching techniques, such as for amplifier have been implemented in (Wang & Chen, 2016; Ratnaparkhi, 2016; Veeranjaneyulu & Anuradha, 2016; Abdulrahman & Jamlos, 2014; Fuzy & Zolomy, 2014; Abdulrahman, 2013; Sharma & PrakashDwivedi, 2013; Mahersi et al., 2013; Kassim & Malek, 2010; Inder, 2009; Ain et al., 2007; Lopez & Gonzalez-Villarruel, 2007). Each of the techniques and approach for the stability and matching techniques depends on their applications and certain specification, such as wider bandwidth, high output power, better power efficiency, immense linearity maximum gain, and also higher *Q*-factors. Subsequently, these techniques also face some challenges such as the techniques are impossible to do adjustment after fabrication (Dellier et al., 2012) and they suffer from the presence of oscillation and temperature variation. In fact, numerous researchers are considering the stability and matching technique issues are the critical issues that need a vital attention in their design circuit to guarantee its correctly operated (Adam et al, 2018; Wang & Chen, 2016; Ratnaparkhi, 2016; Abdulrahman & Jamlos, 2014; Fuzy & Zolomy, 2014;

Abdulrahman, 2013; Sharma & PrakashDwivedi, 2013; Mahersi et al., 2013; Muneeb, 2012; Su et. al, 2011; Kassim & Malek, 2010; Inder, 2009; Ain et al., 2007; Lopez & Gonzalez-Villarruel, 2007).

Furthermore, this issue needs attention and solved at the started of the design procedure where it is still a crucial step in microwave design, especially in microwave amplifier (Le et al., 2013). The stability and matching process is also critical step since adjustment after fabrication is impossible (Dellier et al, 2012) and to guarantee it is operated correctly during the design of any electronic circuit (Adam et al., 2018). The amplifier must be stable in the operating frequency band to avoid the presence of the oscillation and also prevent to generate self-oscillation in some frequencies thus its cannot amplify the signal (Yu-na & Geng, 2012). If the oscillation occurs that means the transistor is operated in an unstable region and the circuits cannot amplify the signal thus it does not function as amplifier. As the results, the whole system may not work well as expected (Su et. al, 2011) and also not correctly operated (Adam et al., 2018). In order to ensure the operating frequency of the amplifier resides within the stable region, a frequency variable mechanism is required. Based on the research carried out by Jain et. al (2014), the placement of dielectric resonator with a constant physical parameter can vary the operating frequency of the two-way power divider; improving its performances for multifrequency operation without changing its physical dimensions. Therefore, the dielectric resonator is implemented as the dielectric resonator matching model to overcome the issues of impossible adjustment after fabrication and self-oscillation in some frequencies. In addition, the different material of DR also can ascertain the operating frequency of the amplifier resides within the stable region.

1.3 Research Objectives

The main objectives of this research are as follows:

a) To evaluate the characteristics of the dielectric resonator on their physical parameter and material with different topologies of parallel microstrip line and dielectric resonator.

b) To develop a dielectric resonator matching model to form as dielectric matching on the input matching of microwaves amplifier for the stability performances.

c) To verify and analyze the dielectric resonator matching model as variable frequency element for the conditional stable and unconditional stable transistors for stability performances of microwave amplifier.

1.4 Research Scope

The research scope of this research work is limited on the dielectric resonator matching model for the stability performances of microwave amplifier. The stability factor or elements and matching techniques are presented by the dielectric matching, especially at an input port as shown in Figure 1.1. The dielectric resonator matching model which incorporating as dielectric matching for the stability elements of the amplifier are investigated which involves the material and physical properties of the matching network.

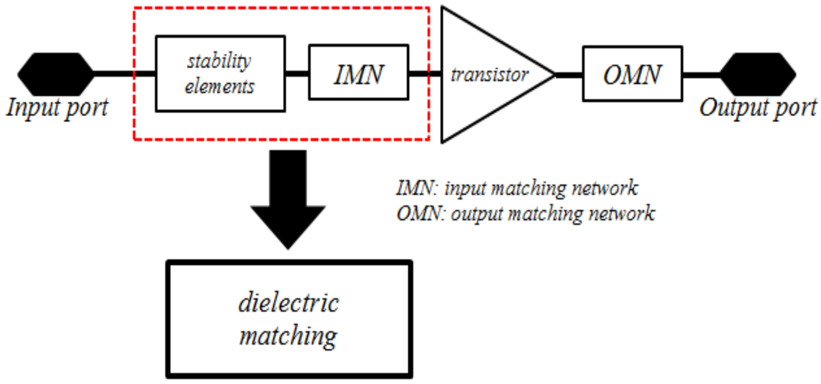

Figure 1.1: The block diagram configuration of a microwave amplifier.

The stability and matching network on microwave amplifier is crucial to accomplish at the beginning design procedure to make sure the circuits are operated in stable condition thus guarantee it is operated correctly. Typically, the stability and matching network of the microwaves amplifier is impossible to do adjustment after fabrication. Thus, the DR is introduced in order to overcome the issues which form as the variable frequency mechanism for stability performances of microwave amplifier in this research work. The investigation of the DR is observed using CST software, which including the parametric study on their physical and material at 5 GHz. Meanwhile, the stability and matching networks on the microwave amplifier is investigated by using ADS software for the conditional stable and unconditional stable transistors. The new dielectric permittivity is represented as the homogeneous DR. The single characteristics of the DR is considering enough since the only stability performances on microwave amplifier is being the vital consideration in this research. The potential in incorporated the dielectric resonator matching model as dielectric matching is successfully avoided the occurrences of the oscillation. Hence, the accuracy and optimum performances, especially stability performances of the microwave amplifier are successfully improved. This shows that the stability factor and matching technique are crucial for the microwave amplifier.

1.5 Thesis Outlines

There is a total of five chapters in this thesis. This chapter gives a brief overview of the stability factor and matching techniques of microwave amplifier and draws attention to the importance of this research. The rest of this thesis is organized as follows.

Chapter 2 contains the literature reviews regarding the microwave amplifier includes their stability elements and matching techniques that approach by the previous researches. In addition, the previous investigation of the DR configurations also reviewed. Meanwhile, Chapter 3 discusses the research methodology of the DR matching model for stability performances of microwave amplifier. The general flow chart of the entire research process also included. In this chapter also elaborates on the parametric study for modeling and designing CDR. In addition, the DR characteristics, microwave amplifier topology and also the fabrication and measurement procedure are presented and discussed.

In Chapter 4 elaborates the obtained results of the DR matching model for stability performances of microwave amplifier. The comparative study between the simulation and measurements also investigated for the best configuration of DR and also to verify the DR matching model through the conditional stable and unconditional stable transistors. Last but not least, Chapter 5 drawn the conclusion regarding this research. Some recommendation for future developments and improvements are also included.

CHAPTER 2

LITERATURE REVIEWS

2.1 Introduction

This chapter discusses the literature reviews of the past research was done by previous researches based on the dielectric resonator and also the stability factor and matching techniques of microwave amplifier. The coupling of microstrip line implementation is also included. Nowadays, a high performance of the resonator is an important element in microwave circuits, such as filter (Sirikphon, 2013; Ain et al., 2010; Iveland, 2007), couplers, antenna (Ullah, 2016; Ullah et al., 2015; 2014; Patel, 2015; Ain et al., 2014), oscillator (Olokede et al., 2017; Huang et. al, 2014; Yousaf & Ahmad, 2013; Liang et. al, 2013; Kejia et al., 2013; Ugurlu, 2011; Yan, 2008; Mahyuddin, 2006; Mahyuddin et al., 2006a; 2006b), and power divider (Jain et al, 2014). Mainly, the low loss ceramic puck is used to perform as a resonator. The advantages of the resonator, especially the DR have great attention and demand in the recent progress of microwave technology. Their advantages of the DR was successfully attracted many types of research to investigates their ability to perform maximum performance of the applications used.

In addition, by the fast-growing demand in modern communication systems of microwave engineering, the amplifiers have played a vital role in the development of low-cost solutions and high performances (Inder, 2009). The important consideration in the amplifier is the stability and matching network, which makes the system performed well with maximum power transmission in microwaves devices. Therefore, literature reviews to incorporate the dielectric resonator matching model for stability performances of microwave amplifier are explained in this chapter.

2.2 Microwave Amplifier

An amplifier is a most paramount block of the communication systems that amplify the signal, which means increases the strength of the input signal, where amplify the weak signal to a reasonable working level (Ain et al., 2007). Amplification also is the most basic and prevalent microwave circuit functions in modern microwave systems (Pozar, 2005). In general, an amplifier is used to increase the amplitude of a signal waveform without changing the other parameters of the waveform, such as frequency or wave shape (Coates, 2017a; 2017b; Vuppuluri et al., 2015). Furthermore, the amplifier is one of the most commonly used circuits in electronics and also performs a variety of functions in a great many electronic systems. One way to describe an amplifier is by the type of signal, where it is designed to amplify. This is usually referring to a band frequency that the amplifier operated or in some cases that the amplifier performs within an electronic system, such as wideband amplifiers, operational amplifiers, IF amplifiers, and DC amplifiers (Pozar, 2005).

Importantly, each type needs to meet the required amplifier specifications. For example, a low noise amplifier, LNA needs a low-noise device and a low-loss input matching network, while a power amplifier, PA requires a power device and low loss output matching network (Dixit & Nema, 2014; Inder, 2009). In general, the microwave amplifiers have the following characteristics, such as band-limited RF response, less than 100% DC to RF conversion efficiency, nonlinearity that generates mixing products between multiple signals, RF coupled and no DC response, power-dependent amplitude and phase difference between the multiple signals, temperature-dependent gain, and also higher gain at lower temperatures (Inder, 2009). Usually, the performance characteristics of the amplifier can drop by the gain of amplifier, input and output return losses.

The microwave amplifier is also known as the tuned amplifiers, where the operating frequency is governed by a tuned circuit. Their bandwidth also depends on use and may be relatively wide or narrow band. Their input resistance is generally low that acts as gain, but a special feature of the microwave amplifiers are used in the earliest stage of a receiver is low noise performance (Coates, 2017b). In circuits designed to amplify the microwave signals, the load resistor is replaced by either an *LC* parallel resonant circuits or some form of ceramic or crystal filter. These values of the *L* and *C* are such that the load circuits resonate and effectively becomes a high resistance at the center of the amplified frequency band that makes this frequency response curve is sharply peaked over a narrow band of frequencies, called as a bandpass. The bandpass response would passes signals within a frequency range or at the certain band of frequencies and rejected others signals without distorting the input signal or include extra noise that also referred as band selecting (Inder, 2009; Grebennikov, 2005). The *LC* parallel resonant circuit can be electrically presented by a ceramic type resonator known as a dielectric resonator. The finding by Inder (2009) and Grebennikov (2005) gives the idea of using DR as a stability factor element and matching component of the amplifier. Subsequently, the DR also act as variable frequency mechanism through the different angular position of the DR, especially the for multi-permittivity DR. The difference of the dielectric permittivity or dielectric constant, ε_r used to form the multi-permittivity and their angular position of the DR gives changes of the operating frequency result.

A single-stage microwave transistor amplifier could be modeled by the circuit of Figure 2.1, where the matching network is used on both sides of the transistor to transform the input and output impedance, Z_o to the source and load impedances Z_S and Z_L. Microwave transistor amplifiers are rugged, low cost, reliable, and also can easily integrate into both hybrid and monolithic integrated circuitry (Pozar, 2005). For proper designing of the amplifier, there are several aspects are being taken into consideration that discussed details in the following section.

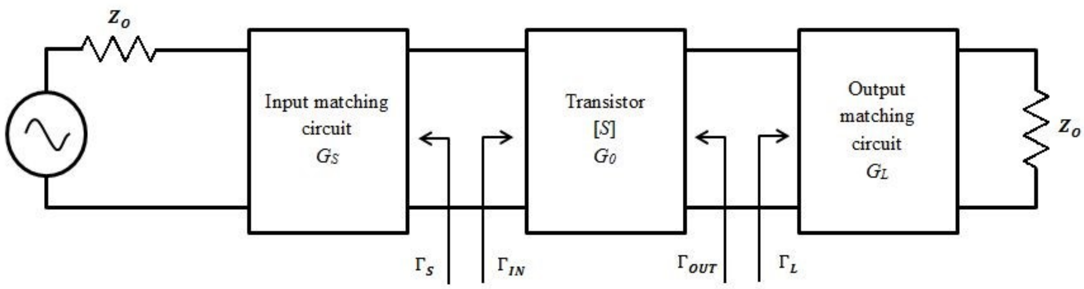

Figure 2.1: General transistor amplifier block diagram (Madhura & Savita, 2015; Ain et al. 2007).

2.2.1 Selection of transistor

Transistors are critical components of modern microwave systems that finding application as amplifiers, oscillators, switches, phase shifters, mixers and also active filters (Pozar, 2005). The proper selections of the transistor used are vital consideration by depends the application would be operated and the performances that are required. In designing an amplifier, the preferred device should have a high degree of stability that ideally should be in unconditional stability condition. But, if the chosen device to be used is operated in conditional stability or potentially unstable condition, the stability circles need to be considered in order to make the device operates in a stable region. The three main properties of an amplifier must be carefully considered, which is noise, power output and gain at the required operating frequency (Alaslami, 2007). In addition, the transistor plays a vital role in the microwave amplifier circuits since these three main properties of an amplifier are heavily dependent on the transistor and technology types.

The pseudomorphic high electron-mobility transistor, pHEMT have been used in design 11 GHz Ku-band amplifier by Ain et. al (2007) since it has a very low noise resistance, capable of reducing the sensitivity of noise performance to variations in the input impedance match that makes it an ideal choice for use in first or single stage of amplifier topologies. In addition, this transistor type also uses in investigation two-stage Ku-band low noise amplifier operating at 18 GHz by Vadalkar (2016) which it is ultra-low noise transistor that provides a high and stable gain at the required frequency along with a low noise figure. Consequently, Bhushan & Khanapurkar (2016) also selected pHEMT transistor type in designing the microwave monolithic circuits which are also ideal for switches and resistive heterojunction, FET mixer. Mojbata et. al (2015) also using this transistor type in designing the wideband noise figure low noise amplifier for 3.5-4.5 GHz. By referring to their datasheet as in Appendix B, this transistor type is categorized in conditionally stable condition when operating at the operating frequency of 5 GHz.

Besides that, a power gallium arsenide field-effect transistor, GaAs FET is designed for general purpose applications in the C-band frequency range that form the operating range of the amplifier is 5 – 6 GHz (Vuppuluri et. al, 2015). This transistor type provides superior power, gain and efficiency. This transistor type is used to design and simulation of a linear amplifier in C-band by Vuppuluri et al. (2015). At the operating frequency of 5 GHz, this transistor type is operated in stable region condition, thus it is considered as the unconditionally stable condition. The datasheet of this transistor type as in Appendix C.

2.2.2 Stability factor analysis of the amplifier

The stability factor analysis of the amplifier is fundamental to microwave circuits because the amplifier would produced oscillation in some operating frequency or some terminal condition (Pozar, 2005). The stability in amplifier circuits indicates how immune it is to self-oscillation that determined through the Rollet's stability. The stability of the amplifier means the transistor is stable when embedded between 50 Ω source and load, and it cannot oscillate (Joseph, 2004). While for the oscillator, stability means the ability of the oscillator to return to the original operating point after experiencing a slight electrical or mechanical disturbance. The stability factor must be less than one or unity for any possibilities of oscillation. The terms of stability for the oscillator is referred to both short and long-term stability and the oscillator should be clean in the sense that it does not pick up unwanted signals and noise in the circuit (Mahyuddin, 2006). The scattering parameter, *S*-parameters of the transistor used provides the necessary values to verification of the stability factor analysis. The stability of the amplifier would influence the overall performances, whether it would realize the optimum performance with the high power output and broadband bandwidth. In a two-port network, the oscillations are possible if the magnitude of either input or output reflection coefficient is greater than unity, which is equivalent to a negative resistance at the port. These oscillations can make the amplifier operated in the unstable region and failed to perform as an amplifier. This situation is referred to as the circuit stabilization. As a result, the performances of the amplifier would be affected and the whole system may not work well (Su et. al, 2011). In the stability factor analysis, there are two conditions either it is unconditionally stable or conditionally stable or potentially unstable. A two-port network is unconditionally stable if the real part of the input and output impedance of the transistor used is greater than zero for all positive real source and load impedance at the operating frequency. Meanwhile, a two-port network is conditionally stable if the real part of the input and output impedance of the transistor used is greater than zero for some positive real source and load impedance in the certain range at the operating frequency (Pozar, 2005). Thus, the absolute stability condition of the amplifier would be defined by using the Rollet's stability factor, K which is given as Eq. 2.1 (Makesh & Shanmuganantham, 2017; Javier, 2017; Wang & Chen, 2016; Ratnaparkhi, 2016; Mahima et. al, 2015; Fallahnejad et. al, 2015; Fallahnejad & Alireza, 2014; Le et. al, 2013; Mahersi et. al, 2013; White, 2013; Yu-na & Geng, 2012; Malcom, 2012; Dellier et. al, 2012; Kassim & Malek, 2010; Shi-Sheng et. al, 2010; Lopez & Gonzalez-Villarruel, 2007; Ain et. al, 2007; Pozar, 2005; Nawaz & Mehmood, 2005; Tan, 2004; Collado et. al, 2004):

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} \geq 1 \tag{2.1}$$

where, $\Delta = S_{11}S_{22} - S_{12}S_{21} < 1$.

Having $K \geq 1$ is necessary, but it is not sufficient for unconditionally stable condition (Pozar, 2005). Thus, Eqs. 2.2 and 2.3 are further analyzed to determine if the two-port network stability is unconditional stable (Makesh & Shanmuganantham, 2017; Kassim & Malek, 2010; Marion & Jeffrey, 1992).

$$B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 > 0 \tag{2.2}$$

$$B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2 > 0 \tag{2.3}$$

As a result, $B_1 > 0$ or $B_2 > 0$ must be met along with $K \geq 1$ to guarantee the unconditionally stable condition. Besides that, the stability condition also would be determined using Eq. 2.4. If $\mu > 1$, the device is unconditionally stable and the larger values of μ imply greater stability (Fallahnejad et. al, 2015; Fallahnejad & Alireza, 2014; Kassim & Malek, 2010; Nawaz & Mehmood, 2005; Post, 2004; Marion & Jeffrey, 1992).

$$\mu = \frac{1-|S_{11}|^2}{|S_{22}-\Delta S_{11}^*|+|S_{12}S_{21}|} > 1 \tag{2.4}$$

If the above equations are simultaneously satisfied, then a two-port network of the transistor is unconditional stable. Thus, at that respective frequency, the two-port network can be designed as an amplifier. If it is vice versa which is conditional stable, the stability circle of the transistor used should be determined for the impedance matching proposed in order to obtain the stability before it could be proceeded to design amplifier. The stability factor or stabilizing network selection and approach is depending on the transistor type, amplifier configuration and also their application. Theoretically, the stable microwave amplifier still works normally even when its environment changes, such as temperature variations and frequency drift. Meanwhile, the unstable amplifier may bring oscillation that would affect the amplifier performances. Thus, the whole systems may not be performed well and their transistor also having the feasibility to be damage (Su et. al, 2011).

Generally, the stability and matching technique of the amplifier is some optimum solutions, where it depends on the circuit requirements, such as the simplicity in practical realization, the frequency BW, minimum NF, design implementation and adjustability, stable operation conditions, linearity, and sufficient harmonic suppression. Thus, many types of stability and matching networks are available (Bhale et. al, 2014; Shreyasi et. al, 2014; Wang & Park, 2013; Han & David, 2006; Grebennikov, 2005; Pozar, 2005, Sun-Wook et. al, 1999), which including lumped elements (Yo-Sheng et. al, 2014), transmission lines (Vimal & Maheshwari, 2016), and tunable matching network (Alimenti et. al, 2014; Fabbro et. al, 2008, Hoarau et. al, 2008).

An overall overview of the stability elements and matching techniques approaches by the previous researchers is presented in Figure 2.4.

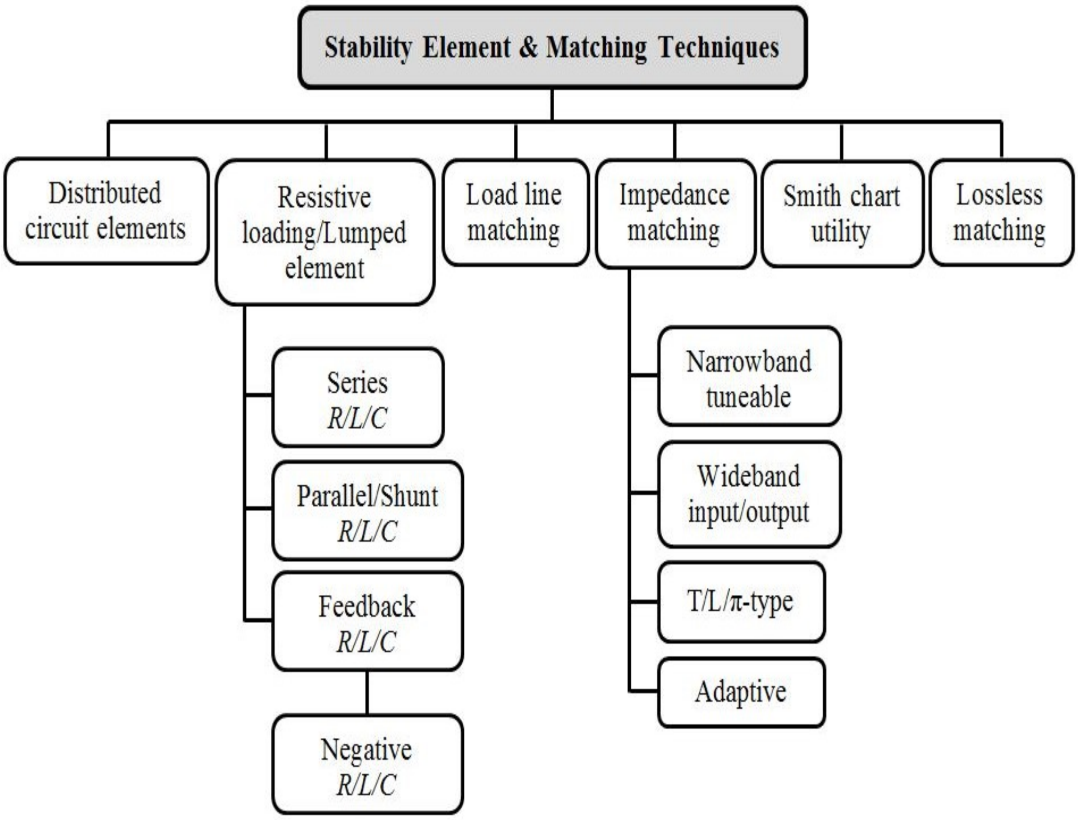

Figure 2.2: An overall overview of research approaches for stability elements and matching techniques.

Usually, two-port network or circuits is used for the analysis of the stability (Le et. al, 2013; Su et. al, 2011; Suarez et. al, 2006) and matching network (Han & David, 2006) on microwave amplifier design. The lumped elements or also known as resistive loading is a classic technique to guarantee the unconditional stability of the microwave amplifier at the operating frequency, but this amplifier is potentially unstable at other frequencies. Usually, when the microwave amplifier is potentially unstable, the two-port network can be stabilized by this technique of the resistive loading.

The resistive loading techniques involve adding series or parallel resistors to the input or output ports (Le et. al, 2013). The stabilizing network selection and approach depends on the transistor type, amplifier configuration, and its final application. A common source FET amplifier has a relatively high input reflection coefficient and typically requires resistive loading to achieve stability. Meanwhile, the resistive loss in LNA application that adding to the amplifier inputs can degrade the NF and should be avoided if possible. However, adding the resistive input loading in a power amplifier is allowed since noise degradation is not an issue for a transmit chain (Kassim & Malek, 2010). The combination of these networks might be necessary in order to get the desired stability results. Besides that, the stability circles also appropriate to be used in order to define the stability of the microwave amplifier.

The resistor loading of series and the parallel resistor is used by Le et. al (2013) purposely to obtain the optimum input power and maximum gain at the operating frequency between 200 MHz and 5 GHz. But, the lossy input network of the series and parallel resistor requires more consideration. Meanwhile, in Kassim & Malek (2010) uses resistive loading of series and parallel resistor with feedback in order to improve the stability. The resistive loading of series and shunt is applied in (Post, 2004) to improve the stability and having better NF at 2 GHz of the operating frequency. The resistive loading with the transmission line is adopted in (Nawaz & Mehmood, 2005), where the transmission line helps to improved stability as well as increased the gain at operating frequency between 500 MHz and 6 GHz. The passive lumped components of *RLC* is applied in (Sharma & PrakashDwivedi, 2013) for the investigation of the stability factor, temperature and maximize the gain at an operating frequency between 8.1 and 10 GHz. The stability is obtained from 1.006 to

2.097 dB in between the operating frequency range. The *RLC* feedback circuits are also used in Vimal & Maheshwari (2016); Senthilkumar et. al (2013); and Sahoolizadeh et. al (2009) to increase the stability factor at the operating frequency of 5.3 GHz as shown in Figure 2.2.

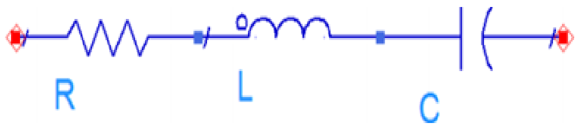

Figure 2.3: The *RLC* feedback circuit for increment stability (Vimal & Maheshwari, 2016; Senthilkumar et al., 2013; Sahoolizadeh et al., 2009).

Meanwhile, the *RC* negative feedback network is used in Su et al. (2011) to improve the stability of the amplifier. Besides that, the series resistor is used to connect to the RF input signal under normal circumstances in order to improve the stability of the RF amplifier. However, this method of stability is not recommended to be used due to the introduction of noise and signal loss (Su et. al, 2011).

The lossless matching network in Figure 2.3 is applied to deliver the maximum power to the load or to perform in a certain desired way, must be properly terminated at both the input and output ports. The matching network is ideally lossless to avoid unnecessary loss power.

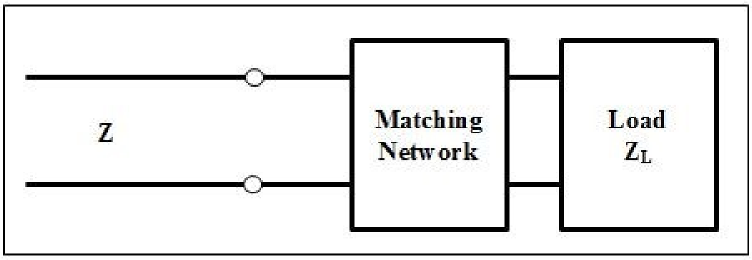

Figure 2.4: A lossless network matching the arbitrary load impedance to a transmission line (Vimal & Maheshwari, 2016; Senthilkumar et al., 2013; Sahoolizadeh et al., 2009).

Meanwhile, the stability and performance are improved by using L-type impedance matching technique on LNA in Makesh & Shanmuganantham (2017) by balancing the trade-off parameters of gain, bandwidth, BW and noise figure, NF. The L-type is form by the inductors and capacitors and the conjugate matching techniques helps in sizing and bias condition of active device used.

The wideband input- and output-impedance matching is used in Yo-Sheng et. al (2014). The input-impedance matching was achieved by taking advantage of the resistive shunt-shunt feedback in conjunction with a parallel *LC* load in order to make the input network equivalent to two parallel *RLC* branches which is known as a second-order wideband bandpass filter, BPF. Meanwhile, the output impedance-matching was achieved by making the output network equivalent to a second-order wideband BPF. In order to extend the bandwidth, both the inductive series- and shunt-peaking techniques are used.

Besides that, the simple and direct manner to derive the stability parameters is using rollet-based single-parameter criteria as in Tan (2004). This derivation is done for unconditionally stability criteria of linear two-ports. The stability circles and the stable region also investigated by Tan (2004a) to deduce the single-parameter geometrical stability criteria for linear two-ports. It is important to properly select the stability factor in microwave amplifier design (Su et. al, 2011). Others previous research investigation regarding the stability factor and matching networks of the microwave amplifier are listed and summarized in Table 2.1.

Table 2.1: The qualitative summary of the stability and matching techniques for a microwave amplifier.

Stability & Matching Networks (Input / Output)	F	A	Issues	Performances	Ref.
Lumped elements (L-shape network: Inductors & Capacitors)	4-8	LNA	• Gain. • NF.	• S_{11}= -50 dB • S_{21}= 13 dB • S_{12}=-15 dB • S_{22}=- 40 dB • NF= 2.2 dB • $VSWR$=1.5 • K=1.07	Makesh& Shanmugananth am, 2017
Load line matching.	2.5	PA	• Linearity. • Efficiency.	• Maximum efficiency power is 66%.	Veeranjaneyulu & Anuradha, 2016
Combination L-L matching circuits.	1-10	LNA	• Gain. • Stability factor. • NF.	• S_{21}= 10 dB • S_{12}=-49.59 dB • NF= 0 dB	Madhura& Savita, 2015
Feedback resistor for improved stability of the circuit (R = 500Ω). Lumped, distributed and radial stub elements for matching.	10	LNA	• Minimum NF. • High gain.	• S_{11}= -17.35 dB • S_{21}= 14.77 dB • S_{12}=-18 dB • S_{22}=-10.24 dB • NF= -0.775 dB	Fallahnejad et al., 2015
Lumped, distributed & radial stub elements.	10-15	LNA	• High gain. • Minimum NF.	• S_{11}= -17.15 dB • S_{21}= 14.35 dB • S_{12}=-17.023 dB • S_{22}=-16.92 dB • NF= -0.92 dB	Fallahnejad & Alireza, 2014
Adaptive (automatic) impedance-matching network (capacitor-matrix)	1.3	PA	• Resonant frequency. • Power transfer efficiency.	• Power transfer efficiency increased up 88% when distances changes 0 to 1.2 m.	Lim et al., 2014
RLC feedback for stabilization. T and L matching network.	6	LNA	• NF. • Gain. • Stability factor.	• S_{11}= -17.2 dB • S_{21}= 14.14 dB • S_{12}=-23.5 dB • S_{22}=-6.29 dB • NF= 1.816 dB • K=1.304	Senthilkumar et al., 2013

F: Frequency (GHz); A: Amplifier topologies

Table 2.1 The qualitative summary of the stability and matching techniques for a microwave amplifier 'Continued'.

Stability & Matching Networks: Input	Stability & Matching Networks: Output	F	A	Issues	Performances	Ref.
Negative feedback circuit for stabilization. Smith Chart and tuning matching.		2.45	LNA	• Improved sensitivity of the systems. • Maximum gain.	• S_{11} & S_{22} = < -15 dB • S_{21}= > 15 dB • NF= < 0.8 dB	Yu-na & Geng, 2012
-	Two variable capacitors	2.14	PA	• Maximum PAE.	• PAE increased by 21.8 % from 33.4% to 55.2 %.	Gao et al., 2010
Smith chart utility		8	LNA	• Gain. • Stability analysis.	• $Gain$=10dB	Fuzy & Zolomy, 2010
Symbolic approach (Heuristic algorithm)-generated design variables values in-terms of these unknowns.		1-3	LNA	• Output power – *maintain the efficiency power at the same maximum level.* • Quality factor, Q. • Enhance efficiency.	• S_{11} & S_{22} =< -10 dB • S_{21}= > 10 dB • NF= < 1 dB	Boughariou et al., 2010
Narrowband tunable impedance-matching network (π-structure with varactors in series with inductors)		1	LNA	• Noise Figure, NF. • Tunable matching network.	• Tuned in a 50% BW. • S_{11}=< -20 dB • S_{21}= > -3 dB	Hoarau et al.,2008
-	Tuneable impedance matching network (coupled inductors)	0.2-0.3	PA	• Efficiency • Maximum power output.	• Useful option for CMOS design when low-Q inductors must be used.	Fabbro & Kayal, 2008
Distributed circuits elements (lumped elements matching & numerical optimization techniques)		1-2	PA	• Broadband matching.	• S_{11} =< -20 dB	Khah et al., 2007

F: Frequency (GHz); A: Amplifier topologies

Referring to the related works summarized in Table 2.1, most of the issues are about gain, stability and noise factor. However, if the stability issues are not solved, the gain and noise factor can significantly be affected. As mentioned previously, the stability factor is influenced by the changes in operating frequency. Some amplifiers can reside in either a stable or unstable region depending on the operating frequency. Subsequently, the external disturbances such as temperature variation can only vary the frequency, thus making the amplifier susceptible to uncertainty in the aspect of stability. Therefore, the operating frequency needs to be easily controlled or adjusted for such cases after fabrication procedures.

The work by Jain et. al (2014) explores the use of CDR as frequency tunable elements. The placement of dielectric resonator with a constant physical parameter can tune the operating frequency of the two-way power divider; improving its performances for multifrequency operation without changing its physical dimensions. The advantages of DR is having high Q-factor, high radiation efficiency and also ease of the electromagnetic coupling made the DR is used to alter the properties of a normal power divider. This DR is provided dielectric loading to the T junction of the divider and also magnetically coupled with the microstrip lines of this power divider. By using the full-wave electromagnetic analysis of the divider structures, the implementation of such DR gives the input return loss better than 20 dB in operation of the divider at multiple frequencies.

2.2.3 Input and output matching network

Another important parameter for an amplifier is a matching network. The primary function is to transform 50 Ω to the required impedance at the input and output interface of the transistor over the operating frequency range (Inder, 2009).

Generally, the input and output impedance of the transistor can be calculated from Γ_{IN} and Γ_{OUT} as represent by Eqs. 2.5 and 2.6 (Malcom, 2012; Pozar, 2005; Nawaz & Mehmood, 2005; Post, 2004).

$$\Gamma_{IN} = S_{11} + \left(\frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}\right) = \frac{S_{11}-\Delta\Gamma_L}{1-S_{22}\Gamma_L} \tag{2.5}$$

$$\Gamma_{OUT} = S_{22} + \left(\frac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}\right) = \frac{S_{22}-\Delta\Gamma_S}{1-S_{11}\Gamma_S} \tag{2.6}$$

The matching networks either input or output matching must provide DC paths for biasing and some active elements. The input and output matching networks follow different design principle based on the specific matching function. The input matching networks circuits usually used to realize the matching between the input port of the amplifier and RF source in order to obtain the maximum power gain of the matching. Mainly, the input matching network circuits would be functioned to solve the problem of stability, gain, input voltage standing wave ratio, VSWR, gain flatness and also boosts the power gain. Thus, the input matching has a lower influence on the efficiency and linearity of the microwave amplifier.

Meanwhile, the output matching networks are used to achieve the matching between the output port of the amplifier and the load. The main functions of the output matching network are included increase the maximum output power, improve the output VSWR, suppress harmonic wave (Wang & Chen; 2016), and also efficiency at the given linearity levels (Fabbro & Kayal; 2008). The higher power level at the output port requires components with high power handling capability and high linearity (Maune et. al., 2011). Therefore, the output matching has the highest influence on the efficiency and linearity of the microwave amplifier. Several types of the matching network are available, however, the factors like complexity, BW, implementation, and adjustability needs to be considered in the matching network selection (Sahoolizadeh et. al, 2009).

In addition, the impedance matching networks need to be matched in order to maximize the power transfer from the receiver to the transmitter or input to the output port (Hoarau et. al, 2008). The consequences of not matching can increase losses in the systems, reduce the power and receiver sensitivity and also decrease the bandwidth of the systems. In any high-frequency amplifier design, the improper matching network or impedance matching let degrade the stability and reduce the circuit efficiency (Jeong et. al, 2015). Thus, the matching network and stability factor is the key to a better microwave amplifier design. The stability factor and matching techniques of the amplifier is necessary to improve the performance of microwave application, such as maximize the total system efficiency of the transmitter and receiver. The crucial of the stability factor and the matching network of the amplifier are widely implemented between radio transmitting, receiving systems and active microwave measurement circuits. Therefore, it is a vital consideration and critical issues in designing the amplifier that necessary to be solved at the beginning step of the design.

2.3 Dielectric Resonator

A dielectric resonator, DR is an electronic component that exhibits resonance for a narrow range of the frequencies, normally in the microwave band that is also known as one of the highest *Q*-factor resonators with low loss. A DR is a piece of un-metalized ceramic with a high dielectric constant, which the electromagnetic fields are confined to the dielectric region and it is immediate vicinity. Typically, DR consists of a "puck" of the ceramic that has a large dielectric constant and low