DESIGN OF 10 GHz NEGATIVE RESISTANCE DIELECTRIC RESONATOR OSCILLATOR

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by

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LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
AC	Alternating current
ADS	Advanced Design System
A_f	Loop gain
AGC	Automatic gain control
BNC	Bayonet Neill Concelman
CST MWS	Computer Simulation Technology Microwave Studio
DBS	Direct broadcast satellite
DC	Direct current
DR	Dielectric resonator
DRO	Dielectric resonator oscillator
DRs	Dielectric resonators
EM	Electromagnetic
F	Noise factor
FET	Field effect transistor
FM	Frequency modulation
GaAs	Gallium Arsenide
HBT	Heterojunction bipolar transistor
HE	Hybrid electric
HEMT	High electron mobility transistor
HF	High frequency
HM	Hybrid magnetic
IL	Insertion loss

IMPATT	Impact avalanche and transit time
LC	Lumped component
MESFET	Metal semiconductor field effect transistor
MIC	Microwave integrated circuit
MOSFET	Metal oxide semiconductor field effect transistor
PCB	Printed circuit board
PHEMT	Pseudomorphic high electron mobility transistor
PIN	Positive Intrinsic Negative
Q	Quality factor
Q_L	Loaded quality factor
Q_u	Unloaded quality factor
RF	Radio frequency
RFC	Radio frequency choke
RFI	Radio frequency interference
RLC	Resistor inductor capacitor
S/N	Signal to Noise ratio
SiGe	Silicon germanium
SMA	Sub-Miniature version A
SWR	Standing wave ratio
TE	Transverse electric
TEM	Transverse electric and magnetic mode
TM	Transverse magnetic
VSWR	Voltage standing wave ratio
WPD	Wilkinson power divider

LIST OF SYMBOLS

Z_0	Characteristic impedance
σ	Conductivity
ε_{eff}	Effective dielectric constant
X_{out}	Imaginary part of output impedance
Γ_{in}	Input reflection coefficient
Γ_L	Load reflection coefficient
Γ_{out}	Output reflection coefficient
μ	Permeability
R_{out}	Real part of output impedance
Z_T	Terminating impedance
Γ_T	Terminating reflection coefficient
λ	Wavelength
λ_g	Wavelength in waveguide
∂	Delta
°C	Degree celcius
μm	Micrometer
$Al_2 O_3$	Aluminium oxide
c	Speed of light
dB	Decibel
dBc/Hz	Decibels below the carrier level in a specified bandwidth of 1 Hz

dBm	Decibel with power reference to 1 mW
f	Frequency
F	Farad
GHz	Gigahertz
K	Stability factor
kHz	Kilohertz
mA	Miliampere
MHz	Megahertz
MHz/volt	Megahert per Volt
mm	Millimeter
nH	Nanohenry
pF	Picofarad
ppm/°C	Temperature coefficient
V	Volt
Zr Sn Ti O	Zirconium tin titanium oxide
β	Coupling coefficient
Ω	Ohm

REKABENTUK PENGAYUN PENYALUN DIELEKTRIK RINTANGAN NEGATIF 10 GHz

ABSTRAK

Pasaran komunikasi wayarles telah mengalami pertumbuhan yang luar biasa dan memandangkan bilangan pengguna wayarles dan jumlah gangguan RF terus meningkat, piawaian komunikasi moden memerlukan hingar fasa berprestasi unggul daripada pengayun tempatan dalam pemancar dan penerima. Hingar adalah salah satu perkara utama dalam pengayun kerana walaupun sedikit, hingar fasa di dalam pengayun membawa kepada perubahan dramatik dalam spektrum frekuensi dan ciri-ciri masanya. Secara umumnya, hingar fasa sesuatu pengayun ini menentukan keupayaan sistem komunikasi secara menyeluruh. Reka bentuk pengayun berhingar fasa rendah menghadapi banyak kekangan pada frekuensi gelombang mikro dan gelombang milimeter. Faktor utama yang membatasi reka bentuk pengayun berhingar fasa rendah pada frekuensi ini adalah penyalun yang faktor kualitinya rendah disebabkan oleh konduktor tinggi dan kehilangan dielektrik. Oleh itu, pada masa kini, DROs digunakan secara meluas di dalam sistem gelombang mikro dan gelombang milimeter. Disertasi ini memberi penekanan kepada kesan menggunakan dwi transistor ke atas frekuensi, kuasa keluaran dan hingar fasa dalam reka bentuk DRO rintangan negatif pada 10 GHz. DRO terdiri daripada siri E2000 bahan jenis penyalun cakera berdiameter 5.1 mm dari Temex Ceramics, GaAs ATF-36077 PHEMT dari Agilent dan Rogers RO4003C PCB dengan pemalar dielektrik sebanyak 3.38 dan ketebalan sebanyak 0.813 mm. Keunikan hasil kerja ini berbanding dengan yang lain adalah transistor dwi rintangan negatif DRO telah direka menggunakan ADS dengan bantuan teknik WPD untuk membahagi dan menggabungkan dua sub-pengayun bagi mencapai kuasa keluaran yang tinggi dan hingar fasa yang rendah. Hasil simulasi DR menggunakan CST MWS telah menghasilkan frekuensi salunan sebanyak 11.255GHz dan menjana kerugian kemasukan sebanyak 1.1918 dB. Hasil simulasi bagi litar skematik transistor dwi rintangan negatif DRO dalam ADS telah menghasilkan frekuensi ayunan sebanyak 10.61 GHz pada kuasa keluaran

sebanyak -58.698 dBm dan hingar fasa sebanyak -103.440 dBc/Hz. Hasil pengukuran mempamerkan frekuensi ayunan sebanyak 11.79805 GHz pada kuasa keluaran sebanyak -1.8 dBm dan hingar fasa sebanyak -81.03 dBc/Hz. Pelaksanaan transistor dwi rintangan negatif DRO telah dibuktikan dalam meningkatkan kuasa keluaran dan mengurangkan hingar fasa berbanding dengan satu transistor rintangan negative DRO. Sebuah bekas logam telah digunakan bagi mengurangkan kemungkinan mana-mana sumber hingar. Oleh itu, sebuah perkakas transistor dwi rintangan negatif DRO telah berjaya dihasilkan dengan hingar fasa rendah dan kuasa keluaran lebih tinggi pada frekuensi ayunan kira-kira, 10 GHz.

DESIGN OF 10 GHz NEGATIVE RESISTANCE DIELECTRIC RESONATOR OSCILLATOR

ABSTRACT

The wireless communication market has been experiencing tremendous growth and since the number of wireless subscribers and the amount of RF interference continue to increase, modern communication standards demand excellent phase noise performance from local oscillators in transceivers. Noise is one of major concern in oscillators because even a small amount of noise in an oscillator leads to dramatic changes in its frequency spectrum and timing properties. In general, an oscillator's phase noise determines the overall communication system's capability. The design of low phase noise oscillators faces many challenges at microwave and millimeter-wave frequencies. The main limiting factor in designing low phase noise oscillators at these frequencies is the low quality factor of resonators due to high conductor and dielectric losses. Therefore, in current microwave and millimeter-wave systems, DROs are widely employed. This dissertation emphasized on the effect of using dual transistors towards the oscillation frequency, output power and phase noise in the design of negative resistance DRO at 10 GHz. The DRO consists of E2000 series material disc type resonator with a diameter of 5.1 mm from Temex Ceramics, ATF-36077 GaAs pHEMT from Agilent and the Rogers RO4003C PCB with dielectric constant of 3.38 and 0.813 mm thickness. The uniqueness of this work compared to others was the dual transistors negative resistance DRO was designed in ADS with the help of WPD techniqueto divide and combine two sub-oscillators in order to achieve higher output power and low phase noise. Since a phase noise exhibited by a 10 GHz DRO in the current market is between -110 dBc/Hz and -120 dBc/Hz, a metal housing was implemented to reduce any possible of noises by preventing the output power from being lost in the radiated fields. The DR simulation result by using CST MWS produced a resonant frequency of 11.255 GHz and generating an insertion loss of 1.1918 dB. The simulation result for dual transistors negative resistance DRO schematic circuit in ADS produced an oscillation frequency of

10.61GHz at output power of-58.698 dBm and a phase noise of-103.440 dBc/Hz. The measurement result exhibited an oscillation frequency of 11.79805 GHz at output power of -1.8 dBm and a phase noise of-81.03 dBc/Hz. The implementation of dual transistors negative resistance DRO was provento enhance the output power and lower the phase noise compared to single transistor negative resistance DRO. Therefore, the dual transistors negative resistance DRO hardware was successfully produced with lower phase noise and higher output power at an oscillation frequency approximately 10 GHz.

CHAPTER 1

INTRODUCTION

1.1   Overview

For the last few decades, a revolution in the wireless communication had been grown where there is a need for several of wireless solutions to take over the common wired systems. The needs of these systems in our daily lives have forced system designers to come up with products which can deliver higher performance at lower costs. Lower power consumption and reduced size are other design goals being aggressively pursued because of the demand to reduce the cost and power consumption by 30% every year (Razavi, 1996).

Oscillator is a basic fundamental system block in every wireless or wired product which represents microwave energy source for most of all microwave systems including radars, communications, navigation or electronic warfare. A typical microwave oscillator consists of an active device (a diode or a transistor) and a passive frequency-determining resonant element. With the rapid advancement of technology, there has been an increasing need for better performance. The emphasize has been done on low noise, small size, low cost, high efficiency, high temperature stability and reliability. Another important parameter that has been investigated in oscillator design is the phase noise, apart from the cost, size and power consumption.

The dielectric resonator oscillator (DRO) presents an interesting solution for fixed-frequency or narrowband tunable applications. A transistor DRO has become the most desirable choice in a vast number of fixed-frequency microwave signal source applications. It can be realized using either silicon Bipolar Junction Transistor (BJT) or Gallium Arsenide Field Effect Transistor (GaAs FET) devices.Asilicon BJT is generally selected for lower phase noise characteristics, while the GaAs FET is required for higher frequencies (GED, 2013). For thesilicon BJT DRO, the maximum oscillation frequency can be reached 20 GHz while for a

GaAs FET DRO can be reached up to 100 GHz. But, in terms of phase noise, the silicon BJT DRO offers lower phase noise (6 to 10 dB less FM noise, very close to the carrier) rather than a GaAs FET DRO which capable of operation at 10 GHz and beyond producing an output power in excess of +10 dBm.

A variety of microwave components which employs dielectric resonators (DRs) have been developed during the past few years, due to the availability of low-cost, temperature-stable and high permittivity materials. Due to their excellent integrability in MIC circuits, DRs can be used directly as the frequency-determining element for realizing a stable microwave frequency source. The primary characteristics of the ceramic material for the DRs are the quality factor, temperature coefficient of the resonant frequency, and dielectric constant. Hence, they become a preferable choice in many fixed-frequency receiver/transmitter local oscillator applications.

1.2   Problem Statement

The design of a negative resistance DRO is emphasized on lower noise, smaller size, lower cost, higher efficiency, higher temperature stability, and improved reliability in order to achieve better performance. A mechanically tuned of a negative resistance DRO which oscillates close to desired oscillation frequency10 GHz was proposed.

A negative resistance DRO configuration design is the relative ease of coupling to a single line, compared to the parallel feedback DRO's configuration design which is double line coupling. However, the single line must have higher gain because of the coupling from the resonator to the microstrip line is not so strong, which includes that the source cannot be connected directly to the ground potential.A negative resistance DRO must have higher gain in order to allow significant coupling from the resonator to the microstrip line, which then resulting in a higher loaded Q factor, lower phase noise and exhibit excellent performance. The configuration of negative resistance DRO with a single microstrip line can be easily

implemented, but typically does not have a tuning range as wide as that obtained with parallel feedback.

Critical to the performance of the negative resistance DROcircuit is the placement of the DR on the gate port, where it is isolated from the output circuitsby the very low drain to gate capacitance inherent in the device. The isolation minimizes interaction between the output and input ports, which allows the resonator to be lightly coupled to the gate, resulting in a very high loaded Q, and therefore minimum phase noise. This limitation can be improved by adding another microstrip line into the design of the negative resistance DRO which will look like a parallel feedback DRO. A high Q resonator is placed between two parallel microstrip lines which is connected between the drain and gate terminals of FET.

Phase noise also contributes as one of the limiting factor in DRO performance which is dependent upon the amount of output power delivered to the load. In other words, phase noise can be lowered by enhancing the output power. Two identical circuits of negative resistance DRO are combined using single DR to improve the RF output power.

1.3   Objectives

Main objectives of this research are stated as follows:

1.   To designand develop single anddual negative resistance DROsthat uses a single DR.

2.   To fabricate, test, measure and compare the performance of single and dual negative resistance DROs in terms of oscillation frequency, output power and phase noise.

1.4   Scope of Research

Since DROs cover wide fields, the scope range will be narrowed and focused on specific aim. The scope of this dissertation will cover all objectives, focusing on designing a negative resistance DRO which oscillates at 10 GHz and exhibits excellent performance (low phase

noiseand high output power).Therefore, parallel feedback DRO topic will not be discussed in this dissertation.

Negative resistance DRO suffers limitations in the frequency range for accurate measurements. The coupling reaches its peak value at higher frequencies for a given microstrip line resulting in excessive loading to the resonator and thus lowered the value of Q. In this frequency range, the measurement of the dielectric properties loses its accuracy because the lowered Q values means inaccuracies in determining the resonant frequencies.

Frequency stability of negative resistance DRO is much better compared to the other free running oscillators but still not as good as the frequency stability of phase-locked oscillators. However, the DRO is more suitable to be applied in this research because of its characteristics such as small size and low cost although it contains a slightly lesser stability specification, but still acceptable.

Another factor that limits the DRO from obtaining the accurate measurement is mechanical tuning bandwidth. The bandwidth is typically tuned to 0.2% of the center frequency but for DRO, it can only be increased up to 3% of center frequency for special applications. Phase noise also contributes as one of the limiting factor of DRO performance but can be improved by implementing the theory analyzed by (Everard, 2001).

A 3D EM model of DR was implemented in the CST MWS to undergo the simulation process. The model was exported to the schematic design of single and dual negative resistance DROs in ADS and simulated to obtain expected result. The simulation and measurement result which contain the result of oscillation frequency (GHz), output power (dBm) and phase noise (dBc/Hz) were then compared between single and dual negative resistance DRO design. The dual negative resistance DRO design was chosen to be the final design as it was assumed to produce good performance rather than single negative resistance DRO.

In the measurement process, the oscillation frequency, output power and phase noise of the oscillator circuit will be measured by a spectrum analyzer, observed, and recorded. Environmental effects might be the major factor that limits the accurate measurement which can be reduced with the help of metal casing since it can block the excessive noise.

The effect of frequency pulling also was not discussed as there was no significant change in output frequency that could justify the effect of frequency pulling.The effects of implementing single transistor and dual transistors towards oscillation frequency, output power and phase noise have been discussed further in the discussion.

1.5   Dissertation Organization

This dissertation was organized into five main chapters. Chapter 1 began with the general overview of an oscillator and proceeded with a DR and a DRO, problem statement, objectives, scope of research and dissertation organization.

Chapter 2 covers the literature review, which is related mostly to the DRO design. In this chapter, theoretical background of microwave oscillator, negative resistance oscillator, feedback oscillator, DR, DRO and WPD are presented. There are also reviews about the coupling of DR and previous published works on the negative resistance DRO are presented.

Chapter 3 discusses the methodology of this research, which has been employed in order to complete the negative resistance DRO design. The DR is modeled in Computer Simulation Technology Microwave Studio (CST MWS) and also the modeling of a DRO circuit is presented. The modeling of other parts of the negative resistance DRO such as DC bias circuit, RF choke network and the integration of all related parts into a complete negative resistance DRO is presented. The fabrication and measurement process is also discussed in this chapter.

Chapter 4 focuses on the results, which have been obtained from the simulation and measurement results of a dual transistors negative resistance DRO. The simulation results obtained are compared with the measurement results in order to analyze factors that affected the results differences. Brief analysis based on the comparisons is discussed in this chapter.

Finally, Chapter 5 contains conclusion based on the experimental results. The contributions of this research are clearly highlighted. Some recommendations for future works are suggested at the end of this chapter in order to improve the oscillator design for future innovations.

CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1   Overview

This chapter evolves towards the overview of the research for designing a negative resistance DROat 10 GHz. Here, the theoretical background has been divided into several sections which include topics and subtopics in detail. In order to achieve objectivesin this dissertation, the theoretical background part is focused mainly on microwave oscillator, negative resistance oscillator, dielectric resonator (DR), and dielectric resonator oscillator (DRO) where the theories and concepts such as characteristics, principle of operation, various oscillators' configuration, and performance have been studied. Furthermore, the related parameters such as the quality factor, coupling coefficient and phase noise also have been discussed in the subtopics while in literature review part, published research that related or similar to this dissertation will be reviewed and summarized.Some ideas and understanding on the design of negative resistance DRO at 10 GHz can be realized in terms of its operation, performance, limitations and suggestion to improve those designs.

2.2   Theoretical Background

2.2.1   Microwave Oscillator

Oscillator is an essential and fundamental system block in every wireless or wired product(Butt *et al*., 2009). Hence, it becomes a logical choice for many fixed-frequency receiver/transmitter local oscillator applications (Pavio and Smith, 1985). It functions as a signal generator in a transmitter while the local oscillator in a receiver is used together with a mixer to convert the received RF signal to an IF signal. The oscillator can be modulated by a low frequency analog or digital signal, where its signal serves as a carrier and the modulating low frequency signal is the information to be transmitted (Mahyuddin, 2006).

When designing an oscillator, characteristics such as good power output, high dc to RF efficiency, low noise, good stability and good frequency tenability are indispensable (Mahyuddin, 2006). The design goals have a significant impact on development of oscillator technology. Apart from the cost, size and power consumption, another important parameter that have been actively investigated in oscillator design is the phase noise. Oscillator phase noise can be effectively reduced by incorporating high-Q resonators (Butt *et al*., 2009).

Oscillators represent the basic microwave energy source for all microwave systems such as radars, communications, navigation, electronic warfare missile(Wan, 2008). A typical microwave oscillator consists of an active device (a diode or a transistor) and a passive frequency-determining resonant element.

All microwave oscillators are designed by adding resonating elements (L, C, or R) in various configurations to different ports of a transistor. These elements generate a negative resistance at a certain resonant frequency and set the device into oscillation. In the case of a DRO, the resonating element is the DR, which can be modeled electrically as an L, C, R network (MITEQ, 2013).

2.2.2 Characteristics of an Oscillator

Recently, wireless communication services have been developed rapidly. Microwave oscillators are very important components in these high frequency systems where the higher frequency signals are required to carry the information and to transmit huge amount of information (Tanaka and Aikawa, 2009, Han-li *et al*., 2012).

There are several parameters or characteristics which are essential in part of an oscillator. The major aspects that have to be analyzed are the output power, operating frequency and tuning range, efficiency, stability, noise, phase noise, harmonic suppression, frequency

stability, quality factor, frequency jumping, pushing and pulling, and spurious outputs. One of the characteristics of an oscillator is the output power which is defined as continuous power generated by an oscillator in watts or milliwatts for continuous wave operation and the peak power or average power generated by an oscillator for pulse operation.

Operating frequency and tuning range are a fixed output frequency or a tunable output frequency range which is used either mechanically or electronically tunable oscillator. The frequency range is determined by the architecture of the oscillator. Tuning for an oscillator can be divided into several categories, which are post-tuning drift, tuning linearity, tuning sensitivity, tuning performance and tuning speed.Stability is the ability of an oscillator to return to the original operating point after experiencing a slight electrical or mechanical disturbance which refers to both short term and long term stability. The oscillator should be clean in the sense that it does not pick up unwanted signals and noise in the circuit (Mahyuddin, 2006).

Another important characteristic of an oscillator is its noise comprised of amplitude modulation noise or amplitude variations of the output signal, FM noise, unwanted frequency variations and phase noise or phase variations. Various noise sources contribute to oscillator noise including the loss of the resonator, the noise sources inside the transistor; noise modulated on the power supply and the noise contributions from the tuning diodes. FM noise is usually measured at about 100 kHz from the carrier in unit of dBc, which means decibels below the carrier level, in a specified bandwidth of 1 Hz. The various noise sources in and outside of the transistor modulate the oscillator, resulting the energy or spectral distribution on both sides of the carrier. Another type of noise that describes an oscillator is a harmonic suppression. The oscillator has a typical harmonic suppression of more than 15 dB. For high performance applications, a low pass filter at the output will reduce the harmonic contents to a desired level (Rohde *et al*., 2005a).

Phase noise, related to short-term frequency stability, is characterized by variations in the output frequency which appears, in the frequency domain, as FM energy around the carrier frequency. It is specified in dBc/Hz and measured at specified offsets from the carrier frequency which is typically 10 kHz and 100 kHz. The phase noise (or FM noise) is produced by thermal noise, shot noise, and flicker noise.

Frequency stability or phase stability refers to the ability of the oscillator to maintain constant frequency of oscillation. In achieving frequency stability, series or parallel resonant circuits are generally used in the terminating network, such as lumped elements, cavities and DRs. A requirement for all resonators is to acquire high Q factor or low loss. By appending a high Q tuning network to the oscillator, this will result in the enhancement of the oscillator stability (Mahyuddin et al., 2006).

As well known, an amplifier and a tuned circuit that arebuilt in an oscillator are functioned to transform the dc energy into RF energy at the desired frequency and acceptable power added efficiency. By depending on the frequencies and configurations, the efficiency of a low noise oscillator varies between the range of 10% to 70%(Rohde *et al*., 2005b). According to Rohde, the main objective of the amplifier and tuned circuit that is built in an oscillator is to gain a frequency output signal which is stable with low phase noise and free of spurious signals at sufficient level.

The unloaded quality factor is the parameter of the DR which influences the oscillator's phase noise. It can be defined as a ratio of the stored energy within the puck to the amount of energy which is dissipated by the resonator and serves as a figure of merit for the device. Unloaded quality factors of 20,000 are now possible to 10 GHz. However, the loaded quality factor will determine the oscillator's phase noise response. The loaded quality factor can be defined as a ratio of the energy stored within the puck per cycle to that delivered to the load per

cycle. The oscillator phase noise is described by Leeson's equation, which demonstrates that the reduction in the loaded Q, resulting from the inclusion of voltage variable frequency control, in the traditional manner, results in a degradation of the oscillator phase noise performance (Warburton, 2005).

The effects of the output frequency of an oscillator can be classified into three categories known as jumping, pushing and pulling frequency. Jumping frequency is a term to describe a discontinuous change in oscillator frequency due to nonlinearities in the device impedance. Meanwhile, frequency pushing is a measure of the sensitivity of the oscillator output frequency to the supply voltage (MHz/volt) which is tested by varying the dc supply voltage of an oscillator with its tuning voltage held constant, where it is typically around ±1V. In other words, frequency pushing characterizes the degree to which an oscillator's frequency is affected by its supply voltage(Rohde *et al*., 2005a). On the other hand, frequency pulling is a measure of the change in frequency to a non-ideal load (load mismatch over 360° of phase noise variation). Frequency pulling is also the change of frequency resulting from partially reactive loads, which is an important oscillator characteristic (MINICIRCUIT, 2013, Mahyuddin, 2006).

Spurious outputs are signals found around the carrier of an oscillator which are not harmonically related. A good, clean oscillator needs to have a spurious free range of 90 dB, but this requirement makes it expensive. Typically, an oscillator have no spurious frequencies other than possibly 60 Hz and 120 Hz pickup (Rohde *et al*., 2005a).

2.2.3 High Frequency Oscillator Design

Both negative resistance and feedback DROs design in this dissertation contain the implementation of a transistor oscillator which concern with nonlinear analysis of high frequency FET and bipolar oscillators. The method of designing a transistor oscillator involves small and large signal which provide all the information needed to design an oscillator. The

design of transistor oscillator has similarity to the design of transistor amplifier, especially dc bias circuits and S-parameters, with the exception of the transistor oscillator is designed to be unstable. There are some requirements have to be taken into considerations concerning generating an oscillation for transistor amplifier and transistor oscillator design. As for transistor amplifier, S_{11} and S_{22} must be less than unity while for transistor oscillator to be unstable, S_{11} and S_{22} must be greater than unity.

Bipolar, MOSFET, MESFET, HEMT and HBT are examples of transistors which can be implemented into the oscillator design method based on the S-parameters datasheet of the transistor correspondingly. Normally, common source or common gate FET configurations are frequently used since it meets the condition of implementing a high degree of unstable device in an oscillator.

By referring to the previous section, resonators play a major part in an oscillator which has been implemented into the oscillator design towards accomplishes a low noise and high frequency stability. They are made of lumped element, a distributed transmission line, a cavity or a dielectric disc.

The approach of S-parameters in small and large signal designs which has been implemented into the oscillator design as a requirement for oscillation to start up. Figure 2.1 shows a two-port transistor oscillator where Z_L is the load impedance and Z_T is the terminating impedance seen by the transistor. The condition for oscillation to start is by the used of terminating network in order provide the $|\Gamma_{out}| > 1$. The frequency of oscillation and power delivery to the load are determined by the load network(Maas, 2003, Mahyuddin, 2006).
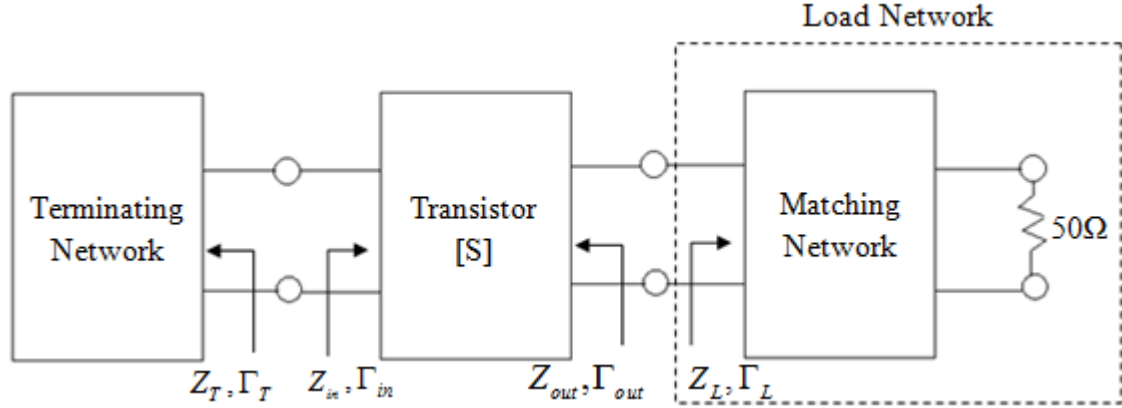
Figure 2.1: Circuit for a two-port transistor oscillator(Maas, 2003, Mahyuddin, 2006).

$$\left| R_{out}\left(V, f_0\right)\right| > R_L\left(f_0\right) \qquad (2.1)$$

$$X_{out}\left(V, f_0\right) + X_L\left(f_0\right) = 0 \qquad (2.2)$$

Where;

R_{out} = real part of output resistance

X_{out} = imaginary part of load resistance

R_L = real part of load resistance

X_L = imaginary part of load impedance

V = voltage across the output resistance (V)

f_0 = carrier centre frequency (Hz)

The above conditions need to be satisfied to make sure that the oscillation occurs at the desired frequency. It is stated that R_{out} is negative. *Equation 2.1* ensures that $|\Gamma_{out}| > 1$ and the *Equation 2.2* determines the oscillation frequency. The network has the potential for oscillation as long as the first equation is satisfied. As an elaboration, the oscillations start to build from the noise level when the power supply voltages of an oscillator are turned on. As a result, the output amplitude will continue to grow until the saturation effects of the device limit it. Decisively, the

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capability of a transistor to start oscillations in a given circuit is determined by the noise level and can be deliberate by small signal techniques. The negative resistance is a function of voltage and as the oscillation power increased, the negative resistance value is reduced. If the negative resistance is kept decreasing to a value lower than the load resistance, the oscillation will cease. This can be overcome by designing the magnitude of the negative resistance at $V = 0$ to be much larger than the load. This condition can be expressed as(Mahyuddin, 2006);

$$K < 1 \qquad (2.3)$$

$$\Gamma_{in}\Gamma_T = 1 \qquad (2.4)$$

$$\Gamma_{out}\Gamma_L = 1 \qquad (2.5)$$

Stability factor must be less than unity for any possibility of oscillation. If it is not satisfied, either the common terminal should be changed or positive feedback should be added. Since $|\Gamma_L|$ and $|\Gamma_T|$ are less than 1, this means that $|\Gamma_{in}| > 1$ and $|\Gamma_{out}| > 1$. It can be verified that if the output port oscillates, the terminating port would also oscillate. The output port oscillates if $\Gamma_{out}\Gamma_L = 1$ which states that (Vendelin et al., 1990);

$$\frac{1}{\Gamma_T} = \Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \quad (2.6)$$

$$\frac{1}{\Gamma_L} = \Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_T}{1 - S_{11}\Gamma_T} \quad (2.7)$$

From *Equation 2.6* and *Equation 2.7*, results in;

$$\Gamma_L = \frac{1}{\Gamma_{out}} = \frac{1 - S_{11}\Gamma_T}{S_{22} - \Delta\Gamma_T} \quad (2.8)$$

Where;

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

Equation 2.8 can be arranged to give:

$$\Gamma_T = \frac{1 - S_{22}\Gamma_L}{S_{11} - \Delta\Gamma_L} \quad (2.9)$$

Equation 2.6 can be written as:

$$\Gamma_T = \frac{S_{11} - \Delta\Gamma_L}{1 - S_{22}\Gamma_L} \quad (2.10)$$

Multiplying *Equation 2.9* by *Equation 2.10* results in:

$$\Gamma_{in}\Gamma_T = 1 \quad (2.11)$$

Therefore, this proves that the terminating port is also oscillating.

The first step to design a transistor oscillator is by selecting a potentially unstable transistor at the frequency of oscillation. If it is found to be stable and not meet the requirement, it can be overcome by incorporating the feedback elements to make it unstable.

The second step to design a transistor oscillator is by designing the terminating network, to achieve $|\Gamma_{out}| > 1$ by choosing Γ_T and Z_T in the unstable zone of the stability circle. When Z_T and the transistor small signal S-parameter have been considered, Γ_{out} is calculated and the condition of $|\Gamma_{out}| > 1$ must be followed. The load is then chosen according to the oscillation conditions as follows:

$$X_L(f_0) = -X_{out}(f_0) \qquad (2.12)$$

$$R_L(f_0) = \frac{1}{3}\left|R_{out}(0, f_0)\right| \qquad (2.13)$$

As to make an oscillator working, Z_L value must be chosen correctly. It is found that the measured oscillation frequency will be shifted from the design value since X_{out} (f_0) used in determining f_0, is assumed to be independent of the amplitude, V. Finally, the last step of designing a transistor oscillator is to design the load matching network to transform a 50 Ω load to Z_L. There is similarity between the large and small signal design approach except for the main difference between them which is the determining of large signal S-parameters device. The large signal S-parameters can be determined either by measurements or by using a large signal device model.

2.2.3.1 Negative Resistance Oscillator

Several solid-state devices exhibit negative resistance under a certain dc biases due to the device physics. These include the Gunn device, impact ionization avalanche transit time (IMPATT) devices, resonant tunneling diodes (RTDs) and transistors (Chang, 1994). In microwave and millimeter wave frequencies it inhibits Gunn and IMPATT, which are two terminal devices. From low RF frequencies to microwave and millimeter wave are two different variations of frequencies that have been used for a transistor.

The most common transistors that have been used in RF frequencies are silicon metal oxide semiconductor field effect transistors (MOSFETs). However, in microwave frequencies, the most common transistors that have been used are bipolar transistors, metal semiconductor field effect transistors (MESFETs), high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs).

In order to produce a sinusoidal steady state RF signal, a solid-state oscillator such as diode and transistor has been used in conjunction with a passive circuit. After an oscillator is properly designed with a stable oscillation state, an oscillation for a startup is triggered with the existence of transient and noise. Thus, a nonlinear active device is essential to overcome this matter and since the device is producing RF power, negative resistance is relevant in the nonlinear active device. The complete analysis of oscillation operation is proven to be difficult due to the active and nonlinear element.

An oscillator can be classified into three individual parts which are; a low loss resonant circuit, a negative resistance device or an active two-port with its S-parameters description, and a coupling circuit which contains a passive lossy load. The resonant circuit functions as energy storage and at the same time controls the frequency while the negative resistance device functions to generate the power to be transferred to the load (Mahyuddin, 2006).

On the basis of negative resistance theory, the DRO is designed to make the resistance generated by the feedback element negative enough to compensate the loss generated by the resonator. As a rule of thumb, at least 1.2 times of the load resistance is required by the negative resistance in series circuit in order to satisfy the start-up condition for the oscillator (Wan, 2008). For oscillation to occur; the Barkhausen criteria must be met which are; the open loop gain must exceed unity and the phase shift around the loop must be equal to an integral multiple of 2π and as such, the phase shifter will operate to keep the output frequency of the oscillator fixed. As the oscillator signal builds up from noise, gain is compressed to unity and steady state oscillation occurs (Warburton, 2005).

The common method in designing an oscillator is by resonating the input port with a passive high Q circuit at the desired frequency of resonance. The transistor will oscillate at both ports and is thus delivering power to the load port by connecting a load to the output port.

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Typically, since a high Q resonance is desirable for minimizing oscillator noise, only parasitic resistance is present at the resonating port. Since the oscillator is oscillating at both ports simultaneously, it is possible to have loads at both the input and output ports if such an application occurs.

Figure 2.2 shows a general circuit of an oscillator, where Z_D is the device impedance and Z_L is the transformed load impedance which seen by the device. Z_D is the output impedance of a terminated transistor, in the case of a transistor oscillator. A terminated three-port transistor transforms into a two-port circuit. Z_o is the output line characteristic impedance, which is 50 Ω for microstrip or coaxial line and several hundreds of ohms for waveguides. The transformer network includes the device package and embedding circuits.
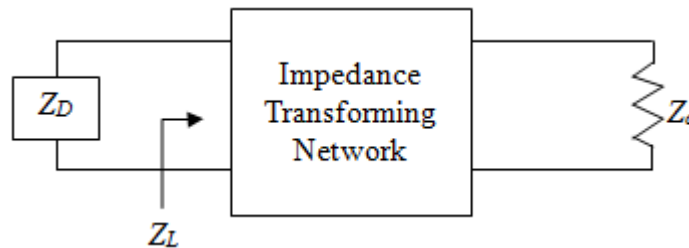
Figure 2.2: General oscillator circuit(Chang, 1994).

The oscillation frequency can be determined by the resonant frequency of the overall circuit. The total amount of reactance or resistance is zero at a resonance when the net resistance or conductance of the circuit is negative which by referring to the negative resistance condition which is common for all two terminal solid-state active devices. As a result, there will be a voltage drop across a positive resistance to be positive and a power will be dissipated in the resistance. In an addition, a voltage drop across a negative resistance is negative which creating power generated in the resistance (Mahyuddin, 2006).

2.2.4   Requirement for Oscillator Design

Oscillator design is very similar to amplifier design. The same transistor, dc bias levels, and the same set of device S-parameters used in amplifier design are used to design the oscillator. The typical oscillator design consists of three parts, the input resonant impedance matching circuit, the active device, and the output impedance matching network. The feedback circuit is usually included in the active device block while the negative resistance is not available.

The oscillator circuits implement steady state operation only when a transistor has been driven into nonlinear operation that its gain averaged over each output cycle drops to a small fraction of the nominal small signal value. Information of transistor parameters in the data sheet only defines the initial conditions of the oscillator circuit, where the transitional and final values are usually unknown. Equivalent circuits and analytical tools of circuit analysis are based upon linearity; state-operating conditions of an oscillator in general cannot be predicted accurately by simple mathematical techniques.

In order to start the oscillation, the output of an amplifying device must be fed back to the input with gain greater than unity and with a phase shift of 0° or some multiple of 360°. This can only occur at one frequency, which will be the frequency of oscillation. If the phase shift through the feedback network and transistor is independent of the transistor operating conditions, the frequency of oscillation will be the same at steady state as it was when oscillations began and it may be predicted accurately by small signal analysis of the initial circuit. There is possibility in predicting the minimum transistor gain that will initiate oscillation but the operating frequency is all about that small signal analysis can yield.

Frequency dependence of passive component values is another complicating factor. It is stated that capacitors larger than a few hundred Pico farads tend to look inductive above about

10 MHz and stray capacitance between turns may cause inductors to become capacitive. In conventional circuit theory, these effects are difficult to design and they may allow a circuit to satisfy the conditions for oscillation at frequencies that are not predicted by circuit analysis. Practically, the results that have been analyzed mathematically do not assured that the circuit will oscillate simultaneously at the intended frequency but instead it may oscillate at a low frequency or even at one or more high frequencies. These can be encountered by employing high quality inductors and by connecting small capacitors in parallel with all bypasses and coupling capacitors(Mahyuddin, 2006).

2.3   Dielectric Resonator

The general concept of an oscillator had been discussed in previous section. The discussion covers the design theory, characterization and requirement for an effective oscillator. The knowledge about DR is essential to be understood before proceeding with the related topic, DRO in order to have knowledge more on the DR's background. Furthermore, the reasons of choosing the suitable DR as the resonator in the condition of high quality factor and to achieve low loss oscillator have been deeply explored. The overall concept of DR design, coupling method, unloaded and loaded quality factor, and insertion loss also have been studied and understood.

2.3.1   Types of Resonator

A better performance of an oscillator will have a stable output frequency which functioned as to lower the frequency modulation (FM) and phase noise. By terminating network with series and parallel circuits, frequency stability can be achieved. The reflection coefficient for a high Q resonator is outer boundary of the Smith Chart upon the phase depending on the transmission line length between resonator and the active device.

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There are several examples of resonator that can resonate at the desired frequency depends on their own features. Most commonly resonators are; a DR, LC circuit, ceramic piezoelectric devices and YIG-based device. After implemented into an oscillator design, these resonators can be mechanically tuned at a desired fixed frequency. The resonator part is a critical part in oscillator design since it coupled inadequately to the circuit, thus contributing to high loss and so the Q. Supposedly, the resonator is the dominant in oscillator frequency setting rather than the transistor because of the high Q, low noise characteristic and thermally more stable (Chang *et al.*, 2002). The higher loss in the resonator, the more difficult to satisfy the gain conditionwhich is $|S_{21}| > 1$.

Distributed or lumped resonators and integrated resonators are the types of microstrip resonators. Distributed or lumped have the same parallel tuned circuit as the LC resonators. The lumped resonators can be generated by using a printed transmission line instead of the lumped inductor, and still maintaining the capacitance. The transmission line tends to suffer from losses due to the material been used where the typical value of Q is around 240. With suitable layout and material been used, the value of Q is possible until up to 300 (Rohde *et al.*, 2005a). In contrast with the integrated resonators, it can be generated not only using PCB material but in GaAs or in Silicon. Usually, a high resonator consists of two coupled inductors has been used since the elements themselves are not resonant and are much shorter than quarterwave length and merely appropriate for two or more coupled transmission lines. The rate of change of phase against frequency in the configuration will be faster with a higher Q which can be as much as ten times as the Q of a single tuned circuit.

It was first presented by R. D. Richtymer that cylindrical dielectric structure would act like a resonator. Many years after that discovery, such circuits containing DRs are realized (Ugurlu, 2011). The shape of the DR is usually a disc or short solid cylinder, but can also be made into a tabular, spherical, parallel piped, or rectangular shape. The most frequently used DR

shapes are disc and puck since they can be easily manufactured than other shapes (Bing *et al*., 2009).

The most popular resonator is the ceramic type of resonator which can be used either in filter or in oscillator. It is based on a quarterwave arrangement and can be made from low loss coaxial line or waveguide. The ceramic is silver plated and can be modeled as a quarterwave section of TEM transmission line with a high relative dielectric constant ranging from 33 to 88.

It is known that a requirement for all resonators is acquire high Q for low loss and stable oscillation. Lumped element, which has been mentioned before, fails to perform since its Q is limited to only a few hundred. Cavity resonator, however, has Q of thousands but it is not suited for miniature microwave integrated circuit and in addition, it also suffers from frequency drift caused by dimension expansion due to temperature variation. Soon after low loss ceramic dielectric material with controllable temperature coefficients became available at reasonable cost, the DR became a widely employed component in microwave circuits, predominantly in filters and solid-state oscillators (Tobar *et al*., 1999). Therefore, in achieving a high Q with low loss and stable oscillation, DR is the right candidate for such task.

2.3.2   Theory of Dielectric Resonator

Resonators are an important component in microwave circuits. They play a major role in frequency definition in oscillators where they store energy at the resonant frequency in the electric and magnetic fields. The important characteristics of the microwave resonators are the resonant frequency, quality factor (Q), which defines the bandwidth of the resonance and the input impedance of the resonator (Ugurlu, 2011). There are several kinds of resonant circuits which include lumped element resonant circuits, transmission line distributed resonant circuits, and cavity resonators.

DR is the frequency-determining element of the DRO for realizing a stable microwave frequency source. It is made of the material with high dielectric constant, high Q factor, and low temperature coefficient (Bing *et al*., 2009). The dielectric constant, ε_r varies from 20 to 80. DRs have been widely used to make temperature compensated stable oscillators. But for most applications they also need to have low noise characteristics as close as a few hundreds of Hz off the carrier. During the past several years, a variety of microwave components which employ DRs have been developed due to the availability of low-cost, temperature-stable, high permittivity materials. Since the sizes of DRs are small depends on the material and the frequency and can be as small as a few centimeters and they are the most preferable resonator in high frequency applications(Ugurlu, 2011).

The DR functions as a resonator due to internal reflection of the electromagnetic waves at the high dielectric constant material or air boundary. The interface between the air and the high dielectric constant material can be explained as a hypothetical magnetic wall (covered by a perfect magnetic conductor (PMC)), on which the normal component of the electric field and the tangential component of the magnetic field will vanish at the boundary. Hence, most of the energy will be internally reflected. The reflection coefficient increases as the ratio of the dielectric constant of the DR to air increases.

As in a conventional metal cavity, an infinite number of modes can exist in a DR. The most commonly utilized mode in a cylindrical DR is called the $TE_{01\partial}$ mode. Some call it a "magnetic dipole mode" because of this mode appears as a magnetic dipole, instead of using the term $TE_{01\partial}$. This particular mode for a given diameter or length ratio has the lowest resonant frequency and therefore is designated the fundamental mode.

The most important properties for a DR in microwave circuit applications are dielectric constant, ε_r, quality factor, Q, and the temperature coefficient of the resonant frequency. The

dielectric constant, ε_r of the material determines the resonator's dimension for a given frequency. The unloaded quality factor, Q_u depends on both dielectric and environmental losses. The Q factor is a measure of the energy stored in the field inside the resonator as compared to the energy lost or dissipated per cycle.

The next issue is to couple the DR to the microwave circuit. The simplest way is to place it on top of a microstrip substrate. The lateral distance between the DR and the microstrip conductor determines the amount of coupling between the resonator and the microstrip line. The entire device is usually enclosed in a metal shielded box which is used to prevent radiation losses and to shield the circuit from stray external fields (Pan, 1991).

2.3.2.1 Electric and Magnetic Field Patterns

There are many field patterns or mode present in a DR depending on the shape of the DR. Cylindrical shape which operates at $TE_{01\partial}$ mode is the most popular shape of the DR that has been used recently in the industry until now (Hunter, 2001). There are four different basic modes which present in a dielectric waveguide; Transverse Electric (TE), Transverse Magnetic (TM), Electric Hybrid (EH) and Magnetic Hybrid (HE) modes.

2.3.2.2 Resonant Frequency

The resonant frequency of the DR is primarily determined by its dimensions and its surroundings. Therefore, the frequency fluctuates very little producing a more stable frequency source with a corresponding improvement in phase noise.Although the geometrical form of a DR is extremely simple, an exact solution of the Maxwell equations is considerably more difficult than for the hollow metallic cavity. For this reason, the exact resonant frequency of a certain amount of mode, such as $TE_{01\partial}$, can only be computed by rigorous numerical procedures. Currently, practical DRs cover a frequency range of 1 to 100 GHz. The lower frequency limit is