DESIGN OF LOW PHASE NOISE VERY HIGH FREQUENCY (VHF) LOW BAND VOLTAGE CONTROLLED OSCILLATOR (VCO) FOR TRANSCEIVER APPLICATION

by

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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

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LIST OF ABBREVIATIONS

2^{nd}	Second
ACP	Adjacent Channel Power
ACR	Adjacent Channel Rejection
ADS	Advanced Design System
AGC	Automatic Gain Control
AM	Amplitude Modulation
BER	Bit Error Rate
BJT	Bipolar Junction Transistor
BOM	Bill of Material
C	Capacitor
CRT	Cathode Ray Tube
DC	Direct Current
Deg	Degree
DegC	Degree Celcius
DTV	Digital Television
EDA	Electronic Design Automation
EIA	Electronic Industries Aliance
EM	Electromagnetic
ESR	Effective Series Resistance
Etc.	Etcetera
FCC	Federal Communications Commission
FET	Field Effect Transistor
Fig.	Figure

FM	Frequency Modulation
Freq	Frequency
FR-4	Flame Retardant – Type 4
GDSII	Graphic Design System II
HB	Harmonic Balance
HP	Hewlett Packett
IC	Integrated Circuit
ISF	Impulse Sensitivity Function
JFET	Junction Field Effect Transistor
KCL	Kirchoff's Current Law
Kv	VCO sensitivity
KVL	Kirchoff's Voltage Law
L	Inductor
LC	Inductor-Capacitor
LNA	Low Noise Amplifier
LO	Local Oscillator
LSSP	Large Signal Scattering Parameter
LTI	Linear Time Invariant
LTV	Linear Time Variant
Max	Maximum
MIM	Metal-Insulator-Metal
Min	Minimum
MoM	Method of Moments
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor

No.	Number
NTI	Nonlinear Time-Invariant
PA	Power Amplifier
PCB	Printed Circuit Board
PLL	Phase-Locked Loop
PM	Phase Modulation
PN	Positive Negative
Q	Quality
RC	Resistor-Capacitor
Ref.	Reference
RF	Radio Frequency
RFC	Radio Frequency Choke
RHP	Right-half-plane
rms	root mean square
RTN	Random Telegraph Noise
Rx	Receiver
SCV	Sub-clutter Visibility
SM	Surface Mount
SMA	Sub-Miniature version A
S/N	Signal-to-Noise
SOLT	Short, Open, Load, Thru
S-parameter	Scattering Parameter
SRF	Self Resonance Frequency
SSB	Single Sideband
Temp	Temperature

TIA	Telecommunications Industry Association
Tx	Transmitter
US	United States
VCO	Voltage Controlled Oscillator
VHF	Very High Frequency
vs.	versus

REKABENTUK OSILATOR KAWALAN VOLTAN (VCO) FREKUENSI SANGAT TINGGI (VHF) ALUR RENDAH YANG BERFASA HINGAR RENDAH UNTUK APLIKASI ALAT HUBUNG

ABSTRAK

Penyelidikan teknologi alat hubung bagi Frekuensi Sangat Tinggi (VHF) alur rendah kini adalah kurang kerana sistem komunikasi hari ini banyak menggunakan alur frekuensi yang lebih tinggi. Sesungguhnya, alur rendah masih diperlukan dalam bidang tertentu, seperti keselamatan awam disebabkan lingkungannya yang luas dan tepat. Tesis ini menyelidiki peningkatan fasa hingar bagi Osilator Kawalan Voltan (VCO) alur rendah. Varaktor saling balik, induktor linearasi, dan jaringan bias hingar rendah telah dikemukakan. Penempatan tepat bagi kapasitor bypass, chok, dan manik ferit, juga pemilihan betul bagi bahagian lain dalam rekabentuk ini telah dipelajari dan dimasukkan. Rekabentuk penghantar VCO termasuk sebuah osilator diikuti dengan sebuah penyangga dan sebuah bantalan penurun. Rekabentuk penerima VCO adalah serupa tetapi ditambahkan dengan sebuah penapis pada pengeluarnya demi merendahkan harmonik sebelum dituju ke pencampur. Ko-simulasi Momentum telah diperkenalkan dan didapati lebih tepat dibandingkan dengan kaedah simulasi biasa. Fasa hingar penerima VCO yang dinilaikan adalah lebih kurang -126 dBc/Hz pada jarak 12.5 kHz dan lebih kurang -136 dBc/Hz pada jarak 25 kHz. Fasa hingar penghantar VCO yang dinilaikan adalah lebih kurang -134 dBc/Hz pada jarak 12.5 kHz dan lebih kurang -141 dBc/Hz pada jarak 25 kHz. Kedua-dua VCO telah menepati perincian, iaitu kurang daripada -118 dBc/Hz pada jarak 12.5 kHz dan kurang daripada -133 dBc/Hz pada jarak 25 kHz. VCO ini bersesuaian dalam aplikasi rumahtangga dan keselamatan awam.

DESIGN OF LOW PHASE NOISE VERY HIGH FREQUENCY (VHF) LOW BAND VOLTAGE CONTROLLED OSCILLATOR (VCO) FOR TRANSCEIVER APPLICATION

ABSTRACT

There is little research in transceiver technology for Very High Frequency (VHF) low band nowadays because many communication systems today use higher frequency bands. However, low band is still required in specific fields, such as public safety due to its extensive and precise coverage. This thesis researches improvement in the phase noise of the low band Voltage Controlled Oscillator (VCO). As such, the back-to-back varactor, the linearizing inductor, and the low noise biasing network are introduced. Sensible placement of the bypass capacitor, choke, and ferrite bead as well as proper selection of parts have been studied and implemented. The transmitter VCO design comprises of an oscillator cascaded with a buffer and a pad attenuator to improve the output matching. The receiver VCO has a similar design but added with a filter at the output to suppress its harmonics before injected into the mixer. Momentum co-simulation is introduced and proven as a closer correlated simulation method compared to conventional simulations. The receiver VCO measured phase noise is around -126 dBc/Hz at 12.5 kHz offset and around -136 dBc/Hz at 25 kHz offset. The transmitter VCO measured phase noise is around -134 dBc/Hz at 12.5 kHz offset and around -141 dBc/Hz at 25 kHz offset. Both VCOs phase noise comply with the specifications of < -118 dBc/Hz at 12.5 kHz offset and < -133 dBc/Hz at 25 kHz offset. Such VCO is suitable in both domestic and public safety applications.

CHAPTER 1

INTRODUCTION

1.1 Background

The Voltage Controlled Oscillator (VCO) is often referred as the center operating engine of all transceiver systems as it is shared by both the receiver (Rx), as Local Oscillator (LO), and by the transmitter (Tx), as Radio Frequency (RF) source, as shown in Fig. 1.1. Therefore, very stringent requirements are placed on the spectral purity of VCOs, making its design a critical sub-circuit to the overall transceiver system performance. Being the block model within the Phase Locked Loop (PLL) which generates oscillation frequency, as depicted in Fig. 1.2, the design of VCO is a major challenge and has thus extensively been researched over the past decades, as evidenced by the large number of publications (Craninckx and Steyaert, 1995a；Craninckx and Steyaert, 1995b; Craninckx and Steyaert, 1997；Samori *et al.*, 1998a；Samori and Laicaita, 1998b；Zannoth *et al.*, 1998；Margarit *et al.*, 1999；Hegazi, Sjoland and Abidi, 2001；Zanchi *et al.*, 2001；Tiebout, 2001；Fong *et al.*, 2003；Perticaroli, Palma and Carbone, 2011).

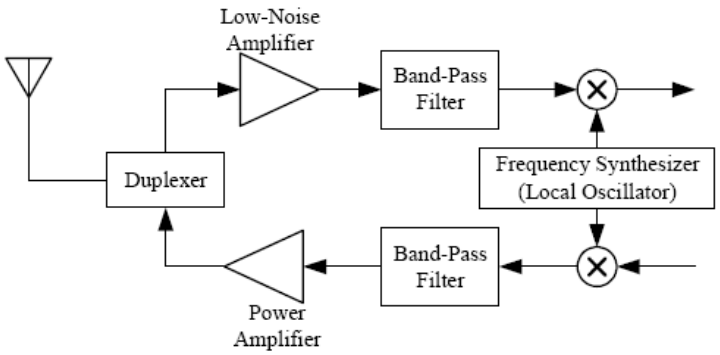

Figure 1.1: VCO used as LO in Rx and RF source in Tx (Zhu, 2005)

The electromagnetic (EM) spectrum is the total range of frequencies of EM radiation. It extends from the audio waves (15 Hz) to the light waves (900000 GHz). The range of spectrum frequencies used for broadcast communications is called the "broadcast frequency spectrum". This spectrum is split into bands, in which the Very High Frequency (VHF) low band, or also known as 'low band', ranges from 25 MHz to 50 MHz.

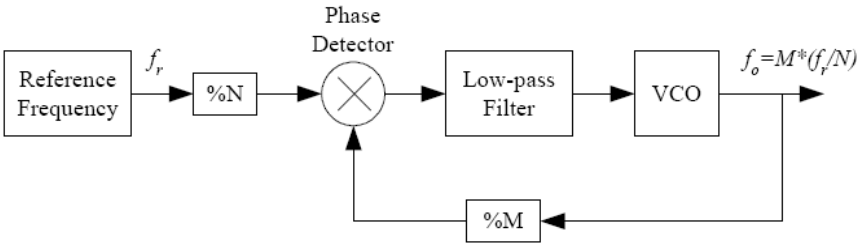

Figure 1.2: Block diagram of PLL (Zhu, 2005)

1.2 Applications of VHF Low Band

In the United States (US), the Federal Communications Commission (FCC) controls RF assignments for non-governmental use. The FCC has divided up the available frequencies into different groups and assigned each group to a specific use. The VHF low band is among the 5 primary bands which the FCC has reserved for exclusive use by the public safety agencies. For instance, many fire agencies in New York, New Hampshire, Pennsylvania, and Maine rely on low band operations due to the excellent coverage and range achievable in this band (Low Band, 2005).

Under the FCC rules, any organization and individual that provides some type of public safety mission can be assigned frequencies from this Public Safety Radio Pool. Such qualifying organization and individual include: police, fire, emergency medical services, veterinarians, animal hospitals, disaster relief

organizations, blood banks, heart and lung centers, school bus services, botanical gardens, departments of agricultures and environmental resources, beach patrols, retirement facilities and home for the aged, mental health institutions, rehabilitation centers, electric power cooperatives, state reservations and tribal councils, Universities, water control boards, as well as emergency repair services for public communications facilities (Veeneman, 2002).

1.3 Advantages of VHF Low Band

While today's communication trend seems to be migrating towards the higher spectrum from 800/900 MHz to a few GHz, it remains a fact that the VHF low band is still popularly used in the community, even still, the popularity continues to grow rapidly. Such popularity in usage relies much on the many advantages available in low band, which is yet irreplaceable by any of the higher band (Low Band, 2005).

1.3.1 Precise Transmission

The atmosphere that surrounds the earth acts to attenuate and refract radio signals. The magnitude of attenuation and refraction depends on the frequency of the signal. The lower is the frequency, the less the attenuation, or loss of signal. VHF low band has such a precise area of broadcast because the ionosphere does not usually reflect the signal far beyond its immediate surroundings. Communication is thus optimal for reaching a target in close vicinity without interfering with broadcasts. Unlike the higher frequencies, low band signal is not obscured by buildings or tarnished by naturalistic sounds in the atmosphere, or by conflicting signals from nearby equipments (Mateo, 1999).

1.3.2 Extensive Coverage

One major advantage is the extensive effect it has on range. Each agency has a particular geographic area, in which they need solid radio coverage. VHF low band signals travel farther than higher frequencies because low band frequencies tend to follow the curvature of the earth. Rural businesses, farming operations, towing companies, and other uses that need service over a wide area will find that low band is an excellent choice for dependable radio communications. This is because rural areas usually have small buildings and a large geographic area to cover (Frequency and Spectrum, 2008).

1.3.3 Ample Spectrum Availability

Channel loading is a term used to describe the number of users assigned to the same frequency. Channel loading is so heavy in some areas that additional users are no longer allowed on particular channels. As many applications today have migrated to 800/900 MHz operations, there is ample spectrum available at VHF low band, greatly simplifying the frequency coordination effort and shortening the overall licensing procedure. Furthermore, the FCC declared that all television programming have to be switched to digital technology in 2009, this enables system operators to consolidate the information that was being broadcast for television and free up low band frequency (Frequency and Spectrum, 2008).

1.3.4 Exemption from Narrow Band Requirements

In an effort to improve spectral efficiency, the FCC has mandated that all new licenses granted after Jan 1, 2011 must be narrowband, for public safety agencies and business users. All of these systems must be converted or relicensed to narrowband

operation by Jan 1, 2013. However, this rule only applies for operation from 150 MHz to 512 MHz. VHF low band systems are exempted from such requirement, meaning that low band equipment put into service today will not become obsolete in 2013. So, low band makes sense for those agencies and businesses that need new systems or expansions of operations (Veeneman, 2002).

1.4 Problem Statement

As stated in Section 1.3, current communication is advancing towards the higher frequency bands, as a result, most research effort today is conducted on developing a low noise VCO in the GHz range (Lee *et al.*, 2011； Huang and Mao, 2011； Ham and Hajimiri, 2000； Yu, Meng and Lu, 2002； Li, 2003； Badillo and Kiaei, 2003； Eo, Kim and Oh, 2003； Hamano, Kawakam and Takagi, 2003). Research conducted on VHF low band remains little due to its limited application which is required only in specific field, such as public safety. Nonetheless, phase noise research in this band is critical because noise tends to occur in low frequencies. This is especially true for radiant energy, which can interfere with, and even blockade low band signals. According to the FCC, the most common sources of low band noise are industrial equipments, power lines, and home appliances, such as microwaves, vacuum cleaners, and dimmers (Frequency and Spectrum, 2008).

Phase noise is one of the major limiting factors affecting the VCO performance. Any system that requires a VCO for reference frequency generation can suffer from it. Phase noise directly affects short-term frequency stability, Bit-Error-Rate (BER), Signal to Noise and Distortion (SINAD), Adjacent Channel Rejection (ACR) for Rx, and Adjacent Channel Power (ACP) for Tx. Phase and fluctuation has therefore long been the subject of theoretical and experimental

investigation (Lee *et al.*, 2011； Huang and Mao, 2011； Baghdady, Lincoln and Nelin, 1965； Cutler and Searle, 1966； Leeson, 1966； Rutman, 1978； Abidi and Meyer, 1983； Weigandt, Kim and Gray, 1994； McNeil, 1994； Craninckx and Steyaert, 1995a； Craninckx and Steyaert, 1995b； Razavi, 1996). The ultimate goal of designing a perfect VCO is to produce a signal whose spectrum would consist of a single line of infinitesimal width. In reality, no perfect VCO has yet been discovered and virtually impossible so it seems, for all oscillators universally exhibit line width broadening of varying degree in their output power spectra. Such line width broadening produces phase noise, and is caused by noise inherent in the oscillator.

The accuracy in signal transmission is extremely crucial in ensuring instant and valid information is properly communicated. Improvement in phase noise results in substantial BER improvement of all communications. For all Doppler radar designs, improving the Sub-Clutter Visibility (SCV) is the bottom line, as this allows the radar to see small moving objects in the screen. Improving the phase noise increases the cancelled Signal-to-Noise (S/N) ratio, thereby improving the SCV. Low phase noise is also a key element in a missile illuminator as a signal injection with poor phase noise can result in the loss of the intended target in aim.

1.5 Research Objectives

The objectives of this research are:

- To design and propose a VCO design with low phase noise, so that when incorporated into a transceiver system, the ACR, ACP, and Hum & Noise of the system would comply with the Telecommunications Industry Association / Electronic Industries Alliance (TIA/EIA-603-B) standard (TIA, 2002).

- To study a better simulation technique using the Advanced Design System (ADS) Momentum co-simulation, that is more precise and co-related.
- To implement and characterize the proposed VCO design with main concentration on the evaluation of the phase noise parameter.

1.6 Requirements

The requirements for the researched VCO are

- To design a low phase noise VCO which is able to meet the specifications listed in Table 1.1.

Table 1.1: Phase noise specifications of VCO

Parameter	**Freq Offset (kHz)**	**At Room Temperature**
		25 deg C
Phase Noise (dBc/Hz)	12.5	< -118
	25	< -130

Phase noise proportionally affects the ACR, ACP, and Hum & Noise parameters of a transceiver system. FCC adopts the TIA/EIA-603-B standard, whereby Table 1.2 lists an excerpt of the TIA/EIA-603-B specifications for the affected parameters. ACR is defined as the ratio of the level of an unwanted input signal that causes the SINAD produced by a wanted signal 3 dB in excess of the reference sensitivity to be reduced to the standard SINAD, to reference sensitivity (TIA, 2002). The Rx VCO phase noise specification is approximated from the ACR specification, as

$$Phase\_Noise = -ACR - SINAD - Attn_{IF\_Filter}, \quad (1.1)$$

where *Phase_Noise* is the phase noise specification, *ACR* is the ACR specification as listed in Table 1.2, *SINAD* is 15 dB, which is the sum of the 12 dB reference with the 3 dB excess margins, and $Attn_{IF\_Filter}$ is the attenuation of the Intermediate Frequency (IF) filter, which is about 54 dB for the 270 kHz bandwidth ceramic IF filter of a low band Rx system. Similarly, ACP is defined as the ratio of the total output power of a Tx system under defined conditions and modulation, to that part of the output power that falls within a specified pass band centered on the nominal frequency of either of the adjacent channel or channels further offset above or below the assigned carrier frequency. The Tx VCO phase noise specification is approximated from the ACP specification, as

$$Phase\_Noise = ACP - Tx\_Amp - 10log\left(f_{offset}\right), \tag{1.2}$$

where *ACP* specification as listed in Table 1.2, *Tx_Amp* is the gain in the low band Tx system, which is around 16 dB, and f_{offset} is the offset from the carrier frequency.

Table 1.2: ACR, ACP, Hum & Noise specifications (TIA, 2002)

Parameter	Offset (kHz)	Specifications (25 degC)
Rx Adjacent Channel Rejection (ACR)	12.5	> 50 dB
	25	> 60 dB
Tx Adjacent Channel Power (ACP)	12.5	< -60 dB
	25	< -70 dB
Hum & Noise	12.5	< -34 dB
	25	< -40 dB

- To design a Rx VCO that is able to meet the requirements in Table 1.3.

Table 1.3: Design specifications of Rx VCO.

	Specifications
LO Freq Range (MHz)	46.7 – 52.7
Lower End Guard Band (MHz)	> 3
Higher End Guard Band (MHz)	> 3
Oscillator Output Power (dBm)	> 14
Oscillator 2nd Harmonics Output Attenuation (dBc)	> 44
Feedback Output Power (dBm)	> 0
Phase Noise at 12.5kHz (dBc/Hz)	< -118
Phase Noise at 25kHz (dBc/Hz)	< -130
Hum & Noise at 12.5kHz (dB)	< -34
Hum & Noise at 25kHz (dB)	< -40

The requirements are developed from the Rx system of a public safety transceiver, such that the Rx VCO is able to integrate into the system as a LO that supports a high side injection for a bandwidth of 36 MHz to 42 MHz, and to produce a 10.7 MHz IF signal when down converted through a mixer.

- To design a Tx VCO that is able to meet the requirements in Table 1.4.

Table 1.4: Design specifications of the Tx VCO.

	Specifications
Freq Range (MHz)	36 – 42
Lower End Guard Band (MHz)	> 3
Higher End Guard Band (MHz)	> 3
Oscillator Output Power (dBm)	> 3
Oscillator 2nd Harmonics Output Attenuation (dBc)	> 15
Feedback Output Power (dBm)	> 0
Phase Noise at 12.5kHz (dBc/Hz)	< -118
Phase Noise at 25kHz (dBc/Hz)	< -130
Hum & Noise at 12.5kHz (dB)	< -34
Hum & Noise at 25kHz (dB)	< -40

The requirements are developed from the Tx system of a public safety transceiver, such that the Tx VCO is able to integrate into the system as a modulating source in which the signal is injected into the power amplifier (PA).

1.7 Research Scopes and Limitations

The research scopes and limitations are outlined as follows:

- To design the VCO oscillator, through theoretical calculation.
- To design the VCO oscillator, with ADS Scattering Parameter (S-parameter) and Harmonic Balance (HB) simulation, using different component models: lump component model, RF component model, and Momentum co-simulation model.
- To design the VCO buffer and pad attenuator, with ADS Large Signal S-parameter (LSSP) simulation, using different component models: RF component model and Momentum co-simulation model.
- To implement and evaluate the VCO buffer and pad attenuator. The co-relativity of the simulated results to the actual measured results is analyzed.
- To design the Rx pre-mixer low pass filter, through theoretical calculation.
- To design the Rx pre-mixer low pass filter, with ADS LSSP simulation, using different component models: lump component model, RF component model, and Momentum co-simulation model.
- To implement and evaluate Rx pre-mixer low pass filter. The co-relativity of the simulated results to the actual measured results is analyzed.

- To design and implement the Rx VCO. The co-relativity of the simulated results to the actual measured results is analyzed.
- To design and implement the Tx VCO. The co-relativity of the simulated results to the actual measured results is analyzed.
- The research only focuses on the phase noise improvement of the VCO.
- The bandwidth of the VCO is limited to 6 MHz according to the operating bandwidth in the low band range required for a public safety transceiver unit.
- Other limitations encountered in this research include the Printed Circuit Board (PCB) fabrication technology, the components placed, as well as the equipments applied for evaluation.

1.8 Research Contribution

Using the low-phase-noise design technique, which is detailed in Chapter 3, both the Rx and Tx VCOs designed in this research are able to generate RF signals of remarkably low phase noise level, in which, when incorporated into a transceiver system, would be able to comply with the FCC specifications. Thereby, the major contribution of this research is to support two-way communication systems and base stations, used in the public safety pool in the US, as well as other countries adopting such specifications. Despite this, other contributions of this research are as follows:

- By disabling the Tx VCO, the design could operate as a single Rx VCO, and vice versa. Single way communications applying only either VCO include broadcast systems, radar systems, missile illuminators etc.
- Unlike S-parameter simulation, co-relativity for HB simulation has long been an issue. Noises in VCO as well as parts parasitic are highly

unpredictable. This research provides an improved simulation method in predicting the performance of a VCO design. This, in turn, contributes to cycle time and cost reduction for the design.

- The VCO buffer and attenuator designs could be used as reference for oscillator as well as RF amplifier designs of other frequency bands.

1.9 Thesis Organization

This thesis is organized into six chapters to cover the entire research work and the theory related to the design. In chapter 2, literature review is detailed. This chapter documents the theory of noise in VCO, the development of various phase noise models, as well as methods in phase noise reduction.

Chapter 3 explains the methodology of the research. This includes the derivation of the mathematical model for the common gate Field Effect Transistor (FET) Colpitts oscillator, the overview of ADS simulation, and selection of components. The test methodology in evaluating the prototype is also detailed.

Chapter 4 describes the design and simulation of the VCO, which covers the oscillator circuitry, the buffer and pad attenuator circuitries, as well as the Rx pre-mixer low pass filter circuitry.

Chapter 5 reports the measured results of the hardware and further compares and discusses the data with the simulated results. The phase noise performance of the design is further analyzed and detailed in this chapter.

Finally, in chapter 6, the overall performance and findings of the research is concluded. Future work is recommended for further improvement of the design.

CHAPTER 2

LITERATURE SURVEY

2.0 Introduction

Resonance signal generated by oscillators suffer from fluctuations in both amplitude and phase. Such fluctuations are caused by internal noise generated by the components as well as external interference. Fluctuation in amplitude tends to be suppressed by the nonlinear characteristics of the oscillator; however, phase fluctuation is accumulated over a period of time. Phase fluctuation, also referred to as phase noise, has hence, been the key interest to researchers. Several models have been developed to formulate a more accurate phase noise performance and shall be detailed in this chapter. The characteristics of phase noise as well as other noises affecting the oscillator, with methods in noise reduction are also well elaborated.

2.1 Noise

The major source of noise in an oscillator is the active device, usually the transistor. The noise sources in any oscillator circuit ultimately combine to form amplitude modulation (AM) noise and phase modulation (PM) noise. The AM noise component is usually ignored because the gain limiting effects of the circuit control the output amplitude, allowing little variation due to noise. The PM noise is of great concern because its magnitude is typically greater than the AM noise contribution and directly affects the frequency stability of the oscillator (Siweris and Schiek, 1985) and related noise sidebands.

The designer has limited control over the noise sources in a transistor. For example, the bulk resistance of a transistor, upon which thermal noise depends on, is

an unchangeable, intrinsic property of the device. However, using knowledge on how noise affects oscillator waveforms, the designer is able to substantially improve phase-noise performance by the selection of bias point and signal level. The main mechanisms for noise in a semiconductor device include both thermal fluctuations in minority carrier flow as well as bulk and depletion area generation-combination events (Buckingham, 1983). The effects of these processes are categorized as thermal noise, shot noise, partition noise, burst noise, and flicker noise.

2.1.1 Thermal Noise

At any temperature above absolute zero, thermal agitation causes electrons in any conductor or semiconductor to be moving at random. At any one instant of time, the electrons may be concentrated in some areas more than others. These concentrations produce thermal noise. Thermal noise is generated by the random thermal motion of the electrons and is unaffected by Direct Current (DC), since typical electron drift velocities in a conductor are much less than thermal electron velocities. In a resistor R, thermal noise can be represented by a series voltage with the spectral density of

$$\frac{\overline{V^2}}{\Delta f} = 4kTR\,, \tag{2.1}$$

where k is the Boltzmann's constant, T is the absolute temperature in ^{0}K, and Δf is the bandwidth (Manasse, Ekiss and Gray, 1967). Thermal noise is present in any linear passive device. In bipolar devices, the parasitic resistors can generate the thermal noise. For Metal Oxide Semiconductor Field Effect Transistors (MOSFETs),

the resistance of the channel also generates thermal noise with the spectral density given by

$$\frac{\overline{V^2}}{\Delta f} = \frac{2}{3} \cdot \frac{4kT}{g_m}, \tag{2.2}$$

where g_m is the conductance of the channel (Razavi, 2001).

2.1.2 Shot Noise

Shot noise is associated with a DC and is presented majorly in diodes and transistors. It is the fluctuation of the DC and is usually modeled as a noise current source with the spectral density of

$$\frac{\overline{I^2}}{\Delta f} = 2qI, \tag{2.3}$$

where q is the charge of an electron, I is the DC, and Δf is the bandwidth (Spangenburg, 1957).

In transistors, each current path will have its own associated shot noise. For example, a Bipolar Junction Transistor (BJT) has shot noise for each of the emitter, base, and collector currents (Thornton, 1966). An additional source of noise resulting from shot noise is called partition noise. Partition noise occurs at current junctions and is caused by each electron in making a decision to go one way or another. A statistical fluctuation in the collector and base currents equating to noise occurs (Krauss, Bostian and Raab, 1980). In a BJT, the majority of electrons flow from the emitter into the collector. A fraction of the emitter current must also flow to the base.

The splitting of the emitter current into the base and collector current components provides this basic partition noise contribution.

2.1.3 Flicker Noise

Flicker noise is found in all active devices as well as in some discrete passive elements. It is not a broadband phenomenon like thermal and shot noise; in fact, it is mainly caused by traps associated with contamination and crystal defects. The flicker noise is also called as $1/f$ noise because it displays a spectral density of the form

$$\frac{\overline{I^2}}{\Delta f} = K_1 \frac{I^a}{f^b}, \tag{2.4}$$

where I is the DC, K_1, a, and b, are constants. The nonlinear performance of oscillators transforms this low frequency $1/f$ by up-conversions into the near-sidebands of the fundamental oscillation signal. The spectrum of $1/f$ noise varies inversely with frequency and thus is only noticeable at low frequencies and near sidebands. The low frequency performance is shown in Fig. 2.1. The upper frequency at which the $1/f$ noise sinks into the noise floor caused by thermal and shot noise is called $1/f$ corner frequency. This corner frequency is typically between 100 Hz to 1 MHz and the low frequency limit of $1/f$ noise has been followed to 10^{-7} Hz.

A contributor to $1/f$ in a device is called Random Telegraph Noise (RTN), also known as burst noise. RTN is the observed phenomenon whereby device current switches between several discrete values at random times. RTN is closely linked with $1/f$ noise in that it has spectral components which contribute to low frequency

noise (Kogan, 1966). A plot showing the RTN noise characteristics is shown in Fig. 2.2.

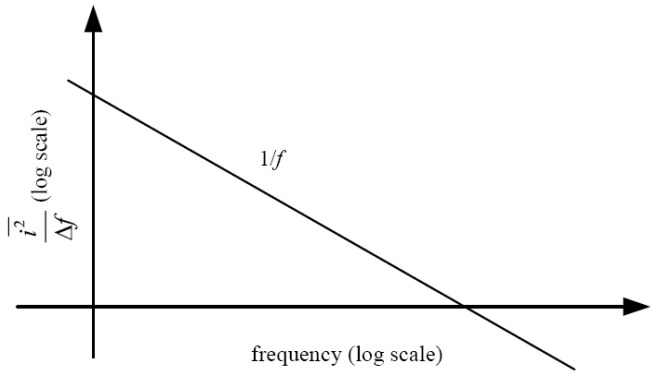

Figure 2.1: Spectral density of flicker noise versus (vs.) frequency

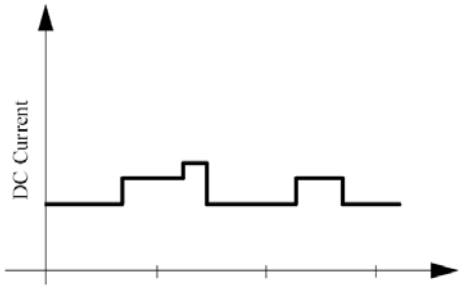

Figure 2.2: General RTN characteristic

2.2 Phase Noise

The signal shown in Fig. 2.3 is an ideal oscillating signal produced by an ideal oscillator, in which the signal as a function of time is

$$V_{out}(t) = V_o \cos[\omega_o t], \tag{2.5}$$

where V_o is the nominal amplitude and ω_o is the nominal frequency at time t. In frequency domain, this signal is presented by a single spectral line. However, in

practical oscillation system, the instantaneous frequency and magnitude of oscillation are not constant. These will fluctuate as a function of time as

$$V_{out}(t) = [V_o + E(t)]cos[\omega_o t + \varphi_o], \tag{2.6}$$

where $E(t)$ is the random amplitude fluctuations and ϕ_o is the random phase fluctuations. In frequency domain, the signal is no longer a discrete spectral line; rather, a spread of spectral lines both above and below the nominal signal frequency, as shown in Fig. 2.4, in the form of modulation sidebands due to the random fluctuations in phase and amplitude.

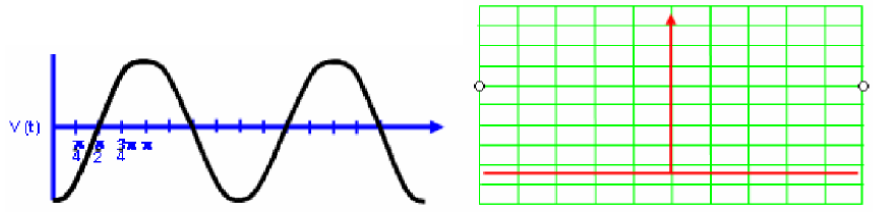

Figure 2.3: An ideal oscillating signal in time domain and frequency domain

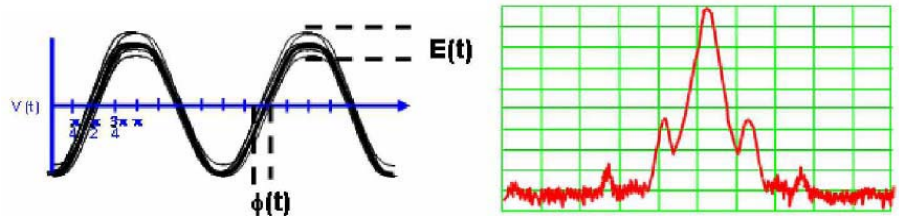

Figure 2.4: A practical oscillating signal in time domain and frequency domain

These modulation sidebands are generally referred to as phase noise sidebands (Xie *et al.*, 1998) and are usually characterized in terms of the single sideband (SSB) noise spectral density. It is defined as the SSB power due to phase fluctuations

referenced to the carrier frequency power in 1 Hz bandwidth at a specific offset frequency from the carrier divided by the signal's total power, with unit dBc/Hz:

$$L\{\Delta\omega\} = 10 \cdot log\left[\frac{P_{sideband}(\omega_o + \Delta\omega, \quad 1\,Hz)}{P_{carrier}}\right], \tag{2.7}$$

where $P_{sideband}(\omega_o + \Delta\omega, \quad 1\,Hz)$ represents the SSB power at a frequency offset of $\Delta\omega$ from the carrier with a measurement bandwidth of 1 Hz as visualized in Fig. 2.5, and $P_{carrier}$ is the power of the carrier signal.

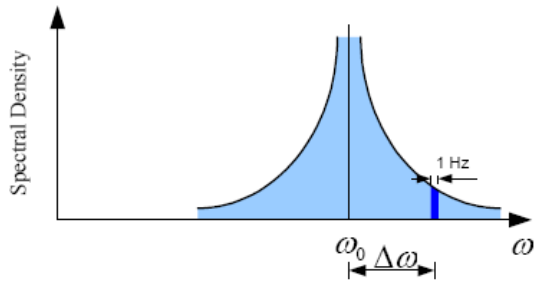

Figure 2.5: Phase noise referenced to the carrier frequency power in 1 Hz bandwidth

The advantage of this parameter is its ease of measurement. Its disadvantage is that it shows the sum of both amplitude and phase variations. However, it is important to understand the amplitude and phase noise separately because they behave differently in the circuitry. For instance, the effect of amplitude noise is reduced by the intrinsic amplitude limiting mechanism in oscillators and can be practically eliminated by the application of a limiter to the output signal, while the phase noise cannot be reduced in the same manner.

The destructive effect of phase noise can be significantly seen in the front-end of a super-heterodyne transceiver. Recapitulating the transceiver block diagram

in Fig. 1.1, the LO that provides the carrier signal for both mixers is embedded in a frequency synthesizer. If the LO is noisy, both the down-converted and up-converted signals are corrupted. As shown in Fig. 2.6, a large interferer in an adjacent channel may accompany the wanted signal. When two signals are mixed with the LO output exhibiting phase noise, the down-converted band consists of two overlapping spectra, with the wanted signal suffering from significant noise due to the tail of the interferer signal. This effect is referred to as "reciprocal mixing" (Krafcsik and Dawson, 1986). Therefore the output spectrum of a LO has to be extremely sharp. Such stringent requirements impose a great challenge in low-noise oscillator design.

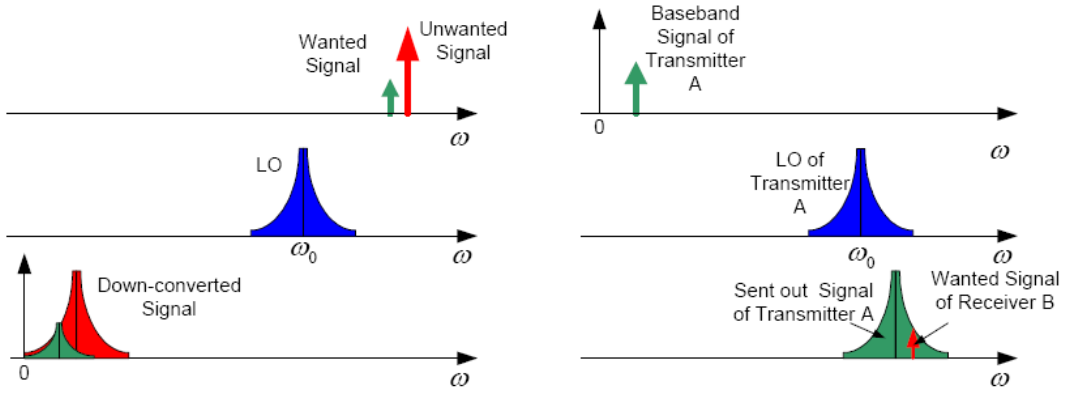

Figure 2.6: Effect of phase noise onto the wanted signal

Over the years, several phase noise models have been studied and developed to predict the phase noise performance of the oscillator and, thus, in pursuance of further improvement. Some of the commonly used models are detailed in the following sub-sections.

2.2.1 Leeson's Model

D. B. Leeson proposed an empirical phase noise model to describe the phase noise depicted in Fig. 2.7. Noise prediction using Leeson's model (1966) is based on

the time-invariant properties of the oscillator such as the resonator Quality (Q), feedback gain, output power, and noise figure. According to this model, the phase noise generated by an oscillator can be expressed as:

$$L\{\Delta\omega\} = 10 \cdot \log\left\{\frac{2FkT}{P_S} \cdot \left[1 + \left(\frac{\omega_o}{2Q_L\Delta\omega}\right)^2\right] \cdot \left[1 + \frac{\Delta\omega_{1/f^3}}{|\Delta\omega|}\right]\right\}, \tag{2.8}$$

where $L\{\Delta\omega\}$ is SSB noise spectra density in units of dBc/Hz. The symbol k is the Boltzmann's constant, T is the absolute temperature in ^{0}K, P_S is the carrier power, ω_o is the oscillation frequency, and $\Delta\omega$ is the offset frequency from ω_o. Q_L is the loaded Q of the oscillator resonator, F is the noise figure of the oscillator, and $\Delta\omega_{1/f^3}$ is the corner frequency between $1/f^2$ and $1/f^3$ region.

As shown in Fig. 2.7, the general phase noise output spectrum of an oscillator consists of 3 distinct sections allocated in the sideband. Immediately surrounding the carrier frequency there exists a region of noise which decay as $1/f^3$. At some frequency offset called the $1/f^3$ – $1/f^2$ corner frequency, the noise spectrum changes to a $1/f^2$ dependence. The $1/f^2$ region continues on to the phase noise floor of the circuit. The noise floor of the circuit is a result of thermal and shot noise sources. The noise floor exists across all frequencies, even in the $1/f^2$ and $1/f^3$ region. The relative power associated with each section depends on each section's corner frequency and the noise floor level. The $1/f^2$ region is unavoidable as it is a result of the characteristics of the resonator. Any Inductor-Capacitor (LC) resonator will have a voltage dependence which varies as $1/f$ from the center frequency. Since power is proportional to voltage squared, the resulting power spectrum is

therefore $1/f^2$. The $1/f^3$ region comes from up-converted $1/f$ noise of the device. The $1/f^3$ dependency appears when $1/f$ is multiplied by the $1/f^2$ characteristic of the resonator.

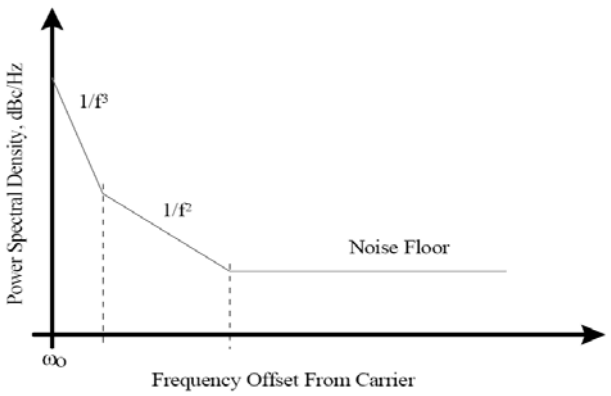

Figure 2.7: SSB oscillator phase noise output spectrum

In Leeson's model, $\Delta\omega_{1/f^3}$ is equal to the $1/f$ noise corner frequency of the device. In practice, however, $\Delta\omega_{1/f^3}$ is rarely equal to the $1/f$ noise corner frequency of the device. An existing problem is that the noise figure of an oscillator is extremely difficult to predict (Robins, 1982). The factor F remains a co-relation factor which can only be determined by measurement of the phase noise spectrum of the oscillator. Since F and $\Delta\omega_{1/f^3}$ must almost always be measured from the oscillator spectrum, the predictive power of Equation 2.8 is quite limited. From Equation 2.8, it can be seen that the corner frequency at which the $1/f^2$ sinks into the noise floor is exactly equal to the resonator half bandwidth, $\omega_o/2Q$. This also is not completely justifiable.

In short, according to Leeson's model, the only way to improve $L\{\Delta\omega\}$ is to increase the output power or increase the loaded Q of the resonator. The oscillator

must be designed in such a way that the transistor does not saturate. Saturation lowers the Q of the entire oscillator circuit, thus increasing phase noise and harmonics level (Rhea, 1990).

2.2.2 Linear Time Invariant (LTI) Model

It is convenient to model an LC cross-coupled oscillator as a one-port negative resistance model as shown in Fig. 2.8. In this model, the transconductance of the active circuit, G_m, must compensate for the loss caused by the parasitic resistance, R_p, in the tank, which is simply modeled as a parallel resistor.

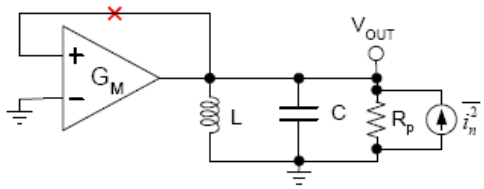

Figure 2.8: One-port negative resistance oscillator with noise current in the tank

The thermal noise it generates, is modeled as a noise current, $\overline{i_n^2}$, parallel with the tank. The thermal noise introduces the phase noise at the output of the oscillator. The transfer function from the noise current to the output voltage in closed-loop operations is derived as

$$T^2_{noise,\,R_p}(s) = \frac{\overline{V_n^2}}{\overline{i_n^2}} = \left[\frac{sL}{1 - sL\left(G_m - 1/R_p\right) + s^2LC}\right]^2, \qquad (2.9)$$

where $T^2_{noise,R_p}(s)$ is the transfer function of the phase noise of the oscillator and $\overline{V_n^2}$ is the output voltage. With $G_m = 1/R_p$, it can be shown that the transfer function at small offset frequency, $\Delta\omega$, is approximated as (Craninckx and Steyaert, 1995).

$$T^2_{noise,R_p}(\Delta\omega) = \left[\frac{1}{2j}\cdot\sqrt{\frac{L}{C}}\cdot\frac{\omega_o}{\Delta\omega}\right]^2, \tag{2.10}$$

where T^2_{noise,R_p} is the equivalent impedance of the tank at the frequency $\omega_o \pm \Delta\omega$.

Accordingly, the one-side spectral density of the output noise voltage is

$$\overline{V^2_{on,g_p}(\Delta\omega)} = 4kTg_p\cdot\left(\frac{\omega_o}{2\Delta\omega}\right)\cdot\left(\omega_o^2L^2\right), \tag{2.11}$$

where $\overline{V^2_{on,g_p}(\Delta\omega)}$ is the output noise voltage at offset frequency $\Delta\omega$ and g_p is the conductance, that is $g_p = 1/R_p$. The noise voltage described here actually includes both the amplitude noise (AM noise) and the phase noise (PM noise). If the oscillator employs an Automatic Gain Control (AGC) circuit, the AM noise will be removed for frequency offset less than the AGC bandwidth. In addition, the nonlinearity of the oscillator determines oscillation amplitude and it can be viewed as an internal AGC mechanism in oscillators. Therefore, even when there is AM noise, it will decay away with time and thus has little effect on output phase noise. Neglecting the AM noise results in a 0.5 factor multiplied to Equation 2.11. So, the spectral density of the noise voltage is