<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>1.8GHz balanced low noise amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Yip, Sui Chun (葉瑞珍)</td>
</tr>
<tr>
<td><strong>Citation</strong></td>
<td>Yip, S. C. (2012). 1.8GHz balanced low noise amplifier (Outstanding Academic Papers by Students (OAPS)). Retrieved from City University of Hong Kong, CityU Institutional Repository.</td>
</tr>
<tr>
<td><strong>Issue Date</strong></td>
<td>2012</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/2031/6736">http://hdl.handle.net/2031/6736</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>This work is protected by copyright. Reproduction or distribution of the work in any format is prohibited without written permission of the copyright owner. Access is unrestricted.</td>
</tr>
</tbody>
</table>
Department of Electronic Engineering

FINAL YEAR PROJECT REPORT

Project Title

1.8GHz balanced low noise amplifier

Student Name: Yip Sui Chun
Student ID: 
Supervisor: Prof. Xue, Quan
Assessor: Prof. Chan, C.H.

Bachelor of Engineering (Honours) in Electronic and Communication Engineering (Full-time)
Student Final Year Project Declaration

I have read the student handbook and I understand the meaning of academic dishonesty, in particular plagiarism and collusion. I declare that the work submitted for the final year project does not involve academic dishonesty. I give permission for my final year project work to be electronically scanned and if found to involve academic dishonesty, I am aware of the consequences as stated in the Student Handbook.

Project Title: 1.8GHz balanced low noise amplifier

Student Name: Yip Sui Chun

Student ID:

Signature: ____________________________ Date: 20.04.2012
Contents

Contents.................................................................................................................................................i
List of Figures...........................................................................................................................................ii
List of Tables...............................................................................................................................................iv
Acknowledgement ......................................................................................................................................v
Abstract ...................................................................................................................................................vi
Chapter 1 - Introduction .........................................................................................................................1
Chapter 2 - Theory ..................................................................................................................................3
  2.1 Microwave Amplifier .........................................................................................................................3
  2.1.1 Current-voltage characteristics of a BJT transistor .................................................................4
  2.1.2 Biasing Networks for BJT ..........................................................................................................6
  2.1.3 Specifications of an amplifier ......................................................................................................8
     2.1.3.1 Gain .......................................................................................................................................8
     2.1.3.2 Linearity .............................................................................................................................10
     2.1.3.3 Power added efficiency ......................................................................................................12
     2.1.3.4 Noise ..................................................................................................................................13
  2.2 Low noise amplifier ........................................................................................................................14
     2.2.1 Path loss in communication link ............................................................................................16
     2.2.2 Definition of noise factor ........................................................................................................17
     2.2.3 Noise in amplifier .....................................................................................................................18
     2.2.4 Noise in transistor ....................................................................................................................19
  2.3 Balanced amplifier ..........................................................................................................................22
     2.3.1 Balanced amplifier ...................................................................................................................22
     2.3.2 Branch-line coupler ...............................................................................................................24
Chapter 3 – Methodology .......................................................................................................................28
  3.1 Single-ended low noise amplifier .................................................................................................29
  3.2 Conventional balanced low noise amplifier ..................................................................................31
  3.3 Proposed balanced low noise amplifier .........................................................................................34
Chapter 4 – Simulated and measured Results .......................................................................................42
  4.1 Single-ended low noise amplifier .................................................................................................42
  4.2 Conventional balanced low noise amplifier ..................................................................................44
  4.3 Proposed balanced low noise amplifier .........................................................................................47
Chapter 5 Discussion .............................................................................................................................50
  5.1 Analysis of results ...........................................................................................................................50
     5.1.1 Single-ended low noise amplifier .........................................................................................50
     5.1.2 Conventional balanced low noise amplifier ...........................................................................50
     5.1.3 Proposed balanced low noise amplifier ...................................................................................52
  5.2 Comparison .......................................................................................................................................53
     5.2.1 Comparison between the single-ended and proposed balanced amplifiers .......................53
     5.2.2 Comparison between the conventional and proposed balanced low noise amplifiers .........56
     5.2.3 Comparison of different biasing conditions .........................................................................57
  5.3 Analysis error ...................................................................................................................................60
Conclusion...............................................................................................................................................62
Reference..................................................................................................................................................63
List of Figures

Figure 1.1 Typical RF Front-end structure of a receiver ................................................................. 1
Fig.2.1 Typical amplifier structure .................................................................................................. 4
Fig.2.1.1(i) Terminals of BJT ......................................................................................................... 4
Fig.2.1.1(ii) Characteristic curve for i_B-V_{BE} ........................................................................ 5
Fig.2.1.1(iii) Characteristic curves for I_C-V_{CE} ................................................................. 5
Fig.2.1.2(i) Transistor biasing blocks .......................................................................................... 6
Fig.2.1.2(ii) Reactive elements in biasing network ................................................................. 7
Fig.2.1.2(iii) Biasing network ..................................................................................................... 7
Fig.2.1.3.1(i) Power ratio ........................................................................................................... 9
Fig.2.1.3.1(ii) Gain VS Input power .......................................................................................... 9
Fig.2.1.3.1(iii) Impedance matching for maximum gain ....................................................... 10
Fig.2.1.3.2 (i) Input and output spectrum of a transistor .................................................... 11
Fig.2.1.3.1(ii) Corresponding harmonics of transistor’s output .......................................... 11
Fig.2.1.3.3(i) Power added efficiency .................................................................................. 12
Fig.2.1.3.3(ii) Power added efficiency of input and output ................................................. 13
Fig.2.2(i) Typical transmitter components ............................................................................. 15
Fig.2.2(ii) Typical receiver components .................................................................................. 15
Fig.2.2.1 Ideal path loss model ............................................................................................. 16
Fig.2.2.2 Signals in receiver module ...................................................................................... 17
Fig.2.2.3 SNR in amplifier ....................................................................................................... 18
Fig.2.2.4(i) BJT model with noise source ........................................................................... 19
Fig.2.2.4(ii) Shot noise of BJT transistor .......................................................................... 20
Fig.2.2.4(iii) Equivalent BJT network .............................................................................. 21
Fig.2.2.4(iv) Standard noisy transistor model ................................................................. 22
Fig.2.2.4(v) Low noise amplifier configuration .............................................................. 22
Fig.2.3.1 Configuration of a balanced amplifier ........................................................................ 23
Fig.2.3.2(i) Configurations of a branch-line coupler .......................................................... 24
Fig. 2.3.2(ii) Four port network of branch-line coupler .......................................................... 24
Fig. 2.3.2(iii) Branch-line coupler in even mode .................................................................... 25
Fig. 2.3.2(iv) Branch-line coupler in odd mode ................................................................. 26
Fig. 3.1 Impedance matching of the single-ended amplifier ..................................................... 30
Fig. 3.2(i) Configuration of the conventional balanced amplifier .............................................. 31
Fig. 3.2(ii) Configuration of conventional branch-line coupler ............................................. 32
Fig. 3.2(iii) Simulated S-parameters of conventional branch-line coupler ............................... 33
Fig. 3.2(iv) Simulated phase difference between the two output ports of conventional branch-line coupler
.................................................................................................................................................. 33
Fig. 3.3(i) Configuration of proposed balanced low noise amplifier .......................................... 35
Fig. 3.3(ii) Configuration of proposed hybrid coupler .............................................................. 36
Fig. 3.3(iii) Variables of transmission lines of proposed hybrid coupler .................................... 36
Fig. 3.3(iv)(a) Values of proposed input hybrid coupler ......................................................... 36
Fig. 3.3(iv)(b) Values of proposed output hybrid coupler ......................................................... 36
Fig. 3.3(v)(a) Layout of proposed input hybrid coupler ............................................................ 37
Fig. 3.3(v)(b) Layout of proposed output hybrid coupler .......................................................... 37
Fig. 3.3(vi) Simulated S-parameters of propose hybrid coupler ............................................... 37
Fig. 3.3(vii) Simulated phase difference between the two output ports of proposed hybrid coupler
.................................................................................................................................................. 38
Fig. 3.3(viii) Layout of proposed balance low noise amplifier .................................................. 38
Fig. 3(i) Network Analyzer ...................................................................................................... 39
Fig. 3(ii) Spectrum Analyzer .................................................................................................. 39
Fig. 3(iii) Noise Figure Analyzer ............................................................................................ 40
Fig. 4.1(i) Hardware of single-ended low noise amplifier ......................................................... 42
Fig. 4.1(ii) Simulated and measured noise figure of single-ended low noise amplifier .............. 42
Fig. 4.1(iii)(a) Simulated S-parameters of single-ended low noise amplifier ............................ 43
Fig. 4.1(iii)(b) Measured S-parameters of single-ended low noise amplifier .............................. 43
Fig. 4.2(i) Hardware of conventional balanced low noise amplifier ........................................ 44
Fig. 4.2(ii) Simulated and measured noise figure of conventional balanced amplifier ............ 44
Fig. 4.2(iii)(a) Simulated S-parameters of conventional balanced low noise amplifier .................. 45
Fig. 4.2(iii)(b) Measured S-parameters of conventional balanced low noise amplifier .............. 45
Fig. 4.2(iv) Measured 1-tone test of conventional balanced low noise amplifier ...................... 46
Fig.4.2(v) Measured 2-tones test of conventional balanced low noise amplifier ........................................... 46
Fig.4.3(i) Hardware of proposed balanced low noise amplifier ................................................................. 47
Fig.4.3(ii) Simulated and measured noise figure of proposed balanced low noise amplifier ...................... 47
Fig.4.3(iii)(a) Simulated S-parameters of proposed balanced low noise amplifier .................................... 48
Fig.4.3(iii)(b) Measured S-parameters of proposed balanced low noise amplifier .................................... 48
Fig.4.3(iv) Measured 1-tone test of the proposed balanced low noise amplifier ........................................ 49
Fig.4.3(v) Measured 2-tones test of the proposed balanced low noise amplifier ........................................ 49
Fig.5.2.1(i) Measured noise figure of single-ended and proposed balanced low noise amplifiers ............... 54
Fig.5.2.1(ii) Measured return losses of single-ended and proposed balanced low noise amplifiers .......... 55
Fig.5.3.1(iii) Measured gain of single-ended and proposed balanced low noise amplifiers ....................... 55
Fig.5.2.2(i) Measured noise figure of conventional and proposed balanced low noise amplifiers .............. 56
Fig.5.2.2(ii) Measured return losses of conventional and proposed balanced low noise amplifiers .......... 56
Fig.5.2.2(iii) Measured noise figure of conventional and proposed balanced low noise amplifiers .......... 57
Fig.5.2.3(i) Measured noise figure of proposed balanced amplifier with different biasing conditions ..... 58
Fig.5.2.3(ii) Measured $|S_{11}|$ of proposed balanced amplifier with different biasing conditions ............... 58
Fig.5.2.3(iii) Measured $|S_{22}|$ of proposed balanced amplifier with different biasing conditions ............... 59
Fig.5.2.3(iv) Measured gain of proposed balanced amplifier with different biasing conditions ............... 59

List of Tables

Table.3.1 Parameters of layout of single-ended low noise amplifier......................................................... 31

Table.3.2 Parameters of layout of conventional balanced low noise amplifier........................................ 34

Table.3.3 Parameters of layout of proposed balanced low noise amplifier............................................. 38
Acknowledgement

I would like to express my profound gratitude to my supervisor and instructor, Prof. Quan Xue and Dr. Leung Chiu respectively. They had given me considerate guidance, support and encouragement through the project. Also, I would like to thank Prof. C.H. Chan for dedicating his time and effort in assessing my project. Special thank goes toward my tutor, Andrew Lam who spent time on giving me guidance and technical support. Last but not least, I would like to thank all engineers and technicians in Applied Electromagnetic Laboratory for their kind help.
Abstract

A low noise amplifier is important to a receiver in the Wireless Communication. As it is the key component to boost the signal and minimize the noise produced by itself, it can much extend the distance between the transmitter and the receiver.

A traditional low noise amplifier achieves low noise but without good input matching. Then the balanced amplifier is a practical method to improve the input matching.

This report presents a new balanced low noise amplifier with size reduction. The amplifier was designed at the centre frequency of 1.8GHz, and it consists of three main parts, namely input branch-line coupler, two pieces of well biased transistor, and output branch-line coupler. The input branch-line coupler not only divides signal into two paths with equal magnitude and 90° out-of-phase, but also provides optimum source impedance for the biased transistor to minimize noise figure. Similarly, the output branch-line coupler not only combines signals, but also provides optimum load impedance to maximize gain.

Both input and output branch-line couplers were designed with the general port impedance but not purely resistive 50Ω port. It results in non-standard values of both characteristic impedances and electrical lengths of the four branch lines, where its size is similar to the conventional coupler. Conventional balanced low noise amplifier was also designed for comparison.

The new design achieves about 36% size reduction compared with conventional design with similar performances. The impedances of both input and output ports are matched.
measured $S_{11}=-13.4\text{dB}$ and measured $S_{22}=-17.3\text{dB}$. Measured gain and noise figure are $14.5\text{dB}$ and $2.7\text{dB}$, respectively.
Chapter 1- Introduction

In the receiver of wireless communication, the desired and unwanted signals increase when passing through each device. Those unwanted signal is the electrical noise. Fig. 1.1 shows the basic components of a typical RF Front-End Structure. The pink and blue waves show the magnification in magnitude of desired and unwanted signals respectively passing through each device.

Figure 1.1 Typical RF Front-end structure of a receiver

Therefore, a low noise amplifier is important as it is the key component to boost the signal and minimize the noise produced by itself, so that the distance between the transmitter and the receiver can be much extended. Considering the function of low noise amplifier, noise figure is the most concerned figure.
For a traditional single-ended low noise amplifier, the input matching network of it is designed to have low noise figure which is not matched to the input port. It results the imperfect matching of the whole amplifier and not good input return loss. Due to the efficiency consideration, the return loss becomes a second vital figure of merit to be considered for the low noise amplifier.

The project is aimed at improving the return loss of a low noise amplifier, a conventional balanced amplifier configuration is used have better matching to input port at 1.8GHz. However, the size of the conventional balanced amplifier is large.

So that, another objective is set to reduce the size of it, by using hybrid coupler to replace the conventional branch-line couplers with matching networks in the balanced amplifier to achieve the size reduction with similar performances.

The proposed balanced low noise amplifier can be applied in the receiver at 1.8GHz, which is for the DECT indoor wireless communication.
Chapter 2 - Theory

An amplifier is a device that has an output signal that (a) is a function of its input signal, (b) is at a higher power level than the input signal, and (c) has a gain expressed as a transfer function and often in positive dB. [1]

Microwave amplifiers are classified into three types according to their power handling properties. They are the low noise amplifier, general purpose amplifier and power amplifier respectively. Low noise amplifier is used for low power handling while general purpose amplifier is used for medium power handling. Both of them use linear design technique. On the other hand, power amplifier is used for high power handling using non-linear design technique.

2.1 Microwave Amplifier

The amplifier structure is shown in the Fig.2.1. It contains two main parts, impedance matching network and dc biasing network at both the input and output end of the transistor. Moreover, the figure shows the voltage waveforms at different positions. The input voltage level shifts upward because of the addition of the dc voltage. Then this input voltage signal gets amplification after passing through the transistor. Finally, the output voltage level resumes the position when passing through the output dc biasing network.
2.1.1 Current-voltage characteristics of a BJT transistor

Bipolar transistors (BJT) has three terminals, they are the emitter, base, and collector as in Fig.2.1.1(i). It is useful in amplifiers because the currents at the emitter and collector are controllable by a relatively small base current. [2]

The relationship between the direct current (DC) through a BJT and the DC voltage across its terminals is called the current-voltage characteristic of the BJT. [2]
Fig. 2.1.1(ii) shows the $i_B$-$v_{BE}$ characteristic curve and the load line. For the $i_B$-$v_{BE}$ characteristic curve, at each point, it has a set of base current and base-to-emitter voltage. The load line can be found by simply using KVL, it has the slope of $-\frac{1}{R_B}$.

In Fig.2.1.1(iii), fix $V_{be}$ as a constant as about 0.7V. When the output voltage $V_{CE}$ is small, $I_C$ is almost zero in the cutoff region of a BJT. Afterwards, $I_C$ increases as $V_{CE}$ increases in the active region. Moreover, when $I_b$ is increased, larger $I_c$ is resulted. The figure shows the differences when $I_{b4} > I_{b3} > I_{b2} > I_{b1}$.

Furthermore, the power consumption of a BJT is about the product of $I_C$ and $V_{CE}$. In the figure, Point 1 has higher $I_b$, $I_c$ and $V_{ce}$ than Point 2, power consumption is greater at Point 1. Therefore, different biasing condition is chose for different power handling of a transistor.
2.1.2 Biasing Networks for BJT

Vce and Vbe are chose to have well designed biasing condition. In Fig2.1.2(i), the RF input and output signals are connected to high pass filters (HPF) to allow RF signal flowing through but block DC and small frequency signals to protect the RF source and load. In contrast, the two DC supply are connected to low pass filters (LPF) to allow DC and small frequency signals to pass through but block the RF signal to protect the DC sources.

Practically, capacitors and inductors are used in Fig.2.1.2(iii). Both the inductance and capacitance of the capacitors and inductors have large values. In a practical capacitor and inductors in Fig.2.1.2(ii), there are parasitic elements which are unavoidable. They are the parasitic resistor in series with the ideal capacitor and parasitic capacitor in parallel and parasitic resistor in series to the ideal inductor. At low frequency, the effect of the parasitic elements can be omitted but they have problems in high frequency. Parasitic elements between the output and input may form a feedback path causing oscillation at the high
frequency. When larger values of capacitor and inductor are used, the effect of the parasitic elements become larger and dominant, then worse performance is resulted.

The required capacitance and inductance can be calculated by the formula below.

\[ |Z_L| \geq 10Z_0 \]
\[ L \geq \frac{10Z_0}{\omega} \]
\[ |Z_C| \leq 0.1Z_0 \]
\[ C \geq \frac{10}{\omega Z_0} \]

At DC and low frequency, the two bypass DC capacitors connecting the DC sources are used to filter the unwanted signal from DC supply. The inductors act as short circuit allowing DC to pass through. In contrast, the DC block capacitors act as open circuit to block the DC signal to protect the RF input and output ports.

At high frequency up to GHZ, bypass DC capacitors act as short circuit to ground to protect the DC supply from RF signals. Inductors work as RF choking forming open circuit and also a part of matching network. In contrast, DC block capacitors are short circuit to RF port and also a part of matching network.
Moreover, the biasing network at base can be replaced by a resistor, but given that the Rb is high enough.

### 2.1.3 Specifications of an amplifier

To characterize the quality of an amplifier, some specifications need to be considered. Different kinds of amplifiers may focus on different particular specifications. In this report, only four of them are introduced.

#### 2.1.3.1 Gain

Amplifier is used to amplify AC/RF signal. It is useless for an amplifier without gain.

The gain or transducer gain or \(|S_{21}|\) is the power ratio of output power to input power.

\[
G = \frac{P_{\text{out}(W)}}{P_{\text{in}(W)}}
\]

Normally, it is measured in dB.

\[
G(\text{dB}) = P_{\text{out}}(\text{dBm}) - P_{\text{in}}(\text{dBm}) = 10 \log_{10} \left( \frac{P_{\text{out}(W)}}{P_{\text{in}(W)}} \right)
\]

In Fig.2.1.3.1(i) and Fig.2.1.4.1(ii), they show that the amplifier has a constant gain which is a linear transfer function for a certain range in the power ratio of input power and output power.
Moreover, impedance matching technique pushes the gain by eliminating unwanted reflections. The gain of a transistor amplifier attends the maximum value if the impedance is matched where the requirement is the impedance need to be matched at both input and output ports.

Then the transducer gain (G) can be derived as the following.

\[ G = \frac{1 - |s|^2}{|1 - \text{in}^*|} |S_{21}|^2 \frac{1 - |L|^2}{|1 - \text{out} L|^2} \]

\[ G = \frac{1 - |s|^2}{|1 - S_{11}^*|} |S_{21}|^2 \frac{1 - |L|^2}{|1 - out L|^2} \]

\[ G = \frac{(1 - |s|^2)|S_{21}|^2 1 - |L|^2}{|(1 - S_{11}^* L) - S_{12}S_{21}| s |L|^2} \]

\[ G(\text{dB}) = 10\log G \]

It can be simplified for maximum gain.

For \( s = \text{in}^* \) \hspace{1cm} For \( L = \text{out} \)

\[ G = \frac{1}{|1 - s|^2} |S_{21}|^2 \frac{1 - |L|^2}{|1 - S_{22} L|^2} \]

\[ G = \frac{1 - |s|^2}{|1 - S_{11}^*|} |S_{21}|^2 \frac{1}{1 - |L|^2} \]

Fig.2.1.3.1(i) Power ratio

Fig.2.1.3.1(ii) Gain VS Input power
2.1.3.2 Linearity

An ideal transistor amplifier is a linear device but the practical one is only linear for a certain range and non-linear for others. The output, for example, the output power increases when the input power is increased as in Fig.2.1.3.1(i). However, when a certain point is arrived, the amplifier becomes saturated and strongly non-linear. The output power cannot be increased anymore and keep more or less the same, distortion is resulted. 1-dB gain compression point ($P_{1\text{dB}}$) is always used to denote this. $P_{1\text{dB}}$ is the power level where the amplifier’s gain is compressed by 1 dB.

As a practical transistor is a non-linear device, harmonics are produced by its non-linear transfer function. For example, the input signal (a) is a cosine function, then the output signal (b) is a function of input signal which contains different power order of the input signal.
\[ a = A \cos \omega t \]
\[ b = f(a) = s_0 + s_1 a + s_2 a^2 + s_3 a^3 + \ldots \]
\[ b = s_0 + s_1 (A \cos \omega t) + s_2 (A \cos \omega t)^2 + s_3 (A \cos \omega t)^3 + \ldots \]
\[ b = t_0 + t_1 \cos \omega t + t_2 \cos 2\omega t + t_3 \cos 3\omega t + t_4 \cos 4\omega t + \ldots \]

Each term of these n-th power orders of input signal is actually a n-th order harmonic of the signal as in Fig.2.1.3.2(ii).

![Fig.2.1.3.2 (i) Input and output spectrum of a transistor](image)

![Fig.2.1.3.1(ii) Corresponding harmonics of transistor’s output](image)
2.1.3.3 Power added efficiency

Power added efficiency (PAE) is to measure the amount of input power is successfully added to the amplifier’s output. The Drain efficiency of the collector efficiency is the power ratio of RF output to RF input with the DC power feeding into the drain or collector of the amplifier as in Fig.2.1.3.2(i).

The Drain efficiency or collector efficiency \( \frac{P_{\text{out}(W)}}{P_{\text{in}(W)}} \times 100\% \)

\[
\text{PAE} = \frac{P_{\text{out}(W)} - P_{\text{in}(W)}}{P_{\text{dc}(W)}} \times 100\%
\]

In the Fig.2.1.3.2(ii), PAE of input and output in both logarithmic and linear scales are shown. Higher power mode has higher efficiency.

Fig.2.1.3.3(i) Power added efficiency
2.1.3.4 Noise

Electrical noise is a random electrical signal. Some noises are generated due to laws of nature, and some noises are generated depended on manufacturing quality and semiconductor defects. In communication systems, noise is always unwanted as undesired random disturbance of useful signal. [3]
However, noise does not equal to the interference produced by cross-talk, jamming, electromagnetic interference EMI, etc. Also, noise does not equal to the distortion which is the unwanted signal generated by non-air electronic circuit itself.

The measure of noise is to know the amount of noise introducing into the system during the amplification.

More information of noise will be discussed in the introduction of low noise amplifier on Chapter 2.2.

2.2 Low noise amplifier

Low noise amplifier is used to boost the signal and minimize the noise produced by itself, so that the distance between the transmitter and the receiver can be much extended.

Considering the function of low noise amplifier, noise figure is the most concerned figure.

In both receiver and transmitter of wireless communication, the desired and unwanted signals increase when passing through each device, which is shown in Fig 2.2(i) and Fig 2.2(ii). In the output end of the transmitter, the magnitude of useful signal is much greater than that
of the unwanted signal, the effect of noise therefore can be neglected. However, in the output end of the receiver, the magnitude of useful signal is more or less similar to that of the unwanted signal. Therefore, noise need to be considered in the receiver, and it need to be handle carefully.

Fig.2.2(i) Typical transmitter components

Fig.2.2(ii) Typical receiver components
2.2.1 Path loss in communication link

In an ideal path loss model, the free-space path loss \( L_{\text{path}} \) is defined.

\[
L_{\text{path}} = \frac{P_t}{P_r} = \left(\frac{4\pi R}{\lambda}\right)^2 = \left(\frac{4\pi R}{c}\right)^2 = \frac{16\pi^2}{c^2} R^2 f^2
\]

\[
L_{\text{path}} = 10 \log \frac{16\pi^2}{c^2} + 2 \times 10 \log R + 2 \times 10 \log f
\]

In a real radio propagation model, the path loss is affected by some random factors such as environment (indoor or outdoor), weather (humidity, raining, snowing, etc.), existence of any other channels and obstacles and the distance from ground.

\[
L_{\text{path}} = \alpha R^m f^n
\]

\[
L_{\text{path}} = 10 \log \alpha + 10m \log R + 10n \log f
\]

where \( \alpha, m \) and \( n \) are different random factors in different propagation models.

It is obviously seen that the path loss is proportional to the distance between the transmitter and receiver.
2.2.2 Definition of noise factor

Signal to noise ratio (SNR) = \( \frac{\text{Signal power}}{\text{Noise power}} \)

Noise factor / Noise figure (F) = \( \frac{\text{SNR}_1}{\text{SNR}_2} \)

NF (dB) = 10 log F

From the path loss definition,

\[ L_{\text{path}} = \alpha R m f_n \] and \( L_{\text{path}} = \frac{P_t}{P_{s1}} \).

From the definition of noise factor,

\[ F = \frac{P_{s1}/P_{n1}}{P_{s2}/P_{n2}} \]

\[ = \frac{P_t}{\alpha R m f_n} \frac{P_{n2}}{P_{s2}P_{n1}} \]

From the equations, it is obvious that when the noise factor of the receiver (F) decreases, the distance between the receiver and transmitter (R) will increase.
2.2.3 Noise in amplifier

For the amplifier,

\[
\text{Input SNR} = \frac{\Psi_i}{\Pi_n}
\]

\[
\text{Output SNR} = \frac{\text{Gamp} \Psi_i}{\text{Gamp} \Pi_n + \Pi_{\text{namp}}}
\]

where Gamp is the gain of the amplifier, \(\Psi_i\) and \(\Pi_n\) are the input signal and noise powers respectively, \(\Pi_o\) and \(\Pi_{no}\) are the output signal and noise powers respectively, \(\Pi_{namp}\) is the noise power generated by the amplifier.

Then the noise factor is defined as the degradation ratio of SNR.

\[
F = \frac{\text{Input SNR}}{\text{Output SNR}} = \frac{\Psi_i/\Pi_n}{\Pi_o/\Pi_{no}}
\]

\[
= \frac{\Psi_i}{\Pi_n} \frac{\text{Gamp} \Psi_i}{\text{Gamp} \Pi_n + \Pi_{namp}}
\]

\[
= 1 + \frac{\Pi_{namp}}{\text{Gamp} \Pi_n}
\]

\[
\geq 1
\]
F ≥ 1 means any components always degrade the SNR.

### 2.2.4 Noise in transistor

The noise of the transistor is determined by shot noise, flicker noise and burst noise. The base current shot noise and the collector current shot noise are represented by current noise sources at the base and collector respectively in Fig.2.2.4(i). Shot noise source is dominant in the model.

![BJT model with noise source](image)

Shot noise exists because of several causes such as the random emission of carriers across a barrier, random tunneling of carriers, generation or recombination processes in bulk and depletion region, thermal fluctuations triggering a relaxation current through diffusion. [4]
In a microscopic view of the transistor in Fig.2.2.4(ii), shot noises occur between the base-emitter, base-collector and collector-emitter. The shot noise current sources have their values stated in the figure.

\[ \sqrt{i_{cb}^2} = \sqrt{\frac{2q_{BE}I_{BE}\Delta f}{\Delta f}} \]

\[ \sqrt{i_{ce}^2} = \sqrt{\frac{2q_{GE}I_{GE}\Delta f}{\Delta f}} \]

Fig.2.2.4(ii) Shot noise of BJT transistor

In Fig.2.2.4(iii), the transistor network generating noise power \( P_n \), can be equivalent to a resistor network with equivalent noise temperature which is higher than the room temperature.

\[ P_n = kT_e\Delta f \]

\[ > kT\Delta f \]

\[ \sqrt{\nu_n^2} = \sqrt{4kT_eR\Delta f} \]

\[ > \sqrt{4kTR\Delta f} \]
There are other noise sources. They are the thermal noise due to the distributed gate resistance, source resistance, drain resistance, gate tunneling current and junction diodes, hot electrons and substrate noise, etc.[4]

Finally, the two-port network noisy transistor is formed in Fig.2.2.4(iv). For a well-biased transistor, it has the noise F as the equation.

\[
F = F_{\text{min}} + \frac{4rn|\Gamma_s - \Gamma_{\text{opt}}|^2}{(1 - |\Gamma_s|^2)(1 + \Gamma_{\text{opt}}]^2}
\]

where Fmin is the minimum noise, \( r_n = R_n/Z_0 \) and \( \Gamma_{\text{opt}} \) is the optimum reflection coefficient. These three values are given in datasheet.

For the application of low noise amplifier, least noise is preferred. Therefore, \( s \) is chosen to be equal to \( \Gamma_{\text{opt}} \), then the second term of the equation will be eliminated and \( F = F_{\text{min}} \) theoretically.
However, as the input matching network of the low noise amplifier in Fig.2.2.4(v) is matched to get minimum noise figure but mis-matched to the input port, then the network is not good matched and fails to meet the return loss specification. This is a common weakness of an low noise amplifier.

![Fig.2.2.4(iv) Standard noisy transistor model](image)

2.3 Balanced amplifier

2.3.1 Balanced amplifier

The design of balanced amplifier to obtain good input and output matching that can significantly improve the return losses of the single-ended amplifier. The most common configuration of a balanced amplifier is shown in Fig.2.3a. It is composed of two single-ended amplifier connected by two branch-line couplers with input and output networks.
Comparing to a single-ended amplifier, the balanced amplifier has the following advantages.

(i) Provide high degree of stability.

Stability and input/output impedance matching can be improved by the balanced design even if the single amplifier of each branch is highly mismatched and with a very high gain.

Therefore, single amplifier of each branch can be mismatched to achieve a better circuit performance.

(ii) Provide a 3-dB higher linearity

(iii) Even when one of the amplifiers fails, the circuit can still operate with reduced gain

(iv) Provide a good input/output matching

Matching networks provide proper terminations on the amplifier inputs and outputs.
2.3.2 Branch-line coupler

The branch-line coupler is also called 3-dB coupler. When it is placed at input end and output end, it acts as 3-dB power divider and 3-dB power combiner respectively. A branch-line coupler has the configuration as Fig2.3.2(i).

![Fig.2.3.2(i) Configurations of a branch-line coupler](image)

All the four ports are terminated by Zo. All the transmission lines are \(\frac{\lambda}{4}=90^\circ\) with characteristic impedances of Zo=50Ω and \(\frac{Z_0}{\sqrt{2}}=35.36\Omega\) respectively. The input power at Port 1 divides equally between Port 2 and Port 3 while zero power is received at Port 4 as it is isolated. And the phase difference between Port 2 and Port 3 is 90°.

Due to the symmetry of the configuration of the branch-line coupler, even-and-odd method is used to analysis. The four port network is then simplified in Fig2.3.2(ii).

![Fig.2.3.2(ii) Four port network of branch-line coupler](image)
In even mode, same sources are inputting into Port 1 and Port 4 with the magnitude of $a_1 = a_2 = \frac{1}{2}$ in Fig. 2.3.2(iii). The orange dash line is the line of symmetry. Because of the even symmetry, the current flowing the vertical branches is zero and the maximum voltages meet at the points of line. Thus the mid-points are open-circuited and the vertical branches become $\frac{\lambda}{8}$ shunt transmission lines.

The shunt open-circuited $\frac{\lambda}{8}$ stub has the ABCD matrix:

$$
\begin{bmatrix}
A & B \\
C & D_{\text{shunt}}
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ j \tan \beta \ell & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ j & 1 \end{bmatrix}
$$

The ABCD matrix of the upper part or lower part of the circuit:

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\ j \sqrt{2} \sin \beta \ell & \cos \beta \ell \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j & 1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} -1 & j \\ j & -1 \end{bmatrix}
$$
Reflection coefficient in ABCD parameters:

\[ S_{11} = \varepsilon = \frac{A + \frac{B}{Z_0} - C \sqrt{\frac{1}{2}} D}{A + \frac{B}{Z_0} + C \sqrt{\frac{1}{2}} D} = 0 \]

Transmission coefficient in ABCD parameters:

\[ S_{21} = T_e = \frac{2}{A + \frac{B}{Z_0} + C \sqrt{\frac{1}{2}} D} = \frac{-1}{\sqrt{2}} (1+j) \]

In odd mode, asymmetrical sources of \( a_1 = \frac{1}{2} \) and \( a_4 = -\frac{1}{2} \) inputting into Port 1 and Port 4 respectively in Fig.2.3.2.(iv). The orange dash line is the line of anti-symmetry. Because of the odd symmetry, maximum current flowing the vertical branches and the voltages at the points of vertical branches is zero. Thus the mid-points are short-circuited and the vertical branches become \( \frac{\lambda}{8} \) short-circuit stub.

Fig.2.3.2(iv) Branch-line coupler in odd mode
The shunt short-circuited $\frac{\lambda}{8}$ stub has the ABCD matrix:

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}_{\text{shunt}} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/j \tan \beta \ell & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -j & 1 \end{bmatrix}
$$

The ABCD matrix of the upper part or lower part of the circuit:

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -j & 1 \end{bmatrix} = \begin{bmatrix} 1/j \sqrt{2} & 0 \\ 0 & -j \sqrt{2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ -j & 1 \end{bmatrix}
$$

Reflection coefficient in ABCD parameters:

$$
S_{11} = \frac{A + B - C - D}{A + B + C + D} = 0
$$

Transmission coefficient in ABCD parameters:

$$
S_{21} = T_o = \frac{2}{A + B + C + D} = \frac{-1}{\sqrt{2}} (1-j)
$$

By superposition,

Reflected wave at Port 1: $b_1 = \frac{1}{2} e + \frac{1}{2} o = 0$

Reflected wave at Port 4: $b_4 = \frac{1}{2} e - \frac{1}{2} o = 0$

Transmitted wave at Port 2: $b_2 = \frac{1}{2} T_e + \frac{1}{2} T_o = \frac{-i}{\sqrt{2}}$

Transmitted wave at Port 3: $b_3 = \frac{1}{2} T_e - \frac{1}{2} T_o = \frac{-1}{\sqrt{2}}$
Chapter 3 – Methodology

The project has divided into mainly three stages. They were the single-ended low noise amplifier, conventional balanced low noise amplifier and the proposed balanced low noise amplifier respectively. The designed frequency was 1.8GHz and the biasing condition were 3V and 20mA for the transistor BFP640.

In the first stage, in order to study the characteristics of a simple low noise amplifier, a single-ended low noise amplifier was designed. As the input matching network of the single-ended low noise amplifier was designed for low noise figure but not looking for the input port, the circuit was not good matched and failed to meet the specification of return loss.

To overcome this problem, a balanced amplifier configuration has been used. It came to the second stage of the project, a conventional balanced low noise amplifier has been designed, which was composed of two single-ended amplifiers connected by two branch-line couplers with input and output matching networks. The return loss problem could be solved as the matching networks were matched to the input and output ports. However, a new challenge has met that the conventional balanced low noise amplifier was quite large in size.
Size reduction was then the target of the third stage. In this stage, a proposed balanced low noise amplifier has been designed with proposed hybrid couplers. A researcher has proposed a new branch-line coupler that generalized the concept of original branch-line coupler into arbitrary port impedances which were limited by purely resistive loads. In this project, the concept has been further generalized into which terminated the four ports to arbitrary reactive loads. It was believed that size could be reduced by combining the two matching networks with a branch-line coupler in input and output matching networks of the whole balanced amplifier into only one proposed hybrid coupler. The proposed hybrid couplers have functioned as the matching networks and conventional branch-line couplers of input and output of the whole balanced amplifier.

Each design talked above are going to be described more detail in the coming paragraphs.

3.1 Single-ended low noise amplifier

To fulfill the main functions of a low noise amplifier, the design of single-ended low noise amplifier should have minimum noise figure and maximum gain. These required

\[ s = \text{opt and } \text{load} = \text{out'} \] as in Fig.3.1(i).

From the datasheet of the BJT transistor BFP640, it was given that at 1.8GHz,
\[ \text{opt} = 0.17\angle -127^\circ \]. Then,

\[ \text{out} = S22 + \frac{S12S21}{1-S11}s = 0.4357\angle -36.8238^\circ . \]

\[ Z_{\text{opt}} = \frac{1+\text{opt}}{1-\text{opt}}Z_0 = 39.3631-j11.066 \]

\[ Z_{\text{out}} = \frac{1+\text{out}^*}{1-\text{out}^*}Z_0 = 82.2847-j53.0454 \]

\text{opt and out}^* \text{ were not matched to the input and output port impedances of 50}\Omega \text{ respectively.}

![Fig.3.1(i) Impedance matching of the single-ended low noise amplifier](image)

The design of single-ended low noise amplifier has the layout as Fig.3.1(ii) with the dimensions in Table.3.1.

![Fig.3.1(ii) Layout of single-ended low noise amplifier](image)
### Parameters of layout of single-ended low noise amplifier

<table>
<thead>
<tr>
<th>Parameters</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values (mm)</td>
<td>4.10</td>
<td>20.40</td>
<td>8</td>
<td>5.06</td>
<td>5</td>
<td>3</td>
<td>47.76</td>
<td>6</td>
<td>2.28</td>
<td>13.68</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>k</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values (mm)</td>
<td>43</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 3.1 Parameters of layout of single-ended low noise amplifier

### 3.2 Conventional balanced low noise amplifier

The configuration of a balanced amplifier, and details of it and the branch-line coupler has been introduced in Chapter 2.3.

Here, for the balanced low noise amplifier, main purpose of the branch-line couplers was to match the input and output port impedances at one side of its ports and match to $\Gamma_{\text{opt}}$ and $\Gamma_{\text{out}}^*$ on the other side as shown in Fig. 3.2(i).

![Fig. 3.2(i) Configuration of the conventional balanced amplifier](image-url)
The conventional balanced low noise amplifier has used the conventional branch-line coupler. The configuration of conventional branch-line coupler was shown in Fig.3.2(ii). It has terminated the four ports into $50\,\Omega$ which is the same as port impedance in RF. For the input branch-line coupler in the conventional balanced amplifier, Port 1 and Port 4 were terminated to $Z_0=50\,\Omega$ while Port 2 and Port 3 were terminated to $Z_{opt}^*$. For the output branch-line coupler, Port 1 and Port 4 were terminated to $Z_{out}$ while Port 2 and Port 3 were terminated to $Z_0$.

In the simulation of the conventional branch-line coupler alone, it showed that at the target frequency 1.8GHz, the two output ports had the gain of -3dB so that it could act as 3dB power divider and power combiner in input-end and output-end respectively, also, the return losses of it had the value near to -30dB in Fig.3.2(iii). Moreover, the two output ports were $90^\circ$ out of phase shown in Fig3.2(iv).
Fig. 3.2(iii) Simulated S-parameters of conventional branch-line coupler

Fig. 3.2(iv) Simulated phase difference between the two output ports of conventional branch-line coupler

Then the conventional balance low noise amplifier has been designed with the layout of Fig. 3.2(v). Also, the dimensions of the design were stated in Table 3.2.
3.3 Proposed balanced low noise amplifier

The purpose of the proposed balanced low noise amplifier was to reduce the size of the conventional low noise balanced amplifier without degrading its performances. The configuration of it is shown in Fig.3.3(i) which was consists of only three main parts, namely, the input proposed hybrid coupler, two pieces of well-biased transistors and the output proposed hybrid coupler. The proposed hybrid couplers were used to replace the conventional branch-line couplers and the size-demanding matching networks in the conventional balanced amplifier design.
For the proposed balanced low noise amplifier, only one side of ports of the proposed input and output hybrid couplers were connecting to transistors in either input or output matching network. So for each proposed hybrid coupler, two ports were changed to be terminated by reactive loads instead of $Z_0$ as in Fig3.3(ii).

To achieve the outcome, as in Fig.3.3(iii), 90° and 50Ω of one transmission line were kept, electrical lengths and characteristic impedances of the other three transmission lines were variables to be tuned. These values were then simulated by software Microwave Office. Simulated values were stated in Fig.3.3(iv)(a) and Fig.3.3(iv)(b) for proposed input hybrid coupler and output hybrid coupler respectively. With these values, the layouts of them have been drawn as Fig.3.3(v)(a) and Fig.3.3(v)(b) respectively.
Similar to the conventional branch-line coupler, the proposed hybrid couplers have two output ports with the gain of -3dB so that it could act as 3dB power divider and power combiner in input-end and output-end at the target 1.8GHz respectively, also, the return losses of it have the values of -15dB and -60dB in Fig.3.3(vi). Moreover, the phase difference
between the two output ports was also 90° out of phase shown in Fig3.3(vii). For the input proposed hybrid coupler, it not just divided the signal into two equal paths with equal magnitude and 90° out of phase but also provided optimum source impedance for the biased transistor to get minimum noise figure. Similarly, for the output coupler, it not just combined the two signals together but also provided optimum load impedance to get maximum gain.

Fig. 3.3(vi) Simulated S-parameters of propose hybrid coupler

Fig.3.3(v)(a) Layout of proposed input hybrid coupler

Fig.3.3(v)(b) Layout of proposed output hybrid coupler
Then the proposed balance low noise amplifier has been designed with the layout of Fig. 3.3(v). Also, the dimensions of the design were stated in Table 3.3.

Fig. 3.3(vii) Simulated phase difference between the two output ports of proposed hybrid coupler

<table>
<thead>
<tr>
<th>Parameters</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values(mm)</td>
<td>22.4</td>
<td>4.04</td>
<td>6.57</td>
<td>5</td>
<td>31.02</td>
<td>26.4</td>
<td>26.95</td>
<td>31.26</td>
<td>22.11</td>
</tr>
</tbody>
</table>

Fig. 3.3(viii) Layout of proposed balance low noise amplifier

<table>
<thead>
<tr>
<th>Parameters</th>
<th>j</th>
<th>k</th>
<th>l</th>
<th>m</th>
<th>n</th>
<th>o</th>
<th>p</th>
<th>q</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values(mm)</td>
<td>32.82</td>
<td>29.44</td>
<td>23.89</td>
<td>19.93</td>
<td>20.55</td>
<td>23.82</td>
<td>32.85</td>
<td>7.28</td>
<td>5</td>
</tr>
</tbody>
</table>
### Table 3.3 Parameters of layout of proposed balanced low noise amplifier

<table>
<thead>
<tr>
<th>Parameters</th>
<th>s</th>
<th>t</th>
<th>u</th>
<th>v</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values(mm)</td>
<td>8</td>
<td>0.5</td>
<td>15.47</td>
<td>14.48</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The above layouts have been fabricated using PCB Wangling with dielectric constant of 2.65 and thickness of 1.5mm. Then the hardware circuits were tested and measured by the following three analyzers in Fig.3(i), Fig.3(ii) and Fig.3(iii).
Four kinds of measurements were needed to take, namely the noise figure, S-parameters, 1-tone test and 2-tones test.

Noise figure was one of the most important parameters, it was measured by the Noise Figure Analyser.

S-parameters included the gain and return losses. Return losses were the second concern of the project to test whether the designs fulfil the general specification of -10dB or not. All the S-parameters were measured by the Network Analyser.

1-tone test could show the relationship among the input power, the output powers of fundamental and second harmonic signals. Theoretically, the output power of the fundamental signal is proportional to the input power until a saturation point was met. During this period, the gain is kept constant and as the slope of the curve is linear. The saturation point is called the 1dB compression point. $P_{1\text{dB}}$ is the power level where the amplifier’s gain
is compressed by 1dB. Maximum output power is attained at this point. After this point, the output power of the fundamental signal is limited. Second harmonic signal power level appears when the fundamental signal keeps increasing.

2-tones test could show the linearity of an amplifier. IMD3 increased as the output power of the fundamental signal increased. IMD3 is the Third-Order Intermodulation Distortion. Because of the third-order nonlinearity of the amplifier, two large undesired signals at the adjacent channels create a third-order intermodulation product at the desired channel. When the power of the overlapping third-order intermodulation product is very large, the weak desired signal would be corrupted during signal filtering process.[5] In the experiment, RF input signal with two closely spaced signals at frequencies of f1 and f2 with small difference of 500kHz. The third-order non-linearity of the amplifier generated two third-order intermodulation products at 2f1-f2 and 2f2-f1 respectively.

Both the 1-tone test and the 2-tones test were measured by the Spectrum Analyser.
Chapter 4 – Simulated and measured Results

4.1 Single-ended low noise amplifier

The single-ended low noise amplifier has been fabricated as in Fig.4.1(i). Fig.4.1(ii) shows that the simulated and measured noise figures of it at 1.8GHz were 0.7dB and 1.8dB respectively.

Fig.4.1(i) Hardware of single-ended low noise amplifier

Fig.4.1(ii) Simulated and measured noise figure of single-ended low noise amplifier
Fig. 4.1(iii)(a) and Fig. 4.1(iii)(b) showed the simulated and measured S-parameters of the conventional balanced low noise amplifier respectively. The simulated $S_{11}$, $S_{12}$, $S_{21}$ and $S_{22}$ at 1.8GHz were -3.25dB, -24.0dB, 20.9dB and -65.3dB respectively. On the other hand, the measured $S_{11}$, $S_{12}$, $S_{21}$ and $S_{22}$ at 1.8GHz were -4.7dB, -23.1dB, 12.8dB and -19.8dB respectively.

![Simulated S-parameters of single-ended low noise amplifier](image)

Fig. 4.1(iii)(a) Simulated S-parameters of single-ended low noise amplifier

![Measured S-parameters of single-ended low noise amplifier](image)

Fig. 4.1(iii)(b) Measured S-parameters of single-ended low noise amplifier
4.2 Conventional balanced low noise amplifier

The conventional balanced low noise amplifier has been fabricated as in Fig.4.2(i).

Fig.4.2(ii) showed that the simulated and measured noise figures of it at 1.8GHz were 1.9dB and 2.7dB respectively. The measured noise figure was around 3dB in the range of 1.4GHz to 2GHz.

Fig.4.2(i) Hardware of conventional balanced low noise amplifier

Fig.4.2(ii) Simulated and measured noise figure of conventional balanced amplifier
Fig. 4.2(iii)(a) and Fig. 4.2(iii)(b) showed the simulated and measured S-parameters of the conventional balanced low noise amplifier respectively. The simulated S11, S12, S21 and S22 at 1.8GHz were -15.2dB, -24.9dB, 14.5dB and -18.1dB respectively. On the other hand, the measured S11, S12, S21 and S22 at 1.8GHz were -10.9dB, -29.5dB, 15.8dB and -18.1dB respectively.
Fig. 4.2(iv) showed the measured result of 1-tone test of the conventional balanced low noise amplifier. $P_{1\text{dB}}$ compression point was at maximum output power of fundamental signal of about 6.5dBm.

Fig. 4.2(iv) Measured 1-tone test of conventional balanced low noise amplifier

Fig. 4.2(v) showed the measured result of 2-tones test of the conventional balanced low noise amplifier. IMD3 increased as the output power of the fundamental signal increased.

Fig. 4.2(v) Measured 2-tones test of conventional balanced low noise amplifier
4.3 Proposed balanced low noise amplifier

The proposed balanced low noise amplifier has been fabricated as in Fig.4.3(i).

Fig.4.3(ii) showed that the simulated and measured noise figures of it at 1.8GHz were 1.1dB and 2.7dB respectively. The measured noise figure was around 3dB in the range of 1.5GHz to 2GHz.

Fig.4.3(i) Hardware of proposed balanced low noise amplifier

Fig.4.3(ii) Simulated and measured noise figure of proposed balanced amplifier

Fig.4.3(iii)(a) and Fig.4.3(iii)(b) showed the simulated and measured S-parameters of the proposed balanced low noise amplifier respectively. The simulated S11, S12, S21 and
S22 at 1.8GHz were -13.4dB, -17.3dB, 14.5dB and -17.3dB respectively. On the other hand, the measured S11, S12, S21 and S22 at 1.8GHz were -12.6dB, -15.9dB, 22.0dB and -23.5dB respectively.

Fig.4.3(iii)(a) Simulated S-parameters of proposed balanced low noise amplifier

Fig.4.3(iii)(b) Measured S-parameters of proposed balanced low noise amplifier
Fig. 4.3(iv) showed the measured result of 1-tone test of the proposed balanced low noise amplifier. $P_{1\text{dB}}$ compression point was at maximum output power of fundamental signal of about 10dBm.

![Fig. 4.3(iv) Measured 1-tone test of the proposed balanced low noise amplifier](image1)

Fig. 4.3(iv) Measured 1-tone test of the proposed balanced low noise amplifier

Fig. 4.3(v) showed the measured result of 2-tones test of the proposed balanced low noise amplifier. IMD3 increased as the output power of the fundamental signal increased.

![Fig. 4.3(v) Measured 2-tones test of the proposed balanced low noise amplifier](image2)

Fig. 4.3(v) Measured 2-tones test of the proposed balanced low noise amplifier
Chapter 5 Discussion

5.1 Analysis of results

5.1.1 Single-ended low noise amplifier

It has been expected that the every measured performance was worse than the
simulated performance, just like the measured noise figure here which has been larger than
the simulated result. Good noise figure of 1.8GHz has been measured.

The S-parameters of it have similar results for the simulation and measurement. It has
a very stable gain slope. However, the measured gain, |S21| has been much less than that of
simulation. Reasons are summarized at the end of the Chapter 5. The limitation of single-
ended low noise amplifier could be observed that the input return loss (S11) was larger than
the general specification of -10dB so it failed to be matched to the input port impedance.

5.1.2 Conventional balanced low noise amplifier

The measured noise figure has similar shape as the simulated result but with
frequency shift. At 1.8GHz, the design has the lowest measured noise figure through the
frequency range from 1GHz to 3GHz. And it has been more or less around 3dB in between
1.4GHz and 2GHz.
The shapes of the measured S-parameters results were not very similar to the simulated results. The gain has been constant during the range from 1.5GHz to 2GHz about 15dB. At 1.8GHz, its gain was 15.8dB. From 1.5GHz to 2GHz, both S11 and S22 were less than general specification of return loss of -10dB which had a physical meaning that the reflected power was less than 10% of the incident power. Also, the networks were well matched.

Considering the noise figure, gain and return losses condition, the usable range was from 1.5GHz to 2GHz where the bandwidth was 0.5GHz

In the 1-tone test, input power has been gradually increased and the output powers of fundamental and second harmonic signals have been measured. The output power of the fundamental signal was proportional to the input power until the $P_{1\text{dB}}$. During this period, the gain has been kept constant and as the slope of the curve was linear. $P_{1\text{dB}}$ has been measured at about 6.5dBm output power of the fundamental signal. It was observed that after this point, the output power of the fundamental signal was limited. On the other hand, the second harmonic signal power was observed.
In the 2-tones test, linearity of the conventional balanced low noise amplifier has been measured. The relationship between the IMD3 and output power of the fundamental signal has been plotted. IMD3 increased as the output power of the fundamental signal increased. Intermodulation distortion (IMD) is defined as the non-linear distortion characterized by the appearance of frequencies, in the output, equal to the sums and the differences of the integral multiples, i.e. of harmonics, of the component frequencies present in the output.[1]

5.1.3 Proposed balanced low noise amplifier

The measured noise figure has different shape to the simulated result. At 1.8GHz, the design has an almost lowest measured noise figure through the frequency range from 1GHz to 3GHz. And it was more or less around 3dB in between 1.6GHz and 2GHz.

Also, the shapes of the measured S-parameters results have not been very similar to the simulated results. The gain was quite constant during the range from 1.4GHz to 2.2GHz about 15dB. At 1.8GHz, its gain was 14.5dB. From 1.5GHz to 2GHz, both S11 and S22 were less than general specification of return loss of -10dB. So that the reflected powers were less than 10% of the incident powers. Also, the networks were well matched.
Considering the noise figure, gain and return losses condition, the usable range was from 1.6GHz to 2GHz where the bandwidth is 0.4GHz.

In the 1-tone test, output powers of fundamental and second harmonic signals have been measured. The output power of the fundamental signal has proportional to the input power until the $P_{1\text{dB}}$. During this period, the gain has been kept constant and as the slope of the curve was linear. $P_{1\text{dB}}$ has been measured at about 10dBm output power of the fundamental signal. It was observed that after this point, the output power of the fundamental signal was limited. Second harmonic signal power level was observed.

In the 2-tones test, linearity of the proposed balanced low noise amplifier was measured. The relationship between the IMD3 and output power of the fundamental signal was plotted. IMD3 increased as the output power of the fundamental signal increased.

5.2 Comparison

5.2.1 Comparison between the single-ended and proposed balanced amplifiers

Both the single-ended and proposed balanced amplifiers has kept little variance in the range from 1.7GHz to 2.1GHz. the proposed balanced low noise amplifier has a larger noise
figure about 1dB more than that of the single-ended low noise amplifier including the target 1.8GHz in Fig.5.2.1(i). This was the little trade-off between noise figure and return losses.

![Measured noise figure of single-ended and proposed balanced low noise amplifiers](image)

**Fig.5.2.1(i) Measured noise figure of single-ended and proposed balanced low noise amplifiers**

In Fig.5.2.1(ii), only the output return loss of S22 of the single-ended low noise amplifier has satisfied the general specification of -10dB, the input return loss (S11) was only -4dB which was failed to meet the specification. On the other hand, both the input and output return losses of the proposed balanced amplifier have satisfied the specification. In another word, one of the objectives of the project has been achieved.
In Fig. 5.2.1(iii), the gain of the single-ended low noise amplifier has been constant from 1.8GHz to 2.6GHz while the gain of the proposed balanced low noise amplifier has been constant from 1.4GHz to 2GHz. At the target frequency of 1.8GHz, the gain of proposed balanced low noise amplifier has 3dB more than that of the single-ended low noise amplifier. This was the function of the branch-line coupler.
5.2.2 Comparison between the conventional and proposed balanced low noise amplifiers

The conventional and proposed balanced low noise amplifiers have similar performances. The following three figures have showed the difference of noise figure, return losses and gain between them respectively.

**Fig. 5.2.2(i) Measured noise figure of conventional and proposed balanced low noise amplifiers**

**Fig. 5.2.2(ii) Measured return losses of conventional and proposed balanced low noise amplifiers**
5.2.3 Comparison of different biasing conditions

Different biasing conditions were applied to the designs. Only the results for the proposed balanced low noise amplifier have been recorded in this report. The noise figure of the proposed balanced low noise amplifier has been the least for biasing 3V20mA. It could be explained that the design was designed for the noise figure at this biasing condition 3V20mA at the beginning design process. Return losses of all the biasing condition have fulfilled the general specification and biasing condition of 3V20mA has the largest gain.
Fig. 5.2.3(i) Measured noise figure of proposed balanced amplifier with different biasing conditions

Fig. 5.2.3(ii) Measured $|S11|$ of proposed balanced amplifier with different biasing conditions
Fig. 5.2.3(iii) Measured $|S22|$ of proposed balanced amplifier with different biasing conditions

Fig. 5.2.3(iv) Measured gain of proposed balanced amplifier with different biasing conditions
5.3 Analysis error

There were differences between the simulated and measured results. Some reasons have been summarised below. Firstly, the simulation was an ideal case, it assumed the electrical lengths, characteristic impedances, etc. were ideal, and there were no junction and continuity problems. However, in practical, problems existed and the elements used were non-ideal, as it has been mentioned in the Chapter 2.1.2 that the package of element has parasitic elements.

Secondly, the sloping lines of the proposed hybrid couplers had effects as how the four transmission lines were placed to form the coupler which might have different results.

Thirdly, during the printing and fabrication, the dimensions of the designs may have been slightly different.

Lastly, the ground handling issue might be a factor too. In the hardware of the designs, grounding of the circuit on the upper layer of the PCB board has achieved by making the via holes and connecting the upper layer circuit to the lower layer ground plate by a wire. Sometimes, the vla holes were further away from the point that connects to ground, then the
circuit went through a long wire before going to the ground of the lower layer plate. Also, the
wires used might introduce unwanted inductive effect to the circuit.
Conclusion

In conclusion, developing from the single-ended low noise amplifier, then the balanced low noise amplifier, a final 1.8GHz balanced low noise amplifier has been designed with a new idea of a nonstandard branch-line coupler with reactive port impedances.

The proposed coupler has functioned as power division and power combination going into and going out of the transistors respectively, and also it has worked as the impedance matching to the input and output ports.

The proposed balanced low noise amplifier has return losses of S11 and S22 equal to -13.4dB and -17.3dB respectively, 14.5dB gain and 2.7dB noise figure.

The proposed balanced low noise amplifier has achieved the project goal that it reduces the size from a conventional balanced low noise amplifier by 36%.
Reference:


3. P.11,Chapter 7, Lecture note of EE4107 Foundations of Microwave Solid State Circuits, City University of Hong Kong


5. <<Equalization of Third-Order Intermodulation Products in Wideband Direct Conversion Receivers>>, Jarkko Jussila, Member, IEEE, and Pete Sivonen, Member, IEE