ENABLING ANTENNA TECHNOLOGY FOR HIGH-SPEED WIRELESS COMMUNICATION

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STATEMENT OF CANDIDATE

I, Jiasheng He, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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Date:7 November 2016

ABSTRACT

To accelerate the path towards 5th generation wireless system, high-performance antennas as the interface between the external environment and radio system are playing an important role. They are required to provide efficient wireless communication of high-speed data, high definition video, cloud application and so on by future wireless smart devices.

There are two sections in this project. The first section is the design, simulation, optimization and fabrication a low-cost quasi-Yagi antenna, which can operate at 60GHz wireless band. The second section is doing the basic wireless link performance measurement. Through experiment to demonstrate the influence of transmitter power level, antenna gain and transmission distance on received power in 60GHz point-to-point wireless transmission. Furthermore, through measurement results analysis to prove high-gain electromagnetic bandgap resonator antenna (ERA) can improve the wireless communication efficiency.

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Chapter 1

Introduction

An antenna, which converts electric power into radio waves or converts radio waves into electric power, is an electrical device and generally used with a radio transmitter or radio receiver. In transmission, a transmitting antenna radiates the energy from a radio transmitter, which supplies an electric current oscillating at radio frequency, as electromagnetic waves/radio waves. In reception, a receiving antenna intercepts some of the power of an electromagnetic wave converts a weak electric voltage at its terminals [48]. A transmitting antenna and a receiving antenna constitute the wireless communication link which is the interface between the external environment and radio system. An efficient antenna system can be achieved by a good performance antenna. A good performance antenna starts with an appropriate antenna design. In the antenna design, there are many parameters need to be considered, such as radiation pattern, input impedance, main/side lobe, radiation efficiency, directivity, gain, bandwidth and front-to-back ratio to match the system design objectives [40]. Furthermore, the construction of antenna and the cost for fabrication should not be ignored.

Selecting an appropriate operating frequency before antenna design is very important. Currently there is considerable demand for spectrum in 2.4GHz band, this lead to 2.4GHz band becomes quite congested and many Radio Local Area Network (RLAN) system are expected shift to 5GHz band [1]. However, demand for broadband multimedia applications as exceed 5GHz band availability has been predicted by Industry Canada [7]. Because digital wireless communications will always require higher throughout than is available, the Wireless Gigabit Alliance (WiGig) developed and promoted a specification for wireless communications technology operating in 60GHz band at speeds in the multi-Gigabit range. WiGig promoted the IEEE 802.11 protocol and announced it in May 2009. In 2010, the IEEE 802.11ad was officially approved by the IEEE [30]. There is 3-7 GHz of bandwidth available worldwide, which has slightly different in different countries. Compared with other wireless platforms, 60GHz band has a great advantage in frequency reuse within a very localized region of air space because 60GHz band exhibits a attenuation rate over distance due to walls and oxygen. [18] Furthermore, the advantages of the 60GHz band such as simple flexible transmission rules and lack of incumbent user can increase the transmission speed in next-generation WiFi, and some indoor point-to-point applications for high-definition video streaming from smart devices and fast files transfer between computers with other smart devices. Based on 2.4GHz and 5GHz band are congested and the advantages of 60GHz band, an antenna will be designed to operate at 60GHz band.

Table 1.1: 802.11ad Features

Characteristic	Description
Operating frequency range	60GHz ISM Band
Maximum data rate	7Gbps
Typical distances	1-10 meter
Antenna technology	Uses beamforming

Table 1.2: Worldwide Spectrum Available at 60GHz [15]

Region	Allocation(GHz)
Australia	59.40-62.90
USA and Canada	57.05-64.00
European Union	57.00-66.00
China	59.00-64.00
Japan	59.00-66.00
South Korean	57.00-64.00

1.1 Project Objectives

1. Review of electromagnetism and antenna technology.
2. Familiars with Computer Simulation Technology (CST) Microwave Studio for antenna design.
3. Understand 60GHz antenna design and know how to optimize it.
4. Familiars with antenna simulation and theoretical analysis.
5. Setup 60GHz antennas link and measure the performance of antennas.
6. Through experiment to demonstrate the influence of transmitter power level, antenna gain and transmission distance on received power.

1.2 Thesis Overview

In this section, a general description of the thesis will be outlined. The project plan, which contains the project specifications and deliverables, is attached in Table 1.4. This project is supervised by Professor Karu Esselle and Doctor Basit Zeb from the Department of Engineering, Macquarie University. In order to make sure the problems can be solved in time, the project is conducting successfully and deliverables are feasible, a regular meeting with academic supervisor each week was setup from the beginning. The consultation attendance form is attached in the Appendix at the end of the document.

The structure of this thesis is as follow:

Chapter 3 provides the background, types and parameters of different kinds of antenna. In the antenna types, dipole antenna, monopole antenna, array antenna, loop antenna, aperture antenna and microstrip antenna will be introduced. There are five main antenna characteristics which are radiation pattern, bandwidth, efficiency, impedance and gain will be highlighted. Moreover, the basic concepts of extremely high frequency and three regions of electromagnetic field will be provided in this chapter.
Chapter 4 gives the literature reviews about different kinds of microstrip antenna design and comparison with microstrip line feeding, coaxial probe feeding, proximity coupled feeding and aperture coupled feeding. Furthermore, related work will be discussed to find out an appropriate design for the project.
In chapter 5, a 60GHz quasi-Yagi antenna will be designed, optimized and simulated in the CST Microwave Studio. Through adjusting the main design parameters of quasi-Yagi antenna to optimize the antenna characteristics such as reflection coefficient, voltage standing wave ration (VSWR), gain and radiation pattern is main content of this chapter.
Chapter 6 gives a basic wireless link performance measurement using 60GHz transmitting antenna and receiving antenna. The experiment principles, equipment set up, procedures, calculations and analysis will be provided. Through experiment to demonstrate the influence of transmitter power level, antenna gain and transmission distance on received power in 60GHz point-to-point transmission. Furthermore, through measurement result analysis to prove high-gain electromagnetic bandgap (EBG) resonator antenna (ERA) can improve the wireless communication efficiency.
Chapter 7 concludes and summarizes the whole project and discuss the potential future research.

1.2.1 Project Baseline Review

1. Time Budget Review
   This project was launched from 1 August, 2016. The report and poster have to hand out on 7 November, 2016 and 11 November, 2016. The presentation will be held on 14 November, 2016. The baseline plan was created to utilize all available day throughout the whole semester 2 of 2016 including the mid-term break, for project activities.

Table 1.3: Time Budget Review Summary

Estimated work	89 days
Relised work	89 days
Complection	100 %

Table 1.4: Detailed Project Time Line

Task	Start date	End date	Days	Completion
Understanding project scopes and deliverable	01/08/2016	05/08/2016	5	100%
Project plan and specification	06/08/2016	10/08/2016	5	100%
Literature review and relative paper study	10/08/2016	04/09/2016	25	100%
Understanding project scopes and deliverable	01/08/2016	05/08/2016	5	100%
CST Microwave studio study and practice	29/08/2016	04/09/2016	7	100%
Antenna Design and optimization	05/09/2016	17/10/2016	41	100%
Simulation analysis	03/10/2016	17/10/2016	15	100%
Measure equipments study and practice	18/10/2016	24/10/2016	7	100%
Antenna fabrication	25/10/2016	28/10/2016	3	100%
Antenna Measurement	25/10/2016	29/10/2016	5	100%
Thesis draft	25/10/2016	31/10/2016	7	100%
Thesis finalist	1/11/2016	7/11/2016	7	100%
Abstract	8/11/2016	11/11/2016	4	100%
Poster	8/11/2016	11/11/2016	4	100%
Presentation	8/11/2016	14/11/2016	7	100%

2. Financial Budget Review
   The project was allocated financial budget of $300. Due to the fabrication complexity, the electronics engineering services in the Macquarie University can not support small-dimension antenna fabrication. After discussion with supervisors, this antenna design will be sent to Lintek Australia [25] for fabrication. The cost of fabrication is $759.
   The purchase order form and invoice are attached in the Appendix at the end of document.

Chapter 2

Background

2.1 Antenna History

In 1886, the first wireless electromagnetic system was built by Professor Heinrich Rudolph. This system proved the existence of electromagnetic waves predicted by James Clerk Maxwell. In 1901, Guglielm Marconi was able to send signal over 200m. From Marconis inception through the 1940s, antenna technology was mainly focused on wire related radiating elements and frequency up to Ultra high frequency(UHF). In this period, modern antenna technology was launched and new element such as Yagi-Uda antenna (1920s), horn antenna (1939) and antenna arrays (1940s) were primarily introduced. While the Second World War launched a new era in antennas. During 1960s to 1980s, advances made in computer architecture and technology has made great advance in modern antenna technology. A patch antenna which is the original type of microstrip antenna was described by John Howell in 1972. This situation lead to an even greater influence on antenna technology in the 1990s and beyond. In 1992, Marty Cooper led the Motorola group developed the first portable cell phone [48]. After this a large number of research focus on making antennas not only smaller but also more efficient, especially apply to personal wireless communication devices.

2.2 Antenna Types

Antenna can be classified in various methods. Almost every antenna in all over the world can be understood as some combination or derivative of the antennas listed in this part.

- Dipole Antenna
- Monopole Antenna
- Array Antenna
- Loop Antenna

- Aperture Antenna
- Microstrip Antenna

(a) Monopole Antenna

(b) Horn Antenan

(c) Array Antenna

(a) Microstrip Patch Antenna [36]

Figure 2.1: Different Types of Antenna

2.2.1 Dipole Antenna

The dipole is one of the simplest and most typical antenna on a large class of antennas. A basic dipole antenna has two identical conductive such as metal rods or wires arranged symmetrically, with one side of the balanced feedline from the transmitter or receiver attached to each. The half-wave dipole which is the most common type has two resonant elements just less than a quarter wavelength length. This antenna directive gain can achieve a small value low to 2.15dBi, practically the lowest directive gain of any antennas. Yagi-Uda antenna, patch antenna (often used in arrays), log-periodic dipole array antenna and corner reflector antenna is also a kind of dipole antenna.

2.2.2 Monopole Antenna

A monopole antenna, which is a class of radio antenna, consists a single conductor such as a metal road. It usually be mounted perpendicularly over some type of conductive surface. One side of the feedline from the receiver/transmitter is connected to the lower

end of the monopole antenna, and the other side is connected to ground, which is often the Earth, or the artificial ground plane. Monopoles antenna are used for coverage of an area, because they have an omnidirectional pattern and vertical polarization. Therefore, large monopole antennas are used in Medium Frequency (MF), Low Frequency (LF) and Very Low Frequency (VLF) bands for broadcasting and small monopole antennas are used in High Frequency (HF), Very High Frequency (VHF) and Ultra High Frequency (UHF) bands as nondirectional antennas on portable radios.
Whip antenna, mast radiator antenna, T and inverted L antenna, inverted F antenna and umbrella antenna is a kind of monopole antenna.

2.2.3 Array Antenna

In Array Antenna, there are multiple antenna working together as a single antenna. It has arrays of identical driven elements and dipoles fed in phase normally, giving increased gain over that of a single dipole.
Collinear antenna, reflective array antenna, phased array antenna, curtain array antenna, batwing antenna and microstrip antenna is a kind of array antenna.

2.2.4 Loop Antenna

A loop antenna is a radio antenna consisting a loop or coil of wire, electrical conductor (e.g. tubing) with its ends connected to a balanced transmission line. There are two different antenna designs within this physical description. One is large resonant loop antenna with circumference of a wavelength. Its operation is similarly to the half-wave dipole. The other one is small loop antenna, also called a magnetic loop antenna, which is much smaller than a wavelength. It is not sensitive to nearly electrical noise when it interacts directly of radio wave magnetic field. Meanwhile, it has a low radiation resistance (much smaller than the loss resistance), this lead to it is not desirable and efficient for transmitting. Therefore, small loop antenna is used as receiving antenna at low frequency and for direction finding antenna.

2.2.5 Aperture Antenna

Aperture antenna which is mainly used at microwave frequency, has a small dipole or a loop feed antenna inside a three-dimension guiding structure [31]. It can be used over a wide frequency range through tuning or replacing the feed antenna because its non resonant structure.
Parabolic antenna, horn antenna, slot antenna and dielectric resonator is a kind of aperture antenna.

2.2.6 Microstrip Antenna

Microstrip antenna was conceived around 1950s and it can be fabricated as a kind of printed or patch antenna. It has a radiating patch on one side of dielectric substrate such as printed circuit board (PCB) and a continuous metal layer which forms a ground plane on the other side [13]. The shapes of radiating patch are diverse, they can be rectangular, square, circular, equilateral triangle and any continuous shape. In order to simplify design and performance prediction, the regular patch shapes are used in a large number of design. Typically, the dielectric constants of substrate are from 2.2 to 12 and the conductors are copper or gold [35].
Recently, microstrip antennas are getting more popular and be used in a wide range of application because they are relatively easy to design and advantage in fabrication from the two dimensional physical geometry. Furthermore, they are relatively light weight, thin profile configurations, low volume and low fabrication cost. However, there are some disadvantages of themselves which are large ohm loss in the feed structure of arrays, high value dielectric constant substrate leads to narrow bandwidth and poor efficiency, excitation of surface waves, somewhat lower gain and poor end-fire radiator [35].
Some of these limitations can be minimized and the performance of antenna can be improved by using some special techniques, for example, using array configuration to increase the gain of antenna.

2.3 Antenna Parameters

2.3.1 Radiation Pattern

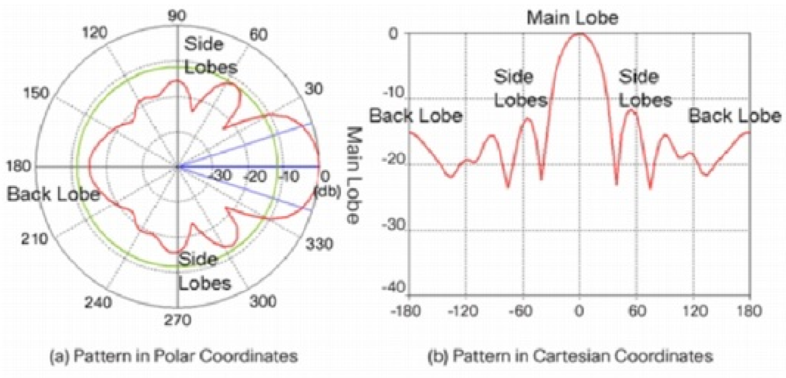


Figure 2.2: Radiation Pattern [9]

The radiation pattern of an antenna is a graphical depiction of the relative field strength transmitted from or received by antenna at different angles.

It is usually represented by polar plots of horizontal and vertical cross sections or a three-dimensional graph. The radiation pattern of ideal isotropic antenna is equally in all directions which looks like a sphere. Some nondirectional antennas such as dipole antennas and monopoles antennas, emit equal power in all horizontal directions and the power reducing at higher or lower angles. Their omnidirectional pattern looks like a torus. In a directional antenna, its radio waves are in a particular direction and lobe in this direction is bigger than other direction which is named main lobe. The other lobes of directional antenna are called side lobes which usually represent unwanted radiation.
An example radiation pattern image is shown on Figure2.2, which is represented in Cartesian and polar coordinates.

2.3.2 Bandwidth

The range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard, this is the defines of bandwidth by IEEE [28].
In definition, bandwidth is overall effectiveness of an antenna through a range of frequencies. In practice, bandwidth is typically quoted in terms of Voltage Standing Wave Ratio (VSWR). The frequency range determines the VSWR bandwidth where it is less or equal to 1.5. 3dB return loss is another frequently used value which can be used to characterize bandwidth for resonant antenna.

2.3.3 Efficiency

Antenna efficiency is the ratio of power actually radiated from an antenna to the electrical power it receives from another antenna. Efficiency can be defined as the ration of radiated power to the total power used by antenna.

$$\varepsilon_R = \frac{P_{radiated}}{\mathrm{P}_{\mathrm{totalpower}}} \tag{2.1}$$

where
ε_R is antenna efficiency
$P_{radiated}$ is antenna radiated power [W]
$P_{totalpower}$ is antenna total power [W]

$$P_{totalpower} = P_{radiated} + P_{loss} \tag{2.2}$$

where
$P_{totalpower}$ is antenna total power [W]
$P_{radiated}$ is antenna radiated power [W]
P_{loss} is antenna loss power [W]

$$\varepsilon_T = M_L \times \varepsilon_R \tag{2.3}$$

where
ε_T is antenna total efficiency
M_L is antenna loss due to impedance mismatch
ε_R is antenna radiation efficiency

The higher efficiency antenna means there is more power present at its input radiated away. On the other hand, the power efficiency antenna, there is more power absorbed as losses within itself or mismatching with impedance.

2.3.4 Impedance

Normally, there are two categories for antenna impedance, which are 50Ω and 75Ω. A mismatching antenna will not radiate power, therefore, a well-matched antenna is playing an important role in wireless communication. The specification of impedance is input reflection coefficient (S11) or Voltage Standing Wave Ratio (VSWR). For a well-matched antenna, its input reflection coefficient should less or equal to -10dB and VSWR should less or equal to 2:1.

2.3.5 Directivity and Gain

In the antenna parameters, the directive and gain of antenna are playing an important role.
The directivity of antenna, which is a component of its gain, is a figure of merit in electromagnetics. In mathematically, the equation for directivity is:

$$D = \frac{1}{\frac{1}{4\pi}\int_{2\pi}^{0}\int_{\pi}^{0}|F(\theta,\phi)|^2 \sin\theta d\theta d\phi} \tag{2.4}$$

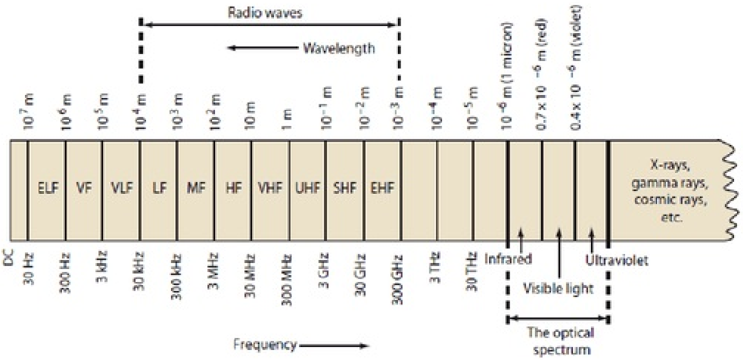
where
D is the directivity of antenna
$F(\theta, \phi)$ is the normalized radiation pattern of antenna.

The gain or power gain of an antenna can be defined as the ratio of antenna radiation intensity in a particular direction (typically the direction of peak radiation) to the radiation intensity of an isotropic antenna. In most of cases the unit of gain is dBi (decibel over isotropic). An antenna with higher gain will radiate most of its power preferentially in particular directions, but a low-gain antenna will emit radiation in all directions equally. The antenna with high value of gain has the advantage of better signal quality and longer range in particular, but must be careful when matching another antenna.

$$G = \varepsilon_R \times D \tag{2.5}$$

where
G is th gain of antenna
D is the directivity of antenna
ε_R is antenna radiation efficiency

2.4 Extremely High Frequency (EHF)



1. The electromagnetic frequency spectrum ranges from dc to light. The lower radio frequencies are designated mainly by frequency. The optical ranges are referred to by wavelength.

Figure 2.3: Electromagnetic Frequency Spectrum Ranges

Extremely high frequency is the International Telecommunications Union (ITU) designation for the band of radio frequencies in the electromagnetic spectrum from 30 to 300 gigahertz. Radio waves in this band are named millimeter band or millimeter wave (mmW), have wavelengths from 10 to 1 mm. It is longer than infrared waves or x-rays, but shorter than radios or microwaves.
Radio waves in EHF band have high atmospheric attenuation and free space loss compared to lower bands. Therefore, they are a short range and can only be used over few kilometers. However, the short wavelength is useful for densely packed communications network especially suitable for indoor personal area networks. Millimeter waves allow high digital data ratios which can reach 10Gbit/s and more. Their propagation characteristic let them useful in a variety of applications, specially for large amounts data transmission. In microwave frequencies and below, the wireless data ratios are limited to around 1Gbit/s which is much less than the millimeter wave. What is more, short wavelength makes very small antennas necessary and possible while Integrated circuits(ICs) keep the circuitry small. A small antenna can steer and focus the energy for greater power, gain and range [49].

Advantages of EHF

- Higher transmission rate.
- More Bandwidth is available.
- Reduces hardware size
- The radio spectrum is still undeveloped.

Disadvantages of EHF

- Higher costs in manufacturing.
- Extremely high frequencies have significant attenuation.

Table 2.1: Comparison of Different Frequency and Their Applications

Name	Frequency (Hz)	Wavelength	Main Application
Very low frequency(VLF)	3-300k	10-100km	Navigation,time standards
Low frequency(LF)	30-300k	1-10km	Marine and aircraft navigation
Medium frequency(MF)	300k-3M	100m-1Km	Meium-wave broadcast(AM)
High frequency(HF)	3-30M	10-100m	Ship and aircraft communications, short-wave broadcasting, amateur radio
Very high frequency(VHF)	30-300M	1-10m	TV broadcast, Land mobile
Ultra high frequency(UHF)	300M-3G	10cm-1m	Aircraft radar,cell phones and mobile radio, Personal-area networks
Super high frequency(SHF)	3-30G	1-10cm	Radio astronomy and space research, Satellite broadcast, Electronic communications for public and private sectors
Extremely high frequency(EHF)	30-300G	1mm-1cm	Various radars for satellite communications, Terrestrial communications, Millimeter wave relay for public use

2.5 Three Regions of Electromagnetic Field

Typically, there are three regions of space around the antenna which are reactive field, radiating near-field and radiating far-field.

1. Reactive field
   The extent of reactive field is $0 < d < \frac{\lambda}{2\pi}$ where d is the distance between transmitting antenna with receiving antenna and λ is the wavelength. In this region the relation between the strengths of the E and H field is very intricate. In order to calculate the reactive field power, both E and H field need to be measured and phase relationship and the angle between them must be know. Therefore, it is too complex to find out the power density in this regions.

2. Radiating near-field
   The extent of radiating near-field is $\frac{\lambda}{2\pi} < d < \frac{2\mathrm{D}^2}{\lambda}$ where D is the largest dimension of the antenna. Compared with the reactive field, the E and H field relation is more predictable, but still complex not only in measurement and calculation but also exist unanticipated conditions.

3. Radiating far-field
   Typically the radiating far-field is defined as the distance around the antenna is $r > \frac{2\mathrm{D}^2}{\lambda}$. The radiation pattern of the antenna under test is essentially independent of the distance of the source antenna in this region. Therefore, a large number of antenna performance such as gain, radiation patterns can be measured in this field.

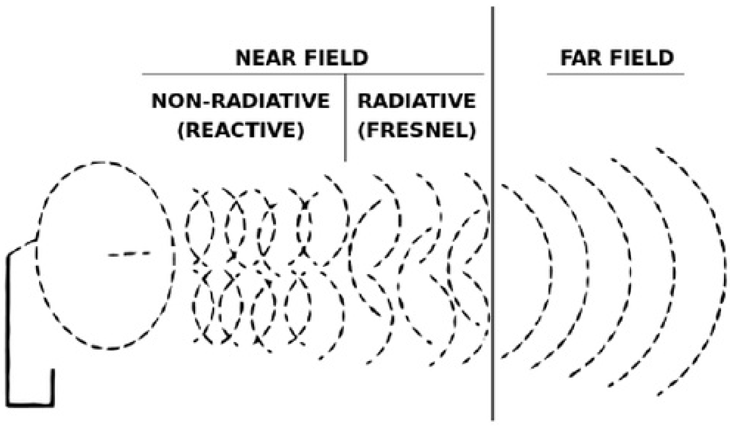


Figure 2.4: Three Regions [51]

Chapter 3

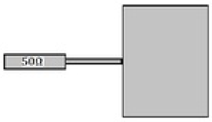
Literature Review

3.1 Feeding Techniques

There are four most popular microstrip feeding techniques which are microstrip line feeding, coaxial probe feeding, proximity coupled feeding and aperture coupled feeding [5]. These four feeding techniques can be classified into two main categories, microstrip line feeding and coaxial probe feeding are in contacting methods, proximity coupled feeding and aperture coupled feeding are in no-contacting methods.
Contacting methods are pretty widely used in a large number of antenna design [47] because they are not only easy to design and analyze but also easy to fabricate. Compared with contacting methods, non-contacting methods are relatively complex in both design and analysis. When using these methods, designers have to consider dielectric constant and thickness of two substrates, effects of the coupling capacitor between the patch and feeding line. However, using aperture coupled feeding technique can achieve wider bandwidth.

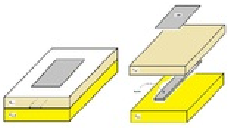
Table 3.1: Comparison of Four Feeding Methods

Characteristics	Microstrip line feeding	Coaxial probe feeding	Proximity coupled feeding	Aperture coupled feeding
Feed radiation	More	More	Minimum	Less
Reliability	Better	Poor	Good	Good
Impedance matching	Easy	Easy	Easy	Easy
Fabrication	Easy	Soldering and drilling needed	Alignment required	Alignment required
Bandwidth	2-5%	2-5%	2-5%	13%

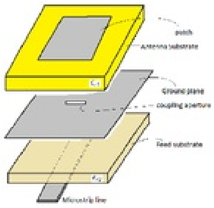


(a) Transmission line feeding

(b) Coaxial probe feeding



(c) Proximity coupled feeding



(d) Aperture coupled feeding

Figure 3.1: Four Feeding Methods

3.1.1 Transmission Line Feeding

Printed transmission lines are widely used in the microstrip antenna design, because of they are reality light weight, high efficiency, more reliable, easy for fabrication and low cost [42] [32]. There are six different transmission lines, which are microstrip line, stripline, suspended stripline, slotline, coplanar waveguide and finline, are generally used in the design. Therefore, get the knowledge about the basic principles of transmission liens are very useful for the further antenna design.

Microstrip Line

Microstrip is one of the most popular structure used in microstrip antenna design and development because of it is very easy in fabrication and troubleshooting. It can be modified to suspended microstrip line, inverted microstrip line and shielded microstrip line. They can support low to high radiation. Their impedance range is from 20 to 120 and quality factor (Q factor) is from 100 to 250.

- Advantages:
  1. Smaller size
  2. Easy to manufacture
  3. Easy to tune and troubleshoot
- Disadvantages:
  1. Higher loss
  2. Unwanted radiation

Stripline

Stripline looks like a sandwich structure, its ground planes exist on both side of the substrate and the metal strip lies at the middle. Compared with the microstrip line structure, stripline structure provides medium for electromagnetic waves. The impedance range they can support is from 35 to 250Ω and quality factor of them is around 400.

- Advantages:
  1. Good electromagnetic waves shielding
  2. Low attenuation loss
  3. Wider bandwidth
  4. Better isolation
- Disadvantages:
  1. Complex and expensive in manufacture
  2. Complex in tuning and troubleshooting
  3. Compare to microstrip line, stripline trace width is smaller in same impedance and height

Suspended stripline

Suspended stripline structure is enclosed, strip inside is etched out on a thin substrate. Shielded high-quality suspended stripline, shield suspended stripline and shielded suspended double-substrate stripline are a kind of suspended stripline. They have low radiation and their impedance range is from 40 to 150Ω. However, the quality factor them offer is very high which is up to 500.

- Advantages:
  1. No spurious radiation
  2. Low attenuation loss
  3. High Q factor
  4. Wider bandwidth of operation
- Disadvantages:
  1. Complex and expensive in manufacture
  2. Complex in tuning and troubleshooting

Slotline

Slotline is a kind of planar transmission line. Small narrow slot is etched out on one side of the dielectric substrate, but no metallic on the other side. In this design, the slotline characteristic impedance depends on the slotline width. As the increase in slotline width, the impedance will increase as well.
Slotline can be modified to antipodal slotline and bilateral finline. In slotline, the radiation is medium, quality factor is around 100 and impedance is from 60 to 200Ω.

- Advantages:
  1. Can be etched along with microstrip line on same PCB
  2. Easy to manufacture
  3. Easy to tune and troubleshoot
- Disadvantages:
  1. Can not be used in broadband circuit designs

Coplanar waveguide

Coplanar waveguide has a conductor strip between two ground planes which are on one side of substrate [20] [41]. The conductor strip and the space between the strip and ground planes determine the coplanar waveguide characteristic impedance. The impedance will decrease along with the increase in the strip width.
In symmetrical coplanar waveguide and shielded coplanar waveguide, the radiation is medium, quality factor is about 150 and impedance is from 20 to 250Ω.

- Advantages:
  1. Low dispersion
  2. Easy to achieve due to etching on one side
  3. Good broadband performance
- Disadvantages:
  1. Expensive in manufacture
  2. Relative thick substrate

Finline

Finline can be modified to bilateral slotline, antipodal finling and antipodal overlapping finline. They can support transverse electromagnetic (TEM mode). Therefore, radiation of finline is zero. However, they can support 10 to 400Ω impedance range and the quality factor is around 500.

- Advantages:
  1. Low dispersion
  2. Broader bandwidth
  3. Easy for isolator and circulator design
- Disadvantages:
  1. Complex in assembly
  2. Complex and expensive in manufacture

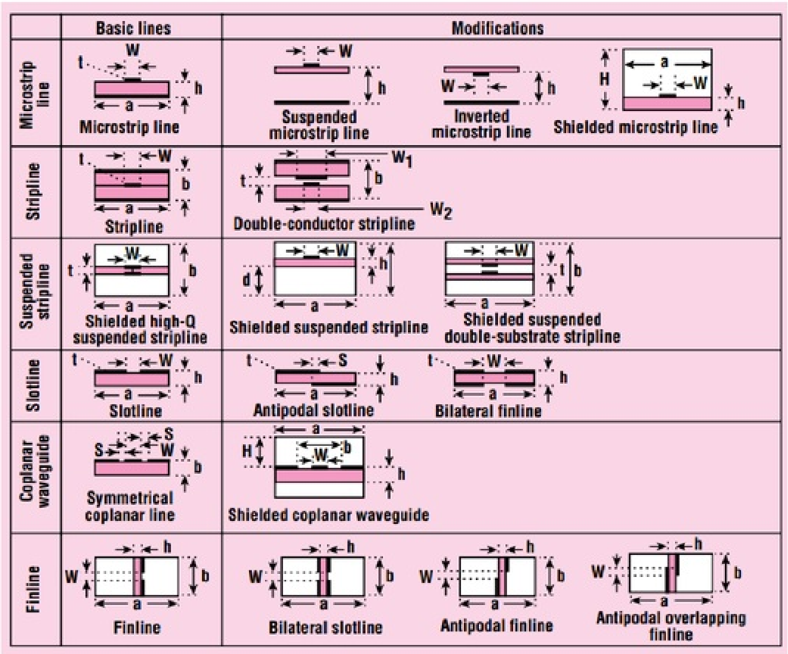


Figure 3.2: Types of Printed Transmission Line

3.1.2 Coaxial Probe Feeding

In coaxial probe feeding, a 50Ω coaxial cable and N type coaxial connector [39] can easy to match 50Ω input impedance. The N type coaxial connector is located on the ground plane of microstrip antenna. Meanwhile, the center connector of the coaxial is passed through the substrate and soldered to the patch on the other side of substrate.

3.1.3 Proximity Coupled Feeding

Two substrates are required in proximity coupled feeding. The patch is located on the top of upper substrate, feeding line is located between two substrates and the ground plane is on the bottom of lower substrate.

3.1.4 Aperture Coupled Feeding

In aperture coupled feeding, there are two substrates as well. Unlike the proximity coupled feeding, the ground plane of aperture coupled feeding is located between two substrate and has a rounded or rectangular aperture. The patch is located on the upper substrate and the feeding line is on the bottom of lower substrate.

3.2 Quasi-Yagi Antenna Design

A typical Yagi-Uda antenna has a driven element, a reflector and one or more directors [22]. It can generate end-fire beam through matching appropriate phase and amplitude conditions (opposite phase and equal amplitude) for the closely-spaced driven dipole, reflector and director [19]. In the Yagi-Uda antenna a few elements are fed directly, therefore some other elements are used to receive their excitation by near field coupling. For example, reflector and director are design to change the pattern through feed. Compared with some other designs the microstrip Yagi-Uda Antenna has more advantages such as relatively high gain, easy to fabricate and low manufacture cost [43]. It can be used in HF, VHF and UHF. microstrip Yagi-Uda antenna has been designed through wire dipole or print dipole antenna, until 1991, the first microstrip Yagi-Uda antenna were presented by John Huang [17]. Recently, because of relatively good performance of microstrip Yagi-Uda antenna, it has drawn much attention. It was not only presented [32] but also optimized [21] in millimeter-wave band.
According to literature review study, the shapes of microstrip Yagi-Uda antenna are diverse [52] [24]. In order to achieve a better performance or meet the special requirements, in the quasi-Yagi antenna, the driven dipole and directors can be placed on both sides of the substrate [53], using the truncated ground as the reflector [32] [8] or even no reflector [27].

1. Simplified feed for modified microstrip Yagi antenna design
   In the simplified feed for modified microstrip Yagi antenna design [53], on the top

layer of substrate are a microstrip line, one of the parallel lines, one arm of the printed dipole antenna (driven dipole) and the director element. On the other side of substrate, there are a ground plane acts as a reflection element, another parallel line and the other arm of the dipole antenna (opposite direction driven dipole). In this design, the driven dipole is fed by an uni-planar microstrip-to-coplanar strip(CPS) transition as a broadband balun which is achieve by matching T-junction through extend the microstrip line by a half wavelength. The geometry of the antenna is shown on Figure 3.3. In some other design [10], a half wavelength long delay line is designed to create an unbalanced condition of the antenna operation. However, this kind of design will affect the antenna radiation pattern within matching bandwidth [53].

This Yagi-Uda Antenna was design on Rogers Dourid/RT6010 substrate which dielectric constant is 10.2 and thickness is 0.635mm. Its dimensions are shown on Table 3.2.

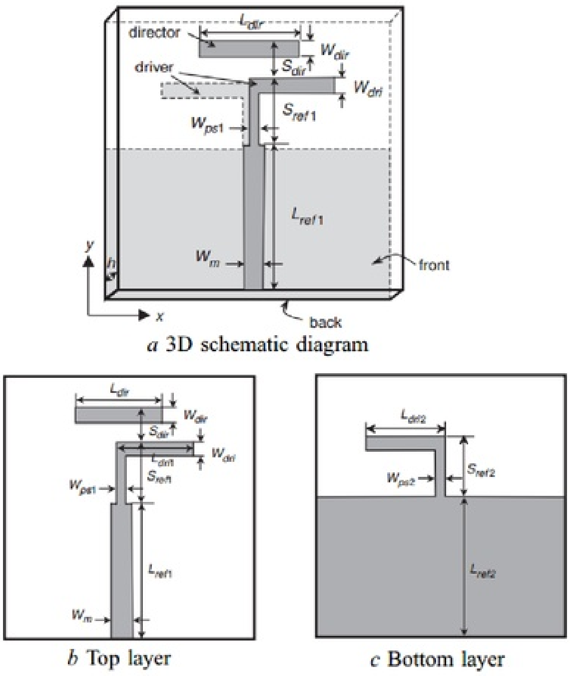


Figure 3.3: Geometry of Simplified Feed for Modified Printed Yagi Antenna [53]

Table 3.2: Parameter Values of the Simplified Feed for Modified Printed Yagi Antenna [53]

Parameter	Values(mm)
W_m	0.9523
L_{ref1}	16
L_{ref2}	16
W_{ps1}	0.4442
W_{ps2}	0.4442
S_{ref1}	7.5
S_{ref2}	7.5
W_{dri}	0.6
W_{dir}	0.6
S_{dir}	2.58
L_{dir}	2.84

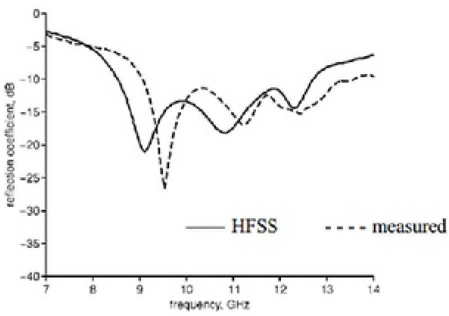


Figure 3.4: Reflection Coefficient of Modified Printed Yagi Antenna [53]

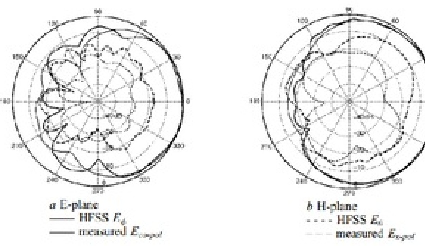


Figure 3.5: Radiation Patterns of Modified Printed Yagi Antenna at 10 GHz [53]

After the simulation and measurement, the 10dB return loss bandwidth of the antenna over 40% in the range from 7 to 14GHz. At 10GHz, its radiates end-fire patterns with cross-polarization level was around -20dB and front-back ration was about 15dB.

2. Slot-line-fed Quasi-Yagi antenna design
   In Slot-line-fed Quasi-Yagi antenna design [44], all elements are located on the top layer of the substrate. The antenna contents a slot line as the feed, a ground plane which is used as a reflector, a driven element and a director. In this design, the feed line impedance is lower than the input impedance at the driven element. In order to improve the impedance matching, the authors extend the distance between two feed lines step by step. The configuration of the antenna is shown on Figure 3.6.
   This Yagi-Uda Antenna was design on Rogers Dourid/RT6010 substrate which dielectric constant is 10.2 and thickness is 0.635mm. Its dimensions are shown on Table 3.3.

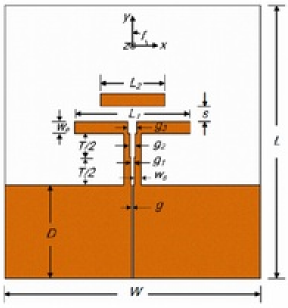


Figure 3.6: Configuration of Slot-line-fed Quasi-Yagi Antenna [44]

Table 3.3: Parameter Values of Slot-line-fed Quasi-Yagi Antenna [44]

Parameter	Values(mm)
T	10
L_1	20
L_2	9.5
W_e	2
W_s	1
s	1.
g	0.14
g_1	0.2
g_2	0.3
g_3	0.4

According to the simulation and measurement result, the 10dB return loss bandwidth of the antenna was approximately 55% and its front-to-back ratio is higher then 18dB. Furthermore, the gain of antenna in operating band width was between

4.9 with 5.6dBi.

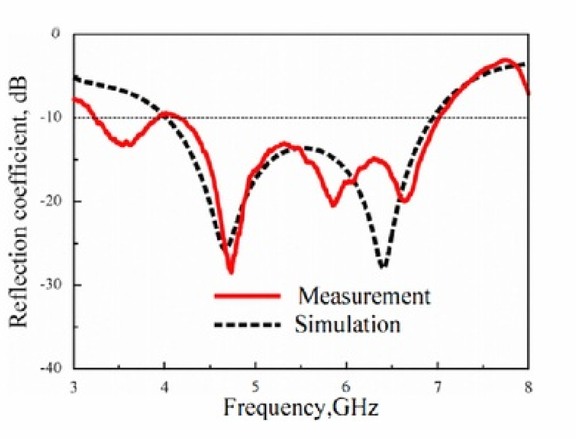


Figure 3.7: Reflection coefficient of Slot-line-fed Quasi-Yagi Antenna [44]

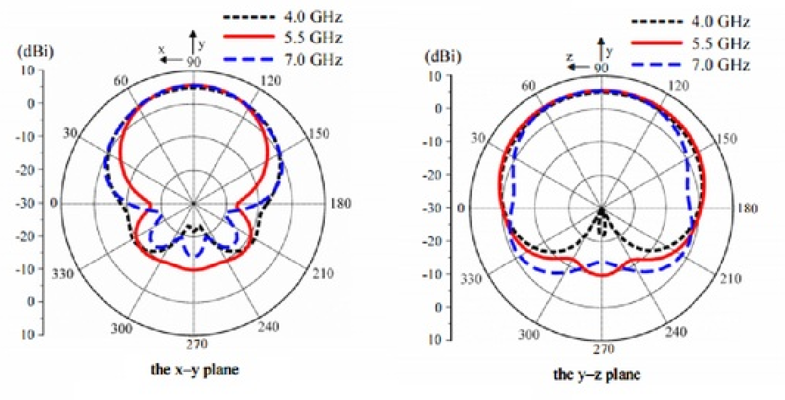


Figure 3.8: Radiation patterns of Slot-line-fed Quasi-Yagi antenna [44]

3. Simple broadband planar CPW-Fed Quasi-Yagi Antenna design
   In simple broadband planar CPW-Fed Quasi-Yagi Antenna design, all elements are on the one side of substrate. This antenna has two directors, a driven element, two parallel strips and a ground plane acts as a reflector. These two strips are connected to the driven element on one end and on the other end, one strip is connected to the feed and the other strip is connected to the ground. In this antenna, balun design is not necessary but both sides of the substrate must be etched.

This Yagi-Uda Antenna was design on Rogers Dourid/RT6010 substrate which dielectric constant is 10.2 and thickness is 0.635mm. Its dimensions are shown on Table 3.4.

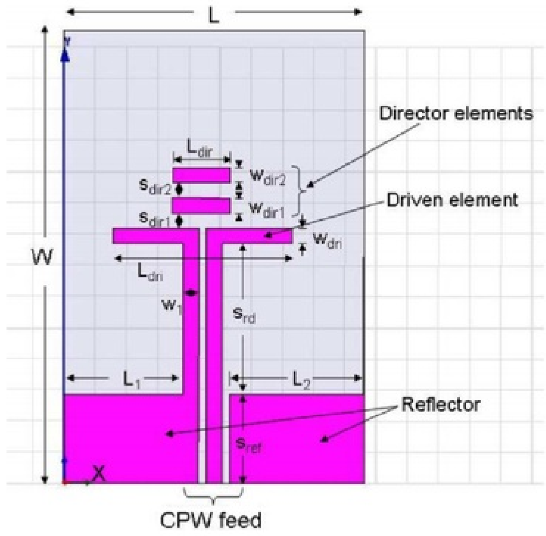


Figure 3.9: Configuration of CPW-Fed Quasi-Yagi Antenna [20]

Table 3.4: Parameter Values of CPW-Fed Quasi-Yagi Antenna [20]

Parameter	Values(mm)
L	19.2
W	29
L_{dir}	3.37
S_{dir1}	0.96
S_{dir2}	0.96
W_{dir}	0.96
W_{dir1}	0.96
W_{dir2}	0.96
L_{dri}	11.5
W_1	1
L_1	7.61
L_2	8.61
s_{rd}	9.69
s_{ref}	5.69

According to the measurement result, the gain of this antenna was between 3.4

with 7.4dBi from 8-12GHz and the peak gain appeared at 10GHz. Furthermore, this antenna achieved 44% 10dB return loss bandwidth.

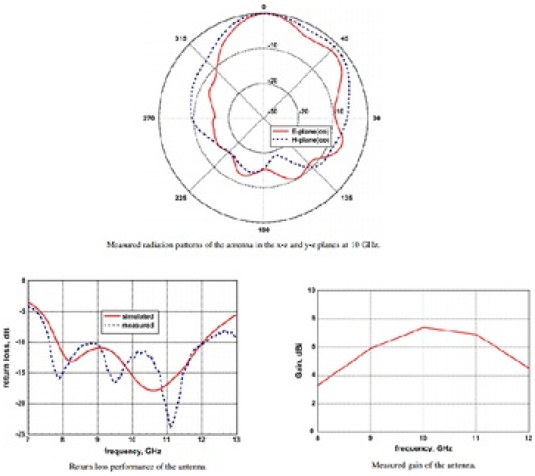


Figure 3.10: Simulation and Measurement Results of CPW-Fed Quasi-Yagi Antenna [20]

Through background learning and literature review, the antenna basics were familiarize. In this chapter, there are three antenna designs were provided. Although the slot-line-fed quasi-Yagi antenna can provide high bandwidth, its structure is relatively complex. Therefore, my quais-Yagi antenna design will start with simplified microstrip line feeding.

Chapter 4

Antenna Design

In this chapter, a 60GHz quasi-Yagi antenna design, optimization, simulation and fabrication is presented. This antenna elements design is based on the classic Yagi-Uda dipole antenna which contains driven element, reflector and one or more directors. The driven element is fed by a microstrip line and a parallel coplanar strip lines (CPS) on opposites sides of the dielectric substrate. The antenna design, optimization and simulation are achieved by using Computer Simulation Technology Microwave Studio (CST MWS) which not only provides a variety of functions and tools for each stage of antenna design but also has different simulation methods to meet the needs. Due to fabrication complexity, the antenna had to be sent outside to fabricate.

4.1 Design Procedure

4.1.1 Initial Design

At the beginning of design, a suitable substrate for 60GHz frequency band is pretty important. A low-loss Rogers RT/Duroid 5880 substrate is used in many 60GHz microstrip design [6] [16]. It is high frequency laminate which is used in microstrip and stripline circuits, millimeter wave applications, point-to-point digital radio antennas and so on. The dielectric constant of this substrate is 2.2 and the standard substrate thickness is 0.254mm. The substrate data sheet is attached in Appendix. 18-microns-thick copper will be used as quasi-Yagi antenna elements.
Secondly, the microstrip line need to be designed to match 50Ω impedance. The microstrip line width can be calculated through the formula below [26] [14]:

$$Z_0 = \frac{87}{\sqrt{\varepsilon_\mathrm{r} + 1.14}} \ln(\frac{5.98\mathrm{H}}{0.8\mathrm{W} + \mathrm{T}}) \tag{4.1}$$

where
Z_0 is the impedance [Ω]
ε_r is the substrate dielectric constant
H is the substrate thickness [m]

W is the width of microstrip line [m]
T is the patch thickness [m]

In the design, the substrate thickness is 0.254mm, substrate dielectric constant is 2.2, thickness of patch is 18μm and the impedance required is 50Ω. After calculation, the width of microstrip line is 0.75mm.
This quasi-Yagi antenna feeding network does not need any additional devices such as CPS balun, microstrip-to-slot transition or T-junction. Because in this antenna, there is a CPS line between the microstrip line and driven element, acts as a quarter wavelength transformer. By using this feeding structure, the antenna is operating in the odd-mode at all frequency. [53].
The quasi-Yagi elements have to design after the feeding structure was determined. In classic Yagi-Uda antenna there are three main elements, which are driven element, reflector and one or more directors. The length of these three elements and the spacing between each others can influence the gain, radiation pattern, VSWR and other characteristics.
According to the Yagi-Uda antenna design guidelines [13]. The driven element is slightly less than half wavelength, which typically between 0.45 with 0.49 wavelength.
The reflector is located behind the driven element which reflect and help to transmit the energy in a particular direction and play an important role in determine the antenna front-to-back ratio. Typically, the length of reflector is 0.5 to 0.55 wavelength, approximate by 5% longer than the driven element.
The director of Yagi-Uda antenna is the shortest element which length is typically about 0.4 to 0.45 wavelength approximate by 5% shorter than the driven element. However, the length of director will vary depending on the director spacing and the number of directors. Better result of gain and directionality can be achieved when additional directors are added. As the number of directors is increased, the effect of adding director will decrease and levels out after 12 directors. At the same time, more directors in a quasi-Yagi antenna will lead to larger size and higher fabricating cost. Therefore, in most of the cases, the number of directors is 6 to 12. The distance between directors is around 0.15 to 0.4 wavelength.
The printed Yagi antenna operating band covers from 57 to 63GHz, the center frequency is 60GHz where wavelength of quasi-Yagi antenna is about 3.37mm. According to the Yagi antenna design guidelines the initial parameters of quasi-Yagi antenna can be obtained. The geometry of quasi-Yagi antenna is shown on Figure 4.1.

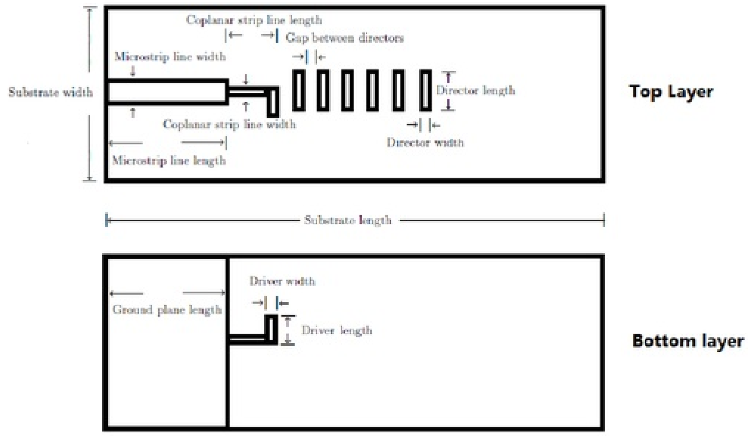


Figure 4.1: Geometry of Quasi-Yagi Antenna

Table 4.1: Parameters of the Initial Design

Parameter	Values(mm)
Wavelength	3.37
Substrate width	10
Substrate length	25
Microstrip line width	0.714
Microstrip line length	9
Ground plane length	9
Coplanar strip line width	0.3
Coplanar strip line length	2.3
Driven element length	1.58
Director length	1.35
Driver and director width	0.3
Gap between directors	0.674

4.1.2 Design and Optimization

In order to improve the quasi-Yagi antenna performance, the microstrip length, CPS length, CPS width, driven element length, directors length, the widths of the driven element and directors and the directors spacing, which are the variation of antenna characteristics, are investigated one by one in frequency range from 57 to 63 GHz.

Each antenna parameter will be modified as follow:

1. Substrate width increased from 6 to 10mm in increment of 1mm. (6, 7, 8, 9, 10mm)
2. Substrate length increased from 20 to 30mm in increment of 2mm. (20, 22, 24, 26, 28, 30mm)
3. Microstrip line width increased from 0.6 to 0.8mm in increment of 0.05mm. (0.6, 0.65, 0.7, 0.75, 0.8 mm)
4. Microstrip line length increased from 7 to 11mm in increment of 1mm. (7, 8, 9, 10, 11mm)
5. CPS width increased from 0.1 to 0.4mm in increment of 0.1mm. (0.1, 0.2, 0.3, 0.4, 0.5mm)
6. CPS length increased from 1 to 4mms in increment of 1mm. (1, 2, 3, 4mm)
7. The widths of the driven element and directors increased from 0.1 to 0.5mm in increment of 0.1mm. (0.1, 0.2, 0.3, 0.4, 0.5mm)
8. Driven element length increased from 0.45 to 0.49 wavelength in increment of 0.01 wavelength. (0.45, 0.46, 0.47, 0.48, 0.49 wavelength)
9. Directors length increased from 0.4 to 0.45 wavelength in increment of 0.01 wavelength. (0.4, 0.41, 0.42, 0.43, 0.44, 0.45 wavelength)
10. Directors spacing increased from 0.1 to 0.5 wavelength in increment of 0.1 wavelength. (0.1, 0.2, 0.3, 0.4, 0.5 wavelength)

After that two or more related parameters will be combined together into three different groups which are substrate size, transmission line and quasi-Yagi elements. Substrate size group contains substrate length and substrate width. Microstrip line length, CPS length and CPS width are three variable parameters in the transmission line group. In quasi-Yagi elements group, there are three variable parameters which are the width of the driven and directors, directors spacing and directors length.

These three groups will be modified as follow:

1. Substrate size:
   - Substrate width was varied from 7 to 9mm in steps of 0.5mm. (7, 7.5, 8, 8.5, 9mm)
   - Substrate length was varied from 26 to 30mm in steps of 1mm. (26, 27, 28, 29, 30mm)
2. Feeding line:

- Microstrip line length was varied from 7 to 9mm in steps of 0.5mm. (7, 7.5, 8, 8.5, 9mm)
- CPS width was varied from 0.3 to 0.5mm in steps of 0.05mm. (0.3, 0.35, 0.4, 0.45, 0.5mm)
- CPS length was varied from 1 to 3mm in steps of 0.5mm. (1, 1.5, 2, 2.5, 3mm)

3. Quasi-Yagi elements:

- The width of the driven and directors was varied from 0.2 to 0.4mm in steps of 0.05mm. (0.2, 0.25, 0.3, 0.35, 0.4mm)
- The directors gap coefficient was varied from 0.2 to 0.4 wavelength in steps of 0.05 wavelength. (0.2, 0.25, 0.3, 0.35, 0.4 wavelength)
- Directors coefficient was varied from 0.42 to 0.44 wavelength in steps of 0.005 wavelength. (0.42, 0.425, 0.43, 0.435, 0.44 wavelength)

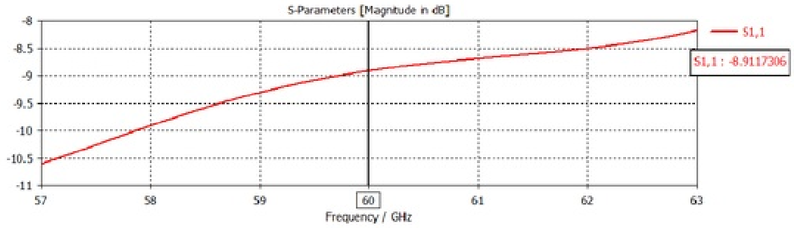
The Yagi-Uda antenna was optimized after simulation and the parameters of it are shown on Table4.2.

Table 4.2: Parameter Values of the Initial Design and Optimized Design

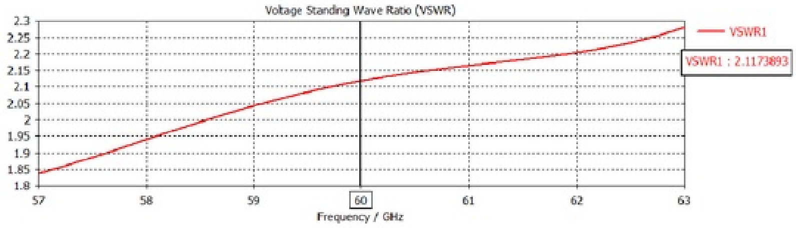
Parameter	Initial Design (mm)	Optimized Design (mm)
Substrate width	10	8
Substrate length	25	30
Microstrip line width	0.714	0.714
Microstrip line length	9	8
Ground plane length	9	8
CPS width	0.3	0.34
CPS length	2.3	2.05
Driven element length	1.58	1.58
Director length	1.35	1.42
Driver and director width	0.3	0.34
Gap between directors	0.674	0.674

4.2 Simulation Results and Analysis

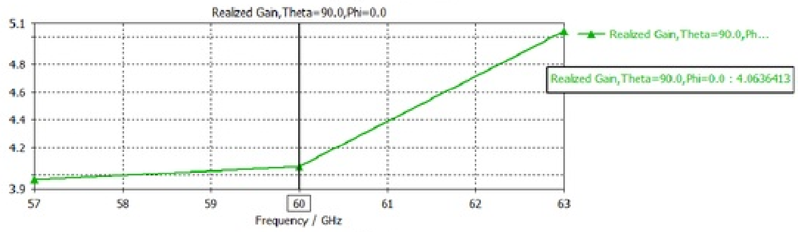
4.2.1 Simulation Results



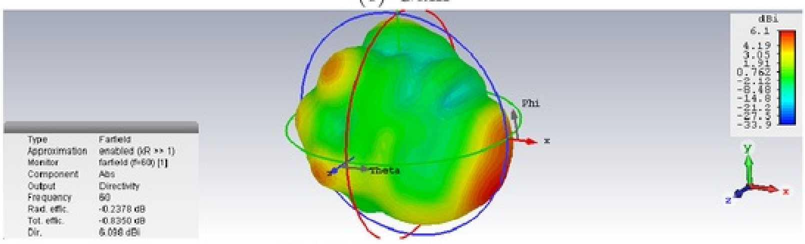
(a) Reflection coefficient



(b) VSWR

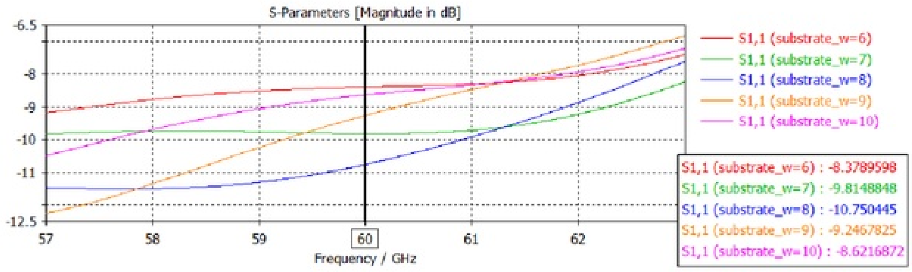


(c) Gain

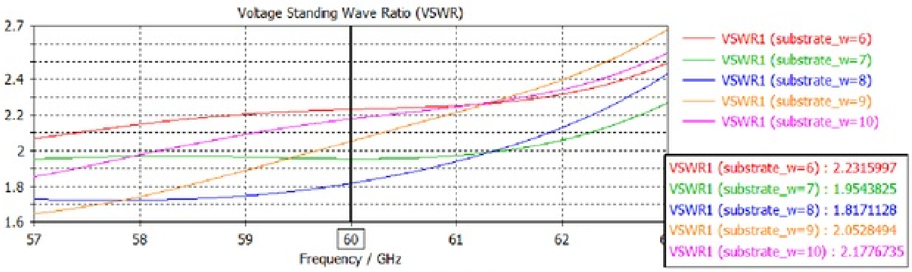


(d) 3D far-field pattern

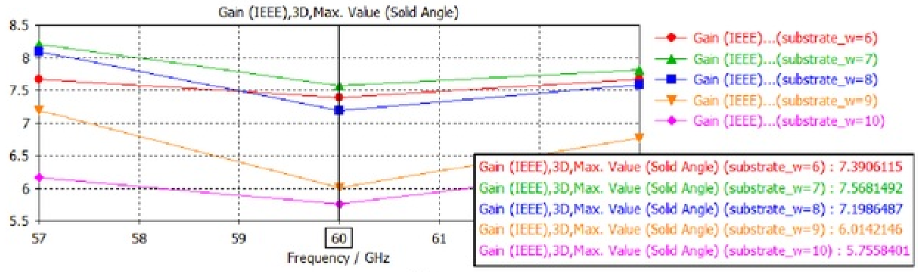
Figure 4.2: Simulation Results of Initial Design



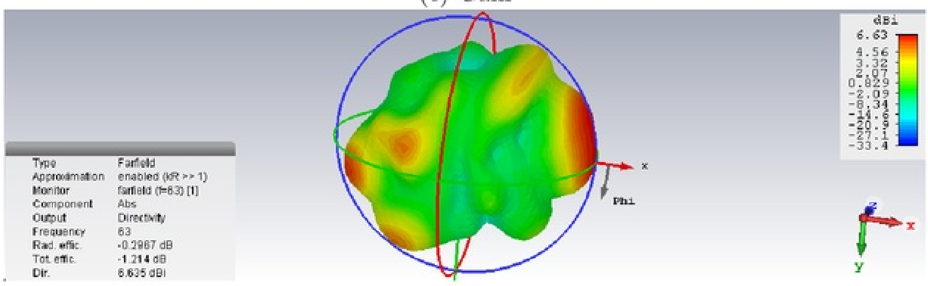
(a) Reflection coefficient



(b) VSWR

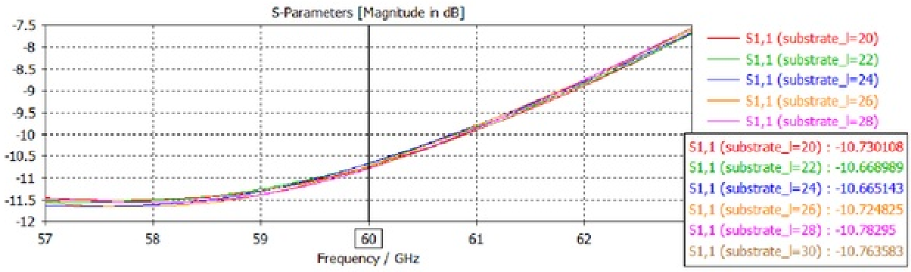


(c) Gain

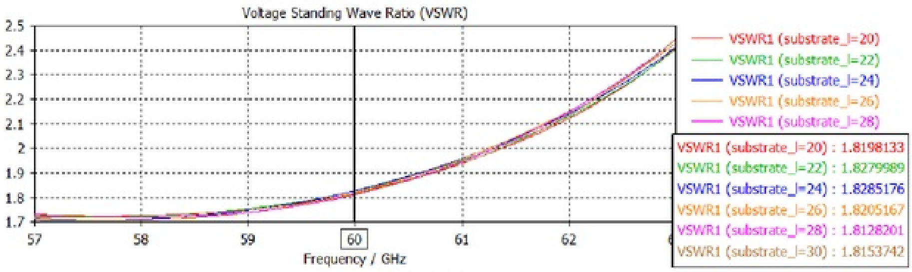


(d) 3D far-field pattern

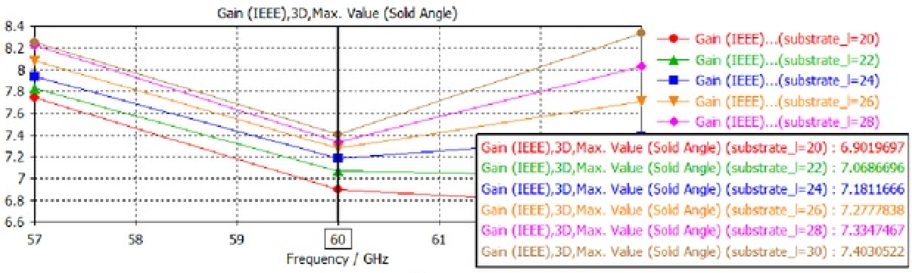
Figure 4.3: Variation in Substrate Width



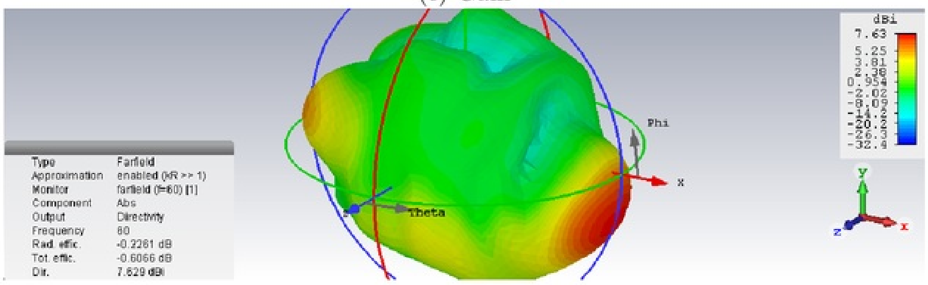
(a) Reflection coefficient



(b) VSWR

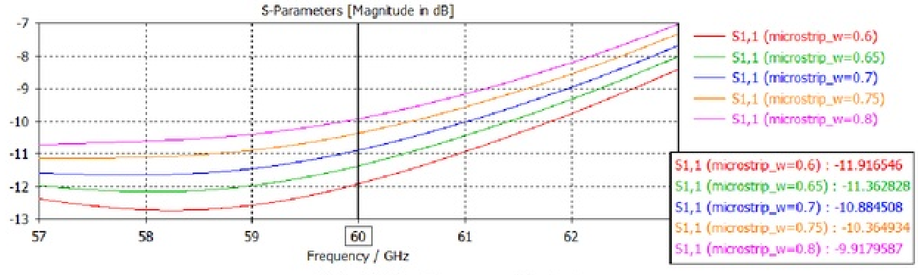


(c) Gain

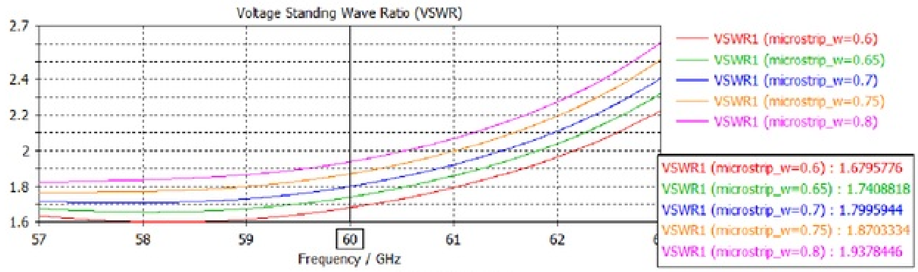


(d) 3D far-field pattern

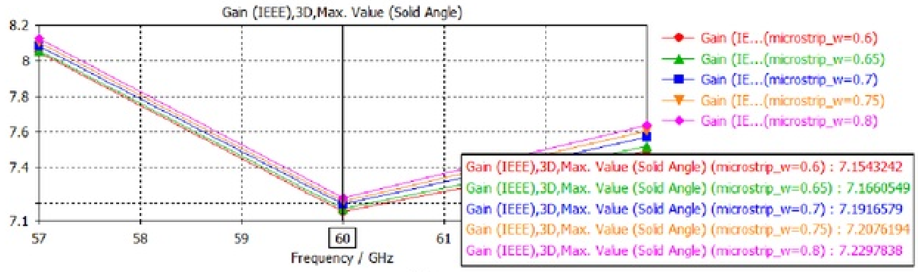
Figure 4.4: Variation in Substrate Length



(a) Reflection coefficient



(b) VSWR



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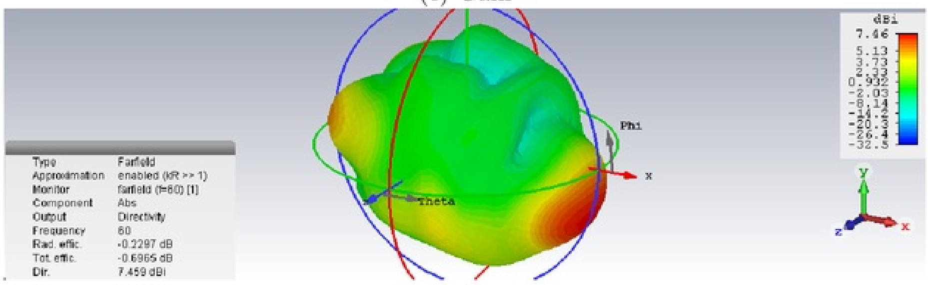
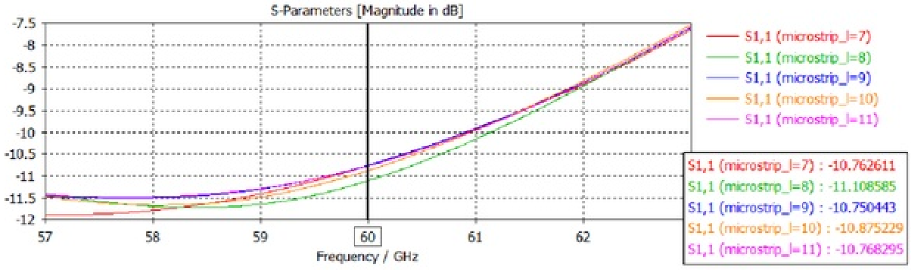
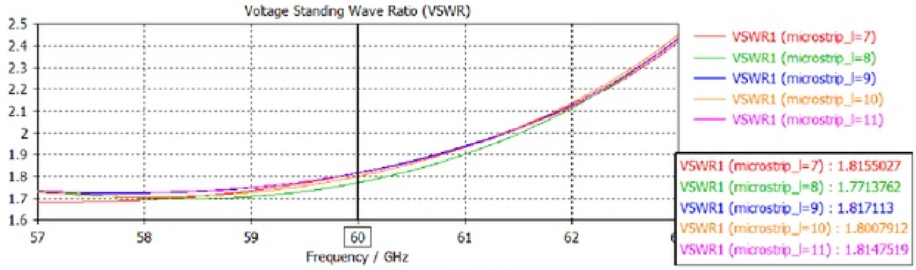


(d) 3D far-field pattern

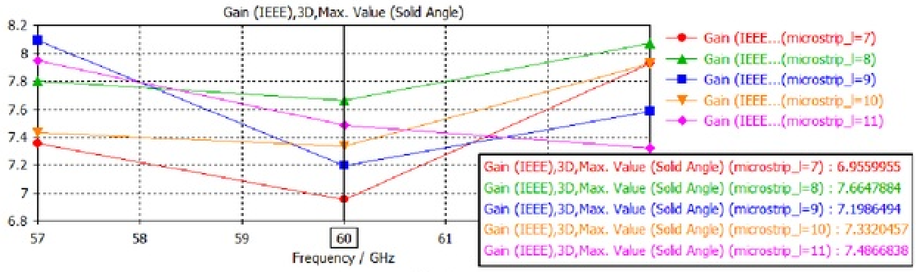
Figure 4.5: Variation in Microstrip Line Width



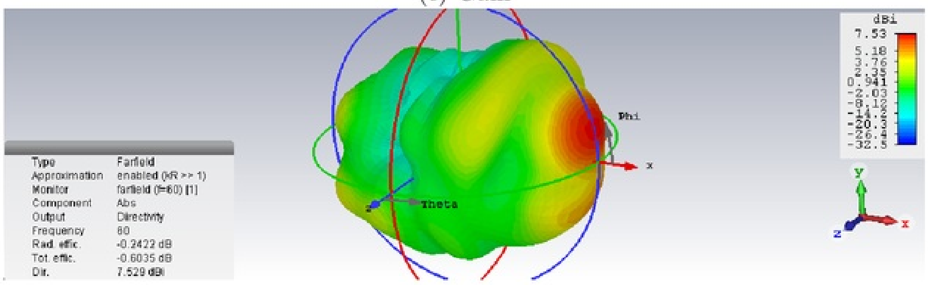
(a) Reflection coefficient



(b) VSWR

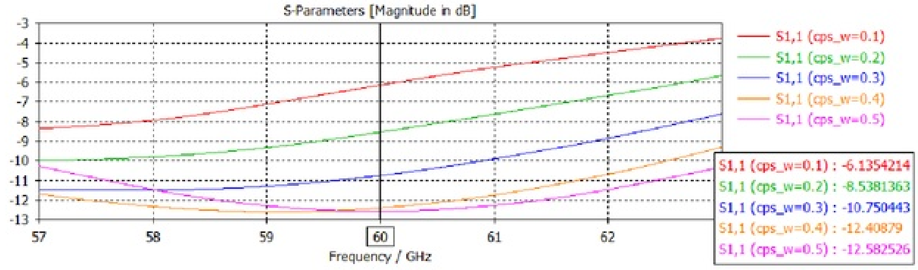


(c) Gain

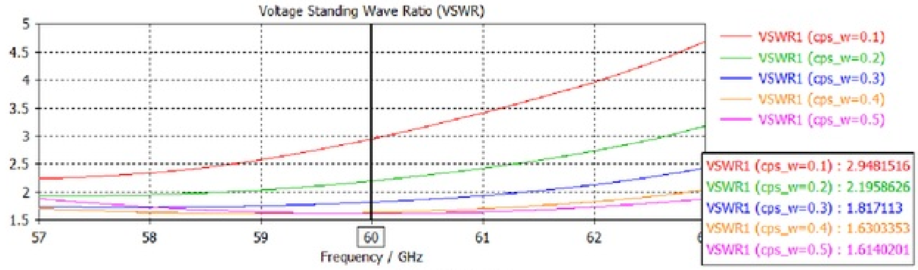


(d) 3D far-field pattern

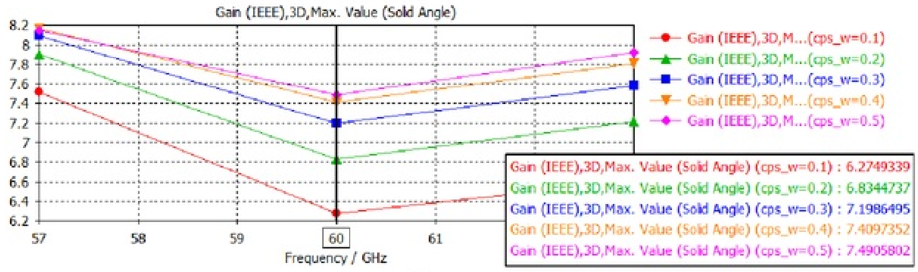
Figure 4.6: Variation in Microstrip Line Length



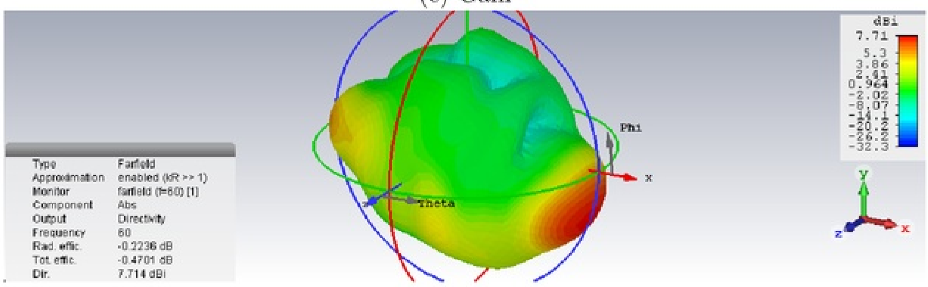
(a) Reflection coefficient



(b) VSWR

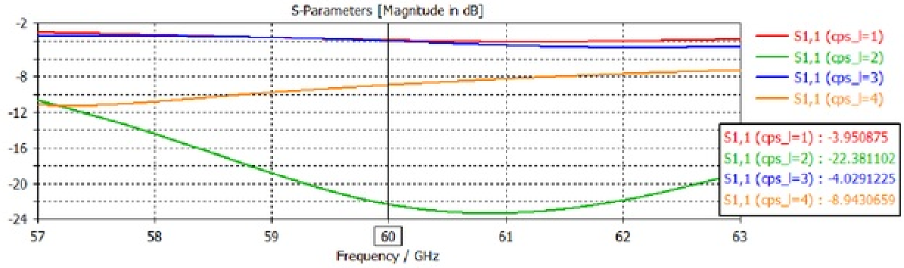


(c) Gain

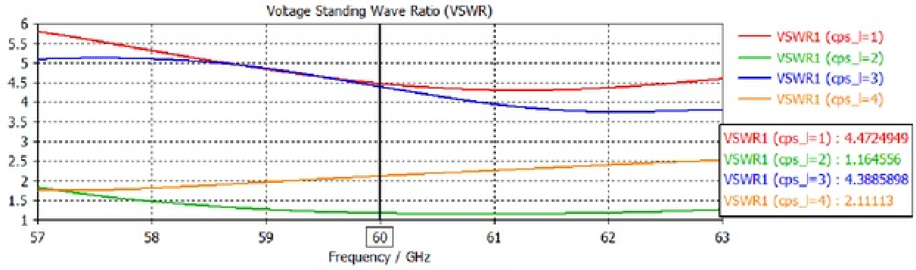


(d) 3D far-field pattern

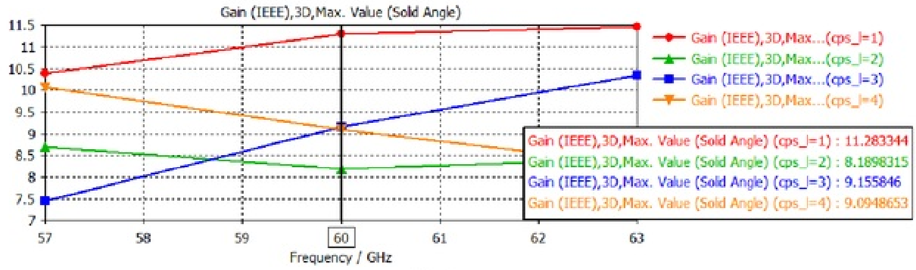
Figure 4.7: Variation in CPS Width



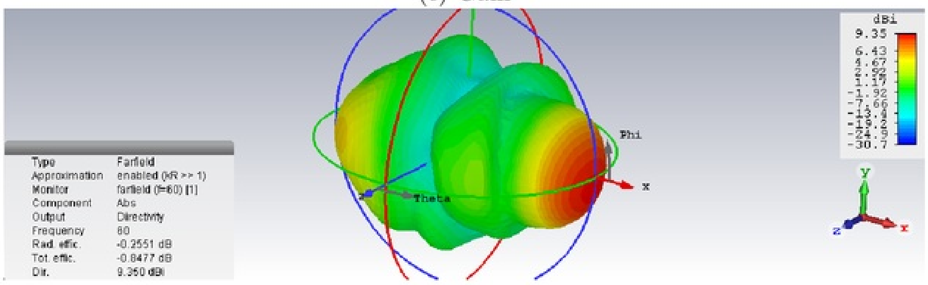
(a) Reflection coefficient



(b) VSWR

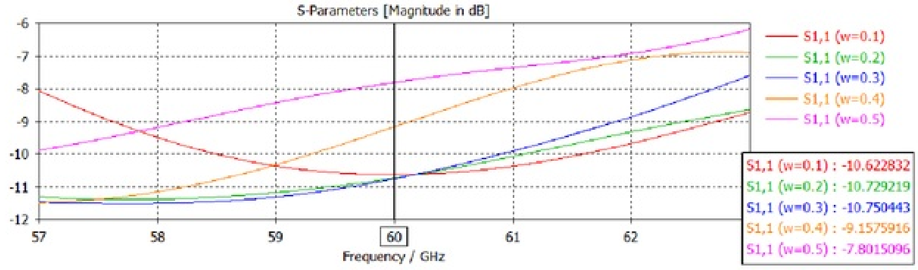


(c) Gain

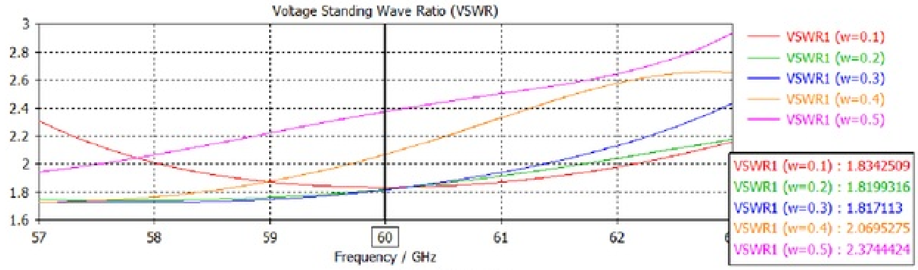


(d) 3D far-field pattern

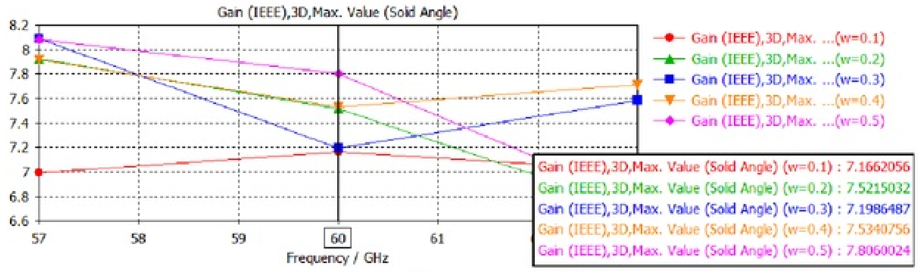
Figure 4.8: Variation in CPS Length



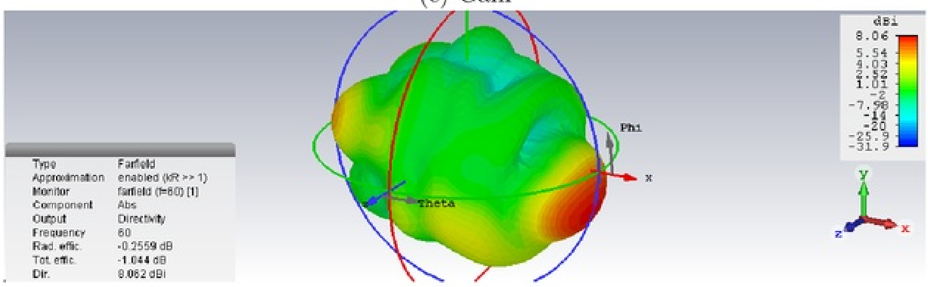
(a) Reflection coefficient



(b) VSWR

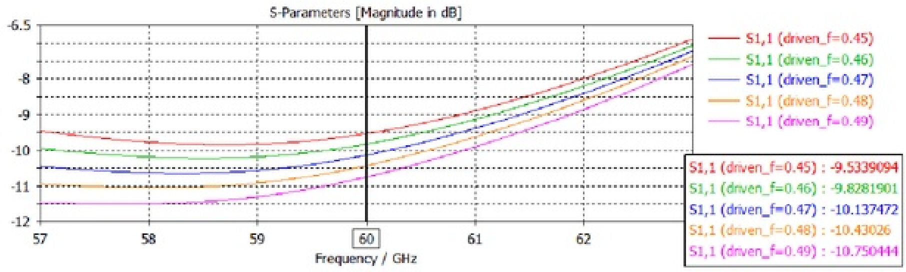


(c) Gain

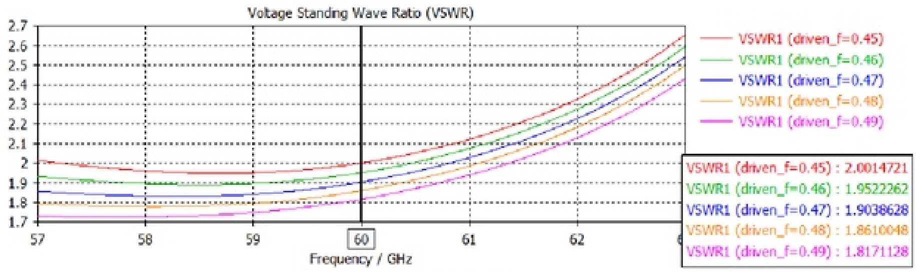


(d) 3D far-field pattern

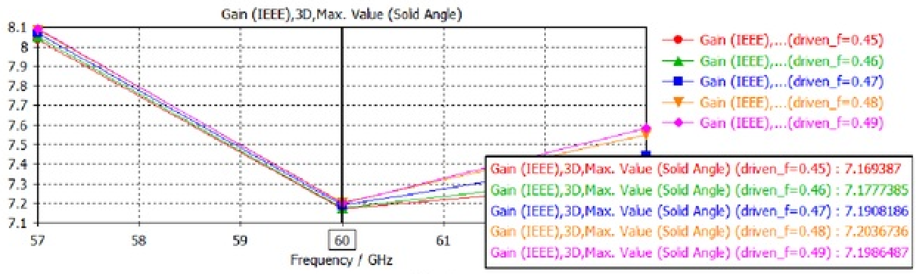
Figure 4.9: Variation in Driven Element and Directors Width



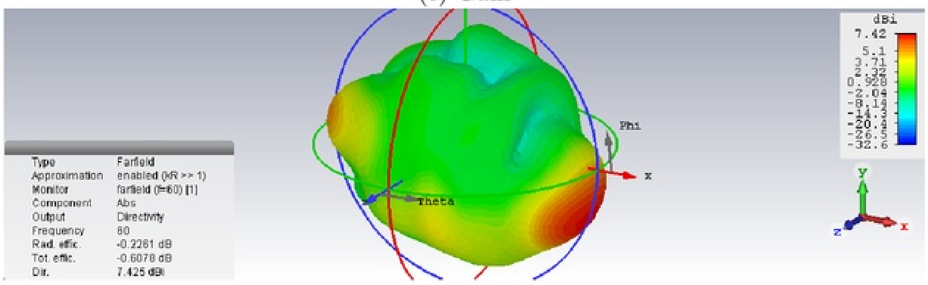
(a) Reflection coefficient



(b) VSWR

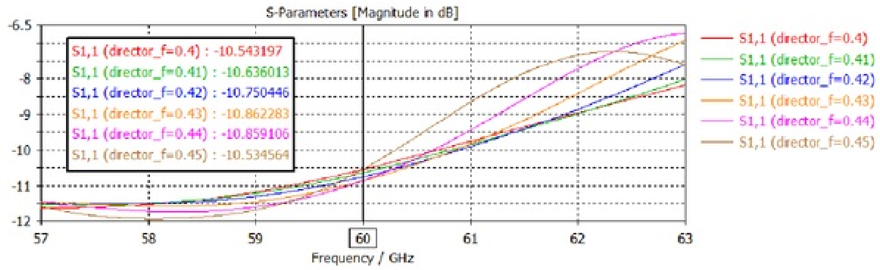


(c) Gain

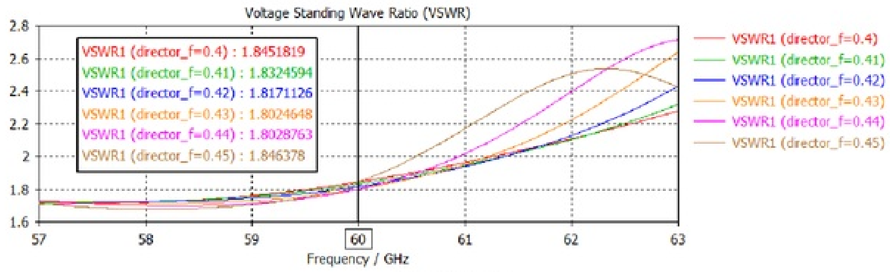


(d) 3D far-field pattern

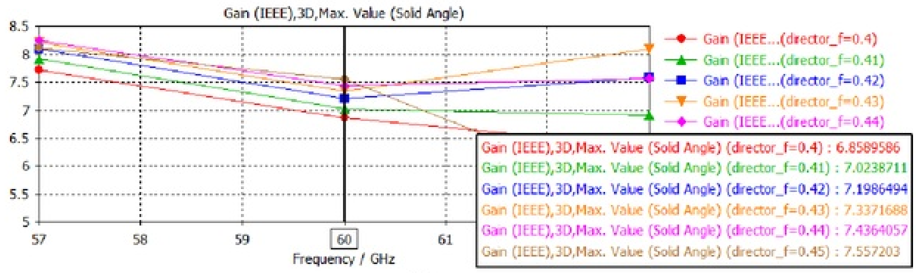
Figure 4.10: Variation in Driven Element Length



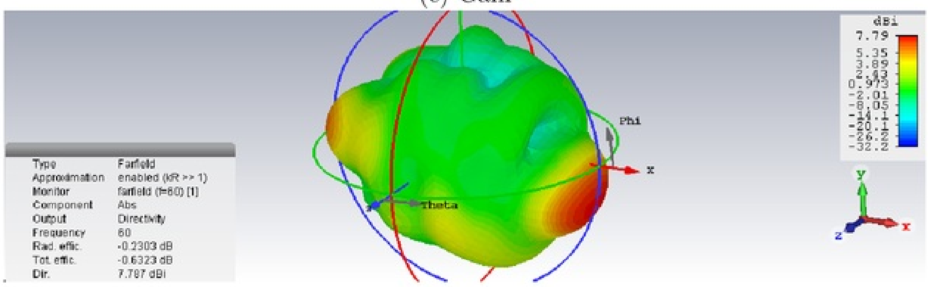
(a) Reflection coefficient



(b) VSWR

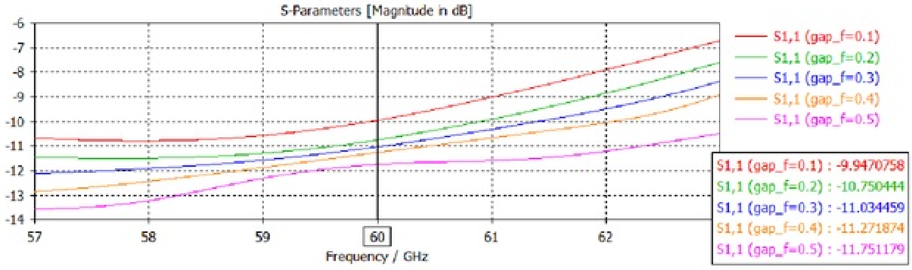


(c) Gain

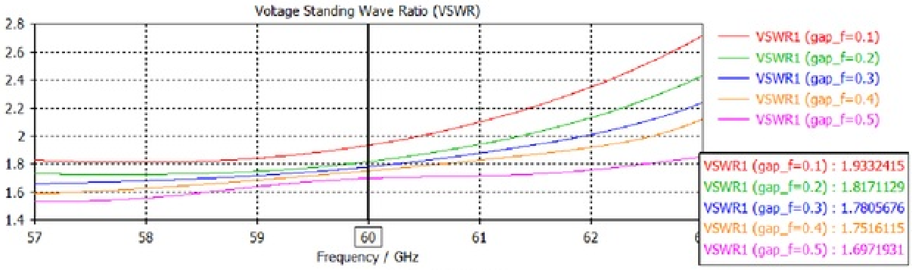


(d) 3D far-field pattern

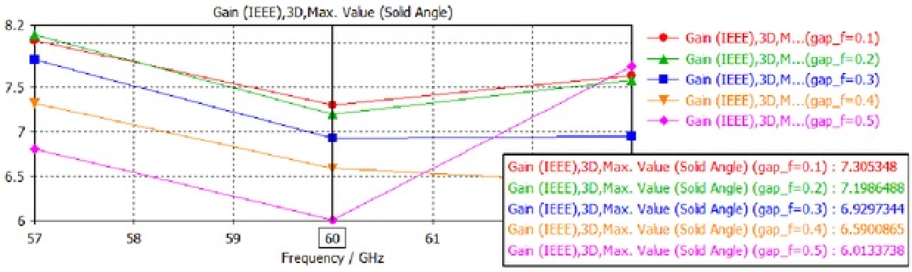
Figure 4.11: Variation in Directors Length



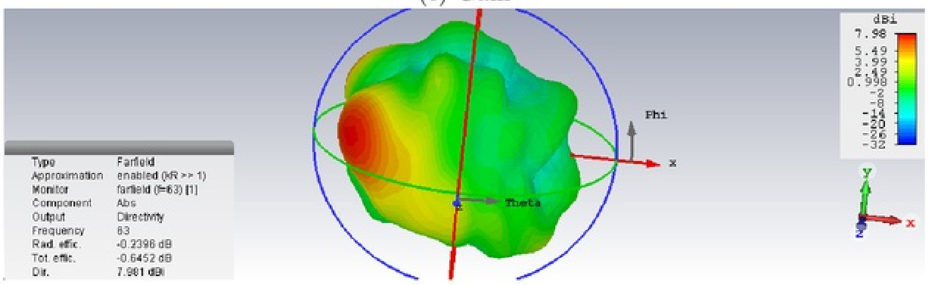
(a) Reflection coefficient



(b) VSWR

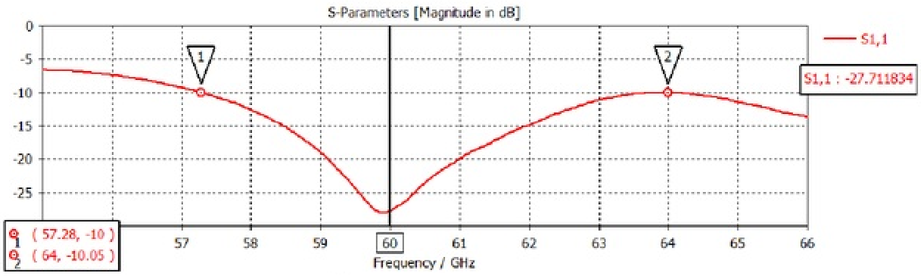


(c) Gain

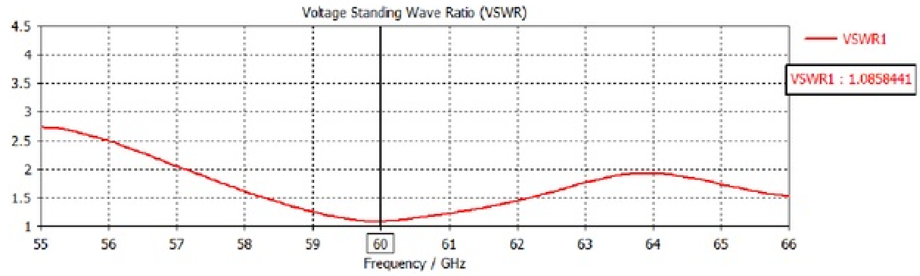


(d) 3D far-field pattern

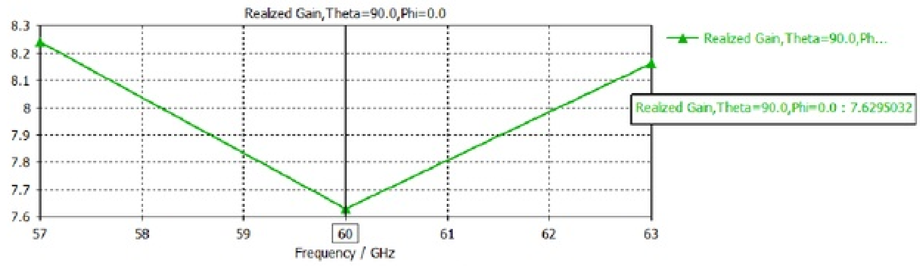
Figure 4.12: Variation in Directors Spacing



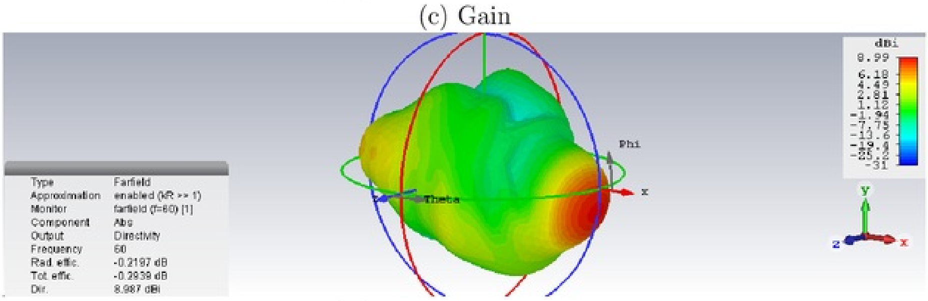
(a) Reflection coefficient



(b) VSWR



(c) Gain



(d) 3D far-field pattern

Figure 4.13: Simulation Results of Optimized Design

4.2.2 Results Analysis

There are three characteristics are interest in a quasi-Yagi antenna, which are reflection coefficient, VSWR and gain.

1. Substrate width

Table 4.3: Simulation Results of Different Substrate Width

Substrate width(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
6	-8.378	2.231	7.390
7	-9.814	1.954	7.568
8	-10.750	1.817	7.198
9	-9.246	2.052	6.014
10	-8.621	2.177	5.755

According to the simulation result of different substrate widths, when substrate width is 6mm, 9mm or 10mm, the reflection coefficient and VSWR are increasing in the frequency from 57 to 63 GHz. In 8mm-width substrate, both reflection coefficient and VSWR remain stable from 57 to 59GHz and rise sharply from 59 to 63GHz. In 7mm-width substrate, reflection coefficient and VSWR values maintain steady between 57GHz with 61GHz, and go up moderately after 61GHz. From reflection coefficient and VSWR simulation results, when the substrate width is 9mm, the rate of increase is the most significantly. Conversely, when substrate width is 7mm, the rate of rise is relatively stable. In 60GHz, 7mm-width substrate can achieves the highest gain which is 7.56dBi. At the same frequency, the 8mm-width substrate is 7.19dBi. Therefore, both 7mm-width and 8mm-width substrate are feasible options,

2. CPS width

Table 4.4: Simulation Results of Different CPS Width

Coplanar strip line width(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
0.1	-6.135	2.948	6.274
0.2	-8.538	2.119	6.834
0.3	-10.750	1.817	7.198
0.4	-12.408	1.630	7.409
0.5	-12.582	1.614	7.490

When CPS width is varied from 0.1 to 0.3mm, reflection coefficient and VSWR values are increasing from 57 to 63GHz. When CPS width is 0.4mm or 0.5mm, reflection coefficient and VSWR drop from 57GHz and then reach the bottom near

60GHz. After that the values will increase with the frequency increase. As is shown clearly from the gain result of different CPS widths in Figure 4.7, wider CPS width can achieve higher gain. The gain value of 0.5mm-CPS width and 0.4mm-CPS width in 60GHz are 7.49dBi and 7.41dBi. In conclusion, 0.5mm is the most suitable width for CPS width.

3. CPS length

Table 4.5: Simulation Results of Different CPS Length

Coplanar strip line width(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
1	-3.950	4.472	11.283
2	-22.381	1.164	8.1898
3	-4.029	4.388	9.155
4	-8.943	2.111	9.094

From the simulation results of different CPS length, the trend of reflection coefficients, VSWRs and gains are very different for these four different CPS lengths. In the reflection coefficient results, the value of 2mm-CPS length is -22.38dB in 60GHz, where 1mm-CPS length is -3.95dB, 3mm-CPS length is -4.02dB and 4mm-CPS length is -8.94dB. Meanwhile, VSWR of 2mm-CPS length is lower than the other three CPS lengths. Although the gain for 2mm-CPS length is less than others, 2mm-CPS length is still most-suitable for this design because it has significant advantage in reflection coefficient and VSWR.

4. Driven Element and Director Width

Table 4.6: Simulation Results of Different Driven Element and Directors Width

Driven element and directors width(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
0.1	-10.622	1.834	7.166
0.2	-10.729	1.819	7.521
0.3	-10.750	1.817	7.198
0.4	-9.157	2.069	7.524
0.5	-7.801	2.374	7.806

According to the simulation results of different driven element and director width, when driven element and director are 0.2 wavelength or 0.3 wavelength, the reflection coefficient and VSWR increase gradually, when they are 0.4 wavelength or 0.5 wavelength, the reflection coefficient and VSWR rise sharply. The trends of 0.1-wavelength width in reflection coefficient and VSWR are quite different with others, reflection coefficient and VSWR drops from 57GHz and then reach the bottom near

60GHz. After that the values will increase with the frequency increase. The lowest gain value in 60GHz is 7.16dBi in 0.1-wavelength width driven element and director. The highest gain in 60GHz can be achieved when driven element and director are 0.5 wavelength, which value is 7.8dBi. What driven element and director width will be used in the final design needs further experiments.

5. Directors Length

Table 4.7: Simulation Results of Different Directors Length

Directors coefficient($\times\lambda$)	Reflection coefficient(dB)	VSWR	Gain(dBi)
0.4	-10.523	1.845	6.858
0.41	-10.366	1.832	7.023
0.42	-10.750	1.817	7.198
0.43	-10.862	1.802	7.337
0.44	-10.859	1.802	7.436
0.45	-9.534	1.846	7.557

According to the simulation results of different directors length, the trend of reflection coefficient and VSWR in different director lengths are similar. When director lengths are from 0.4 wavelength to 0.44 wavelength, reflection coefficient and VSWR will increase with the frequency increase between 57 with 63GHz. When director length is 0.45 wavelength, the reflection coefficient and VSWR values increase from 57GHz and reach the top around 62.5GHz, after that both of characteristics will decrease with the frequency increase. The gain values of director length from 0.4 wavelength to 0.45 wavelength are between 6.85 with 7.55dBi and longer director length can achieve higher gain. Although 0.45-wavelength-length director can achieve the best gain, its gain drops significantly after 60GHz. Through analyzing the reflection coefficient, VSWR and gain of different director lengths, 0.41-wavelength-length and 0.42-wavelength-length director are two most appropriate lengths for director because they are relatively stable from 57 to 63GHz.

6. Directors Spacing

Table 4.8: Simulation Results of Different Directors Spacing

Directors gap coefficient($\times\lambda$)	Reflection coefficient(dB)	VSWR	Gain(dBi)
0.1	-9.947	1.933	7.305
0.2	-10.750	1.817	7.198
0.3	-11.034	1.780	6.929
0.4	-11.271	1.751	6.590
0.5	-11.751	1.697	6.013

From the simulation results, when the spacing between two directors are 0.1, 0.2, 0.3 and 0.4 wavelength, the trend of reflection coefficient, VSWR and gain are same. Reflection coefficient and VSWR will increase along with the frequency increase in the frequency from 57 to 63GHz. When space between two directors is 0.5 wavelength, its reflection coefficient and VSWR are relatively stable between 57 with 63GHz. The gain of directors spacing from 0.4 wavelength to 0.45 wavelength are between 6.01 with 7.3 dBi and small gap between directors can achieve higher gain. Through analyzing the reflection coefficient, in order to balance reflection coefficient, VSWR and gain of different spacing between two directors, 0.3 wavelength spacing is the most appropriate distance between two directors.

7. Substrate Length, Microstrip Line Width, Microstrip Line Length and Driven Dlement Length.

Table 4.9: Simulation Results of Different Substrate Length

Substrate length(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
20	-10.730	1.819	6.901
22	-10.668	1.827	7.068
24	-10.665	1.828	7.181
26	-10.724	1.820	7.277
28	-10.782	1.812	7.334
30	-10.763	1.815	7.403

Table 4.10: Simulation Results of Different Microstrip Line Width

Microstrip line width(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
0.6	-11.916	1.679	7.154
0.65	-11.362	1.740	7.166
0.7	-10.804	1.799	7.191
0.75	-10.364	1.870	7.201
0.8	-9.917	1.937	7.229

Table 4.11: Simulation Results of Different Microstrip Line Length

Microstrip line length(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
7	-10.762	1.815	6.955
8	-11.108	1.771	7.664
9	-10.750	1.817	7.198
10	-10.875	1.800	7.332
11	-10.768	1.814	7.486

Table 4.12: Simulation Results of Different Driven Element Length

Driven element length ($\times\lambda$)	Reflection coefficient(dB)	VSWR	Gain(dBi)
0.45	-9.533	2.001	7.169
0.46	-9.828	1.952	7.177
0.47	-10.137	1.903	7.190
0.48	-10.430	1.861	7.203
0.49	-10.750	1.817	7.198

From the simulation result, different substrate lengths, microstrip line widths, microstrip line lengths and driven element lengths do not affect the trends of antenna reflection coefficient, VSWR and gain. The different values of these four parameters just slightly affect the values of reflection coefficient, VSWR and gain. The simulation result shows that wider microstrip width can achieve better performance in antenna reflection coefficient, VSWR and gain. However, once the thickness and dielectric constant of substrate is fixed, changing the value of microstrip line width will severely impact the impedance. Therefore, the microstrip is fixed in this design. By comparing the simulation result, the most appropriate substrate length is 30mm, microstrip line length is 8mm and driven element length is 0.49 wavelength.

8. Combined Parameters

Table 4.13: The Best Simulation Result of Feeding Line Combinations

Simulation Number	Microstrip line length(mm)	CPS width(mm)	CPS length(mm)	Reflection coefficient(dB)	VSWR	Gain(dBi)
56	7	0.35	2	-26.610	1.097	8.437
6	7	0.35	1	-4.198	4.216	12.111

Table 4.14: The Best Simulation Result of Quasi-Yagi Elements Combinations

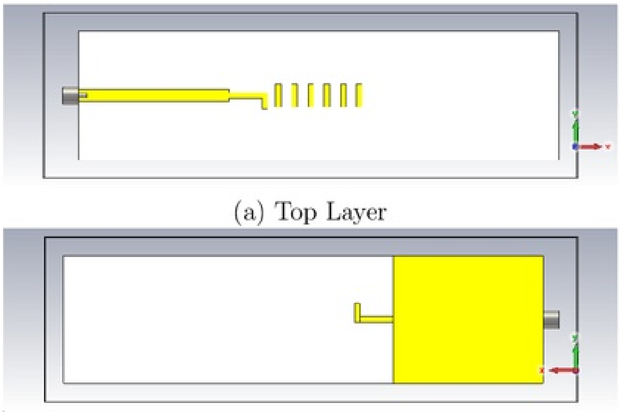
Simulation Number	Director coefficient (wavelength)	Directors gap coefficient (wavelength)	Driven elements and Directors coefficient (wavelength)	Reflection coefficient(dB)	VSWR	Gain (dBi)
119	0.44	0.35	0.35	-31.35	1.057	8.278
87	0.435	0.3	0.25	-22.785	1.156	9.589

Table 4.15: The Best Simulation Result of Substrate Size Combinations

Simulation Number	Substrate length(mm)	Substrate width(mm)	Reflection co-efficient(dB)	VSWR	Gain(dBi)
2	26	7.5	-21.897	1.174	8.287
23	30	8	-21.249	1.189	8.821

By comparing and analyzing the combined parameter results, the CPS length, the size of directors and their spacing are playing an important role in antenna performance. The length of CPS has a large effect on front to back ratio. The size of director and spacing between directors can serious influence radiation in the end-fire direction. Therefore, CPS length, size of director and their spacing are the most critical parameters in quasi-Yagi antenna design.

9. Optimized Design



(a) Top Layer

(b) Bottom Layer

Figure 4.14: Geometry of Optimized Design with Connector in CST

Table 4.16: Simulation Results of Initial Design and Optimized Design

Item	Reflection coefficient(dB)	VSWR	Gain(dBi)
Initial Design	-8.911	2.117	4.063
Optimized Design	-17.711	1.299	7.629

By comparing the simulation result of the initial design and optimized design, the realized gain has been increased near 90% which from 4.063 to 7.63 dBi at 60GHz.It provides 11.2% of 10dB return loss bandwidth. The impedance bandwidth covers the frequency from 57.28 to 64GHz, which means this quasi-Yagi antenna can fully cover the 60GHz licence-free band in Australia and China, and covers more than 95% in USA, Canada and South Korean.

4.3 Antenna Fabrication

Due to the fabrication complexity and the electronics engineering services in the Macquarie University can not support small-dimension antenna fabrication, this antenna will be sent to Lintek Australia [25] for fabrication.

Chapter 5

Wireless Link Performance Measurements

5.1 Introduction and Objectives

When the project started, the plan was to purchased a 60GHz transmitter and receiver development system to test antennas performance. There are two development systems which can support various wireless applications such as point to point millimeter wave (mm-wave) radio development, high resolution imaging and high definition video transmission. One is the 60GHz development system (PEM009-KIT) from Pasternack [29] and the second one is 60GHz transceiver evaluation kit (EK1HMC6350) from Analog Devices [11]. Both of the development systems have 60GHz transmitter motherboard, 60GHz receiver motherboard, USB cable, power supplies, evaluation software and some cables. The system setup and interconnection of these two systems are similar. The transmitter and receiver boards are connected with PC using USB as the interface. Various control parameters such as synch frequency, IF attenuation level and IF bandwidth, of the transmitter and receiver boards can be set up through software on the PC. The transmitter and receiver boards are connected with signal generator and spectrum analyzer separately. While, there are two antennas, one is connected to transmitter board and the other is connected to the receiver board, are used to transmit and receive signal from signal generator to spectrum analyzer. Through signal generator, customized vector modulation (I and Q baseband) and standard modulation formats such as Binary Phase-shift Keying (BPSK) and Quadrature Phase-shift Keying (QPSK) can be generated. According to compare the signal different between the signal generator with spectrum analyzer to find out the performance of different antennas.
Unfortunately, unlike traditional 2.4GHZ and 5GHz, 60GHz development systems and other related products in the market are very expensive. While, the local sales and distributors are only in charge of marketing and can not provide neither detailed information about products capability and specification or after-sale technical support.
Based on these reasons, commercial 60GHz development system was not considered. After discussion with Prof. Karu and Dr. Basit, we decided to do basic wireless link

performance measurement using 60GHz transmitting and receiving antenna. Through experiment to demonstrate the influence of transmitter power level, antenna gain and transmission distance on received power in 60GHz point-to-point transmission.

Figure 5.1: Pasternack 60GHz Development System

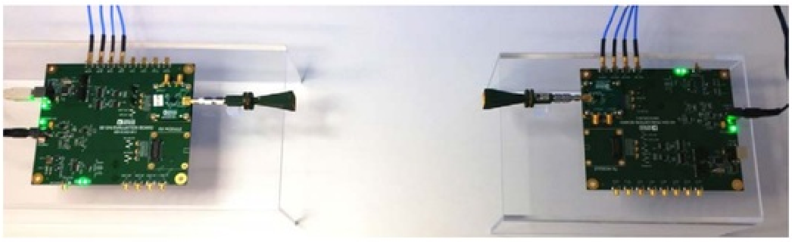


Figure 5.2: Typical HMC6300 and HMC6301 60 GHz Radio Link

5.2 Method

5.2.1 Frris Transmission Equation

The Friis transmission equation was derived by Harald T. Friis in 1945. This equation is used to calculate power fed into the transmitting antenna at its input terminals and power received at the output terminals of the receiving antenna. It gives the amount of power that receiving antenna received in ideal conditions form transmitting antenna. Therefore, in this equation, both antennas must be in far field and in unobstructed free space and bandwidth is narrow enough that a single wavelength can be assumed. [12]. Through this equation, the relationship between transmitter power level, antenna gain, transmission distance and received power in the same frequency can be calculated. Therefore, the experiment will be done base on this equation.

$$P_r = \frac{\mathrm{G_t G_r P_t}\lambda^2}{(4\pi \mathrm{d})^2} \tag{5.1}$$

where:
P_r is received power [dBm]
P_t is transmit power [dBm]
G_r is gain of the receiving antenna [dBi]
G_t is gain of the transmitting antenna [dBi]
λ is free space wavelength [m]
d is separation distance between transmitting antenna and receiving antenna [m]

Or the Friis transmission formula in logarithmic form

$$L_r = L_t + g_t + g_r - 20\log_{10}\frac{4\pi \mathrm{d}}{\lambda} \tag{5.2}$$

where
L_r is the signal level of the receiving antenna at the output terminals [dB]
L_t is the signal level of the transmitting antenna at the input terminals [dB]
g_r is the logarithmic value of G_r
g_t is the logarithmic value of G_t

Considering the misalignment of transmitting antenna and receiving antenna positing and polarization, the Friis transmission equation can be modified as:

$$P_r = G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r) \frac{\mathrm{G_t G_r P_t} \lambda^2}{(4\pi \mathrm{d})^2} \tag{5.3}$$

Where:
$G_t(\theta_t, \phi_t)$ is the gain of transmitting antenna in direction (θ_t, ϕ_t)
$G_r(\theta_r, \phi_r)$ is the gain of receiving antenna in direction (θ_r, ϕ_r)

5.3 Measurement Setup

Our plan was to use the designed quasi-Yagi antenna as the transmitting antenna. But due to fabrication complexity. The antenna had to be sent outside to Lintek Australia [25] for fabrication. As of this writing, the prototype has not arrived. As alternatives, this experiment will use the 60GHz horn antenna from Commonwealth scientific and industrial research organization (CSIRO) as a transmitting antenna. [38].
The aims of this experiment are demonstrating the influence of transmitter power level, antenna gain and transmission distance on received power at the same frequency. Therefore, the accurate gain of each antenna is not necessary in this experiment.

5.3.1 Transmitting and Receiving Antenna Used

Two antennas will be used as transmitting antenna and receiving antenna in this experiment.

1. 60GHz horn antenna
   In the transmitter, a 60GHz horn antenna from CSIRO is fed by a WR15 waveguide to 1.85mm connector. The gain of pyramidal horn antenna can be estimated by following equation:

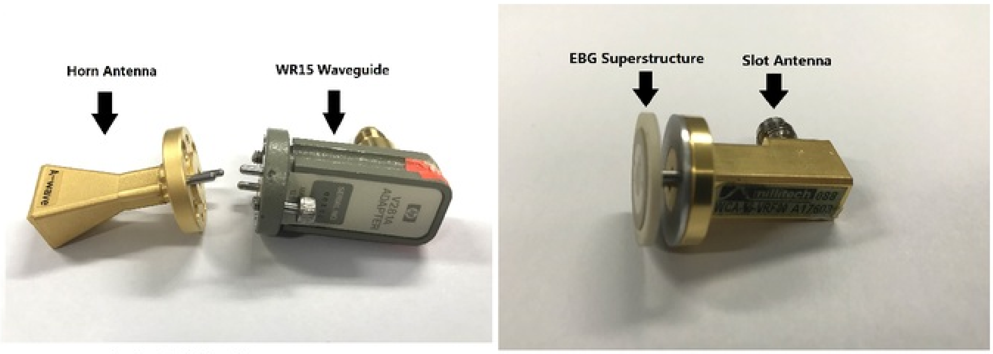
$$G = \frac{4\pi \mathrm{A}}{\lambda^2} e_A \tag{5.4}$$

   where:
   G is the gain of pyramidal horn antenna [dB]
   A is the physical aperture [mm^2]
   λ is the wavelength [mm]
   e_A is aperture efficiency

   By measurement, the height and width of the pyramidal horn antenna is 7.5mm and 11mm. The range of aperture efficiency is between 0.4 to 0.8 in practical horn antenna [50]. Lets take a conservative value, the aperture efficiency of this antenna is 0.7. The gain of the horn antenna at 60GHz will be:

$$G \approx \log_{10}\left(\frac{4 \times 3.14 \times 7.5 \times 11}{5^2} \times 0.7\right) \approx 15dBi \tag{5.5}$$

2. Electromagnetic bandgap resonator antenna (ERA)
   On the receiver, an electromagnetic bandgap (EBG) resonator antenna (ERA) [3] [4], designed by researchers in the Department of Engineering, Macquarie University. This antenna consists two parts: EBG superstructure and waveguide-fed slot antenna which is shown in Figure 5.3. According to the research [3], when only slot-antenna is used, the gain is about 4dBi in the 60GHz band, and when EBG superstructure is placed on the top of the slot feed (to form an ERA), the gain increase to around 15dBi.



(a) 60GHz horn antenna

(b) ERA

Figure 5.3: Transmitting and Receiving Antenna Used

5.3.2 Test Equipments

1. Signal Generator
   The Anritsu MG3690B broadband signal generator [2] in Macquarie University Engineering Laboratory can provide 2GHz to 70GHz radio frequency(RF) and microwave frequencies. Furthermore, both carrier signal and pulse with modulation can be generated through this signal generator.

2. Spectrum Analyzer
   The Rohde and Schwarz FSU67 Spectrum Analyzer [34] in Macquarie University Engineering Laboratory can receive signal in the frequency range from 20Hz to 67GHz.

3. Flexible mm-wave Cable
   Two flexible mm-waave cables from Totoku [46] will be used in this experiment. These cables have 1.85mm female connector at both ends and available to transmit the signal up to 67GHz.

4. Radiation Absorbent Material (RAM)
   Radiation absorbent material is a material to absorb RF radiation. However, RAM cannot absorb radar for all frequencies [45] and the RAM in Engineering Department cannot absorb the frequency higher than 30GHZ. Therefore, the experiment will be done in the normal indoor environment.

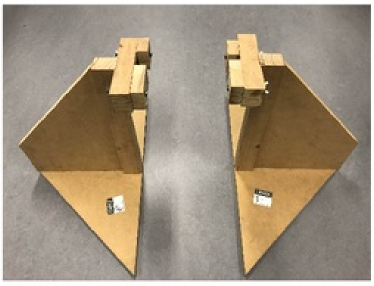
5. Custom holders
   Two wood holders are used to hold the transmitting and receiving antenna. The custom holders have clamps and their height is 50cm.

6. Tubular spirit level and ruler
   In order to enhance the accuracy of the measurement and improve positioning system accuracy, alignment should be given enough attention. Tubular spirit level and ruler can be used in experiment to not only support the system alignment process but also validate the positioning system accuracy and repeatability. [23].

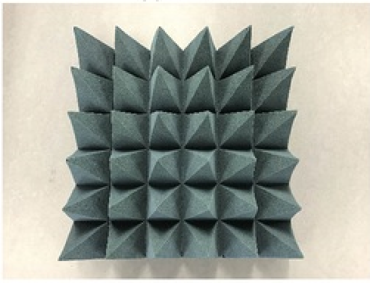
(a) Signal Generator [2]

(b) Spectrum Analyzer [34]

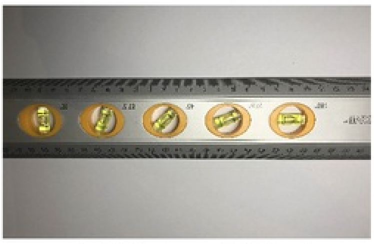
(f) Cable



(d) Holders



(c) Radiation absorbent material



(g) Tubular spirit level

Figure 5.4: Measurement Equipments

5.4 Link Budget Calculation

In the wireless network, communication link performance can be determined using link budget calculation. Therefore, to establish a link budget is one of the most important part in this experiment. The received power in a communication link is typically depends on transmit power, transmitting antenna gain, receiving antenna gain and path loss. Pass loss is an electromagnetic wave power density reduction through space in the signal transmission. It depends on free-space loss, reflection, refraction, diffraction and absorption. Meanwhile, it is influenced by location, distance and height between the transmitting and

receiving antennas. In addition to the free space attenuation, oxygen attenuation is a unique property to 60GHz band which limits space of its link. According to the research by ITU [33], the peak oxygen absorption at sea level in mm-wave is near 60GHz, which around 16dB/km. Therefore, the oxygen attenuation should not be ignored when doing the 60GHz link budget calculation.
To make sure the link is viable, the power, which minus the free space loss, transmitter losses and miscellaneous losses of the link path, must greater than the minimum received signal level. The link margin, which value is positive and should be maximized, is the different between the actual received power and minimum received signal level.

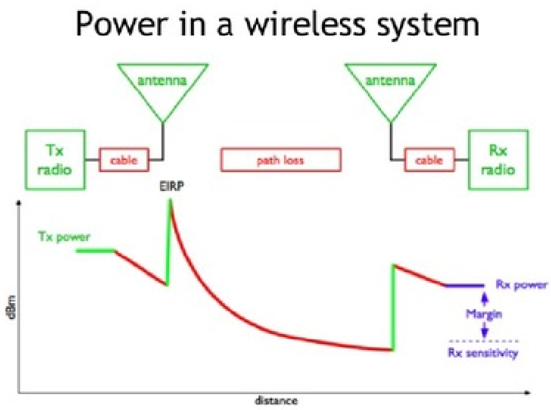


Figure 5.5: Link Budget [37]

A link budget equation might look like:

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX} \tag{5.6}$$

Where:
P_{RX} is received power (dBm)
P_{TX} is transmitter output power (dBm)
G_{TX} is transmitter antenna gain(dBi)
L_{TX} is transmitter losses (eg. coax, connectors) (dB)
L_{FS} is pass loss, usually free space loss (dB)
L_M is miscellaneous losses (eg. body loss fading margin, polarization mismatch) (dB)
G_{RX} is receiver antenna gain (dBi)
L_{RX} is receiver losses (eg. coax, connectors) (dB)

5.4.1 Free Space Path Loss (FSPL)

FSPL is the loss between two antennas where the distance and frequency are known. It defined as the loss between two isotropic antennas in free space, expressed as a power ratio and there are no obstacles surrounding produce diffraction or reflection. The formula of FSPL is:

$$FSPL = 32.4 + 20\log_{10}(f) + 20\log_{10}(d) \tag{5.7}$$

where:
f is measured frequency [MHz]
d is the distance between two antennas [km]

Table 5.1: FSPL for the Distance from 1mm to 1m at 60GHz

Distance (cm)	Free space path loss (dB)
1	27.86
2	33.88
5	41.84
10	47.86
20	53.88
50	61.84
100	67.86

The FSPL is a logarithm function, along with the distance increase, the FSPL will grow rapidly at the beginning and then grow slowly at the fixed frequency.

5.4.2 Cable Loss

From the insertion loss (S21) diagram shown on Figure 5.6, the loss of cable is around 5.9dB at 60GHz.

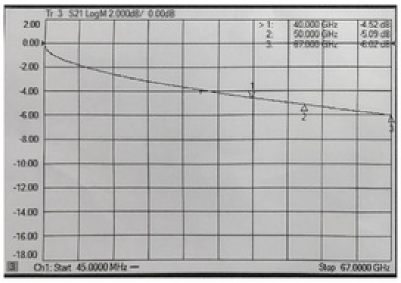


Figure 5.6: Cable Insertion Loss from 40 to 67GHz [46]

5.4.3 Transmitter and Receiver Loss

The signal generator was connected to spectrum analyzer by the cable, the output power on signal generator was set to 0dBm. From the spectrum analyzer, the received power value was -24.81dBm with 15dBm attenuation. The transmitter and receiver loss is:

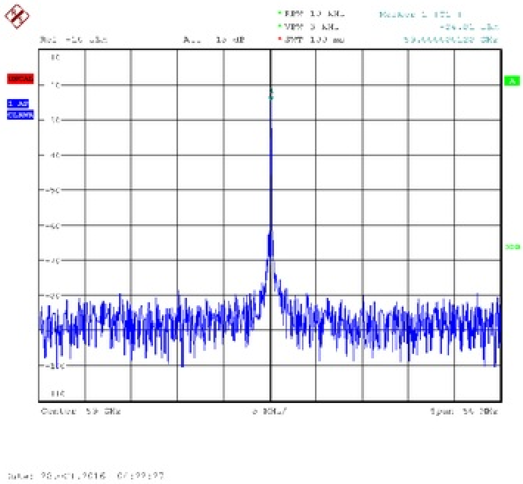


Figure 5.7: Transmitter and Receiver Loss Measurement

$$L_{TXandRX} = P_{TX} - P_{RX} - P_c - A = 0 - (-24.81) - 6 - 15 = 3.81 \tag{5.8}$$

Where:
$L_{TXandRX}$ is the transmitter and receiver loss
P_{TX} is transmitter output power (dBm)
P_{RX} is received power (dBm)
P_c is cable loss
A is attenuation

5.4.4 Link Budget Estimation

The signal generator can generate the power form +30dBm to -20dBm at 59GHz. In order to reduce the experimental error, the power range will be used is from +15dBm to -15dBm. The receiver sensitivity is -80dBm with 15dBm attenuation at 60GHz, therefore the received power level have to higher than -80dBm. Before the experiment, we estimated the longest distance that the signal can be received by spectrum analyzer with the -15dBm output power from signal generator.
According to the link budget calculation result, in order to get the reliable experimental

results, the longest distance between transmitting antenna and receiving antenna should not over 20mm because in the experiment there are miscellaneous loss which can not be estimated before experiment.

Table 5.2: Link Budget Estimation Results

Distance (mm)	Transmitter Power (dBm)	Transmitter Antenna Gain (dbi)	FSPL (dB)	Transmitter and Receiver Loss (dB)	Cables loss(dB)	Transmitter Antenna Gain (dBi)	Receiver Power (dBm)
1	-15	15	27.86	3.81	11.8	4	-39.84
2	-15	15	33.88	3.81	11.8	4	-45.50
5	-15	15	41.84	3.81	11.8	4	-53.46
10	-15	15	47.86	3.81	11.8	4	-59.48
20	-15	15	53.88	3.81	11.8	4	-65.50
50	-15	15	61.48	3.81	11.8	4	-73.46
100	-15	15	67.84	3.81	11.8	4	-79.48

5.5 Procedure

1. Check the equipment. After connected the signal generator with spectrum analyser by low loss cable, there are no signal be shown on spectrum analyser when signal generator generates frequency from 59.01 to 60 GHz. Therefore the frequency for testing will decrease to 59GHz. To avoid high power destroy spectrum analyzer, attenuation is set to 15dBm in spectrum analyzer.

2. Connect horn antenna as transmitting antenna with WR15 to coax adapter. Furthermore, connect a low loss coax cable between coax adapter with signal generator.

3. Connect slot antenna as receiving antenna with spectrum analyzer through a low loss coax cable.

4. Use two custom holders to hold transmitting antenna and the receiving antenna.

5. Set the distance between two antenna to 2cm and check two antennas are in the same horizontal plane.

6. Increase the transmit power from -15 to +15dBm in increment of 5dBm. (-15, -10, -5, 0, 5, 10 and 15 dBm) and record the received power value on spectrum analyser.

7. Change the distance between two antennas to 5cm and check two antennas are in the same horizontal plane.

8. Repeat step 6.

9. Increase the distance between two antennas to 10cm and check two antennas are in the same horizontal plane.

10. Repeat step 6.

11. Replace the slot antenna with ERA as receiving antenna and check the location and position of antenna are same with previous.

12. Repeat step 5 to 10.

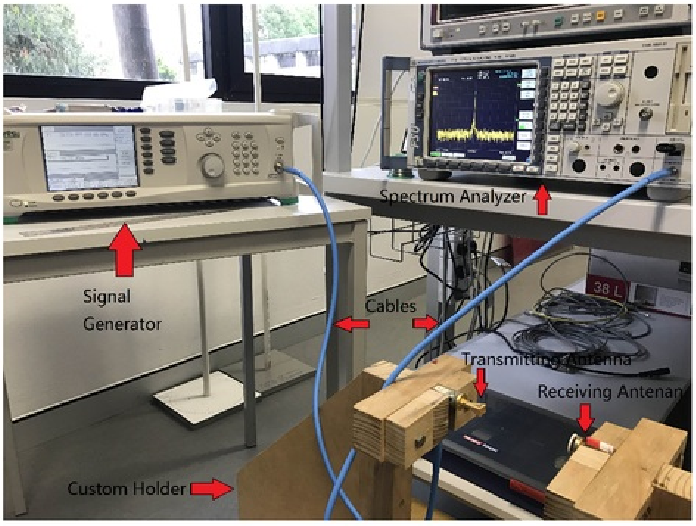
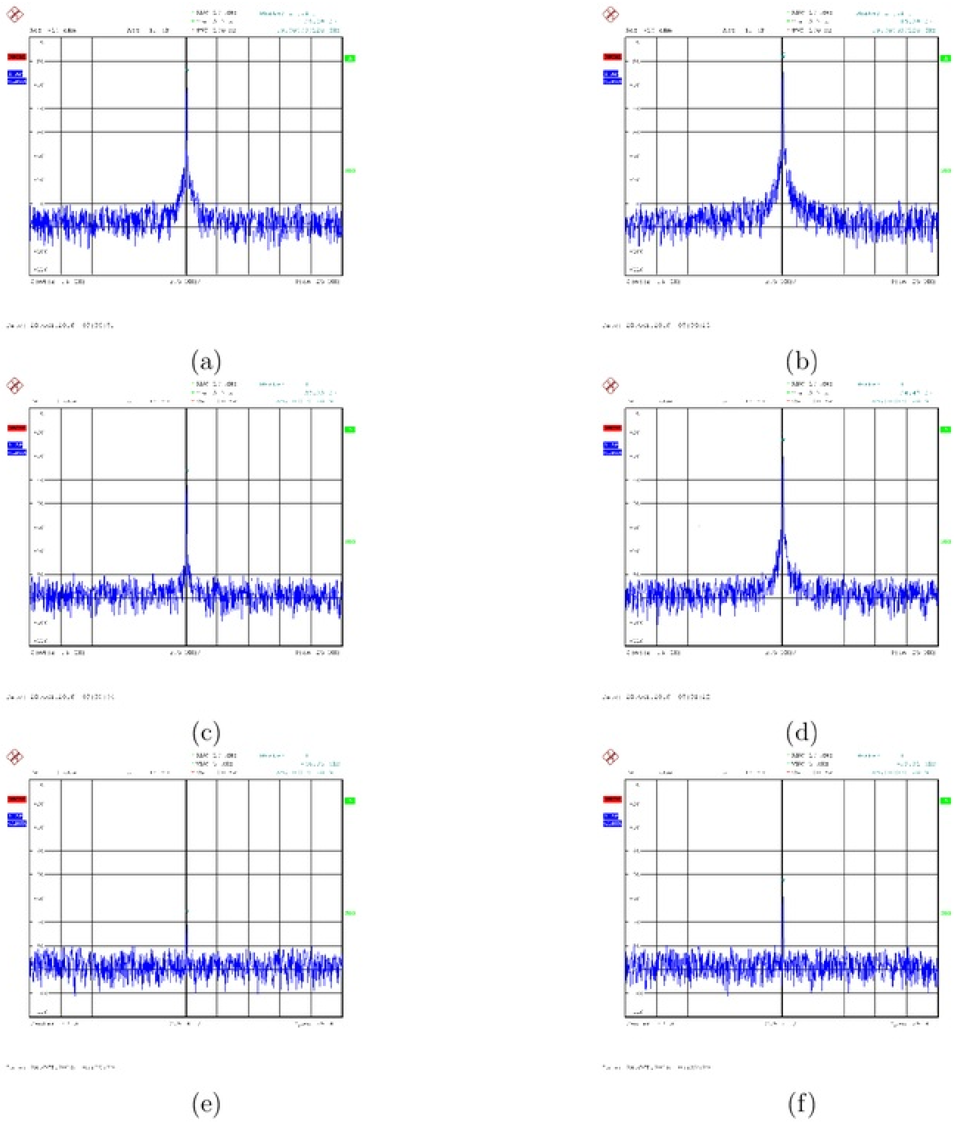


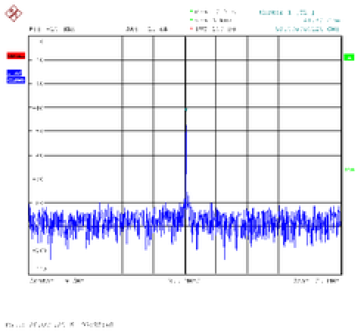
Figure 5.8: Measurement Setup

5.6 Measurement Results and Analysis

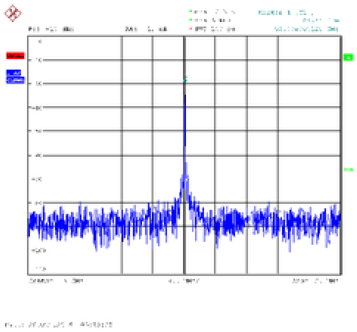


(a) (b) (c) (d) (e) (f)

Figure 5.9: Measurement Results



(g)



(h)

Figure 5.10: Measurement Results

Table 5.3: Measurement Results Pictures Caption

Picture	Receiving antenna	TX (dBm)	Distance (cm)	Display RX (dBm)	RX (dBm)
a	Slot antenna	15	2	-25.08	-10.08
b	ERA	15	2	-19.28	-4.28
c	Slot antenna	15	5	-37.23	-22.23
d	ERA	15	5	-24.47	9.47
e	Slot antenna	-15	5	-66.33	-51.33
f	ERA	-15	5	-53.31	-38.31
g	Slot antenna	15	10	-41.80	-26.80
h	ERA	15	10	-29.83	-14.83

Table 5.4: Receiver Power of Slot Antenna and ERA in 2cm Transmission Spacing

Transmitter Power (dBm)	Distance (cm)	Slot antenna (dBm)	ERA (dBm)	Different (dBm)
-15	2	-39.8	-34.2	5.6
-10	2	-34.4	-29.4	5
-5	2	-30.5	-24.5	6
0	2	-25.7	-19.6	6.1
5	2	-20.3	-14.2	6.1
10	2	-15.5	-10.2	5.3
15	2	-10.1	-4.3	5.8

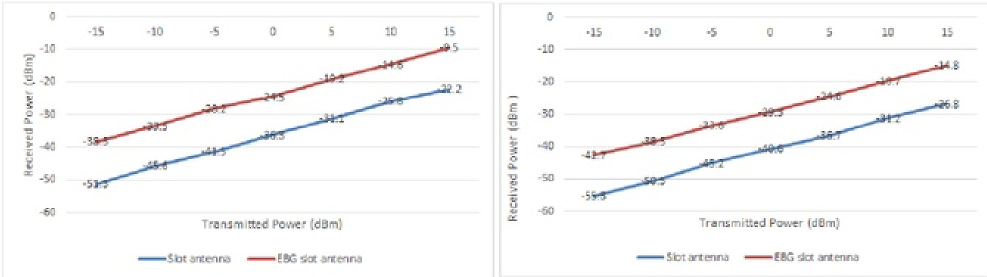
Table 5.5: Receiver Power of Slot Antenna and ERA in 5cm Transmission Spacing

Transmitter Power (dBm)	Distance (cm)	Slot antenna (dBm)	ERA (dBm)	Different (dBm)
-15	5	-51.3	-38.3	13
-10	5	-45.6	-33.5	12.1
-5	5	-41.5	-28.2	13.3
0	5	-36.3	-24.5	11.8
5	5	-31.1	-19.2	11.9
10	5	-25.8	-14.6	11.2
15	5	-22.2	-9.5	12.7

Table 5.6: Receiver Power of Slot Antenna and ERA in 10cm Transmission Spacing

Transmitter Power (dBm)	Distance (cm)	Slot Antenna (dBm)	ERA (dBm)	Different (dBm)
-15	10	-55.3	-42.7	12.6
-10	10	-50.5	-38.5	12
-5	10	-45.2	-33.6	11.6
0	10	-40.6	-29.3	11.6
5	10	-36.7	-24.6	12.1
10	10	-31.2	-19.7	11.5
15	10	-26.8	-14.8	12

Based on the measurement results, when the spacing between two antennas is 2cm, the received power different between slot-antenna and ERA is around 6dBm, which is disagree with the Friis transmission equation. Through analyzing, the reason that causes the error is 2mm spacing between transmitting antenna with receiving antenna does not meet the far-field measurement condition. The maximum radiating structure of the antenna is 11mm. Using the far-field criteria: $r > \frac{2D^2}{\lambda}$, the minimum distance between 2 antennas at least longer than 4.7cm at 59GHz. Therefore, the 2mm-spacing measurement result will not be taken into account.



(a) Received power of two antenna in 5cm (b) Received power of two antennas in 10cm

Figure 5.11: Measurement Results

The experimental results reveal high-gain ERA can achieved higher received power than slot antenna in the same transmission distance with same transmitted power. Therefore, high-gain antennas can transmit more power to the receiver in the same transmission distance or increase the transmission distance with the same transmitted power. In conclusion, in the 60GHz point-to-point wireless link, a high-gain antenna can increase the transmission range or reduce the power requirements for transmitter.

Chapter 6

Conclusions and Future Work

This thesis has reported a 60GHz quasi-Yagi antenna design, optimization, simulation and fabrication. The simulation results shown the quasi-Yagi antenna achieves 7.63dBi at 60GHz and it provides 11.2% of 10dB return loss bandwidth. It covers more than 95% 60GHz license-free band in USA, Canada and South Korean and complete covers 60GHz license-free band in Australia and China.

Furthermore, an experiment was done to demonstrate the influence of transmitter power level, antenna gain and transmission distance on received power in 60GHz point-to-point transmission. The experimental results not only reveal high-gain antennas can transmit more power to the receiver in the same transmission distance or increase the transmission distance with the same transmitted power but also certify high-gain (ERA) can improve the wireless communication efficiency. Therefore, increasing the gain of antenna can improve the efficiency in 60GHz point-to-point transmission.

A 60GHz quasi-Yagi antenna was designed and optimized in this project. Due to lack of antenna design experience, this antenna design was started with simplified microstrip line feeding. There are some other feeding techniques such as slot line feeding and coplanar waveguide feeding that was mentioned in Chapter3 can improve the antenna bandwidth and other characteristics. For further study, I will use different feeding techniques and modify quasi-Yagi elements to increase bandwidth and gain, achieve a good front to back ratio, reduce the size and minimize the manufacturing cost. Furthermore, designing a EBG quasi-Yagi and modifying it for different applications in higher degree studies.

Chapter 7

Abbreviations

5G	5th Generation
BPSK	Binary Phase-shift Keying
CST MWS	Computer Simulation Technology Microwave Studio
EBG	electromagnetic Bandgap
EHF	Extremely High Frequency
ERA	Electromagnetic Bandgap Resonator Antenna
HF	High Frequency
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunications Union
LF	Low Frequency
MF	Medium Frequency
PVB	Printed Circuit Board
QPSK	Quadrature Phase-shift Keying
RLAN	Radio Local Area Network
SWR	Standing Wave Ratio
VHF	Very High Frequency
UHF	Ultra High Frequency
VLF	Very Low Frequency
WiGig	Wireless Gigabit Alliance

Appendix A

Consultation Meeting Attendance Form

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
2	10/08/16	Background	Garson	
4	23/08/16.	Literature review CST.	Garson	
5	31/08/16	Antenna Design [illegible]GHz commercial kit.	Garson	
5	1/09/16	Patch Antenna Design	Garson.	
6	8/09/16	Quasi-Yagi Antenna Design	Garson	
9	10/10/16	Antenna Design	Garson	
10	17/10/16.	Design Optimization	Garson	
10.	20/10/16.	Design Optimization Antenna Measurment.	Garson.	
11	26/10/16	Antenna Fabrication	Garson	
11	28/10/16	Antenna Measurment	Garson.	
12	01/11/16	Report writing	Garson	
12	3/11/16.	Report writing.	Garson	

Appendix B

Purchase Order

B.1 Purchase Order Form

B.2 Antenna Fabrication Invoice

Purchase Order Form

Item No.	Item Description	Price Per Unit	Number of Units	Total
1	Antenna Fabrication Fee	759	1	759
1	1.85mm Female Field Replace 2 hole Flange Mount	249.28	1	249.28
			Total:	1008.28

Student Name: JIASHENG HE

Student Number: 43418945

Project Title: Enabling antenna technology for high-speed wireless communication.

Supervisor Name:

Supervisor Signature:

Date: 2/11/2016

When completed please submit this form to the Laboratory Manager together with supporting quotation information and supplier details. Without this information the purchase order cannot be processed.

Please note that if the total budget exceeds $300, the approval of the Head of Department is required to authorise further purchases.

Proforma

Tax Invoice No: 82497

Date: 02/11/16

Lintek Pty Ltd
20 Bayldon Road
Queanbeyan N.S.W. 2620
Australia
ABN: 74 008 567 020
ACN: 008 567 020
LINTEK
Tel: +61 (02) 6299 1988 Fax: +61 (02) 6297 6958
Email: general@lintek.com.au

Invoice To
MACQUARIE UNIVERSITY
ROOM 128, BUILDING E6B
FACULTY OF SCIENCE DEP OF ENGINEER
MACQUARIE UNI, NORTH RYDE NSW 2109

Order Number: JIASHENG HE

Items	Description	Quantity	Unit Price	Totals
T16379-0	17102016_0	1		670
Freight	D/D: Date: 08/11/16 Con Note: TOLL EXPRESS			20.00

TOTAL INCLUDES SURCHARGE FOR 4 WORKING DAY SURCHARGE

SUB TOTAL EX GST	$	690.00
GST @ 10%	$	69.00
TOTAL INC GST	$	759.00

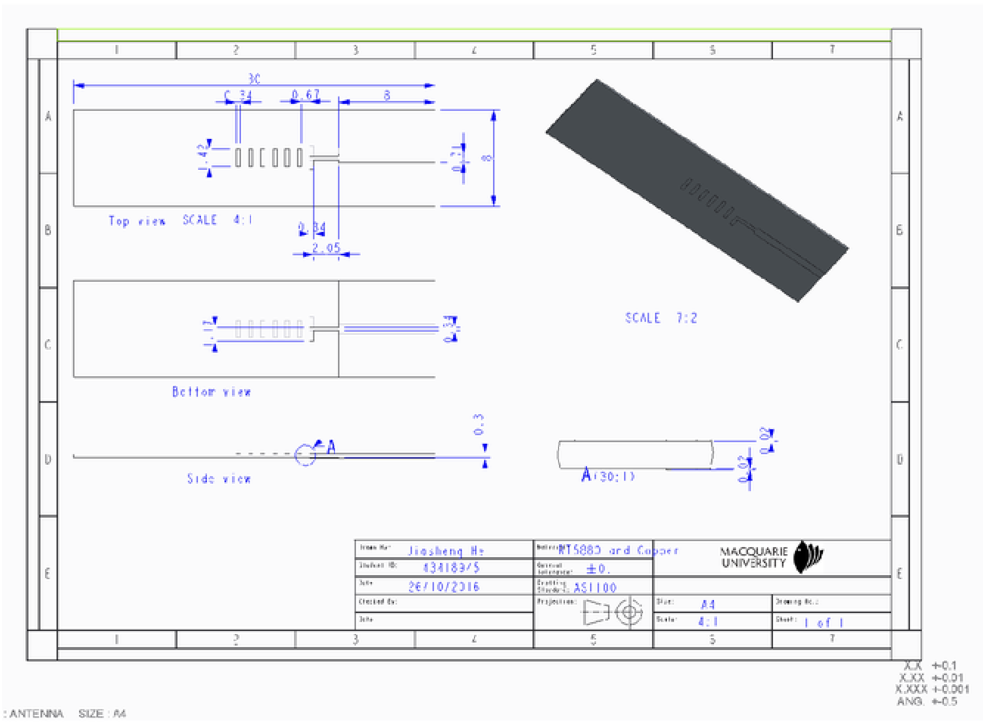
Payment Details:
Bank Name: WESTPAC
Swift Code: WPACAU2S
Branch: FYSHWICK ACT
Account Name: LINTEK PTY LTD
BSB: 032-747
Account No.: 580281

Currency: AUSTRALIAN DOLLARS "

Terms: 30 Days Nett

Appendix C

Antenna Drawing



Appendix D

RT5880 Substrate Data Sheet

PROPERTY	TYPICAL VALUES RT/duroid 5870		TYPICAL VALUES RT/duroid 5880		DIRECTION	UNITS[3]	CONDITION	TEST METHOD
[1]Dielectric Constant, ε_r Process	2.33 2.33 ± 0.02 spec.		2.20 2.20 ± 0.02 spec.		Z Z	N/A	C24/23/50 C24/23/50	1 MHz IPC-TM-650 2.5.5.3 10 GHz IPC-TM 2.5.5.5
[4]Dielectric Constant, ε_r Design	2.33		2.20		Z	N/A	8 GHz - 40 GHz	Differential Phase Length Method
Dissipation Factor, tan δ	0.0005 0.0012		0.0004 0.0009		Z Z	N/A	C24/23/50 C24/23/50	1 MHz IPC-TM-650, 2.5.5.3 10 GHz IPC-TM-2.5.5.5
Thermal Coefficient of ε_r	-115		-125		Z	ppm/°C	-50 - 150°C	IPC-TM-650, 2.5.5.5
Volume Resistivity	2 X 10^7		2 X 10^7		Z	Mohm cm	C96/35/90	ASTM D257
Surface Resistivity	2 X 10^7		3 X 10^7		Z	Mohm	C/96/35/90	ASTM D257
Specific Heat	0.96 (0.23)		0.96 (0.23)		N/A	J/g/K (cal/g/C)	N/A	Calculated
Tensile Modulus	Test at 23 °C	Test at 100 °C	Test at 23 °C	Test at 100 °C	N/A	MPa (kpsi)	A	ASTM D638
	1300 (189)	490 (71)	1070 (156)	450 (65)	X			
	1280 (185)	430 (63)	860 (125)	380 (55)	Y			
ultimate stress	50 (7.3)	34 (4.8)	29 (4.2)	20 (2.9)	X			
	42 (6.1)	34 (4.8)	27 (3.9)	18 (2.6)	Y			
ultimate strain	9.8	8.7	6.0	7.2	X	%		
	9.8	8.6	4.9	5.8	Y			
Compressive Modulus	1210 (176)	680 (99)	710 (103)	500 (73)	X	MPa (kpsi)	A	ASTM D695
	1360 (198)	860 (125)	710 (103)	500 (73)	Y			
	803 (120)	520 (76)	940 (136)	670 (97)	Z			
ultimate stress	30 (4.4)	23 (3.4)	27 (3.9)	22 (3.2)	X			
	37 (5.3)	25 (3.7)	29 (5.3)	21 (3.1)	Y			
	54 (7.8)	37 (5.3)	52 (7.5)	43 (6.3)	Z			
ultimate strain	4.0	4.3	8.5	8.4	X	%		
	3.3	3.3	7.7	7.8	Y			
	8.7	8.5	12.5	17.6	Z			
Moisture Absorption	0.02		0.02		N/A	%	.062" (1.6mm) D48/50	ASTM D570
Thermal Conductivity	0.22		0.20		Z	W/m/K	80°C	ASTM C518
Coefficient of Thermal Expansion	22 28 173		31 48 237		X Y Z	ppm/°C	0-100°C	IPC-TM-650, 2.4.41
Td	500		500		N/A	°C TGA	N/A	ASTM D3850
Density	2.2		2.2		N/A	gm/cm³	N/A	ASTM D792
Copper Peel	27.2 (4.8)		31.2 (5.5)		N/A	pli (N/mm)	1 oz (35mm) EDC foil after solder float	IPC-TM-650 2.4.8
Flammability	V-0		V-0		N/A	N/A	N/A	UL94
Lead-Free Process Compatible	Yes		Yes		N/A	N/A	N/A	N/A

[1] Specification values are measured per IPC-TM-650, method 2.5.5.5 @ ~10GHz, 23°C. Testing based on 1 oz. electrodeposited copper foil. ε_r values and tolerance reported by IPC-TM-650 method 2.5.5.5 are the basis for quality acceptance, but for some products these values may be incorrect for design purposes, especially microstrip designs. We recommend that prototype boards for new designs be verified for desired electrical performance.
[2] Typical values should not be used for specification limits, except where noted.
[3] SI unit given first with other frequently used units in parentheses.
[4] The design Dk is an average number from several different tested lots of material and on the most common thickness/s. If more detailed information is required, please contact Rogers Corporation. Refer to Rogers' technical paper "Dielectric Properties of High Frequency Materials" available at http://www.rogerscorp.com.

STANDARD THICKNESS	STANDARD PANEL SIZE	STANDARD COPPER CLADDING
0.005" (0.127mm) 0.031" (0.787mm) 0.010" (0.254mm) 0.062" (1.575mm) 0.015" (0.381mm) 0.125" (3.175mm) 0.020" (0.508mm) Non-standard thicknesses are available	18" X 12" (457 X 305mm) 18" X 24" (457 X 610mm) Non-standard sizes are available up to 18" X 48" (457 X 1219 mm)	¼ oz. (9 µm) electrodeposited copper foil depending on dielectric thickness ½ oz. (17µm), 1 oz. (35µm), 2 oz. (70µm) electrodeposited, reverse treated EDC and rolled copper foil. Thick metal claddings are also available.
Contact customer service for available thicknesses, panel sizes and claddings.		

The information in this data sheet is intended to assist you in designing with Rogers' circuit materials. It is not intended to and does not create any warranties express or implied, including any warranty of merchantability or fitness for a particular purpose or that the results shown on this data sheet will be achieved by a user for a particular purpose. The user should determine the suitability of Rogers' circuit materials for each application.

These commodities, technology and software are exported from the United States in accordance with the Export Administration regulations. Diversion contrary to U.S. law prohibited.
RT/duroid, Helping power, protect, connect our world and the Rogers' logo are trademarks of Rogers Corporation or one of its subsidiaries.

Helping power, protect, connect our world

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