Studies on circularly polarized antennas for small satellites

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Studies on Circularly Polarized Antennas for Small Satellites

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

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STUDIES ON CIRCULARLY POLARIZED ANTENNAS FOR SMALL SATELLITES

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A thesis submitted to the Nanyang Technological University
in fulfillment of the requirements for the degree of
Master of Engineering

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

Date

Luo Jiayu

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Table of Contents

List of Figures	8
Summary	11
1. Introduction.....	13
1.1 Motivations.....	13
1.2 Objectives	14
1.3 Organization of the Thesis	16
2. Background Knowledge.....	17
2.1 Nano- and Pico- Satellite.....	17
2.1.1 Introduction to Nano- and Pico- Satellite	17
2.1.2 Satellite Subsystems	19
2.1.3 Satellite Antennas	20
2.2 Circularly Polarized Microstrip Patch Antenna	22
2.2.1 Microstrip Patch Antenna Basics	22
2.2.2 Return Loss.....	23

2.2.3 Antenna Gain	24
2.2.4 Circular Polarization	25
2.2.5 Circular Polarization with Single Feed	28
2.2.6 Axial Ratio	28
2.3 Examples of Single Feed Circular Polarization Microstrip Square Patch Antenna operating at 2.4 GHz	29
2.3.1 Single-Feed Square-Ring Microstrip Antenna with Truncated Corners for Compact Circular Polarization Operation [6]	29
2.3.2 Single-Feed Small Circularly Polarized Square Microstrip Antenna [8]	31
2.3.3 High-Gain Compact Circularly Polarized Microstrip Antenna with Superstrate [9]	32
2.3.4 Compact Circularly Polarized Microstrip Antenna with Bent Slots [10]	33
2.3.5 Novel Compact Circularly Polarized Square Microstrip Antenna [11]	34
2.3.6 Compact Microstrip Antennas with Asymmetric-slit Patch Radiators [12]	35
2.3.7 Characteristics of a Compact Circularly Polarized Microstrip Antenna [13] ..	36
2.3.8 Minkowski Fractal Boundary Single Feed Circularly Polarized Microstrip Antenna [14]	38

3. Microstrip Square Patch Antenna with Arc Shaped Edges for Circular Polarization ..	40
3.1 Antenna Design	40
3.2 Results and Discussion.....	45
4. High Gain Microstrip Square Patch Antenna with Slit for Circular Polarization.....	55
4.1 Antenna Design	55
4.1.1 Changing Substrate	56
4.1.2 Adding Slots	58
4.2 Antenna Measurement.....	60
5. Conclusion and Recommendations	67
5.1 Conclusion.....	67
5.2 Recommendations	68
Author's Publication List.....	69
References.....	70

List of Figures

Figure 1. VELOX-I Structure	15
Figure 2. Right-Hand-Circular-Polarization (RHCP) [5]	27
Figure 3. Left-Hand-Circular-Polarization (LHCP) [5].....	27
Figure 4. Microstrip Antenna with Truncated Corners [7]	30
Figure 5. Single-Feed Square-Ring Microstrip Antenna with Truncated Corners [6]	30
Figure 6. Single-Feed Circularly Polarized Square Microstrip Antenna with Slits on Edges [8]	31
Figure 7. High-Gain Compact Circularly Polarized Microstrip Antenna with Superstrate [9].....	32
Figure 8. Compact Circularly Polarized Microstrip Antenna with Bent Slots [10].....	33
Figure 9. Novel Compact Circularly Polarized Square Microstrip Antenna [11]	35
Figure 10. Asymmetric-Slit Compact CPMA [12]	36
Figure 11. Characteristics of a Compact Circularly Polarized Microstrip Antenna [13] .	37
Figure 12. Minkowski Fractal Boundary Single Feed Circularly Polarized Microstrip Antenna [14]	38

Figure 13. Microstrip Square Patch Antenna with Arc Shaped Edges for Circular Polarization	43
Figure 14. Simulated Return Loss of Design 1 to Design 4	47
Figure 15. Simulated Return Loss of Design 5 to Design 8	47
Figure 16. Simulated Axial Ratio of Design 1 to Design 4	48
Figure 17. Simulated Axial Ratio of Design 5 to Design 8	48
Figure 18. E-field of the patch antenna at phase = 0	50
Figure 19. E-field of the patch antenna at phase = 90	50
Figure 20. Fabricated Prototype of Design 8 and the current distribution on the patch radiator	49
Figure 21. Measured and Simulated Return Loss of Design 8	52
Figure 22. Measured Axial Ratio of Design 8	52
Figure 23. Measured radiation patterns of Design 8 at $f = 2.51\text{GHz}$	53
Figure 24. Measured radiation patterns of Design 8 in x-z plane at $f = 2.51\text{GHz}$	53
Figure 25. Return Loss.....	57
Figure 26. Antenna Gain.....	58

Figure 27. Axial Ratio.....	58
Figure 28. Proposed microstrip patch antenna with four arc-shape boundaries on the edges and a slit at the center	59
Figure 29. (a) Fabricated prototype of the proposed square microstrip antenna (Design 5); (b) Simulated surface current (magnitude); (c) Simulated surface current (vector)	62
Figure 30. Measured and simulated return losses for Design 5	64
Figure 31. Measured and simulated axial ratios at the boresight for Design 5.....	64
Figure 32. Measured radiation patterns of Design 5 at $f = 2.415$ GHz.....	65
Figure 33. Measured radiation patterns of Design 5 in x-z plane at $f = 2.415$ GHz.....	66

Summary

Small satellites, especially nano- and pico-satellites, are attracting increasing attentions from educational institutions, business organizations and amateur groups. Nanyang Technological University is developing Singapore's first student satellite – VELOX_I. It is a start of VELOX satellites, which is a series of small satellites and will be launched in the next few years.

There are some main subsystems in a satellite, and communication system is one of the most important subsystems. Antenna is a key part of communication system. The aim of this thesis is to study and design antennas for small satellites communication. The focus will be design of circularly polarized microstrip patch antenna for the future uses of VELOX series satellites.

In this thesis, a novel single-feed circularly polarized microstrip antenna with asymmetric arc-shape boundaries on four edges of a square patch will be presented and investigated. The arc-shape boundaries' dimensions can be adjusted according to practical needs and achieve a good performance, providing a large flexibility in fabrication and implementation. Also, the proposed design shows good circularly polarized radiation and a large antenna size reduction.

Based on this design, a second design is proposed. Compared to previous design, a different substrate is used and a slit is added in the middle of the patch. In this improved design, a high gain is obtained and the circular polarization is realized. Designs with different arc-shape boundaries and slit dimensions are shown and compared.

Experimental results are compared with simulated results and a good agreement is shown.

The proposed antennas could find a potential application in small satellites such as cube-satellites where space is of primary concern.

1.Introduction

1.1 Motivations

Traditional satellites' developments are limited to few organizations and countries, because they require large amount of money and time. In recent years, small satellites, especially nano-satellites or pico-satellites, receive increasing attentions from many educational institutions, since commonly available technology can support their developments, significantly reduces the time and cost, and makes this type of satellites feasible and most importantly affordable.

Generally, small satellites are light in weight compared to traditional satellites, for example, a nano-satellite is an artificial satellite with a wet mass between 1 and 10 kg, and a pico-satellite has a wet mass between 0.1 to 1 kg, where wet mass means mass including fuel. However, depending on the deployment system and launcher's requirements, the mass and size may not exactly within the range and some slight changes are allowed.

As a result of inexpensive nature and short development time of nano- and pico- satellites, project developers are more acceptable with higher risks and mission failure. The designs of these satellites are more open to new technologies. Such technologies not only reduce the size, weight, and cost of the satellite, but also greatly increase the available functionality. Furthermore, due to resource limitations, small satellite developers are

often forced to experiment with the new and innovative designs, techniques, and procedures.

1.2 Objectives

The aim of this thesis is to study and design antennas for nano- and pico- satellites' communication systems. Due to limited size and weight, dipole / monopole antennas and patch antennas are very popularly used in these satellites [1]. Dipole / monopole antennas are commonly applied to Very High Frequency (VHF), which is range from 30 MHz to 300 MHz, or lower range of Ultra High Frequency (UHF), which is range from 300 MHz to 3 GHz. Patch antennas are often used in higher frequency compared to dipole and monopole, because of size and conformal requirements.

The antennas in this thesis are mainly designed for VELOX series satellites, which are mainly made by NTU students and will be launched in 2013 and the next few years.

VELOX-P and VELOX-I are the on-going developed pico- and nano- satellites. The antennas used in them are quarter wave monopoles on 144 MHz (VHF) and 437 MHz (UHF). In order to satisfy the special requirements of the satellites, these antennas should be small in size, light in weight, flexible and non-magnetic. The 10-dB return loss bandwidth should be larger than 15 kHz. Also, according to the successful experiences of other similar satellites, the antenna gain is required to be 2 to 3 dBi or larger. The designs of these antennas are done by previous small satellites groups, although there were some problems during implementation, the monopole antennas are well implemented and give

very good performance. The focus of this thesis will be on the design of microstrip patch antennas for the satellites' future development.

Since higher frequency often gives larger bandwidth, this patch antenna's operating frequency is higher than 144 MHz and 437 MHz, which are currently used in the satellites. The patch antenna is expected to operate at 2.4 GHz, which is the frequency allocated for the amateur-satellites. Also, the antennas should give circularly polarized radiation, which will be discussed later. Furthermore, in order to reduce the patch antenna size and complexity, single coaxial feed and size reduction techniques are applied.

Figure 1 shows the structure design of VELOX-I satellites, which is scheduled to be launched in 2013.

Figure 1. VELOX-I Structure

1.3 Organization of the Thesis

Chapter 1 describes the motivation for doing this project. The objectives are stated and the organization of the thesis is shown in this chapter.

Chapter 2 will give an overview of this project and briefly introduce nano- and pico-satellites. A short introduction for antenna will be given. Particularly, circularly polarized single feed microstrip patch antenna will be studied. Several types of circularly polarized single feed microstrip patch antenna will be shown, compared and evaluated.

Chapter 3 will propose a novel design of circularly polarized single feed microstrip patch antenna. Detailed simulation and measurement results will be presented, providing good circular polarization performance and large size reduction.

Chapter 4 will focus on the performance improvement of the design discussed in Chapter 3. In this chapter, an improved design with higher gain will be presented. Both simulation and testing results will be compared. The main characteristics, such as return loss, radiation pattern and gain, will be investigated.

Chapter 5 will conclude the thesis and give some recommendations for future work and improvement of the project.

2. Background Knowledge

2.1 Nano- and Pico- Satellite

2.1.1 Introduction to Nano- and Pico- Satellite

Previously, communications via satellites, manned exploration of space, and many other complex space missions forced the space industry towards larger, more powerful, more expensive and more complicated satellites. Although small satellites have been available around, they were exclusive to scientific and amateur groups. Now, advanced technologies, mainly the development of microprocessors, enable the wide use of small satellites by reducing their sizes, lowering their costs, and most importantly, increasing their functions. As a viable alternative, small satellites provide cost effective solutions to many traditional problems when there are limitations in money, space, technologies or other aspects.

Interest in small satellites is growing fast world-wide. Universities, research institutions, businesses groups and governments around the world are beginning developing their own small satellite programs. Compared with the conventional space industry, small satellites are much simpler in technology and smaller in size, which lead to their rapid development and low cost.

Table 1. Satellite Classification

Size	Name	Major players	Countries	Missions
150~500 kg	Small satellite	Large satellite companies, government, venture companies	USA, UK, France, Israel, Korea, India, Japan	Earth observation, reconnaissance, environmental/disaster monitoring, space science
20~150 kg	Micro-satellite	Universities, satellite companies, venture companies	USA, UK, Germany, Japan, India, Korea, Taiwan	University satellite (educational), technology demonstration, coarse remote sensing
1~20 kg	Nano-satellite	Universities, venture companies	USA, UK, Canada, Netherlands, Japan etc.	University satellite, technology demonstration, coarse remote sensing
<1 kg	Pico-satellite	universities	Many universities in USA, Canada, Europe, Japan	Mainly educational, technology experiments (CubeSat, PCBsat etc.)

Traditional satellites are large and powerful. For example, a trunk communications satellite, INTELSAT-6 [2], has a design life of 10-14 years, weighs 4600 kg at launch,

and deployed dimensions of 11.8 m high and 3.6 m diameter. It is able to support up to 120,000 two way telephone channels and three TV channels simultaneously. Furthermore, there were consequently development leading satellite costs rising, and a single in-orbit failure would be very expensive. Compared to traditional space satellites, small satellites are much smaller and lighter, and their structures and functions are much simpler and more limited. For example, a nano-satellite has a wet mass between 1 and 10 kg, and a pico-satellite has a wet mass between 0.1 to 1 kg. Also, there is little consequently development needed. Some of them are only designed for a very short life, for instance, a few weeks. This largely reduces the requirements for technologies and materials. All these result in less cost in time and money, as well as lower requirements for technologies and equipment.

There are many ways to classify the satellites. Generally, the methods of classifying satellites in terms of deployed mass are most popular; one of them is shown in Table 1. The boundaries of these classes are an indication of where launcher or cost tradeoffs are typically made.

2.1.2 Satellite Subsystems

In order to work properly, the satellite generally consists of several different subsystems with each their specific tasks. The major satellite subsystems are:

- i. Attitude and Orbit Control System (AOCS)
- ii. Telemetry, Tracking and Command System (TT&C)
- iii. Power System

- iv. Thermal Control System
- v. Communication System

The communication subsystem is very important to a satellite. It has to send various information and data down to the ground station and receive commands from the ground station. There are several constraints which must be considered in designing the satellite communication subsystem.

For our project, the communication subsystem consists of uplink antennas, downlink antennas, uplink receiver, downlink transmitter, microcontrollers and power conditioning /distribution unit. The uplink receiver and downlink transmitter work independently of each other, allowing full duplex operation, i.e. simultaneous downlink transmission and uplink command reception.

2.1.3 Satellite Antennas

Antennas are very important to satellites. They connect the satellites and ground stations, receiving commands from ground station, and sending the required data back. A satellite without antennas is considered to be blind, or even dead.

Operational frequency bands used in this project are the amateur radio frequency bands. In order to minimize interference between different frequency bands, co-operating amateur groups drew band-plans. Frequencies for amateur satellites are also widely used in other services such as remote control. The Radio Amateur Satellite Corporation (AMSAT) can help in the planning of operational, control and telemetry frequencies in order to result best signal quality in conjunction with other amateur satellites and

terrestrial operators on the ground. The bands often used in amateur satellites are: 144 to 148 MHz, 435 to 438 MHz, 1260 to 1270 MHz, 2400 to 2450 MHz and some higher frequencies [3] [4].

When talking about bandwidth, percentage of operational frequency is often used, so that the same percentage at different operational frequency would give different bandwidth. For example, a bandwidth of 1% at operational frequency of 2.4 GHz is larger than that at 400 MHz. Generally speaking, higher frequencies are often used in downlink because the data flow sent from space to earth is large and requires larger bandwidth for signal transmission. Telecommand and handshaking are the main mission for uplink, thus a low data rate is sufficient. In this case, lower frequency with cheaper power generator is preferred.

Many different types of antennas, such as monopole antennas, printed inverted-F-shaped antennas, microstrip patch antennas, helices, and patch-excited cup antennas, have been developed for modern small satellite [1] [5].

In VELOX-P and XELOX-I, the pico- and nano- satellites recently built by NTU, monopole antennas are designed for operational frequencies of 144 MHz (VHF) and 437 MHz (UHF). Four monopole antennas are placed on top corners of the satellite, and treat the satellite chassis structure as ground. Two VHF monopole antennas are orthogonal to the two UHF monopole antennas in order to minimize interference. Moreover, the two monopole antennas operating in the same frequency should be fed with 180 degree phase difference to eliminate co-channel interference and get the best performance. The antenna material needs to be flexible because the antennas will be folded around the

satellite and then be deployed after launching, so they would not require much space during launching. Also, since the attitude control magnets are inside satellite, we must use non-magnetic material.

Although dipole antennas are widely used in small satellites and give very good performance, at higher frequency, at which the microstrip patch antennas' sizes are small enough, microstrip patch antennas have more advantages compared to monopole antennas because they are able to provide circular polarization instead of linear polarization, and their radiation is confined to one direction so that the efficiency is higher. In later part, microstrip patch antennas designed for operational frequency around 2.4 GHz will be studied.

2.2 Circularly Polarized Microstrip Patch Antenna

2.2.1 Microstrip Patch Antenna Basics

In high-performance aircraft, spacecraft, satellite, and missile applications, where size, weight, cost, performance, ease of installation, and aerodynamic profile are constraints, low-profile antennas may be required. Microstrip antennas can be used to meet these requirements. These antennas are low profile, conformable to planar and non-planar surfaces, simple and inexpensive to manufacture using modern printed-circuit technology, mechanically robust when mounted on rigid surfaces, compatible with monolithic microwave integrated circuits (MMICs), and when the particular patch shape and mode

are selected, they are very versatile in terms of resonant frequency, polarization, pattern, and impedance [5].

There are various substrates that can be used for the design of microstrip antennas. The commonly used substrates have dielectric constants around 2.2 to 12. The ones that are most desirable for good antenna performance are thick substrates with lower dielectric constant because they provide better efficiency, larger bandwidth, loosely bound fields for radiation into space, but at the expense of larger elements size [5].

Nowadays, single feed circularly polarized microstrip antennas receive more attention in wireless communication application. Compared to linear polarization, circular polarization (CP) does not consider the orientation of transmitters and receivers, which largely simplifies the transmission system setups. Moreover, the single feed configuration reduces the fabrication complexity, antenna weight and signal loss.

2.2.2 Return Loss

During signal transmission in a telecommunication system, some of the signals will be transmitted while some will be reflected. Return loss is the loss of signal power resulting from the reflection caused by discontinuity such as mismatch between transmission line and antenna. It is an important parameter when measuring how much signal power is transmitted and how much signal power is reflected.

$$RL \text{ (dB)} = 10 \log_{10} \frac{P_i}{P_r}$$

Where RL is the return loss in dB, P_i is the incident power and P_r is the reflected power.

For a good matching and perfect transmission, the return loss should be infinitely low to minimize the reflected power. Signal reflection would reduce transmission power, causing fewer signals transmitted. Also, the reflected signals would interfere with the transmitted signals, thus degradation in signal quality. In reality, for an antenna to work properly, the return loss at its operational frequency band is required to be less than -10 dB.

2.2.3Antenna Gain

Gain is a useful measure to describe the performance of antenna. It takes into account not only the efficiency of the antenna, but also its directional capabilities. The definition of antenna gain is “the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π .” According to the IEEE Standards, “gain does not include losses arising from impedance mismatches (reflection losses) and polarization mismatches (losses)”. [5]

Antenna gain is dimensionless, usually expressed in decibel (dB). In some cases, we deal with relative gain. For example, dBi (decibel isotropic) is ratio between the forward gain of an antenna and the hypothetical isotropic antenna, which distributes energy uniformly in all directions. Sometimes dBd (decibel dipole) is used when comparing the antenna to the power of a lossless dipole antenna. In this case, 0 dBd equals to 2.15 dB, where 2.15 dB is the gain of a dipole antenna. The unit that often used in circularly polarized antenna

is dBiC (decibel isotropic circular). It is the forward gain of an antenna compared to a circularly polarized isotropic antenna.

2.2.4 Circular Polarization

An antenna is a transducer that converts radio frequency (RF) electric current to electromagnetic waves that are then radiated into space. Antenna polarization is considered as an important parameter when selecting and installing antennas. Linear and circular polarizations are most commonly used in wireless communication systems.

Linear polarization largely constrains the antenna's performance and application compared to circular polarization in satellite communications. That is also one of the reasons for us to change monopole antennas to microstrip patch antennas. Although monopole antenna is simple and easy to fabricated, it is linearly polarized.

The efficiency of linear polarization largely depends on the transmitter and receiver antenna positions, and commonly is not high. For example, if the angle between the transmitter polarization and the receiver polarization is θ , then the maximum efficiency would be $\cos^2\theta$. Circular polarization would not have this problem.

Also, the antenna polarization would be changed by certain angle due to the magnetic field above the earth when having space-ground communications, and this would cause some inconvenience or problems to linear polarization, but would have little effects on circular polarization. Moreover, the circular polarization has more advantages compared to linear polarization as discussed below.

During the radio signals transmission, there may be obstacles which absorb or reflect signals in certain polarization. For linear polarization, if the polarization is the same with the absorbing or reflecting polarization of the obstacles, the signal strength will be lost. However, circularly polarized antennas send and receive in all polarization planes, the signal strength will be lost in some planes, but the remaining signals will pass.

Furthermore, reflected signals can weaken the propagating signals when linear polarized signals penetrating obstacles. Reflected linear signals have opposite phase to the transmitting signals, therefore when they are reflected back to the transmitting antenna, the transmitting signals would be weakened. However, in circular polarization, the reflected signals are returned in the opposite orientation, which would not cause much signal degradation or conflict to the transmitting signals. Moreover, circularly polarized signals perform better when encountering obstructions by penetrating or bending around.

Circularly polarized waves radiate energy in every plane including horizontal, vertical and the ones in between. The plane of polarization rotates in a corkscrew pattern in a circularly polarized antenna. One complete revolution of rotation needs one wavelength. There are two directions for rotation: left and right. The rotation is called right hand circular polarization (RHCP) if the rotation is clockwise looking in the direction of propagation, as shown in Figure 2. If the rotation is counter clockwise, the sense is called left-hand-circular-polarization (LHCP), as shown in Figure 3 [5].

Figure 2. Right-Hand-Circular-Polarization (RHCP) [5]

Figure 3. Left-Hand-Circular-Polarization (LHCP) [5]

2.2.5 Circular Polarization with Single Feed

Circular polarization can be obtained if two orthogonal modes are excited with a 90 degree phase difference between them. This can be accomplished by adjusting the physical dimensions of the patch and using either single, or two feeds [5]. However, increasing the feeding points would increase the fabrication complexity, weight and return loss. To overcome the problems in dual-feed arrangements, circular polarization can also be achieved with a single feed. To create a single-feed circular-polarization operation requires a slight perturbation in the antenna structure at appropriate locations to excite orthogonal modes of equal amplitudes and 90 degree phase difference. Various perturbation methods for generating single-feed CP such as truncated corners, slits, notches have been reported in literature [6]-[18][20]-[29].

There are many configurations that can be used to feed microstrip antennas. The four most popular feeding methods are the microstrip line, coaxial probe, aperture coupling and proximity coupling.

2.2.6 Axial Ratio

The axial ratio is the ratio of orthogonal components (vertical and horizontal) of an E-field. A circularly polarized field is made up of two orthogonal E-field components of equal amplitude (and 90 degrees out of phase). In circular polarization, because the components are equal in magnitude, the axial ratio is 1 (or 0 dB). The axial ratio for an ellipse is larger than 1 (>0 dB). The axial ratio for pure linear polarization is infinite, because the orthogonal components of the field are zero.

Axial ratio is important and often used in measuring the circular polarization performance of circularly polarized antennas. Although the ideal value is 0 dB, in reality, the axial ratio which is less than 3 dB is considered circularly polarized. 3-dB axial ratio bandwidth is the bandwidth in which the antenna axial ratio is less than 3 dB. For an antenna to be considered circularly polarized, its operational frequency band should be the band where its return loss is less than -10 dB and its axial ratio is less than 3 dB.

2.3 Examples of Single Feed Circular Polarization Microstrip

Square Patch Antenna operating at 2.4 GHz

2.3.1 Single-Feed Square-Ring Microstrip Antenna with Truncated Corners for Compact Circular Polarization Operation [6]

In this design, a circular polarization design of a single-feed square-ring microstrip antenna with truncated corners is studied. The design is shown in Figure 5.

The design is based on the conventional microstrip antenna with truncated corners, as shown in Figure 4 [7], which is a well-known method of producing a single feed circular polarization operation of the square microstrip antenna by truncating a pair of patch at two opposite corners along the diagonal. Microstrip antenna with truncated corners gives good circularly polarized radiation and is commonly used as GPS antenna [7].

Figure 4. Microstrip Antenna with Truncated Corners [7]

Figure 5. Single-Fed Square-Ring Microstrip Antenna with Truncated Corners [6]

This design can provide the antenna a size reduction of around 19%, as compared to the conventional circularly polarized square microstrip antenna with truncated corners at a

given operating frequency. Also, the required size of the truncated corners for circular polarization operation is larger for the present design than for the conventional design using a square microstrip patch, which suggests that the fabrication tolerance is relaxed for this design.

2.3.2 Single-Feed Small Circularly Polarized Square Microstrip Antenna [8]

This circularly polarized single-feed small microstrip antenna designed to have four slits cutting in the square patch and feeding along the diagonal line. The lengths of the slits can be adjusted to increase its circular polarization performance and reduce the antenna size. The design is shown in Figure 6.

Figure 6. Single-Feed Circularly Polarized Square Microstrip Antenna with Slits on Edges [8]

This design shows good axial ratio bandwidth, which is up to 1.62% of the operational frequency. Also, it has a larger size reduction of about 36% as compared to the size of conventional patch antenna operating at the same frequency.

However, owing to the antenna size reduction, the gain of this design decreases. In order to increase the gain, a superstrate is added, as shown in 2.3.3.

2.3.3 High-Gain Compact Circularly Polarized Microstrip Antenna with Superstrate [9]

Figure 7. High-Gain Compact Circularly Polarized Microstrip Antenna with Superstrate [9]

Based on the design discussed in 2.3.2, a high permittivity superstrate with thickness of about one-quarter wavelength is loaded on the microstrip antenna in order to enhance the

antenna performance. A size reduction of 30% is obtained because of the superstrate as well as the four slits cutting in the patch. Moreover, the antenna gain is largely improved by 5.2 dB, as compared to the original circularly polarized antenna design. In this design, special ceramic material with electric constant of 79 is used as superstrate. The design is shown in Figure 7.

The merit of this design is that the gain is 5.2 dB higher than the gain of design without superstrate. However, the demerit is that the patch antenna is thick, the fabrication is difficult since the substrate and superstrate need to be attached without gap. Also, the ceramic superstrate is expensive.

2.3.4 Compact Circularly Polarized Microstrip Antenna with Bent Slots

[10]

Figure 8. Compact Circularly Polarized Microstrip Antenna with Bent Slots [10]

With a group of four bent slots embedded in and two corners cut on a microstrip patch antenna, circular polarization is easily obtained. Also, this single fed design shows a large size reduction. The design is shown in Figure 8.

In this design, we can conclude that, for a given circular polarization operation, the proposed antenna can reduce the antenna's size more than 50% comparing to the conventional circular polarization design using a truncated corner square patch without slots.

However, the 3 dB axial ratio bandwidth is only around 0.8%. Also, the bent slots are very narrow. This gives very small manufacturing tolerance, and the manufactured antennas' performance would easily deviate from the designed antennas'.

2.3.5 Novel Compact Circularly Polarized Square Microstrip Antenna [11]

In this design, a compact microstrip patch antenna with four slits and a pair of truncated corners is proposed. The asymmetry along the center line of the square patch results good circular polarization performance, because both the inserted slits and truncated corners can excite orthogonal modes on the patch. This effectively lower down the resonant frequency and reduce antenna size by increasing the fundamental mode surface current path. The design is shown in Figure 9.

The proposed compact antenna design can achieve an antenna size reduction of around 36% compared to the conventional square microstrip patch antenna at a given operational frequency. Besides, the truncated corner size is much greater than that for conventional

circularly polarized antenna. This provides a relaxed manufacturing tolerance and makes the fabrication process much easier.

Figure 9. Novel Compact Circularly Polarized Square Microstrip Antenna [11]

However, the axial ratio bandwidth is only 0.8%, which is not good enough. Also, the bent slots are very narrow. This gives very small manufacturing tolerance.

2.3.6 Compact Microstrip Antennas with Asymmetric-slit Patch Radiators [12]

In this design, four compact asymmetric-slit microstrip antennas are proposed and studied for circular polarization. By cutting asymmetrical slits in diagonal directions onto the square microstrip patches, as presented in Figure 10, the circular polarization operation and compact size are realized with single coaxial feed and asymmetric slits.

The gain of this design can be up to 4.5 dBi, which is high compared to other circularly polarized microstrip patch antennas. Also, the antenna is compact. The total size including ground plane is $36 \text{ mm} \times 36 \text{ mm}$.

Figure 10. Asymmetric-Slit Compact CPMA [12]

However, the 10 dB return loss and 3 dB axial ratio bandwidths of the antenna prototype are small, only around 2.5% and 0.5%, respectively.

2.3.7 Characteristics of a Compact Circularly Polarized Microstrip Antenna [13]

Truncating a pair of patch at two opposite corners is a well-known method to produce circular polarization operation in a single feed square microstrip antenna. In this design, it is shown that this method can also be used to a modified square microstrip patch with

four semi-circular grooves along the four edges of the patch of equal dimensions to achieve a CP operation with compact design along with relaxed manufacturing tolerances.

The design is shown in Figure 11.

By comparing to the conventional antenna, the operational frequency of the proposed antenna is lowered by 3.71%. The lowering in the operational frequency corresponds to an antenna size reduction by comparing with conventional circular polarization design at the same operating frequency. The design provides good circularly polarized radiation with 3 dB axial ratio bandwidth of 1.32%.

Figure 11. Characteristics of a Compact Circularly Polarized Microstrip Antenna

[13]

2.3.8 Minkowski Fractal Boundary Single Feed Circularly Polarized Microstrip Antenna [14]

A circularly polarized Minkowski fractal boundary microstrip antenna is presented. Proper fractal dimensions on the antenna edges are chosen and a single coaxial feed is located along the diagonal line in order to get circular polarization. The design is shown in Figure 12.

Figure 12. Minkowski Fractal Boundary Single Feed Circularly Polarized Microstrip Antenna [14]

The fractal cuttings along the four edges of the antenna have flexible dimensions that can be easily changed to adjust the antenna performance. It can be observed that a very good circular polarization with 3 dB axial ratio bandwidth of around 1.4% is achieved. Moreover, the surface area of the microstrip patch antenna is reduced by more than 20%

compared with the conventional patch antennas without much degradation in antenna gain.

However, owing to the sharp corners of the grooves, the antenna gain is small and the radiation efficiency is low. This disadvantage can be rectified by replacing the rectangular-shape grooves by arc-shape grooves which would be discussed.

After comparing previous examples, we can conclude that, an antenna with circular polarization and small size are attracting increasing attention. For a small satellite to give a good performance, a circularly polarized microstrip patch antenna can be used. In the following chapters, designs with excellent circularly polarized performance, compact size, and high gain will be proposed and discussed.

3. Microstrip Square Patch Antenna with Arc-Shape Boundaries for Circular Polarization

3.1 Dipole / Monopole Antenna Design

The aim of this thesis is to study and design antennas for nano- and pico- satellites' communication systems. Due to limited size and weight, dipole / monopole antennas and patch antennas are very popularly used in these satellites. Dipole / monopole antennas are commonly applied to Very High Frequency (VHF), which is range from 30 MHz to 300 MHz, or lower range of Ultra High Frequency (UHF), which is range from 300 MHz to 3 GHz. Patch antennas are often used in higher frequency compared to dipole and monopole, because of size and conformal requirements.

The antennas in this thesis are mainly designed for VELOX series satellites, which are mainly made by NTU students and will be launched in 2013 and the next few years.

VELOX-P and VELOX-I are the on-going developed pico- and nano- satellites. The antennas used in them are quarter wave monopoles on 144 MHz (VHF) and 437 MHz (UHF). In order to satisfy the special requirements of the satellites, these antennas should be small in size, light in weight, flexible and non-magnetic. The 10-dB return loss bandwidth should be larger than 15 kHz. Also, according to the successful experiences of

other similar satellites, the antenna gain is required to be 2 to 3 dBi or larger. The designs of these antennas are done by previous small satellites groups, although there were some problems during implementation, the monopole antennas are well implemented and give very good performance.

Since higher frequency often gives larger bandwidth, patch antennas are designed for the satellites' future uses. The future VELOX satellites would be more powerful and thus require more data transmission. The patch antenna is expected to operate at 2.4 GHz, which is the frequency allocated for the amateur-satellites. Also, the antennas should give circularly polarized radiation, which will be discussed later. Furthermore, in order to reduce the patch antenna size and complexity, single coaxial feed and size reduction techniques are applied.

3.2 Patch Antenna Design

As shown in previous sections, there are various disadvantages in existing designs. The size reduction by using microstrip patches with semi-circular grooves has been proposed by V. R. Gupta and N. Gupta [13]. However, the structure achieved the CP using the conventional symmetrically corner truncating technique which is not novel, and the 10-dB return loss bandwidth and 3-dB axial ratio bandwidth are 3.7% and 1.32%. Nasimuddin et al. proposed a microstrip patch antenna with four compact asymmetric-slit on four corners for circular polarization. The 10-dB return loss bandwidth and 3-dB axial

ratio bandwidth are small, only around 2.5% and 0.5%, though it had shown a good gain improvement [12].

In this thesis, microstrip square patch antennas with arc-shape boundaries on the four edges are proposed and investigated. Circular polarization can be obtained if two orthogonal modes are excited with the same amplitudes and a 90 degree phase difference between them. This can be accomplished by adjusting the physical dimensions of the patch and using either single, or two feeds. However, increasing the feeding points would increase the fabrication complexity, weight and return loss. To overcome the problems in dual-feed arrangements, circular polarization can also be achieved with a single feed. In this design, by cutting asymmetrical arc-shape boundaries on the single-feed square microstrip antenna, circular polarization is achieved. The asymmetrical arc-shape boundaries can be adjusted to create a slight perturbation in the antenna structure to excite orthogonal modes of equal amplitudes and 90 degree phase difference.

The simulation software used in the antenna design is HFSS 13, which is the industry-standard simulation tool for 3D full-wave electromagnetic field simulation and is essential for the design of high-frequency and high-speed component design. HFSS offers multiple state-of-the-art solver technologies based on either the proven finite element method or the well-established integral equation method [19]. The accuracy, capacity, and high performance of HFSS are main reasons for it being used in this design. Scattering matrix, visualized 3D electromagnetic fields, return loss, gain, axial ratio, and other important parameters can be clearly seen. In terms of simulation time, HFSS is

slightly more than 2.5D software such as ADS, Sonnet EM Suite, Zeland IE3D and Microwave Office, but in terms of accuracy, it is superior to them.

Figure 13. Microstrip Square Patch Antenna with Arc Shaped Edges for Circular Polarization

In the design proposed by this thesis, arc-shape boundaries are cut from edges of a square patch. The arc-shape boundaries can result good circularly polarized radiation, as well as

increasing of the excited patch surface current path, which effectively lowers the resonant frequency of the modified square patch, and also reduces the antennas' size for a fixed operating frequency.

The proposed antenna is shown in Figure 13. The square microstrip antenna has a length of $L = 28.8$ mm and is printed on a substrate FR4 with thickness $h = 60$ mil and relative permittivity $\epsilon_r = 4.4$. Along the edges of the patch, there are four arc-shape boundaries with different radii r and distances d from circle center to edge. The circles cut lengths $2l$ along the patch edges, where l is larger than 0 and smaller than $L/2$, and the value of l_1 should be different from l_2 in order to create asymmetry. From Figure 13 it can be seen that $r=l/\sin\theta$ and $d=l/\tan\theta$, where θ is the angle between the radius vector and the perpendicular drop to the edge of the square patch. The single probe feed is placed on the diagonal, and the distances of the probe feed away from the x-axis and y-axis are x_f and y_f , where $x_f = 5$ mm and $y_f = 5$ mm.

In Figure 13, the feeding point is on the diagonal and there are two perturbations caused by the asymmetrical arc-shape boundaries at the two sides of the diagonal. As the electromagnetic wave propagates, the larger arc-shape boundary near the feeding point would create the perturbation and thus the first mode, and then followed by the other arc-shape boundary near the feeding point. By adjusting the dimensions of the arc-shape boundaries, the phase difference between the two modes caused by the arc-shape boundaries can achieve 90 degree while the amplitudes remain the same. In this proposed design, if l_1 is larger than l_2 , the antenna would be left-hand-circular-polarization (LHCP);

and if l_1 is smaller than l_2 , then the antenna would be right hand circular polarization (RHCP).

3.3 Results and Discussion

The arc-shape boundaries' dimensions can be varied to provide circular polarization. According to practical needs, the arc-shape boundaries' dimensions can be changed to meet the required size, shape, and operational frequency, providing a large flexibility in fabrication and implementation. The operational frequency is defined as the minimum axial ratio frequency inside the 10-dB return loss bandwidth. Several simulation results are listed as case studies in Table 2. It can be seen from Table 1 that the angle θ can be varied, and for different θ there are always values of l_1 and l_2 that can present good circular polarization performance.

For different antenna designs, generally the simulated gain is around 1.7 dBic, 10-dB return loss bandwidths is around 5% and the 3-dB Axial Ratio (AR) bandwidth can reach up to 1.28%.

Figure 14 and Figure 15 show the simulated return losses of Design 1 to 4 and Design 5 to 8 respectively in Table 2, and Figure 16 and Figure 17 show their corresponding simulated axial ratio. It is clear that the operational frequency can be adjusted by arc-shape boundaries' dimensions. For example, in Design 4 and 5, the θ values are the same, but by assigning different values to l_1 and l_2 in different design, the operational frequencies, simulated 10-dB return loss bandwidths and the 3-dB Axial Ratio

bandwidths can be changed. These results indicate the resonant behavior of the proposed antenna and the critical dependence of arc cuts on AR bandwidth.

Table 2. Simulated Results of Proposed Microstrip Antennas

Antenna	θ (degree)	l_1 (mm)	$l_2 - l_1$ (mm)	Minimum AR frequency (GHz)	10-dB return loss bandwidth % (GHz)	3-dB AR bandwidth % (GHz)
Design 1	20	5	3.5	2.40	4.92 (2.358 – 2.476)	1.125 (2.412 – 2.385)
Design 2	25	5	3	2.398	5.13 (2.357 – 2.48)	1.21 (2.383 – 2.412)
Design 3	28	8	2.2	2.421	5.12 (2.378 – 2.502)	1.24 (2.406 – 2.436)
Design 4	30	7	2.1	2.408	5.11 (2.366 – 2.489)	1.25 (2.394 – 2.424)
Design 5	30	8	2	2.414	5.05 (2.374 – 2.496)	1.28 (2.399 – 2.43)
Design 6	32	8	1.8	2.409	4.86 (2.369 – 2.486)	1.12 (2.395 – 2.422)
Design 7	35	6	1.8	2.399	5 (2.358 – 2.486)	1.25 (2.383 – 2.413)
Design 8	45	5	1.5	2.38	4.96 (2.342 – 2.46)	1.18 (2.367 – 2.395)

Figure 14. Simulated Return Loss of Design 1 to Design 4

Figure 15. Simulated Return Loss of Design 5 to Design 8

Figure 16. Simulated Axial Ratio of Design 1 to Design 4

Figure 17. Simulated Axial Ratio of Design 5 to Design 8

Figure 18. Fabricated Prototype of Design 8 and the current distribution on the patch radiator

The designed microstrip antenna with $\theta=45$ degree, $l_1=5$ mm and $l_2=6.5$ mm (Design 8) was fabricated and measured to validate the design. The antenna prototype is presented in Figure 18.

The measured antenna gain of Design 8 is about 1.4 dBic, which is slightly smaller than the simulated value. The phase information is presented in Figure 19 and Figure 20.

Figure 19 shows the E-field of the patch antenna at phase = 0, and Figure 20 shows the E-field at phase = 90. As the electromagnetic waves are propagating out from the antenna, a left-hand circular polarization (LHCP) is observed.

Figure 19. E-field of the patch antenna at phase = 0

Figure 20. E-field of the patch antenna at phase = 90

The measured 10-dB return loss bandwidth is 5.58% as shown in Figure 21, which is higher than the simulated value of 4.96%. Figure 22 gives the measured AR at the

boresight of the antenna. The minimum axial ratio frequency is 2.51GHz. The measured 3-dB AR bandwidth is 1.24% (2.495 - 2.526 GHz), and it is also larger than the simulated bandwidth of around 1.18% (2.367 – 2.395 GHz).

Since this antenna is made by milling machine, the size of pin on the milling machine is not small enough to make sure the curves of the arc-shape boundaries are as smooth and accurate as in simulation. Also, the pin would get worn during the fabrication period and the substrate is not perfectly flat, so the thickness of the substrate might be different on different area of the patch. The substrate height could be reduced due to over-milling, and thus the height might not be the same with the designed values. Moreover, there might be undesired radiation due to soldering, especially the soldering on the patch surface. All these would cause a small frequency shift, but the fabricated prototype still performs very well.

The measured radiation patterns for both vertical and horizontal polarization at 2.51GHz are plotted in Figure 23. The two patterns are normalized. We can see that the vertical polarization is just slightly smaller than horizontal polarization, showing a small axial ratio value and a good circular polarization radiation. Figure 24 shows both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP) in x-z plane at 2.51GHz. In the figure, a good left-hand circular polarization radiation (LHCP) pattern is obtained. If the feeding point rotates around the center of patch by 90 degree clockwise or counter-clockwise, then a RHCP will be obtained.

Table 3 compares the existing circularly polarized antennas to the proposed design. In Table 3, we can see that the size reduction of this proposed design is large compared to

the other existing designs. Its return loss bandwidth is good among these designs, and the axial ratio bandwidth is also acceptable.

Figure 21. Measured and Simulated Return Loss of Design 8

Figure 22. Measured Axial Ratio of Design 8

Figure 23. Measured radiation patterns of Design 8 at $f = 2.51\text{GHz}$.

Figure 24. Measured radiation patterns of Design 8 in x-z plane at $f = 2.51\text{GHz}$.

Table 3. Comparison of the Single-feed Circularly Polarized Antennas

Design	Structure	10-dB RL Bandwidth	3-dB AR Bandwidth
Proposed		5%	1.28%
[6]		4.62%	1.33%
[8]		4.7%	1.62%
[9]		2.8%	0.8%
[10]		3.6%	0.8%
[11]		2.5%	0.5%
[12]		4%	1.32%
[13]		5%	1.4%

4. High Gain Microstrip Square Patch Antenna with Slit for Circular Polarization

4.1 Antenna Design

Small circularly polarized microstrip antennas are quite useful in satellite and wireless communication and radio frequency identification (RFID) systems due to their small size, light weight, easy fabrication and conformal to the mounting structure. In order to reduce the fabrication complexity and antenna weight, a single feed is employed in most of small circularly polarized antennas. Various designs of single-feed circularly polarized antennas such as truncated corners, slits and notches have been reported in literature [6]-[18][20]-[29], however, the antenna gains of these designs are generally small.

Xihui Tang et al. proposed a circularly polarized shorted patch antenna on high permittivity substrate with wideband [26]. Its 10-dB return loss (RL) bandwidth is 6.9%, 3-dB axial ratio (AR) bandwidth is 3.7%, and the peak gain is 4 dBic. In [27], a microstrip patch antenna with four compact asymmetric-slit on four corners for circular polarization is proposed by Nasimuddin et al.. Its gain is 4 dBic, however the 10-dB RL bandwidth and 3-dB AR bandwidth are small, only around 2.5% and 0.5%. M. L. Wong et al. proposed a small circularly polarized patch antenna by cutting slots and adding tails at the corners [28]. This design gives a large size reduction of 50% in comparison with a

square patch antenna without any slots or tails. Its gain is 4.6 dBic, however, the 10-dB RL bandwidth is 1.61% and 3-dB AR bandwidth is 0.38%.

Also, in the design proposed in previous chapter, the 10-dB return loss bandwidth is 5% and the 3-dB axial ratio is 1.28%. Also, it showed good circularly polarized radiation and a size reduction of about 35% compared to the conventional patch antenna at a fixed operating frequency. However, the gain of this antenna was small, only around 1.7 dBic. In order to increase the antenna gain, improvements and adjustments are applied to the original design.

4.1.1 Changing Substrate

As mentioned in Chapter 2, many different substrate are used in microstrip antenna design and among them, the thick substrates with lower dielectric constant are most desirable, because they can provide better efficiency, larger bandwidth, and loosely bound and loosely bound fields for radiation into space, which means high gain [5][20].

In previous design, the antenna substrate is FR4 with thickness $h = 60$ mil and dielectric constant $\epsilon_r = 4.4$. To enlarge antenna gain, the original antenna substrate is replaced by other substrates which are thick and have lower relative permittivity. In this chapter, Rogers RT/duroid 5880 is chosen as the new substrate.

The antenna with substrate Rogers RT/duroid 5880 has a dielectric constant of 2.2 and a thickness of 125mil. Since the substrate is changed, the antenna size also needs to be adjusted to operate at around 2.4GHz. In this design, $L = 39.5$ mm. The following figures show some results of a simulation as an example. It is well known that using a thicker

substrate and a lower dielectric constant can increase the bandwidth of a microstrip antenna, but this is not true that just changing a substrate while maintaining the same design can improve the antenna performance. As we can see in the following figures, the circular polarization performance of the antenna is not enhanced.

The simulated S-parameter is shown in Figure 25. The antenna operates around 2.4 GHz and the 10-dB return loss bandwidth is around 80MHz, ranging from 2.33 GHz to 2.41 GHz. The bandwidth can be further improved by adjusting the antenna matching, such as changing the feeding point. Antenna gain is in Figure 26. The gain is around 5.9 dBi, which is much larger than the gain of previous design in Chapter 3. The 3-dB axial ratio is from 2.30 GHz to 2.33 GHz, showing in Figure 27. However, the 3-dB axial ratio bandwidth is not inside 10-dB return loss bandwidth, which means the antenna cannot work as a circularly polarized antenna. As mentioned previously, after changing the substrate, the antenna designs should be optimized in order to enhance the performance.

Figure 25. Return Loss

Figure 26. Antenna Gain

Figure 27. Axial Ratio

4.1.2 Adding Slots

Since the antenna with substrate of Rogers RT/duroid 5880 has high gain but poor circularly polarized performance, slots are added to the patch antenna in order to adjust the circular polarization [22]-[25][29]. Different shapes of slots, such as square shaped

slot, rectangular shaped slot, cross shaped slot, circular slot and ringlike slot, are investigated. Rectangular shaped slot gives the best circular polarization.

Figure 28. Proposed microstrip patch antenna with four arc-shape boundaries on the edges and a slit at the center

In this design, a rectangular slit is created at the center of the square microstrip patch and four arc-shape boundaries are cut from edges. A thick substrate with low dielectric constant is used to improve the antenna gain [5]. Both the slit and the arc-shape

boundaries can result good circularly polarized radiation, as well as increasing of the excited patch surface current path, which effectively lower the resonant frequency of the modified square patch, and also reduce the required antennas size for a fixed operating frequency.

The geometry of the proposed antenna is shown in Figure 28. The square microstrip antenna with length $L = 38.6$ mm is designed on a Rogers RT/duroid 5880 substrate (thickness $h = 125$ mil and relative permittivity $\epsilon_r = 2.2$). The coaxial feed-location is on the diagonal ($x_f = 6$ mm and $y_f = 6$ mm.) Along the edges of the patch, there are four arc-shape boundaries with different radii r and distances d from circle center to edge, θ is the angle between the radius vector and the perpendicular drop to the edge of the square patch. The circles cut lengths $2l$ ($0 < l < L/2$) along the patch edges. From Figure 28, it can be seen that $r = l/\sin\theta$ and $d = l/\tan\theta$, θ is the same for the four arc-shape boundaries while l_1 is different from l_2 in order to create asymmetry. The slit in the middle of the patch has length s and width w .

4.2 Antenna Measurement

The method of obtaining circular polarization is simple and the gain is large compared to designs presented earlier in the literature. The arc-shape boundaries and slot dimensions can be adjusted accordingly to meet the required size, shape, and operational frequency, giving a large flexibility in fabrication and implementation. Different cases have been considered and simulated by varying the dimension parameters as listed in Table 4. The

minimum axial ratio frequency within 10-dB RL bandwidth is taken as operational frequency. As shown in Table 4, the peak gain is 6.93dBic, the maximum simulated 10-dB RL bandwidth is 6.15% and the maximum 3-dB AR bandwidth is 1.42%. Also, it can be seen in Table 4 that the smaller θ corresponds to larger l_1 and difference between l_1 and l_2 , as well as smaller s .

Table 4. Simulation Results of Circularly Polarized Microstrip Antennas

Antenna	θ (degree)	l_1 (mm)	$l_2 - l_1$ (mm)	s (mm)	w (mm)	Minimum AR frequency (GHz)	10-dB RL BW % (GHz)	3-dB AR BW % (GHz)	Gain (dBic)
Design 1	20	12.5	5.8	5	0.9	2.405	6.15 (2.365 – 2.513)	1.41 (2.39 – 2.424)	6.8
Design 2	25	11	5	6	0.8	2.4	6.125 (2.356 – 2.503)	1.42 (2.381 – 2.415)	6.93
Design 3	30	9	4.4	8	0.6	2.4	6 (2.356 – 2.5)	1.42 (2.38 – 2.414)	6.84
Design 4	35	7	4.1	9	0.9	2.39	5.86(2.355 – 2.495)	1.38 (2.375 – 2.408)	6.75
Design 5	45	6	3.5	9	0.9	2.385	5.87 (2.348 – 2.488)	1.42 (2.369 – 2.403)	6.83

(a)

(b)

(c)

Figure 29. (a) Fabricated prototype of the proposed square microstrip antenna (Design 5); (b) Simulated surface current (magnitude); (c) Simulated surface current (vector)

In order to validate the design, Design 5 was fabricated and measured. The antenna prototype of Design 5 and the simulated surface current distribution are presented in Figure 29. The current distribution clearly indicates the tendency of circularly polarized radiation. The comparison between measured and simulated 10-dB return loss performance of Design 5 is shown in Figure 30. The measured value of 6.67% is higher than the simulated value of 6%. From the comparison between measured and simulated axial ratio in Figure 31, it can be seen that the measured and simulated 3-dB axial ratio bandwidths are almost the same.

The shapes of the curves of simulated and measured axial ratio are quite similar. The slight discrepancy between the simulated and measured results is due to the fabrication error on the curved shapes. Since this antenna is made by milling machine, the size of pin on the milling machine is not small enough to make sure the curve as smooth and accurate as in simulation. Also, the pin would get worn during the fabrication period and the substrate is not perfectly flat, so the thickness of the substrate might be different on different area of the patch, and might not be the same with the designed values.

The antenna gain is high over the 3-dB AR bandwidth, and the measured peak gain is 6.9dBic at 2.415GHz, which is frequency with minimal axial ratio. The simulated antenna gain is 6.85dBic at 2.385GHz. Both simulated and measured gains are quite similar to each other.

Figure 30. Measured and simulated return losses for Design 5

Figure 31. Measured and simulated axial ratios at the boresight for Design 5

Figure 32 shows the measured radiation patterns at 2.415 GHz, which is the operational frequency, on vertical and horizontal polarizations. The two patterns are normalized. It is noted that the vertical polarization is almost the same with horizontal polarization at boresight, showing a small axial ratio value and a good CP radiation. Both right-hand CP and left-hand CP at 2.415 GHz are plotted in Figure 33, and a good right-hand CP radiation pattern is obtained.

The measured performances of the proposed antenna are compared with some related published single-feed circularly polarized antenna designs in Table 5. In table 5, it is clear that the gain of proposed design is high compared to the other designs. The 10-dB RL bandwidth and 3-dB axial ratio bandwidth are narrower than design in [26], but larger than designs in [27] and [28]. The overall performance is good compared to the existing designs.

Figure 32. Measured radiation patterns of Design 5 at $f = 2.415$ GHz

Figure 33. Measured radiation patterns of Design 5 in x-z plane at $f = 2.415$ GHz

Table 5. Comparison of the Single-feed Circularly Polarized Antennas

Design	Structure	Gain (dBic)	10-dB RL bandwidth (%)	3-dB AR bandwidth (%)	Substrate Thickness / dielectric constant
Proposed		6.9	6.67	1.42	3.175mm / 2.2
[26]		4	6.9	3.7	3.18mm / 10
[27]		4	2.5	0.5	1.524mm / 3.38
[28]		4.6	1.61	0.381	1.524mm \ 3.367

5. Conclusion and Recommendations

5.1 Conclusion

The aim of this thesis is to study and design antennas for nano- and pico- satellites' communication systems. The focus is the design of circularly polarized microstrip patch antenna for the future uses of VELOX series satellites, which are mainly made by NTU students and will be launched in the next few years.

In chapter 3, a novel single-feed circularly polarized microstrip antenna with asymmetric arc-shape boundaries on four edges of a square patch is presented and investigated. Designs with different dimensions of arc-shape boundaries are listed, and all give good performance. The arc-shape boundaries' dimensions can be adjusted according to practical needs, providing a large flexibility in fabrication and implementation. Also, the proposed design shows good circularly polarized radiation and an antenna size reduction of about 35% compared to the conventional patch antenna at a fixed operating frequency. The proposed antenna could find a potential application in small satellites such as cubesats where space is of primary concern.

Based on this design, a second design is proposed in Chapter 4. Compared to previous design, a different substrate is used and a slit is added in the middle of the patch. In this improved design, a high gain is obtained by using this new substrate which is thicker and has a lower dielectric constant, and the circular polarization performance is realized by

the arc-shape boundaries and a slit. Designs with different arc-shape boundaries and slit dimensions are shown and compared. This design has a high antenna gain of 6.9 dBic, 10-dB return loss bandwidth of 6.67% and 3-dB axial ratio of 1.42%. Experimental results are compared with simulated results and a very good agreement is shown.

5.2 Recommendations

To improve the antenna designs for nano- or mirco- satellites, more works need to be done in the future.

The 10-dB return loss bandwidth and 3-dB axial ratio bandwidth still need enhancement. Both bandwidths are good compared to existing designs in [6]-[18][20]-[29], but more improvement can be done for better performance.

Microstrip patch antenna with coaxial feed usually has small bandwidth, so new feeding methods can be tried, for example, microstrip line feed. The way of creating circular polarization in the proposed designs can be used with microstrip line feed.

Also, when we connect the antenna with monolithic microwave integrated circuit, a match network can be built to have a better match, thus a larger 10-dB return loss bandwidth. Moreover, amplifiers can be added into the circuit to increase the antenna gain.

Author's Publication List

[1] J. Y. Luo, A. Alphones, and C. Jin, "*Microstrip Square Patch Antenna with Arc Shaped Edges for Circular Polarization*," Asia-Pacific Microwave Conference, APMC 2011, Australia, December, 2011.

[2] J. Y. Luo, and A. Alphones, "*High Gain Microstrip Square Patch Antenna with Slit for Circular Polarization*," Submitted to MOTL

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