UNIVERSITI PUTRA MALAYSIA

A HIGH GAIN MICROSTRIP YAGI ANTENNA WITH LARGE BANDWIDTH AT FREQUENCY OF 5.8 GHZ

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

June 2016

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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June 2016

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Presently, unlicensed frequencies have gained a wide popularity due to no license payments need to be paid. These frequencies can be utilized to support point-to-point (P2P) communication, such as Long Term Evolution – Unlicensed (LTE-U). An antenna plays a crucial role in P2P communication system which is used to transmit or receive electromagnetic wave. It is available in many types and microstrip patch antenna is the most widely used in P2P communication due to it has some advantages, such as light weight and easy fabrication.

P2P communication system requires a high gain microstrip antenna with large bandwidth in order to enable connectivity across a large area with high data transmission. Numerous methods have been attempted by some researchers to enhance the gain and bandwidth of the microstrip patch antenna, such as employing Yagi antenna design in microstrip patch antenna. This technique is also known as microstrip Yagi antenna which was first introduced by John Huang in around 1989. This thesis proposes a new configuration of microstrip Yagi antenna in order to upgrade the performance of previous works on microstrip Yagi antenna in terms of gain and bandwidth without increasing surface area size. There are two proposed antennas which were designed, simulated, optimized and fabricated. A 1.575 mm thick Arlon CuClad 217 substrate with dielectric permittivity of around 2.2 is selected as substrate of the proposed antennas.

The first proposed antenna is called Octagon Microstrip Yagi Antenna (OMYA). Initially, the designed model of OMYA is a derivative of the microstrip Yagi antenna which has been introduced by Gerald R. Dejean *et al*. It consists of 2 reflector elements, 1 driven element, two bottom director elements and 2 top director elements. In addition, 4 director elements have been modified from square patch geometry into octagonal-shaped in order to reduce surface-waves at the edge of square patch. According to experimental results, bandwidth and gain of the OMYA are 13.8% and 11.1 dB, respectively.

The second proposed antenna is the OMYA with two material substrates with permittivity of 10.2 and thickness of around 2.5 mm. The two additional substrates were placed above the OMYA. The primary aim of adding those substrates is to enhance the gain of the OMYA. Upon varying the height of air gaps, the maximum gain enhancement can be reached. The experimental measurement shows that the OMYA is capable to generate 19.82% bandwidth after adding the superstrates. In addition, this second proposed antenna yields higher gain of around 13 dB.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

ANTENA MIKROSTRIP YAGI DENGAN GAIN YANG TINGGI DAN BANDWIDTH YANG LEBAR PADA FREKUENSI 5.8 GHZ

Oleh

KAMELIA M. CHATIB QUZWAIN

Jun 2016

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Pada masa kini frekuensi tidak berlesen amat popular ekoran dari ketidakperluan membuat bayaran atas perkhidmatan yang diberikan. Frekuensi-frekuensi ini boleh digunakan untuk menyokong komunikasi dari satu tempat kepada satu tempat yang lain (P2P), seperti Worldwide Interoperability for Microwave Access (WiMAX). Antena memainkan peranan yang penting dalam komunikasi P2P dimana ia digunakan untuk menghantar dan menerima gelombang elektromagnetik. Ia juga tersedia dalam berbagai jenis dan jenis antena mikrostrip patch digunakan dengan meluas dalam komunikasi P2P kerana beberapa kepentingan seperti ringan dan mudah untuk difabrikasi.

Sistem komunikasi P2P memerlukan antena yang mempunyai gain yang tinggi dan bandwidth yang besar untuk membolehkan sambungan untuk liputan kawasan yang luas dengan data transmisi yang tinggi. Berbagai cara telah digunakan oleh penyelidik-penyilidik untuk meninggikan gain dan melebarkan bandwidth antena mikrostrip patch ini. Teknik ini juga dikenali sebagai antena mikrostrip Yagi dimana pertama kali diperkenalkan oleh John Huang pada tahun 1989. Tesis ini memperkenalkan konfigarasi baru antena mikrostrip Yagi untuk menaik taraf prestasi gain dan bandwidth dari pada sebelumnya tanpa meningkatkan ukuran kawasan muka antena. Dua jenis antena telah diperkenalkan dengan melalui proses rekaan, simulasi, peningkatan prestasi dan fabrikasi. Antena yang diperkenalkan menggunakan material Arlon CuClad 217 dengan ketebalan 1.575 mm dan dielectrik permittiviti 2.2.

Jenis antena pertama yang diperkenalkan adalah Octagon Microstrip Yagi Antenna (OMYA). Permulaannya, model OMYA ini adalah terbitan daripada antena mikrsotrip Yagi dimana telah diperkenalkan oleh Gerald R. Dejean *et al*. Antena ini mempunyai 2 elemen reflector, 1 elemen driven, 2 elemen direktor dibahagian bawah dan 2 elemen direktor dibahagian atas. Sebagai tambahan, 4 elemen director telah dimodifikasi daripada geometri patch segiempat

kepada bentuk patch segilapan bertujuan untuk mengurangkan gelombang muka pada bucu patch segiempat. Mengikut kepada keputusan ekperimentasi, bandwidth adalah 13.8% dan gain adalah 11.1 dB.

Jenis antena kedua yang diperkenalkan adalah OMYA dengan dua bahan material yang memiliki dielectric permittivity 10.2 dan ketebalan 2.5 mm. Dua penambahan bahan diletakkan diatas OMYA. Tujuan asal menambah dua bahan ini adalah untuk meningkatkan gain OMYA. Semasa proses pengubahan ketinggian ruang udara, gain yang tinggi akan diperolehi. Pengukuran ekperimentasi menunjukkan OMYA berkebolehan untuk menghasilkan 19.82% bandwidth setelah menambah dua superstrate ini. Sebagai tambahan, antena kedua yang telah diperkenalkan memperolehi gain sebanyak 13 dB.

ACKNOWLEDGEMENTS

All praise and gratitude is due to Allah SWT who guides me to bring forth to light this thesis.

I am profoundly grateful to my advisors, Assc. Prof. Dr. Alyani Ismail and Assc. Prof. Dr. Aduwati Sali, who have given me the guidance and takes so much effort and patience in mentoring me. Without their advice and encouragement, this thesis would not possible.

In addition, I would like to express my heartfelt gratitude to Indonesia Endowment Fund for Education (LPDP) for financing my thesis. This assistance is a warm and bright ray of light representing good and caring people who are attentive to the plight of others. I am also grateful to Mr. Enceng Sulaeman, MT, Bandung State Polytechnic Indonesia, and Mr. Amir, University of Telkom Indonesia, for their interest in microstrip antenna and helpful discussion even by e-mail or face to face.

Not forgetting Mr. Rostam, EMC Lab – Universiti Tun Hussein Onn Malaysia, for providing assistance in measurement setup used in this research. Finally, my life and the entire education are deeply owned to my mother, Emmie Habibah, and my father in the heaven, M. Chatib Quzwain (alm.), who have made constant and incomparable sacrifices in order for my sisters, my brothers and me to fly high and far. I am in endless debt to my beloved family, thank you for always being there for me.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

1-D	-	One Dimensional
2-D	-	Two Dimensional
3-D	-	Three Dimensional
AUT	-	Antenna Under Test
BW	-	Bandwidth
CST	-	Computer Simulation Technology
DNG	-	Double Negative
DPS	-	Double Positive
ENG	-	Epsilon Negative
FBW	-	Fractional Bandwidth
ISM	-	Industrial, Scientific and Medical
MNG	-	Mu Negative
MPA	-	Microstrip Patch Antenna
OMYA	-	Octagon Microstrip Yagi Antenna
P2P	-	Point to Point
PCs	-	Photonic Crystal
SHF	-	Super High Frequency
VSWR	-	Voltage Standing Wave Ratio
VNA	-	Vector Network Analyzer
WiMAX	-	Worldwide Interoperability for Microwave Access

LIST OF NOTATIONS

ε_r	-	Dielectric Permittivity
λ_0	-	Wavelength in Free Space
λ_g	-	Wavelength in Dielectric Substrate
h	-	Substrate Thickness
h_2	-	First Air Gap Thickness
h_3	-	Second Air Gap Thickness
h_{ss}	-	Superstrate Thickness
g	-	Gap
L_R	-	Reflector Length
L	-	Driven Length
W	-	Driven Width
W_f	-	Feedline Width
y_0	-	Inset Depth
S_0	-	Inset Separation
R_T	-	Reflector Top
R_B	-	Reflector Buttom
W_d	-	Side Length of Octagon

CHAPTER 1

INTRODUCTION

1.1 Background

Super High Frequency (SHF) is one of the radio frequencies that is widely used nowadays. This frequency band operates in a range of 3 GHz to 30 GHz [1] and available in licensed and unlicensed. Unlicensed frequency bands are those that can be utilized without having to pay a license, and 5.8 GHz is one of the radio bands that is allocated by the Federal Communications Commission (FCC) for Industrial, Scientific and Medical (ISM) applications [2-4]. These frequencies can be utilized in point-to-point (P2P) communication, for instance, Long Term Evolution – Unlicensed (LTE-U) [3].

The number of applications and users of unlicensed frequency has grown rapidly in recent years thanks to the absence of license payments. It leads to an increase in demands for a huge amount of microwave devices. An antenna is one of the microwave devices which is designed to transmit and receive electromagnetic waves. It can be classified into two main categories: omni-directional antennas and directional antennas.

A directional antenna has a radiation pattern that is more focused than an omni-directional antenna. Thus, the gain of directional antennas is higher than the gain of omni-directional antennas. The gain of an antenna is essentially a specification that quantifies how strong the antenna is able to receive and transmit the radiated Radio Frequency (RF) energy in a particularly radiation [2]. High gain directional antennas direct their energy more narrowly and precisely.

Bandwidth is another antenna parameter which plays a crucial role in P2P communication. It indicates frequency range over the antenna can effectively radiate and receive power. Broadband transmission is required in P2P communication which refers to high transmission rate of data. High bandwidth is capable to provide high volume transmission. Therefore, a wide-band antenna is also needed in P2P communication due to it has capability to accommodate broadband transmission. Hence, high gain and wide-band antennas are required to support P2P communication.

Yagi-Uda antennas and Horn antennas are examples of high gain directional and wide-band antennas. Microstrip antennas are the most popular types of antennas which are fabricated on various material substrates such as Arlon CuClad 217LX. Due to these antennas have several advantages, for instance, light weight and low profile [4], it is widely used in P2P communication. However, microstrip antennas have some disadvantages such as low gain and narrow bandwidth due to they are printed on dielectric substrate.

Some efforts are needed to increase the gain and bandwidth of a microstrip antenna. Electro Magnetic Computer Aided (EM CAD) software is able to design and simulate numerous new types of antennas. Thus, it is used to support antenna designers to simplify the complicated construction, analyze and evaluate the radiation performance, for instance, radiation pattern, gain and return loss.

1.2 Problem Statement and Motivation

In 1985, unlicensed frequencies were allocated by Federal Communication Commission (FCC) for Industrial, Scientific and Medical (ISM) applications. According to Malaysian Communication and Multimedia Commission (MCMC), operating frequency of 5.8 GHz is one of the unlicensed frequencies in Malaysia [5].

Since no license payments need to be paid and its utilization in several P2P radio communications, this frequency has gain more attention from many industries and academics. An antenna with high gain and wide bandwidth is one of the crucial parts in P2P radio communication system, thus the rate of demand for this antenna has increased.

There are a number of types of antenna and microstrip antenna is the most commonly used to support P2P communication due some advantages [4]. On the other hands, this antenna has low gain and narrow bandwidth those become its famous disadvantage. However, various methods associated with microstrip antenna can be done to tackle these drawbacks, such as microstrip Yagi antenna. This antenna is one of microstrip antennas which is adopted by traditional Yagi-Uda antenna [6]. The gain of a microstrip Yagi antenna is higher than a conventional microstrip patch antenna due to having parasitic elements, namely reflector and some director elements.

The first microstrip Yagi antenna was pioneered by John Huang in 1989 [6]. Afterwards, numerous researchers have modified the conventional microstrip Yagi antenna in order to increase the gain and bandwidth [7-12]. Another method that can be applied to increase the gain of microtrip antenna is superstrate layer method [13]. This method can be utilized to enhance gain by adding some high dielectric constant (ε_r) materials above the microstrip antenna.

It is interesting beforehand that the gain and bandwidth are generally key parameters in designing an antenna. Therefore, a high gain and wideband microstrip Yagi antenna design has become one of top trending topics worldwide today. This thesis is a study on the design of a new structure of microstrip Yagi antenna using modified Yagi-Uda method and adding Arlon AD1000 as superstrate in order to increase the gain of the proposed microstrip Yagi antenna at 5.8 GHz without increasing surface area size of the antenna too much. As a result, the present study here focuses on gain and bandwidth enhancement of the conventional microstrip patch antenna.

There are two different types of the proposed antennas, namely octagon microstrip Yagi antenna (OMYA) and the OMYA using double superstrates which demonstrate higher gain and bandwidth with smaller surface size compared to other microstrip Yagi antennas. The validity of the proposed design methodology and parametric analysis are verified using EM CAD software, namely Computer Simulation Technology (CST) simulator [15].

1.3 Research Objectives

The main aim of this thesis is to develop a microstrip Yagi antenna with high gain and large bandwidth at unlicensed frequency of 5.8 GHz. The objectives of this research are:

- To design a microstrip Yagi antenna with high gain using modified Yagi-Uda method and superstrate configuration;
- To obtain high bandwidth for the proposed antennas;
- To fabricate the proposed antennas using standard low cost photolithography fabrication process and measure the performance of the fabricated antennas in terms of gain and return loss.

1.4 Research Scope

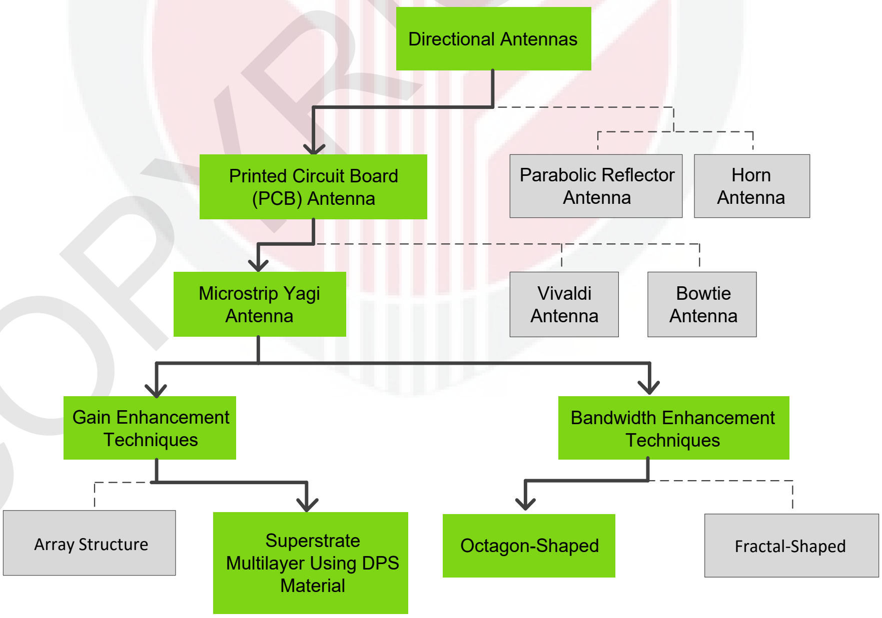

Figure 1.1 Scope of the research

Figure 1.1 depicts the scope of this research where the green boxes represent the configuration that is chosen to obtain the objectives. There are a number of directional antennas, for instance, Parabolic Reflector antennas and Horn antennas [16]. Those antennas have good radiation performances but bulky designs. Meanwhile, Vivaldi antennas, Bowtie Antennas and microstrip Yagi antennas are more compact.

Microstrip patch antenna was chosen as the basic structure of the proposed antenna. As previously mentioned, this antenna has low gain as its drawback and microstrip Yagi antenna is able to address low bandwidth and gain of the conventional microstrip patch antenna by adding some parasitic elements. However, the conventional microstrip Yagi antenna still bulky and gain is still low which may not be suitable for many applications. Many gain and bandwidth enhancement techniques have been reported by some researchers [7-12]. A combination between octagon-shaped patch and superstrate method has been applied on the proposed antennas to enhance the performance of current microstrip Yagi antennas in terms of gain and bandwidth without increasing the surface area size. The OMYA has been designed and fabricated on Arlon CuClad 217LX and covered by two materials of Arlon AD1000 as superstrate multilayer.

1.5 Thesis Outline

This section introduces each chapter in this thesis, which is divided into five chapters. Chapter 1 provides a glimpse introduction to the background, problem statement and motivation, research objectives, research scope and thesis outline. Meanwhile, Chapter 2 mainly consists of literature review. This chapter starts with the review of the microstrip patch antenna, microstrip Yagi-Uda antenna and superstrate method. It also explains a number of previous work papers on high gain antenna.

A design methodology and parametric study of the two proposed high gain directional antennas are presented in Chapters 3. It also covers the selection of the substrate and superstrate layer and the calculation of dimensional parameters. In addition, the antenna fabrication and measurement set up are also provided in this chapter. Chapter 4 focuses on analysis of simulation and measurement results of the two proposed antennas. Lastly, a summary of the conclusions drawn from the research towards this thesis work and some suggestions for future work are presented in Chapter 5.

1.6 Structure of The Thesis

Figure 1.2 shows illustrating the approach of research and the flow of information in this thesis.

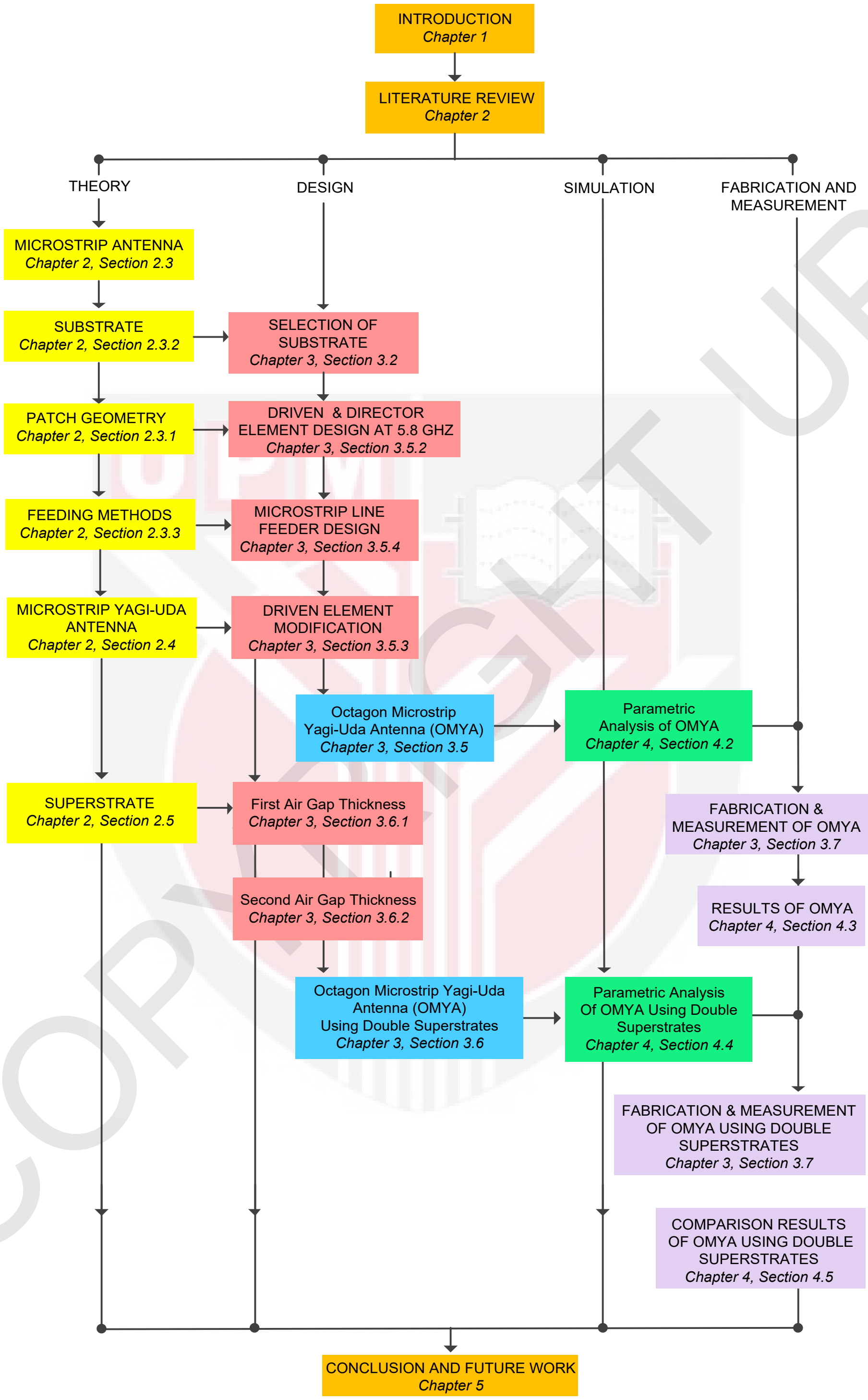

Figure 1.2 The structure of the research in thesis

REFERENCES

[1]. Maitra, A. K. (2004). *Wireless spectrum management*. New York: McGraw Hill.

[2]. Lehpamer, H. (2004). *Microwave transmission networks - planning, design and deployment*. New York: McGraw-Hill.

[3]. http://signalpro.biz/ism1.pdf.

[4]. Chen, Z. N. (2006). *Broadband plannar antennas - design and application*. Singapore: John Wiley & Sons.

[5]. www.skmm.gov.my/skmmgovmy/media/General/pdf/Malaysian_Spectrum_ Allocations_Chart.pdf

[6]. Huang, J. (1989). Planar microstrip yagi array antenna. *Antennas and Propagation Society International Symposium, 1989. AP-S. Digest,* 894-897.

[7]. Padhi, S. K., & Bialkowski, M. E. (2003). A microstrip Yagi antenna using EBG structure. *Radio Science*, *38*(3), n/a–n/a. doi:10.1029/2002RS002697.

[8]. DeJean, G. R., & Tentzeris, M. M. (2007). A new high-gain microstrip yagi array antenna with a high front-to-back (F/B) ratio for WLAN and millimeter-wave applications. *Antennas and Propagation, IEEE Transactions on, 55*(2), 298-304.

[9]. Thai, T. T., DeJean, G. R., & Tentzeris, M. M. (2008). Design and development of a novel compact soft-surface structure for the front-to-back ratio improvement and size reduction of a microstrip yagi array antenna. *Antennas and Wireless Propagation Letters, IEEE, 7*, 369-373.

[10]. Kramer, O., Djerafi, T., & Wu, K. (2010). Vertically multilayer-stacked yagi antenna with single and dual polarizations. *Antennas and Propagation, IEEE Transactions on, 58*(4), 1022-1030.

[11]. Liu, J., & Xue, Q. (2013). Microstrip magnetic dipole yagi array antenna with endfire radiation and vertical polarization. *Antennas and Propagation, IEEE Transactions on, 61*(3), 1140-1147.

[12]. Liu, J., Kang, Y., Chen, J., & Long, Y. (2014). Yagi array of microstrip quarter-wave patch antennas with microstrip lines coupling. *International Journal of Antennas and Propagation, 2014.*

[13]. Kaymaram, F., & Shafai, L. (2007). Enhancement of microstrip antenna directivity using double superstrate configurations. *Electrical and Computer Engineering, Canadian Journal of, 32*(2), 77- 82.

[14]. Abu, M., Hussin, E., Munawar, R., & Rahmalan, H. (2015). Design synthesis of 5.8 GHz octagonal AMC on a very thin substrate. *International Journal of Information and Electronics Engineering, 5*(5), 376.

[15]. Computer Simulation Technology (CST) Microwave Studio.

[16]. Balanis, C. A. (2012). *Antenna theory: Analysis and design* Wiley-Interscience.

[17]. Pozar, D. M. (1992). Microstrip antennas. *Proceedings of the IEEE, 80*(1), 79-91.

[18]. Carver, K. R., & Mink, J. (1981). Microstrip antenna technology. *Antennas and Propagation, IEEE Transactions on, 29*(1), 2-24.

[19]. Garg, R., Bhartia, P., Bahl, I., & Ittipiboon, A. (2000). *Microstrip antenna design handbook*. United State of America: Arthech House.

[20]. Fusco, V. F. (2005). *Foundation of antenna theory and techniques* (First ed.). London: Person Education Limited.

[21]. Sainati, R. A. (1996). *CAD of microstrip antennas for wireless applications*. Boston: Artech House.

[22]. Stutzman, W. L., & Thiele, G. A. (1998). *Antenna theory and design* (Second ed.). New York: John Wiley and Sons.

[23]. Hargin, Bill. (2005). Losing Less from Lossy Line. *Xcell Journal*, *vol.1*, 28-30.

[24]. Bhartia, P., Rao, K. V. S., & Tomar, R. S. (1991). *Millimeter-wave microstrip and printed circuit antennas* (First ed.). Boston: Artech House.

[25]. Huang, J., & Densmore, A. C. (1991). Microstrip yagi array antenna for mobile satellite vehicle application. *Antennas and Propagation, IEEE Transactions on, 39*(7), 1024-1030.

[26]. Engheta, N., & Ziolkowski, R. W. (Eds.). (2006). *Metamaterials physics and engineering explorations*. United States of America: John Wiley & Sons.

[27]. Sugio, Y., Makimoto, T., Nishimura, S.,& Nakanishi, H. (1983). Gain Enhancement of Dielectric Covered Antennas with a Ground Plane. *IEE ICAP, 289-293.*

[28]. Jackson, D. R., & Alexopoulos, N. G. (1985). Gain enhancement methods for printed circuit antennas. *IEEE Transactions on Antennas and Propagation, 33*, 976-987.

[29]. Shen, X., Vandenbosch, G. A., & Van de Capelle, Antoine R. (1995). Study of gain enhancement method for microstrip antennas using moment method. *IEEE Transactions on Antennas and Propagation, 43*(3), 227-231.

[30]. Franciscatto, B., Souza, A., Defay, C., Trang, T., & Vuong, T. (2012). High gain microstrip patch antenna array using multiple superstrate layers for DSRC applications. *Antennas and Propagation in Wireless Communications (APWC), 2012 IEEE-APS Topical Conference on,* 736-739.

[31]. Thevenot, M., Cheype, C., Reineix, A., & Jecko, B. (1999). Directive photonic-bandgap antennas. *Microwave Theory and Techniques, IEEE Transactions on, 47*(11), 2115-2122.

[32]. Kaymaram, F., & Shafai, L. (2007). Enhancement of microstrip antenna directivity using double-superstrate configurations. *Electrical and Computer Engineering, Canadian Journal of, 32*(2), 77-82.

[33]. Yablonovitch, E. (1987). Inhibited spontaneous emission in solid-state physics and electronics. *Physical Review Letters, 58*(20), 2059.

[34]. D. Joannapoulus, J., & Winn, J. (1995). *Photonic Crystals. Molding the Flow of Light*. United States of America: John Wiley & Sons.

[35]. http://www.rf-microwave.com/

[36]. Nasr, M. A., Ouda, M. K., & Ouda, S. O. (2013). Design of star-shaped microstrip patch antenna for ultra wideband (UWB) applications. *Int J Wireless Mob Networks, 5*, 65-73.

[37]. Ben, A., Mischa, D., Ernest, O., Wasim, M., Anthony, B., & David, E. (Eds.). (2007). *Ultra wideband antennas and propagation for communications, radar and imaging*. England: John Wiley & Sons.

[38]. Lin, H., Wu, C., & Yeh, S. (2007). Metamaterial enhanced high gain antenna for WiMAX application. *TENCON 2007-2007 IEEE Region 10 Conference,* 1-3.