CIRCULARLY POLARIZED MULTIPLE INPUT MULTIPLE OUTPUT TRANSPARENT ANTENNA

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To my husband,

my parents,

my family,

& my fellow supervisors,

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ABSTRACT

Circular polarization technology can improve mobile connectivity and mitigate signal losses caused by absorption, reflection and refraction by utilizing all planes in transmitting waves. In this thesis, Circularly Polarized (CP) transparent antenna designs are investigated for broadband applications. Two designs are introduced namely Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) transparent antennas. A silver coated polyester film which is a Transparent Conductive Oxide (TCO) in the shape of film is incorporated in both designs. The film is cut according to design and attached to a glass substrate. SISO antenna is fed by Coplanar Waveguide (CPW) with a circular ring patch radiating element. The existence of tapered split gap and the inequality in CPW ground arm's length has contributed to a 3 dB axial ratio bandwidth from 5.4 to 6.2 GHz. Results show that the proposed antenna has a gain of 0.92 dB and an efficiency of 14% at 5.8 GHz. It is shown that the electron mobility, a parameter that is determined by the material development is a primary limiting factor seen from the 14% efficiency of transparent antenna. The proposed antenna obtained a reflection coefficient response from 2.55 to 6 GHz which covers the desired frequency band. MIMO is designed by combining two aforesaid SISO CP antenna designs, mirrored 180° at y-axis and separated by 1 mm. Measurement results show $|S_{11}|$ and $|S_{22}|$ bandwidth from 2.65 to 6.23 GHz with good isolation of 27 dB at the 5.8 GHz band. Envelope Correlation Coefficient (ECC), Mean Effective Gain (MEG) and Diversity Gain (DG) with measurement values of 0.0007, 0 dB and 10 dB accordingly were discussed in the thesis. These values were calculated using scattering parameters data obtained from the measurement. Both designs are meeting the objectives of this project.

ABSTRAK

Teknologi polarisasi bulatan boleh meningkatkan perhubungan mobiliti dan mengurangkan kehilangan isyarat yang berpunca daripada penyerapan, pantulan dan pembiasan dengan menggunakan semua satah dalam penghantaran gelombang. Dalam tesis ini, reka bentuk antena lut sinar Berpolar Bulatan (CP) telah disiasat untuk aplikasi jalur lebar. Dua reka bentuk diperkenalkan iaitu antena lut sinar CP Kemasukan Tunggal Keluaran Tunggal (SISO) dan Kemasukan Pelbagai Keluaran Pelbagai (MIMO). Filem poliester bersalut perak yang merupakan oksida konduktif lut sinar dalam bentuk filem digunakan pada kedua-dua reka bentuk. Filem ini dipotong mengikut reka bentuk dan ditampalkan pada substrat kaca. Antena SISO disuap dengan Pemandu Gelombang Sesatah (CPW) dengan elemen pemancar berbentuk cincin. Kewujudan jurang pada elemen pemancar dan ketidaksamaan panjang lengan CPW yang telah menyumbang kepada nisbah paksi lebar jalur 3 dB dari 5.4 hingga 6.2 GHz. Keputusan menunjukkan antena yang dicadangkan mempunyai gandaan sebanyak 0.92 dB dan kecekapan sebanyak 14% pada 5.8 GHz. Ini menunjukkan bahawa pergerakan elektron, iaitu parameter yang ditentukan oleh pembuatan bahan adalah faktor pengehad utama yang dapat dilihat dari kecekapan 14% antena lut sinar. Antena ini juga mempunyai lebar jalur dari 2.55 hingga 6 GHz yang meliputi jalur frekuensi yang dikehendaki. Antena lut sinar MIMO direka dengan menggabungkan reka bentuk dua antena lut sinar SISO CP yang dipantul 180° pada paksi-y dan dipisahkan sebanyak 1 mm. Keputusan pengukuran menunjukkan lebar jalur $|S_{11}|$ dan $|S_{22}|$ dari 2.65 hingga 6.23 GHz dengan pengasingan yang baik sebanyak 27 dB pada jalur 5.8 GHz. Pekali Korelasi Sampul (ECC), Min Gandaan Berkesan (MEG) dan Kepelbagaian Gandaan (DG) dengan nilai pengukuran 0.0007, 0 dB dan 10 dB sewajarnya telah dibincangkan dalam tesis ini. Nilai-nilai ini dikira menggunakan parameter penyebaran data yang diperoleh daripada pengukuran. Kedua-dua reka bentuk dikenal pasti telah memenuhi objektif projek ini.

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LIST OF ABBREVIATIONS

AR	-	Axial Ratio
CC	-	Correlation Coefficient
CP	-	Circularly Polarized
CPW	-	Coplanar Waveguide
CST MWS 2014	-	CST Microwave Studio 2014
DG	-	Diversity Gain
DRA	-	Dielectric Resonator Antenna
ECC	-	Envelope Correlation Coefficient
EMT	-	Electromagnetic Transient
FTO	-	Fluorine-Doped Tin Oxide
IEEE	-	Institute of Electrical and Electronics Engineers
ITO	-	Indium Tin Oxide
LHCP	-	Left Hand Circular Polarization
LP	-	Linearly Polarized
LTE	-	Long Term Evolution
MEG	-	Mean Effective Gain
MIMO	-	Multiple Input Multiple Output
NASA	-	National Aeronautics And Space Agency
PET	-	Polyethylene Terephthalate
RFID	-	Radio-Frequency Identification
RHCP	-	Right Hand Circular Polarization
SISO	-	Single Input Single Output
SMA	-	Subminiature version A
TCO	-	Transparent Conductive Oxide

UWB	-	Ultra Wide Band
VLT	-	Visible Light Transmission
VNA	-	Vector Network Analyzer
Wi-Fi	-	Wireless Fidelity
WiMAX	-	Worldwide Interoperability For Microwave Access
WLAN	-	Wireless Local Area Network

LIST OF SYMBOLS

Ω	-	Ohm
Z_∞	-	Impedance at infinite relative permittivity
ε_∞	-	Infinite relative permittivity
T	-	Optical transparency
t	-	Film thickness
δ	-	Skin depth
m	-	Mass of an electron
τ	-	Electron relaxation/scattering time
q	-	Electron charge
N_e	-	Electron density
ω_1	-	Frequency of visible light
R_s	-	Surface resistance
μ_e	-	Electron mobility
ω	-	Microwave frequency
σ	-	Conductivity
ε_r	-	Relative permittivity
λ	-	Wavelength
ρ_e	-	Envelope correlation coefficient
a	-	Actual radius
h	-	height
ε_r	-	Relative permittivity
f_r	-	Resonance frequency
a_e	-	Effective radius
π	-	pi

ε_{req}	-	Equivalent permittivity
t_n	-	Thickness at *n*th layer
ε_{rn}	-	Relative permittivity at *n*th layer
t_{eq}	-	Equivalent thickness
η	-	Efficiency
k	-	Power ratio

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CHAPTER 1

INTRODUCTION

1.1 Introduction

There has been a sizeable amount of research conducted in the last two decades on optically transparent antenna design, enabling it as a result to be deployed on see through surfaces. Such antennas could thus be discreetly installed anywhere without much design issues. One of the several options is to use transparent conductive films, such as Indium Tin Oxide (ITO), Fluorine-doped Tin Oxide (FTO) and silver coated polyester films which also known as AgHT. These films act as conducting elements by allowing electric currents to flow through while maintaining optical transparency [1]. A simple low cost and conformal patch antenna could be designed using these films. With a thin profile and see-through features, this type of antenna can be incorporated on flat surfaces such as glass and mirrors of buildings and automotives where aesthetical value is ever so important [2].

There is a trade-off that must be considered on these conductive films where transparency has to be sacrificed for better conductivity. Lower than 70% transparency has been recorded for AgHT to have an effective conductivity that is enough to ensure good antenna efficiency [3]. Various antenna designs have been reported for Ultra Wide Band (UWB) [4, 5], Wireless Fidelity (Wi-Fi) applications [6] and frequency dependent applications [7]. However, most of them are Linearly Polarized (LP). Compared to LP antenna, Circularly Polarized (CP) antenna is superior in terms of signal resilience to obstructions because of it utilizes all planes in transmitting signal. As a result, signal is not prone to losses due absorption, reflection, refraction and orientation mismatch between transmitter and receiver.

In this thesis, two designs are presented which are Single Input Single Output (SISO) CP transparent antenna and Multiple Input Multiple Output (MIMO) transparent antenna design for 5.8 GHz applications. A detail description on the construction of these two designs are carried out and discussed in this thesis.

1.2 Problem Statement and Motivations

In an age where the world is moving towards modernization, most of buildings, automobiles, communication devices and gadgets are, in addition to the high end functions, relying on aesthetical value for marketing purposes. Figure 1.1, 1.2 and 1.3 shows reflective surfaces and glass are being used in the design of hand phones, buildings and automobiles. The usage of glass and transparent polymer has been extensively incorporated in every design aspect of the aforementioned objects. Sleek and elegant design using glass is definitely a feast to the eyes of people who are looking for futuristic, sophisticated and cutting-edge design in their properties. Antennas, which is to be deployed on these properties for telecommunications purposes had to be visually appealing as well, by hindering it to be an obstruction to the view. This is where transparent antenna comes into the picture. By using glass as a substrate and Transparent Conductive Oxide (TCO) films named AgHT-4, the antenna has a see-through features and could be installed anywhere without worries.

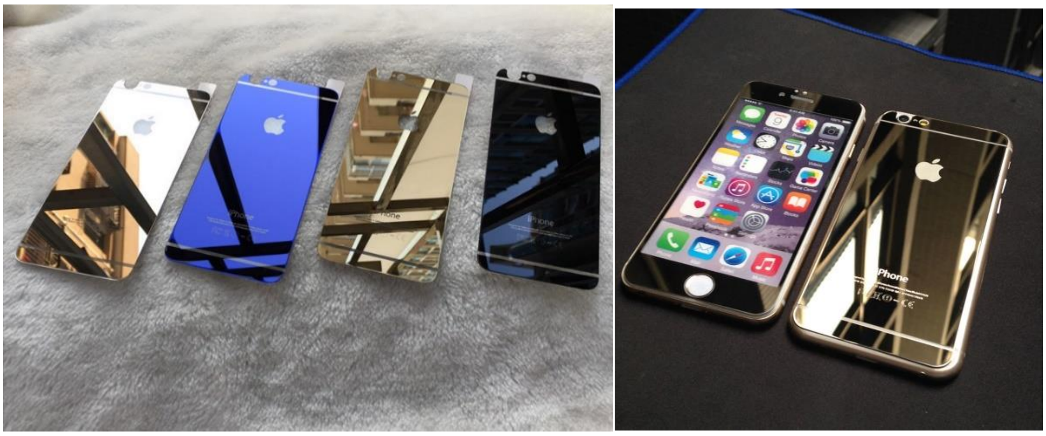

Figure 1.1: The reflective features of iPhone 6 [8].

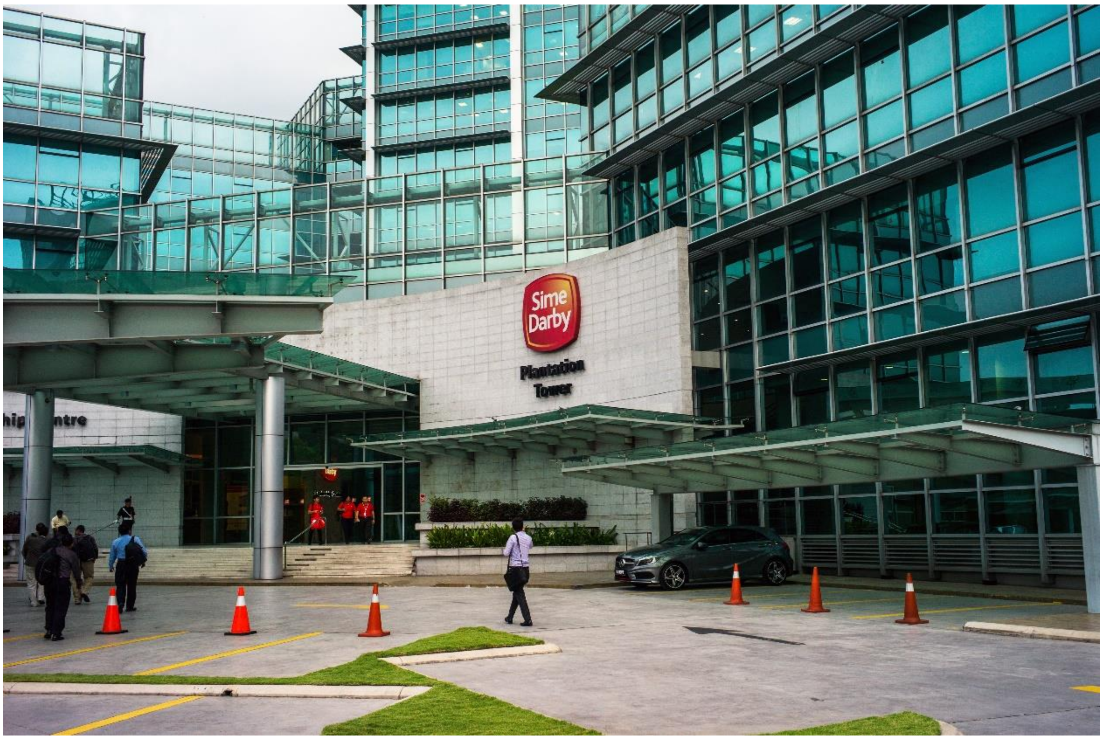

Figure 1.2: Sime Darby Plantation Tower located at Ara Damansara, Malaysia [9].

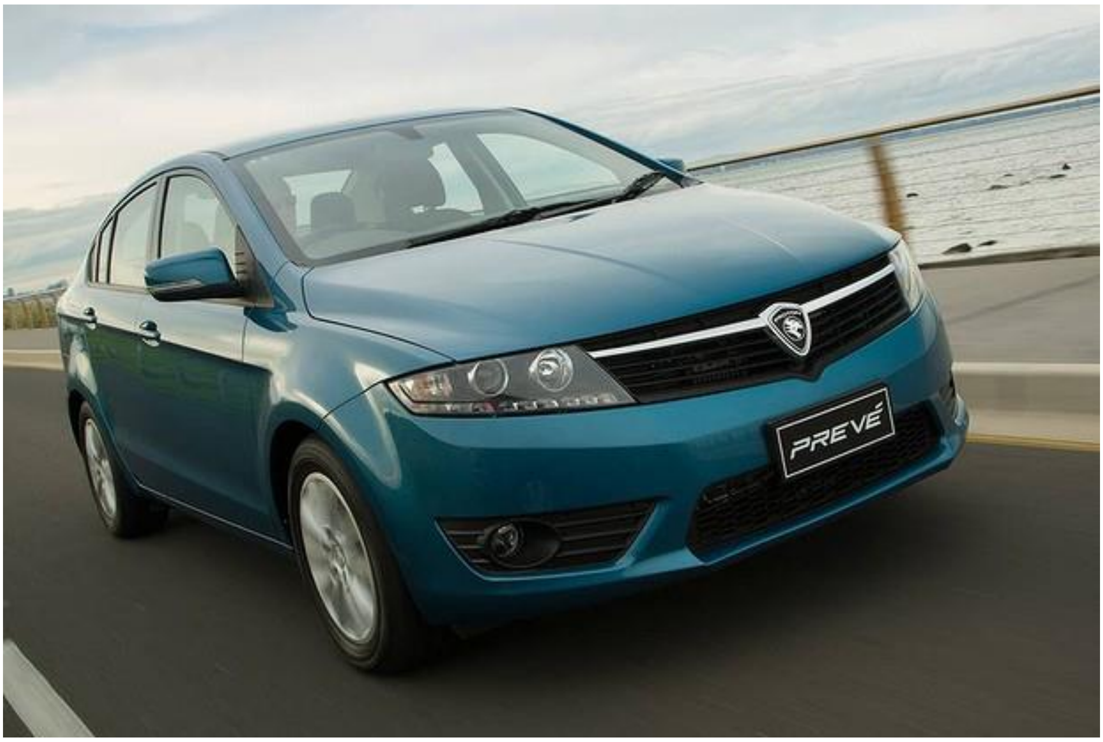

Figure 1.3: Automobiles glass windows [10].

In these modern age as well, with the construction of many high rise buildings will definitely lead to a phenomenon of signal being reflected, refracted and scattered resulting in error and loss of data. Orientation mismatch between transmitter and receiver could also cause these problems of data defect. Nevertheless, a Single Input Single Output (SISO) Circularly Polarized (CP) transparent antenna and Multiple Input Multiple Output (MIMO) transparent antenna will be able to solve these problems. Compared to Linearly Polarized (LP) systems, CP systems are less likely to be influenced by antenna misalignment complications and propagation effects [11]. Apart from it being visually aesthetic, these antennas are also equipped with a CP qualities which can be achieved in CP transparent antenna design and improved capacity benefits by MIMO transparent antenna design that complies with IEEE 802.11n standards [12].

Two techniques have been investigated on CP patch antennas; single [13, 14] and dual feed [15, 16]. Axial Ratio (AR) bandwidth is narrower on a single feed, despite the simplicity in the feeding design. Dual feed can produce a larger AR bandwidth, but the structure is more complex [17]. Transparent CP antenna is scarce, not many research has been done further into this line of work in the past; hence becoming the novelty of this work. MIMO is developed considering that material with less conductivity can reduce coupling effects, even if both ports are placed literally next to each other. Circular polarization to the electric field of each element is also increases the isolation between the two adjacent ports.

1.3 Thesis Objectives

The prime objective of this research is to design SISO CP transparent antenna and MIMO transparent antenna that operable for 5.8 GHz applications. Some of the design requirement for this transparent antenna is suitable radiation pattern, stable gain and it must be circularly polarized. This project involves antenna design and construction, measurements and antenna testing in order to investigate the performance of transparent antenna. The objectives of this project can be summarized as follows:

1. To design SISO CP transparent antenna and MIMO transparent antenna using AgHT-4.
2. To investigate the scattering parameters, bandwidth, radiation pattern, gain, efficiency, Axial Ratio (AR), AR bandwidth, Envelope Correlation Coefficient (ECC), Mean Effective Gain (MEG) and Diversity Gain (DG) of SISO CP and MIMO transparent antenna.

1.4 Scope of Research

Scopes describe the areas covered in a research. In this research, SISO CP transparent antenna and MIMO transparent antenna are designed using CST Microwave Studio 2014 (CST MWS 2014) software. Several techniques have been investigated to achieve CP and how to tackle the sensitive behavior of AgHT-4.

A research on MIMO took place by combining two of the SISO transparent antenna with CP features. These two antennas are fabricated using the same method, as both of them are sharing the same source of material. Measurement is done to prove the legitimacy of the simulations and to validate that both of them can operate properly at 5.8 GHz.

1.5 List of Contributions

There are two main contributions that were highlighted in this thesis which are simplified as follows:

- The successful incorporation of circular polarization technique into transparent antenna technology.
- An improved MIMO transparent design performance by combining two CP antennas in order to achieve polarization diversity.

1.6 Layout of the Thesis

There are a total of five chapters in this thesis. Chapter 2 is focusing on the overviews of transparent antenna and techniques that are required to improve the performance of transparent conductive material are discussed. Some papers on CP antennas was reviewed; focusing on the simplest way to achieve CP and how to incorporate them in transparent antenna design. Several MIMO antennas from different publications are discussed in order to clarify the gaps of this research.

Methods of antenna simulation, fabrication and measurement are described thoroughly in Chapter 3. Flowchart, design specifications, software, fabrication and measurement tools are stated in this chapter. Chapter 4 is discussing on various parametrical studies done in order to achieve optimum design for single element antenna. Comparison between simulations and measurement results are shown in graphs for the ease of analysis. CP is achieved with good AR purity (<3 dB).

MIMO Transparent Antenna for 5.8 GHz Applications are also presented in Chapter 4. Investigations are done to make sure which configuration is producing better isolations and the minimum distance between the two elements without sacrificing its performance. Some of the presented results are S-parameters, gain, radiation pattern, Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Mean Effective Gain (MEG) and total efficiency. Chapter 5 is a summarization of the whole work and conclusions along with future research recommendations.

REFERENCES

1. Kawashima, T., H. Matsui, and T. Tanabe, New transparent conductive films: FTO coated ITO. *Proceedings of the 3rd International Symposium on Transparent Oxide Thin films for Electronics and Optics*, 2003. 445(2): p. 241-244.
2. Azini, A.S., et al. Transparent Antenna Design for Wireless Access Point Application. *PIERS Proceedings*. 2013. Taipei.
3. Yasin, T., R. Baktur, and C. Furse. A comparative study on two types of transparent patch antennas. *XXXth URSI General Assembly and Scientific Symposium*, 2011.
4. Hakimi, S., et al., CPW-Fed Transparent Antenna for Extended Ultrawideband Applications. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: p. 1251-1254.
5. Peter, T., et al., A Novel Transparent UWB Antenna for Photovoltaic Solar Panel Integration and RF Energy Harvesting. *IEEE Transactions Antennas and Propagation*, 2014. 62: p. 1844-1853.
6. Azini, A.S., M.R. Kamarudin, and M. Jusoh, Transparent antenna for WiFi application: RSSI and throughput performances at ISM 2.4 GHz. *Telecommunication Systems*, 2015: p. 1-9.
7. Hautcoeur, J., et al., 60 GHz optically transparent microstrip antenna made of meshed AuGL material. *IET Microwaves, Antennas & Propagation*, 2014. 8: p. 1091-1096.
8. For Apple iPhone 6 Tempered Glass Screen Protector F&B Gold/Blue/Black. 2015; Available from: http://www.ebay.in/itm/For-Apple-iPhone-6-Tempered-Glass-Screen-Protector-F-B-Gold-Blue-Black-/171931983034. [3 April 2015].
9. Cheah, C.S. Industrial And Motors Segments A Drag To Sime Darby’s 3Q FY2015 Profits. 2015; Available from: http://www.bloombergtv.my/industrial-motors-segments-drag-sime-darbys-3q-fy2015-profits/. [25 April 2015].

10. Hagon, T. Proton Preve new car review. 2013; Available from: http://news.domain.com.au/drive/new-car-reviews/proton-preve-new-car-review-20131019-2vt67.html. [25 April 2015].
11. Khalily, M., M.R. Kamarudin, and M.H. Jamaluddin, A Novel Square Dielectric Resonator Antenna With Two Unequal Inclined Slits for Wideband Circular Polarization. *IEEE Antennas and Wireless Propagation Letters*, 2013. 12: p. 1256 - 1259.
12. Van Nee, R., et al., The 802.11n MIMO-OFDM Standard for Wireless LAN and Beyond. *Wireless Personal Communications*, 2006. 37(3-4): p. 445-453.
13. Lai, H.W., K.M. Mak, and K.F. Chan, Novel aperture-coupled microstrip-line feed for circularly polarized patch antenna. *Progress In Electromagnetics Research*, 2014. 144: p. 1-9.
14. Wu, T., et al., Tri-band microstrip-fed monopole antenna with dual-polarisation characteristics for WLAN and WiMAX applications. *Electronics Letters*, 2013. 49(25): p. 2.
15. Lai, X.Z., Z.M. Xie, and X.L. Cen, Design of dual circularly polarized antenna with high isolation for RFID application. *Progress In Electromagnetics Research*, 2013. 139: p. 25-39.
16. Luo, K., et al., Design Of Dual-Feed Dual-Polarized Microstrip Antenna With High Isolation and Low Cross Polarization. *Progress In Electromagnetics Research Letters*, 2013. 36.
17. Khalily, M., M.K.A. Rahim, and A.A. Kishk, Planar Wideband Circularly Polarized Antenna Design With Rectangular Ring Dielectric Resonator and Parasitic Printed Loops. *IEEE Antennas And Wireless Propagation Letters*, 2012. 11: p. 4.
18. Saberin, J.R. and C. Furse, Challenges with Optically Transparent Patch Antennas. *IEEE Antennas and Propagation Magazine*, 2012. 54: p. 10-16.
19. Rahim, S.A., et al., UWB monopole antenna with circular polarization. *Microwave and Optical Technology Letters*, 2012. 54: p. 949-953.
20. Shielded Window Solutions. Uvox Ltd: UK.
21. Azini, A.S., et al., Transparent antenna design for WiMax application. *Progress In Electromagnetics Research*, 2013. 138: p. 133-141.

22. Hakimi, S., et al., CPW-Fed Transparent Antenna for Extended Ultrawideband Applications. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: p. 1251-1254.
23. Simons, R.N. and R.Q. Lee. Feasibility study of optically transparent microstrip patch antenna. *IEEE Antennas and Propagation Society International Symposium*, 1997.
24. Edwards, P.P., et al., Basic Materials Physics of Transparent Conducting Oxides. *Dalton Transactions*, 2004. 9: p. 2995-3002.
25. Porch, A., et al., Electromagnetic absorption in transparent conducting films. *Journal of Applied Physics*, 2004. 95(9): p. 4734-4737.
26. Yasin, T., R. Baktur, and C. Furse. A study on the efficiency of transparent patch antennas designed from conductive oxide films. *IEEE International Symposium in Antennas and Propagation (APSURSI)*, 2011.
27. Saberin, J., *Optically Transparent Antenas for Small Satellites*, in Department of Electrical and Computer Engineering University of Utah, 2010. p. 42.
28. Eng Hock, L. and L. Kwok Wa, Transparent Dielectric Resonator Antennas for Optical Applications. *IEEE Transactions on Antennas and Propagation*, 2010. 58(4): p. 1054-1059.
29. Fang, X. and K.W. Leung. Use of Transparent Dielectric Resonator Antenna as a Light Cover. in *Progress In Electromagnetics Research Symposium Proceedings*, 2013. Taipei.
30. Kirsch, N.J., et al. Optically transparent conductive polymer RFID meandering dipole antenna. *IEEE International Conference on RFID*, 2009.
31. Kirsch, N.J., et al. Performance of transparent conductive polymer antennas in a MIMO ad-hoc network. *IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2010.
32. Peter, T., *Optically Transparent UWB Antenna for Wireless Application & Energy Harvesting*, in School of Engineering and Design. 2012, Brunel University: United Kingdom.
33. Katsounaros, A., et al., Optically Transparent Antenna for Ultra Wide-Band Applications. *Electronics Letters*, 2009. 45: p. 4.
34. Serra, C.C., et al., Mirror-Integrated Transparent Antenna for RFID Application. *IEEE Antennas And Wireless Propagation Letters*, 2011. 10: p. 4.

35. Colombel, F., et al., Ultrathin metal layer, ITO film and ITO/Cu/ITO multilayer towards transparent antenna. *Science, Measurement & Technology, IET*, 2009. 3(3): p. 229-234.

36. Peter, T., et al., A Novel Technique and Soldering Method to Improve Performance of Transparent Polymer Antennas. *IEEE Antennas And Wireless Propagation Letters*, 2010. 9: p. 4.

37. Tamakuma, K. and H. Iwasaki. A small size circularly polarized annular microstrip antenna. *IEEE Antennas and Propagation Society International Symposium*, 2003.

38. James, J.R. and P.S. Hall, *Handbook of Microstrip Antenna*. Vol. 1. 1989: Peter Peregrinus Ltd.

39. Suzuki, Y., N. Miyano, and T. Chiba, Circularly polarised radiation from singly fed equilateral-triangular microstrip antenna. *IEE Proceedings H, Microwaves, Antennas and Propagation, 1987*. 134(2): p. 194-198.

40. Ghobadi, A. and M. Dehmollaian, A Printed Circularly Polarized Y-Shaped Monopole Antenna. *IEEE Antennas And Wireless Propagation Letters*, 2012. 11: p. 22-25.

41. Seo, D. and Y. Sung. Dual-band circularly polarized stack ring antenna with open gap. *IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2015.

42. Jen-Yea, J., et al., Broadband CPW-Fed Circularly-Polarized Slot Antenna With an Open Slot. *IEEE Transactions Antennas and Propagation*, 2013. 61(3): p. 1418-1422.

43. Li, Z., et al., CPW-Fed Broadband Circularly Polarized Planar Monopole Antenna With Improved Ground-Plane Structure. *IEEE Transactions Antennas and Propagation*, 2013. 61(9): p. 4824-4828.

44. Sharawi, M.S., A dual-band dual-element compact MIMO antenna system for mobile 4G terminals. *Microwave Optical Technology Letters*, 2013. 55(2).

45. Foschini, G.J. and M.J. Gans, On limits of wireless communications in a fading environment when using multiple antennas. *Wirel. Pers. Commun.*, 1998. 6(3): p. 331-335.

46. Abouda, A.A. and S.G. HÄaggman, Effect of mutual coupling capacity of MIMO wireless channels in high SNR scenario. *Progress In Electromagnetics Research*, 2006. 65: p. 27-40.

47. Wang, J., Z. Lv, and X. Li, Analysis of MIMO Diversity Improvement Using Circular Polarized Antenna. *International Journal of Antennas and Propagation*, 2014. 2014: p. 9.
48. Nasir, J., et al., A reduced size dual port MIMO DRA with high isolation for 4G applications. *International Journal of RF and Microwave Computer-Aided Engineering*, 2015. 25(6): p. 495-501.
49. Meshram, M.K., et al., A Novel Quad-Band Diversity Antenna for LTE and Wi-Fi Applications With High Isolation. *IEEE Transactions Antennas And Propagation*, 2012. 60(9): p. 4360-4371.
50. Sharawi, M.S., S.S. Iqbal, and Y.S. Faouri, An 800 MHz 2 1 Compact MIMO Antenna System for LTE Handsets. *IEEE Transactions Antennas And Propagation*, 2011. 59(8): p. 3128-3131.
51. Hyok Jae, S., et al., A Method for Improving the Efficiency of Transparent Film Antennas. *IEEE Antennas and Wireless Propagation Letters*, 2008. 7: p. 753-756.
52. Peter, T., et al. Miniature transparent UWB antenna with tunable notch for green wireless applications. *International Workshop on Antenna Technology (iWAT)*, 2011. 2011.
53. Available from: http://www.silhouetteamerica.com/shop/machines/cameo. [2 June 2014]
54. Wei-Chung, W., S. Jia-Yi, and C. Chiao-Feng, A Dual-Broadband Circularly Polarized Slot Antenna for WLAN Applications. *IEEE Transactions Antennas and Propagation*, 2014. 62(5): p. 2837-2841.
55. Khalily, M., et al., Omnidirectional Circularly Polarized Dielectric Resonator Antenna for 5.2-GHz WLAN Applications. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: p. 443-446.
56. Xiang, Z., Q. XuLin, and L. RongLin, A Dual-Broadband MIMO Antenna System for GSM/UMTS/LTE and WLAN Handsets. *IEEE Antennas and Wireless Propagation Letters*, 2012. 11: p. 551-554.
57. CST MICROWAVE STUDIO 2014. 2015, CST Computer Simulation Technology AG.
58. Balanis, C.A., *Antenna theory: analysis and design*. Vol. 1. 2005: John Wiley & Sons.

59. Ali, W.K.W. and S.H. AI-Charchafchi. Using equivalent dielectric constant to simplify the analysis of patch microstrip antenna with multi-layer substrates. *IEEE Antennas and Propagation Society International Symposium*. 1998. Atlanta, GA, USA.

60. Baggen, R., S. Vaccaro, and D.L. del Rio. Design Considerations for Compact Mobile Ku-Band Satellite Terminals. *The Second European Conference on Antennas and Propagation EuCAP*, 2007.

61. Blanch, S., J. Romeu, and I. Corbella, Exact representation of antenna system diversity performance from input parameter description. *Electronics Letters*, 2003. 39(9): p. 705-707.

62. Sharawi, M.S., Printed Multi-Band MIMO Antenna Systems and Their Performance Metrics [Wireless Corner]. *IEEE Antennas and Propagation Magazine*, 2013. 55(5): p. 218-232.

63. Longfang, Z., D. Abbott, and C. Fumeaux, Omnidirectional Cylindrical Dielectric Resonator Antenna With Dual Polarization. *IEEE Antennas and Wireless Propagation Letters*, 2012. 11: p. 515-518.

64. Volakis, J.L., *Antenna Engineering Handbook*, Fourth Edition. 2007: McGraw-Hill Education.

65. Singh, H.S., et al., Low mutual coupling between MIMO antennas by using two folded shorting strips. *Progress In Electromagnetics Research B*, 2013. 53: p. 205-221.

APPENDIX A: List of Author's Publication

1. W. I. Wahid, M. R. Kamarudin, M. Khalily, and T. Peter, "Circular Polarized Transparent Antenna for 5.8 GHz WLAN Applications," *Progress In Electromagnetics Research Letters*, vol. 57, pp. 39–45, 2015. (Indexed by SCOPUS)