ULTRA WIDEBAND BUTLER MATRIX FOR BEAM-FORMING NETWORK

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This thesis is dedicated to,

my husband, Mohd Ridhuan bin Mohd Sharip,

my beloved parent, Abg Zaidel bin Abg Pauzi and Siti Aishah Abdullah @Alice Bong Mun Jin,

my parent-in-law, Mohd Sharip bin Abd Talib and Norma Ab Rahman

and

all my siblings and in-laws

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ABSTRACT

The need of having passive microwave devices that can operate in Ultra Wideband (UWB) frequency range has been arising these days due to their features that capable in bringing significant advances in wireless communications such as low power consumption, minimal interference and large channel capacity. However, the low power consumption has led to short range communication. Butler Matrix Beam Forming System is one of the solutions to solve such issue. Multilayer UWB couplers and multilayer UWB phase shifter are possible devices to develop a compact system design of Butler Matrix for UWB as the crossover function has been eliminated by this technique. New designs of multilayer UWB couplers and multilayer UWB phase shifters, which are used to construct the UWB Butler Matrix are introduced. These two main components are designed to function in the UWB frequency range to permit construction of the UWB Butler Matrix. In this research, the proposed UWB Butler Matrix achieves an improvement of 18.6% wider bandwidth compared to available UWB Butler Matrix and 31.1% size reduction compared to planar configurations of Butler Matrix. Simulation results are obtained by using Computer Simulation Technology Microwave Studio 2012. All measurements of S-parameters and phase differences performances are performed using a Vector Network Analyzer. Meanwhile, the measurements on beam directions of the UWB Butler Matrix are steered towards a particular direction by switching the input port accordingly. The switched beam antenna array system shows that four orthogonal beams are produced at four different directions. All measurements result show a very good agreement with the simulation results.

ABSTRAK

Keperluan untuk mempunyai peranti gelombang mikro pasif yang boleh beroperasi dalam julat frekuensi Jalur Lebar Ultra (UWB) telah semakin meningkat pada hari ini kerana ciri-ciri mereka yang mampu membawa kemajuan dalam komunikasi tanpa wayar seperti kuasa yang rendah, gangguan yang minimum dan kapasiti saluran yang besar. Walau bagaimanapun, kuasa yang rendah telah membawa kepada komunikasi jarak pendek. Sistem Butler Matrix Membentuk Pancaran adalah salah satu penyelesaian untuk menyelesaikan isu tersebut. Struktur berbilang-lapisan pengganding UWB dan berbilang-lapisan penganjak fasa UWB adalah peranti yang mungkin boleh digunakan untuk membina saiz reka bentuk Butler Matrix yang lebih kompak untuk kegunaan dalam julat frekuensi UWB kerana fungsi penyeberang telah dihapuskan dengan menggunakan teknik berbilang-lapisan ini. Reka bentuk terbaru berbilang-lapisan pengganding UWB dan berbilang-lapisan penganjak fasa UWB yang diguna untuk membina UWB Butler Matrix diperkenalkan. Kedua-dua komponen utama direka untuk berfungsi dalam julat frekuensi UWB untuk membenarkan pembinaan Butler Matrix UWB. Dalam kajian ini, Butler Matrix UWB yang dicadangkan mencapai peningkatan sebanyak 18.6% jalur lebar yang lebih luas berbanding dengan Butler Matrix UWB sedia ada dan pengurangan saiz sebanyak 31.1% berbanding dengan konfigurasi satah Butler Matrix. Keputusan simulasi diperolehi dengan menggunakan *Computer Simulation Technology Microwave Studio 2012*. Semua pengukuran S-parameter dan perbezaan fasa dilakukan dengan menggunakan Penganalisa Rangkaian Vektor. Sementara itu, keputusan ukuran kajian menunjukkan arah radiasi Butler Matrix yang dikemudikan mengikut arah yang ditentukan mengikut perubahan input. Sistem membentuk pancaran menunjukkan bahawa empat pancaran ortogon dihasilkan di empat arah yang berbeza. Semua keputusan pengukuran menunjukkan perkaitan yang amat baik dengan keputusan simulasi.

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LIST OF ABBREVIATIONS

UWB	-	Ultra Wideband
RF	-	Radio Frequency
GHz	-	Gigahertz
CST	-	Computer Simulation Technology
VNA	-	Vector Network Analyzer
SNR	-	Signal-to-Noise Ratio
DOA	-	Direction of Arrival
FIR	-	Finite Impulse Response
GSM	-	Global System for Mobile
MHz	-	Megahertz
PCS	-	Personal Communication System
WLAN	-	Wireless Local Area Network
UMTS	-	Universal Mobile Telecommunications System
MATLAB	-	Matrix Laboratory
CPW	-	Co-planar Waveguide
dB	-	Decibel
P1	-	Port 1
P2	-	Port 2
P3	-	Port 3
P4	-	Port 4
P5	-	Port 5
P6	-	Port 6
P7	-	Port 7
P8	-	Port 8
3-D EM	-	Three-Dimensional Electromagnetic

TLM	-	Transmission-Line Matrix
FCC	-	Federal Communications Commission
ICU	-	Intensive Unit Care
EM	-	Electromagnetic
FR4	-	Flame Resistant 4
SMA	-	SubMiniature version A

LIST OF SYMBOLS

d_n	-	Number of the input port
N	-	Matrix order
Z_{0e}	-	Characteristic impedance of even-mode analysis
Z_{0o}	-	Characteristic impedance of odd-mode analysis
C	-	Coupling factor
Z_0	-	Characteristic impedance
λ	-	Free space wavelength
c	-	Speed of light
Γ	-	Reflection coefficient
ΔS_{21}	-	Phase shift across the main line
ΔS_{43}	-	Phase shift across the reference line
f_c	-	Center frequency
f_H	-	High frequency
f_L	-	Low frequency
ε_r	-	Dielectric constant of the substrate
w_p	-	Patch's width
l_p	-	Patch's length
w_s	-	Slot's width
D_s	-	Diameter of the elliptical for the slot
D_m	-	Diameter of the elliptical for the microstrip patch
l_s	-	Slot's length
λ_e	-	Effective wavelength
ε_e	-	Effective permittivity
h	-	Height of substrate

$\leq$	-	Less then
Ω	-	Ohm
λ_g	-	Guide wavelength
w_m	-	Width of the 0º phase shift microstrip transmission line
α	-	Output for phase differences of Butler Matrix
β	-	Phase difference between consecutive output ports
d	-	Distance
θ	-	Phase angle
w_f	-	Width of the input and output ports
l	-	Length of the coupled structure
w_c	-	Maximum width of the coupled patches
n	-	Integer to change the shape of the coupler
W	-	Width of the substrate
L	-	Length of the substrate
Z_{air}	-	Impedance of free space
dm	-	Width of the rectangular microstrip patch
ds	-	Width of the rectangular slot
l_m	-	Length of the rectangular microstrip patch
D_p	-	Diameter of the elliptical-slot for the microstrip patch
s	-	Diameter of the phase shifter’s centre slot

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Ultra wideband (UWB) technology refers to any system that occupies more than 25% of the bandwidth of the center frequency or any system that has a bandwidth greater than 1 GHz with return loss performance of at least -10 dB [1]. The use of UWB holds many benefits, including an ability to penetrate obstacles, ultra high accuracy down to the centimeter level, accurate ranging, resistance to jamming, high data rates, and low power consumption. Earlier, UWB technology is equally suited to military applications to be used as radar and tracking devices. However, due to its benefits and attractive features, the Federal Communications Commission (FCC) of the United States allocated the frequency band 3.1 GHz to 10.6 GHz as an unlicensed operations band for UWB systems [2], with the intention that society at large benefit from this technology as well. Since then, a rising interest on UWB has made the technology grows to a new level and more applications have been explored such as in medical and communication applications.

As an example, in medical applications, UWB can be used to detect breast cancer [3-4] and to monitor patients [5-7] in the intensive care unit (ICU), emergency room, home health care settings, and in rescue operations, where at a certain level, UWB systems can detect heartbeats under ruins, soil, or snow [8]. However, due to low power consumption, UWB holds one great disadvantage which is narrow communication range. Smart antenna system is one way to improve the problems holds by UWB technology.

Smart antenna has two types: the switched-beam array antenna and adaptive array antennas [9]. For the switched-beam array antenna, the system is capable of forming multiple fixed beams and to focus only its main beam on the desired location. This leads to maximizing the energy at the desired location, enhancing the received signals. The system detects signal strength, selects one of several fixed beams, and switches from one beam to another as the user moves. Meanwhile, in an adaptive array system, the antenna array is capable of automatically changing the beam pattern in accordance with the changing signal environment. At the same time, the adaptive array system introduces the maximum beam signal in the desired direction and nulls the other, interfering directions. Therefore, this system is able to control the radiation pattern, hence leading to increased antenna system capacity.

One of the most widely known switched-beam systems for beam-forming networks is the Butler Matrix [10]. The Butler Matrix is an N×N network consisting of N inputs and N outputs. Orthogonal beams pointed at different angles can be generated in switched beam antenna systems by connecting an N×N Butler Matrix to an N-element array antenna [11]. The Butler Matrix circuit is widely used in various beam antenna linear array systems to produce multiple beams. This circuit has the ability to form orthogonal beams. Comparing the Butler Matrix with other switched-beam array antenna such as the Blass Matrix, the Butler Matrix requires fewer microwave couplers [12]. Recently, a lot of efforts have been done on Butler Matrix design to be implemented into UWB technology. Few techniques have been proposed which has been presented and reported in [10-11, 13-19].

1.2 Problem Statement and Motivations

A Butler Matrix consists of three main components; 3-dB couplers, crossovers and 45^o phase shifters. These three main components must be designed to function in the UWB frequency range to permit construction of the UWB Butler Matrix. Design of a UWB Butler Matrix is achieved in [17], where the authors design the UWB Butler Matrix onto planar configurations and good agreement between both simulated and measured results of the UWB Butler Matrix is achieved. However, the use of a five-section coupled-line coupler and phase shifter, together with two two-section Schiffman C-sections in this design, requires a very narrow slot, which makes fabrication very difficult. In addition, this Butler Matrix is bulky, due to the large number of multiple coupled sections. Therefore, a simpler and more compact system design UWB Butler Matrix should be designed due to recent technology where simpler and compact system design are needed in an environment of ever increasing technological complexity.

To obtain simpler and compact system design with UWB performance, the multilayer technique is chosen. In multilayer technique, simplicity and compactness in the system design is achieved due to elimination of the crossovers. The multilayer UWB Butler Matrix is designed to replace the UWB Butler Matrix in [17] with similar performance, to increase the competitiveness of the UWB Butler Matrix in wider industrial applications.

Several UWB Butler Matrix designs employing the multilayer technique has been designed in the range of 3.1 GHz to 10.6 GHz where, the simulation result for multilayer UWB Butler Matrix designs has shown good performance within the frequency range of 3.1 to 10.6 GHz [11, 14-15, 18-19]. However, performance were limited to simulated results, and no verification or measurement has been made to prove the performance of the UWB Butler Matrix [18-19]. In [11, 14-15], measurement is made to verify the performance of the UWB Butler Matrix. The authors claim that good performance for simulated and measured results is observed from 3 GHz to 9.2 GHz [14-15] and from 4.5 to 8.8 GHz [11],which shows that the whole UWB coverage is still not achievable. The largest discrepancies between the simulated and measured results occur in the range 3 GHz to 4.5 GHz and 9 GHz to 11 GHz [11]. This is due to the phase shifter used in the Butler Matrix design, where the result of the phase shifter shows that the performance was in the range 4 GHz to 8.5 GHz. Improvement to the couplers and phase shifters in the UWB Butler Matrix, along with an improved fabrication process, must be demonstrated to achieve better results both in simulated and measured results.

1.3 Objectives of Research

The objectives for this research are stated as follows:

i. To design, simulate, optimize and fabricate compact size UWB coupler and UWB phase shifter which cover from 3.1 GHz to 10.6 GHz using multilayer technology.

ii. To construct a compact system design UWB multilayered Butler Matrix system design by using the designed UWB coupler and UWB phase shifter and eliminate the function of crossover.

iii. To integrate UWB Butler Matrix with available antenna array to perform as switched-beam antenna array.

1.4 Scope of Research

This research focuses on the design of a UWB Butler Matrix that can operate within the UWB frequency range, 3.1 GHz to 10.6 GHz. The development of a UWB Butler Matrix comprised of UWB couplers and UWB phase shifters, various structures of UWB couplers and UWB phase shifters that are designed, simulated, optimized, fabricated, and measured. The chosen UWB couplers and UWB phase shifters are combined to form a UWB Butler Matrix. Integration of the existing UWB antenna to the output ports of the designed Butler Matrix is carried out to build a switched-beam antenna array system. The novelty of this research includes design of the couplers, phase shifters and the Butler Matrix that operated in UWB. Simulated and measured results of the UWB Butler Matrix aim for operation is in a frequency range of 3.1 GHz to 10.6 GHz.

The simulation and optimization process of individual components and the Butler Matrix is performed using Computer Simulation Technology (CST) Microwave Studio software onto a Rogers RO4003C board with thickness of 0.508 mm and dielectric constant of 3.38. To ensure that performance in the measured results is comparable with the simulated results, fabrication and measurement processes are performed, and the results are measured using a vector network analyzer (VNA). All simulated and measured results, including return loss, isolation, phase differences between output ports, and coupling effect of all designed components, were carried out and carefully discussed. Integration of UWB Butler Matrix has been done with existing UWB antenna to perform the UWB switched-beam antenna array. To observe the antenna’s beam direction, radiation pattern measurement of the UWB switched beam antenna array was taken.

1.5 Contribution of the Research

For this research, three major contributions are introduced which include:

i. The design of new multilayer UWB coupler and its investigation on the effect of the microstrip patch shape and slot at ground plane to the coupler's performance. In addition, air gap and misalignment parametric studies are performed to observe on how these circumstances affecting the simulation and measurement results of the designed coupler.

ii. The design of new multilayer UWB phase shifter. The new multilayer UWB phase shifter is designed with the implementation of tapered-line transmission line and centre slot which result in size reduction compared to the available multilayer UWB phase shifter.

iii. The design of new multilayer UWB Butler Matrix. In previous work, several Butler Matrix designs have been reported in the range of 3.1 GHz to 10.6 GHz. However, none of them achieve optimum performance in the frequency range of 3.1 GHz to 10.6 GHz with bulky size. In order to reduce the size and enhance the bandwidth performance of the Butler Matrix, multilayer technique is employed in the design. By employing this technique, compact Butler Matrix is achieved due to elimination of the crossovers. Both simulated and measured results of the compact multilayered UWB Butler Matrix show improved performance in the desired frequency range. The proposed UWB Butler Matrix achieves an improvement of 18.6% wider bandwidth compared to available UWB Butler Matrix and 31.1% size reduction compared to planar configurations of Butler Matrix.

1.6 Thesis Outline

This thesis is organized into seven chapters. In Chapter 1, the overview of the whole project is discussed. This includes overview of the project background, problem statement, significance of the research, research objectives, explanation on the research scope and last but not least, the thesis organization.

Chapter 2 focuses on the literature reviews. Introduction and basic concepts of ultra wideband, smart antenna system, array factor, Butler Matrix, coupler and phase shifter are further discussed in this chapter. The theory of the design development is introduced. Comparison between available designed of the main components and also Butler Matrix itself are described.

Chapter 3 discusses the methodology of this research project. The research workflows of the whole research are presented in this chapter. The design parameters and specifications are also introduced in this chapter. The simulation software, Computer Simulation Technology (CST) Microwave Studio and MATLAB are utilized to get a clear visualization of overall design. In addition, the measurement process including the use of Vector Network Analyzer (VNA) is introduced.

In Chapter 4, the design of the coupler for this research is presented. Three designed couplers are introduced. The simulation and measurement results for all designed couplers are discussed and analysed on the parametric study of the coupler including the air gap analysis and alignment analysis are explained. Elaboration on the couplers results are also discussed in this chapter.

Chapter 5 introduces the designed phase shifter. Four designed couplers are introduced in this chapter. Simulation and measurement results of the designed phase shifters are discussed. Two analyzes on the phase shifter, which is on the stepped impedances and tapered transmission line also are elaborated in details at this chapter.

Proposed Butler Matrix design is further discussed in Chapter 6. The result for the whole Butler Matrix as the beam forming system is elaborated. The implementation of the 0º phase shift microstrip transmission line into the Butler Matrix design is further conversed in this chapter. Both simulation and measurement results in term of scattering parameter, phase differences between each consecutive ports and phasor beam directions are described in details at this chapter.

In the last chapter, Chapter 7, this research work is concluded. In addition, the finding of the project, key contributions and recommendations for future works are proposed and described in this chapter. Last but not least, the list of references and appendices are provided at the end of this thesis.

REFERENCES

[1] Siwiak, K. (2001). Ultra-Wide Band Ratio: Introducing a New Technology. *Conference in Vehicular Technology*. Rhodes, Greece, 1088-1093

[2] Fiske, D.(2002). *New Public Safety Applications and Broadband Internet Access Among Uses Envisioned by FCC Authorization of Ultra-Wideband Technology.*

[3] Lazaro, A., Girbau, D. and Villarino, R. (2009). *Simulated and experimental investigation of microwave imaging using UWB.* Progress In Electromagnetics Research. 94, 263-280.

[4] Maskooki, A., et al. (2009). *Frequency domain skin artifact removal method for ultra-wideband breast cancer detection.* Progress In Electromagnetics Research. 98, 299-314.

[5] Yong, X., et al., (2007). An Overview of Ultra-Wideband Technique Application for Medical Engineering. *International Conference on Complex Medical Engineering.*23-27 May 2007. Beijing, 408-411.

[6] Ziganshin, E.G., Numerov, M.A. and Vygolov. S.A. (2010). UWB Baby Monitor. *5th International Conference on Ultrawideband and Ultrashort Impulse Signals (UWBUSIS),* 6-10 Sept. 2010.Sevastopol, 159-161.

[7] Immoreev, I. and T. Teh-Ho, *UWB Radar for Patient Monitoring.* IEEE Aerospace and Electronic Systems Magazine, 2008. 23(11), 11-18.

[8] Pan, J. (2008). *Medical applications of ultra-wideband (UWB).*

[9] Balanis, C.A. (2005). *Antenna Theory : Analysis and Design*. (Third Edition) United States: John Wiley & Sons.

[10] Denidni, T.A. and Libar, T.E. (2003). Wide Band Four-port Butler Matrix for Switched Multibeam Antenna Arrays. *14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications (PIMRC)*. 7-10 Sept. 2003.2461 – 2464.

[11] Ibrahim, S.Z. and Bialkowski. M.E. (2009). Wideband Butler Matrix in microstrip-Slot Technology. *Asia Pasific Microwave Conference (APMC)*. 7-10 Dec. 2009Singapore, 2104-2107.

[12] Nedil, M., Denidni, T.A. and Talbi, L. (2006). *Novel butler matrix using CPW multilayer technology*. IEEE Transactions on Microwave Theory and Techniques. 54(1), 499-507.

[13] Traii, M., et al. (2008). *A New Design of Compact 4 X 4 Butler Matrix for ISM Applications.* International Journal of Microwave Science and Technology.

[14] Abdelghani, L.M., Denidni, T.A. and Nedil, M. (2012). Ultra-broadband 4x4 compact Butler matrix using multilayer directional couplers and phase shifters. *Microwave Symposium Digest (MTT).*

[15] Abdelghani, L., Denidni, T.A. and Nedil, M. (2012). Design of a new Ultra-wideband 4x4 Butler matrix for beamforming antenna applications. *IEEE Antennas and Propagation Society International Symposium (APSURSI).*

[16] Gruszczynski, S. and Wincza, K. (2009). *Broadband 4X4 Butler Matrices as a Connection of Symmetrical Multisection Coupled-line 3-dB Directional Couplers and Phase Correction Networks.* IEEE Transactions on Microwave Theory and Techniques. 57(1), 1-9.

[17] Krzysztof W., Gruszczynski, S. and K. Sachse.(2011). Ultrabroadband 4X4 Butler Matrix with the use of multisection coupled-line directional couplers and phase shifter. *Microwaves, Radar and Remote Sensing Symposium.* Kiev, Ukraine.

[18] Bialkowski, M.E., et al. (2008). Design of Fully Integrated 4x4 and 8x8 Butler Matrices in Microstrip/slot Technology for Ultra Wideband Smart Antennas. *IEEE Antennas and Propagation Society International Symposium (AP-S 2008)*. San Diego, CA.

[19] Yu-Chuan, S., et al. (2008). UWB Switched-Beam Array Antenna Employing UWB Butler Matrix. *International Workshop on Antenna Technology : Small Antennas and Novel Metamaterials, (iWAT 2008)*. Chiba.

[20] Pham, N.T., Lee, G.-A. and Flaviis, F.D. (2005). Microstrip Antenna Array with Beamforming Network for WLAN Applications. *Antennas and Propagation Society International Symposium.*

[21] Mallaparapu, U., et al.(2011). *Non-blind adaptive beam forming algorithms for smart antennas.* International Journal of Research and Reviews in Applied Sciences. 6(4), 491-496.

[22] Rani, C.S., et al., (2009). *LMS and RLS algorithms for smart antennas in a WCDMA mobile communication environment.* ARPN Journal of Engineering and Applied Sciences. 4(6), 78-88.

[23] Casini, F., et al. (2007). A novel design method for Blass matrix beam-forming networks. *European Radar Conference, EuRAD 2007.*

[24] Rotman, W. and Turner R. (1963). *Wide-angle microwave lens for line source applications.* IEEE Transactions on Antennas and Propagation. 11(6), 623-632.

[25] Wright, J.S., Chudobiak, W.J. and Makios, V. (1976). *A microstrip and stripline crossover structure (letters).* IEEE Transactions on Microwave Theory and Techniques. 24(15), 270.

[26] Hiranandani, M.A. (2005).Widening butler matrix bandwidth within the X-band.*IEEE Antenna and Propagation Society International Symposium*.

[27] Moody, H.(1964). *The systematic design of the Butler matrix.* IEEE Transactions on Antennas and Propagation. 12(6), 786-788.

[28] Kaifas, T.N. and Sahalos, J.N. (2006). *On the design of a single-layer wideband Butler matrix for switched-beam UMTS system applications [Wireless Corner]*. IEEE Antennas and Propagation Magazine. 48(6), 193-204.

[29] Jizat, N.M., Rahim, S.K.A. and Rahman, T.A. (2010). Dual Band Beamforming Network Integrated with Array Antenna. *2010 Fourth Asia International Conference* in *Mathematical/Analytical Modelling and Computer Simulation (AMS).*

[30] Abdulrahman, A.S.A., (2010). *Ultra Wideband Butler Matrix Beam Forming Network Using Mutilayer Technology*. Master in Engineering (Electrical). Universiti Teknologi Malaysia.

[31] Ahmad, S.R. and Seman, F.C. (2005). 4-port Butler matrix for switched multibeam antenna array. *Asia-Pacific Conference in Applied Electromagnetics.*

[32] Ibrahim, S.Z. and Rahim, M.K.A. (2007). Switched Beam Antenna using omnidirectional antenna array. *Asia-Pacific Conference* in *Applied Electromagnetics, APACE 2007.*

[33] Mariadoss, P.Q., Rahim, M.K.A. and Abd Aziz, M.Z.A. (2005). Butler matrix using circular and mitered bends at 2.4 GHz.*IEEE 7th Malaysia International Conference on Communication.*

[34] Kaifas, T.N. and Sahalos, J.N. (2006). *On The Design of a Single-layer Wideband Butler Matrix for Switched-beam UMTS System Applications [Wireless Corner]*. IEEE Antennas and Propagation Magazine, 48(6).

[35] Gruszczynski, S., Wincza, K. and Sachse, K. (2007). *Compact Broadband Butler Matrix in Multilayer Technology for Integrated Multibeam Antennas.* Electronics Letters. 43(11).

[36] Zheng, S., et al. (2007). *Broadband Butler Matrix with Flat Coupling.* Electronics Letters. 43(10).

[37] Nedil, M., et al. (2010) Novel ultra-wideband Butler matrix for wireless underground mines. IEEE *Antennas and Propagation Society International Symposium (APSURSI)*. 11-17 July 2010. Toronto, 1-4.

[38] Traii, M., et al.(2010). Novel UWB Multilayer Butler Matrix. *Antennas and Propagation Society International Symposium (APSURSI)*. 11-17 July 2010. Toronto, 1-4.

[39] Schiffman, B.M. (1958). *A New Class of Broadband Microwave 90-degree Phase Shifters.* IRE Transactions on Microwave Theory and Techniques. 6(2), 232-237.

[40] Abbosh, A.M. and Bialkowski, M.E. (2007). *Design of Compact Directional Couplers for UWB Applications.* IEEE Transactions on Microwave Theory and Techniques. 55(2), 189.

[41] Abbosh, A.M. (2007). *Ultra-Wideband Phase Shifters.* IEEE Transactions on Microwave Theory and Techniques. 55(9), 1935-1941.

[42] Abdelghani, L., Denidni, T.A. and Nedil, M. (2011). Design of a broadband multilayer coupler for UWB beamforming applications. *Proceedings of the 41st European Microwave Conference*. Manchester, UK.

[43] Pozar, D.M. (2005). *Microwave Engineering*. (3rd Edition). J. Wiley & Sons, Inc.

[44] Tsung-Nan, K., et al. (2006). *A compact LTCC branch-line coupler Using Modified-T equivalent-circuit model for transmission line.* IEEE Microwave and Wireless Components Letters. 16(2), 90-92.

[45] Jizat, N.M. (2010). *Reduced size cascaded Butler Matrices for dual band dual beam applications.* Master in Engineering (Electrical). Universiti Teknologi Malaysia.

[46] Ginzton, E.L. and Goodwin, P.S. (1950). *A Note on Coaxial Bethe-Hole Directional Couplers.* Proceedings of the IRE. 38(3), 305-309.

[47] Kim, D.-H., et al. (2002). A study on broadband multi-hole directional coupler. *3rd International Conference on Microwave and Millimeter Wave Technology (ICMMT 2002).*

[48] Arriola, W.A., Young, L. J. and Seok, K. I. (2011). *Wideband 3 dB Branch Line Coupler Based on lambda /4 Open Circuited Coupled Lines.* IEEE Microwave and Wireless Components Letters. 21(9), 486-488.

[49] Pon, C. (1961). *Hybrid-Ring Directional Coupler for Arbitrary Power Divisions.* IEEE Transactions on Microwave Theory and Techniques. 9(6), 529 - 535.

[50] Yongjin, K., Byungje, L. and Myun-Joo, P. (2005). Compact three section coupled line couplers. *Asia-Pacific Microwave Conference Proceedings (APMC).*

[51] Muraguchi, M., Yukitake, T. and Naito, Y. (1983). *Optimum design of 3-dB branch-line couplers using microstrip lines.* IEEE Transactions on Microwave Theory and Techniques. 31(8), 674-678.

[52] Riblet, G.P. (1978). *A directional coupler with very flat coupling.* IEEE Transactions on Microwave Theory and Techniques. 26(2), 70-74.

[53] Lange, J. (1969). Interdigitated strip-line quadrature hybrid. *International Microwave Symposium, G-MTT*. Dallas TX, USA, 10-13.

[54] Nedil, M. (2008). *A new Ultra-wideband beamforming for wireless communications in underground mines.* Progress In Electromagnetics Research M. 4, 1-21.

[55] Zhang, Q. and Khan S.N. (2009). *Compact Broadside Coupled Directional Coupler Based on Coplanar CRLH Waveguides.* Journal of Electromagnetic Waves and Applications. 23, 267-277.

[56] Nedil, M. and Denidni, T.A. (2008). *Analysis and Design of an ultra wideband directional coupler.* Progress In Electromagnetics Research B. 1, 291-305.

[57] Tanaka, T., Tsunoda, K. and Aikawa, M. (1988). *Slot-coupled directional couplers between double-sided substrate microstrip lines and their applications.* IEEE Transactions on Microwave Theory and Techniques. 36(12), 1752-1757.

[58] Tanaka, T., Tsunoda, K. and Aikawa, M. (1988). New slot-coupled directional couplers between double-sided substrate microstrip lines, and their applications. *Microwave Symposium Digest IEEE MTT-S International*.

[59] Ronde, F.C.d.(1970). A New Class of Microstrip Directional Couplers. *International Microwave Symposium, G-MTT*. Newport Beach, CA, USA, 184-189.

[60] Garcia, J.A. (1971). *A Wide-Band Quadrature Hybrid Coupler*. IEEE Transactions on Microwave Theory and Techniques. 19(7), 660.

[61] Schiek, B. (1974). *Hybrid Branchline Couplers - A Useful New Class of Directional Couplers.* IEEE Transactions on Microwave Theory and Techniques. 22(10), 864-869.

[62] Hoffmann, R.K. and Siegl, J. (1982). *Microstrip-Slot Coupler Design-Part I: S-Parameters of Uncompensated and Compensated Couplers.* IEEE Transactions on Microwave Theory and Techniques. 30(8). 1205.

[63] Sfar, I., et al. (2011). Limitation of a Five-Port Reflectometer using Planar Elliptic Couplers for UWB applications. *11thMediterranean Microwave Symposium (MMS).* 8-10 September 2011. Hammamet, 299-304.

[64] Bialkowski, M.E. and Jellett S.T. (1994). *Analysis and Design of a Circular Disc 3-dB Coupler.* IEEE Transactions on Microwave Theory and Techniques. 42(8). 1437-1442.

[65] Bialkowski, M.E., Seman, N. and Leong, M.S. (2009). Design of a compact ultra wideband 3-dB Microstrip-slot coupler with high return losses and isolation. *Asia Pacific Microwave Conference (APMC).*7-10 December 2009. Singapore, 1334-1337.

[66] Muklas, N.S, et al.(2013). *A Design of Compact Ultra Wideband Coupler for Butler Matrix.* Wireless Personal Communications. 70(2), 915-926.

[67] Muklas, N.S., Rahim, S.K.A. and Seman, N. (2011). Ultra wideband coupler design for Butler Matrix application. *17th Asia-Pacific Conference on Communications (APCC).*

[68] Seman, N. and Bialkowski, M.E. (2009). *Design and analysis of an ultrawideband three-section microstrip-slot coupler*. Microwave and Optical Technology Letters. 51(8), 1889-1892.

[69] Levy, R. (1963). *General synthesis of asymmetric multi-element coupled-transmission-line directional couplers.* IEEE Transactions on Microwave Theory and Techniques. 11(4), 226-237.

[70] Levy, R. (1964). *Tables for Asymmetric Multi-Element Coupled-Transmission-Line Directional Couplers.* IEEE Transactions on Microwave Theory and Techniques. 12(3), 275-279.

[71] Marynowski, W., et al. (2008). Investigations of broadband multilayered coupled line couplers. *14th Conference on Microwave Technique*. 23-24 April 2008. Prague, 1-4.

[72] Shelton, J.P. and Mosko, J.A. (1966). *Synthesis and Design of Wideband Equal Ripple TEM Directional Couplers and Fixed Phase Shifters.* IEEE Transactions on Microwave Theory and Techniques. 14(10), 462.

[73] Meschanov, V., et al. (1994). *A New Structure of Microwave Ultrawide-band Differential Phase Shifters.* IEEE Transactions on Microwave Theory and Techniques. 42(5), 762-765.

[74] Chai, D., et al., (2003). *Asymmetric Teflon-based Schiffman Phase Shifters.* Electronics Letters. 39(6), 529-530.

[75] Guo, Y., Zhang, Z. and Ong, L. (2006). *Improved Wideband Schiffman Phase Shifter.* IEEE Transactions on Microwave Theory and Techniques. 54(3), 1196-1200.

[76] Sorn, M., Lech R., and Mazur J. (2012). *Simulation and Experiment of a Compact Wideband 90º Differential Phase Shifter.* IEEE Transactions Microwave Theory and Techniques. 60(3). 494-501.

[77] Guo, L. and Abbosh A. (2013). *Ultra-wideband phase shifter using broadside-coupled microstrip coplanar waveguide*. 2013 Asia-Pacific Microwave Conference Proceedings (APMC). 5-8 November 2013. Seoul, Korea. 951-953.

[78] Zheng, S.Y., Chan, W.S. and Man, K.F. (2009). Broadband parallel stubs phase shifter. *Asia Pacific Microwave Conference (APMC).*7-10 December 2009. Singapore. 1368-1371.

[79] Yifan, W. and Bialkowski, M.E. (2010). UWB phase shifter with parallel stubs terminated with virtual short and ground slots. *EuropeanMicrowave Conference (EuMC).*28-30 September 2010. Paris. 1166-1169.

[80] Xinyi, T. and Mouthaan. K. (2009). Design of a UWB phase shifter using shunt λ/4 stubs. *IEEE MTT-S International Microwave Symposium Digest.*7-12 June 2009. Boston, MA. 1021-1024.

[81] Huang, P.S. and Lu H.C. (2012). *Improvement of the Phase Shifter in 90º Power Splitter for UWB Applications.* IEEE Microwave and Wireless Components Letters. 22(12). 621-623.

[82] Guo, L. and Abbosh A. (2013). *Multilayer phase shifter with wide range of phase and ultra-wideband performance*. 2013 Asia-Pacific Microwave Conference Proceedings (APMC). 5-8 November 2013. Seoul, Korea. 16-18.

[83] Seman, N., Bialkowski, M.E. and Khor, W.C. (2007). Ultra wideband vias and power dividers in microstrip-slot technology. *Asia-Pasific Microwave Conference (APMC).* 11-14 December 2007. Bangkok, 1-4.

[84] Haynes, T. (1998) *A Primer on Digital Beamforming*.

[85] Abbosh, A.M. (2009). *Effect of tapering shape on performance of broadside-coupled directional couplers.* Microwave and Optical Technology Letters. 51(5), 1285-1288.

[86] Choi, S.H., et al. (2004). *A new ultra-wideband antenna for UWB applications.* Microwave and Optical Technology Letters. 40(5), 399-401.

[87] Li, P., Liang, J. and Chen, X. (2006). *Study of printed elliptical/circular slot antennas for ultrawideband applications.* IEEE Transactions on Antenna and Propagation. 54(6), 1670-1675.

[88] *CST Microwave Studio*. 2013

[89] Hirtenfelder, F. (2007). Effective Antenna Simulations using CST MICROWAVE STUDIO®. *2nd International ITG Conference on Antennas.*

[90] Demming-Janssen, F. and Koch, W. (2006). 3D Field simulation of sparse arrays using various solver techniques within CST MICROWAVE STUDIO®. *3rd European Radar Conference (EuRAD).*

[91] *Handbook "CST MICROWAVE STUDIO® Workflow and Solver Overview"*. 2008: Computer Simulation Technology (CST).

[92] Aleksi, I., Kraus, D. and Hocenski, Z. (2011). Multi-language programming environment for implementation of SONAR signal processing by linking with MATLAB External Interface and FFTW. *ProceedingsELMAR.*

[93] *MATLAB*. 2013.

[94] Luhe, H. and Jianli, C. (2010). The application guide of mixed programming between MATLAB and other programming languages. *The 2nd International Conference on Computer and Automation Engineering (ICCAE).*

[95] *MATLAB Programming Language*. 2013.

[96] Birkbeck, N., Levesque, J. and Amaral, J.N. (2007). A Dimension Abstraction Approach to Vectorization in Matlab. *International Symposium on Code Generation and Optimization.*

[97] Fiedziuszko, S.J., et al. (2002). *Dielectric materials, devices, and circuits.* IEEE Transactions on Microwave Theory and Techniques. 50(3), 706-720.

[98] Rogers Corporation. *RO4000 Series High Frequency Circuit Materials*. 2013.

[99] *FR4 Data Sheet*. 2013.