DUAL-SERIES 2 × 4 SWITCHED-BEAM NOLEN MATRIX FOR FIFTH GENERATION WIRELESS COMMUNICATION SYSTEM

NAZLEEN SYAHIRA BINTI MOHD SUHAIMI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

APRIL 2018

Specially dedicated and thankful to my beloved parents and family,
my inspirational supervisor, Dr Norhudah Seman,
my friends, lecturers & WCC staffs for their
endless support, encouragement and motivation throughout my research study.
A warm thanks to all

ACKNOWLEDGEMENT

Working on this research project was an infinite and rewarding experience. This dissertation is dedicated to everyone in the field of radio frequency and microwave who embarks the journey of broadening the knowledge and transcendent passion for radio frequency and microwave.

First and foremost, it is my immense pleasure to express my sincere gratitude to my supervisor, Associate Professor Dr. Norhudah binti Seman whom her extensive knowledge in the engineering field, especially in the radio frequency have been instrumental in the success of this research project. Her insightful advice, noble guidance and patience throughout the short time made it such a fantastic experience for me to overcome all the obstacles that I have encountered. I take this opportunity to record my sincere thanks to Professor Amin Abbosh for supervising me as well as Emad Al-Abbas for sharing his knowledge during my research attachment in The University of Queensland (UQ), Australia.

I would like to extend my utmost gratitude to all technical staffs of Wireless Communication Centre (WCC) and The University of Queensland, Australia who have assisted me in using the network analyzer and other related equipment in the laboratory. Last but not least, I would like to dedicate my regards and blessing towards all of my family members and fellow friends for staying beside me through thick and thin as well as giving me moral support during the execution of this research project.

ABSTRACT

A new evolvement towards 5G technology requires a super high frequency to provide large channel capacity, low power consumption and low interference. Up to the present, the passive microwave devices with the super high frequency range are becoming necessity to be deployed due to the great features that are capable in representing significant advances in wireless communications. However, high interference occurs due to multiple signals coexisting in the super high frequency. Integration of switched-beam antenna that employs scanning of multi-beams with a proposed Nolen Matrix can be a solution to overcome this issue. The coupler with loaded T-shaped stubs, loaded stubs and Schiffman phase shifters as well as edge chamfered inset feeding microstrip patch array antenna are designed as the key components for the dual-series 2×4 switched-beam Nolen matrix. The loaded T-shaped stubs are introduced at each side of the microstrip lines nearby the square patch of the couplers to achieve various coupling values. All simulation results are obtained using Computer Simulation Technology software. The S-parameter measurement of the proposed couplers and dual-series 2×4 switched-beam Nolen matrix are performed using vector network analyzer, while its radiation pattern measurement is executed in an anechoic chamber. The amplitude and phase imbalances are ± 1 dB and 5° between 24.75 GHz and 27.25 GHz for the proposed couplers as well as between 25.75 GHz and 26.25 GHz for the phase shifters, respectively. Whereas, the respective amplitude and phase imbalances of 2×4 switched beam Nolen matrix are ± 3.5 dB and 10° across the designated frequency range of 25.75 GHz to 26.25 GHz. Meanwhile, at the center frequency of 26 GHz, the simulated and measured main beam directions are 10° and 12°, respectively when signal is fed at port 1, whereas -31° and -31.5°, respectively at port 2, with the highest measured gain of 10.19 dB and percentage of radiation efficiency of 59.98 %.

ABSTRAK

Perkembangan baru ke arah teknologi 5G memerlukan rangkaian frekuensi amat tinggi untuk menyediakan kapasiti saluran yang besar, penggunaan kuasa rendah dan gangguan rendah. Kini, peranti gelombang mikro pasif dengan frekuensi amat tinggi menjadi keperluan untuk digunakan kerana kehebatan ciri-cirinya yang mampu mewakili kemajuan yang signifikan dalam komunikasi tanpa wayar. Namun, gangguan tinggi berlaku disebabkan oleh kewujudan pelbagai isyarat bersama dalam julat frekuensi amat tinggi. Gabungan suis alur antena yang menggunakan pengimbasan pelbagai alur dengan matrik Nolen dapat menyelesaikan masalah ini. Pengganding dengan pemasangan puntung berbentuk T dan penganjak fasa Schiffman serta antena tatasusunan mikrojalur suapan sisipan bersisi serong direkabentuk sebagai komponen utama bagi dua siri 2×4 suis alur matrik Nolen. Pemasangan puntung berbentuk T diperkenalkan di setiap sisi garisan mikrostrip berdekatan tampalan empat segi pengganding bagi mencapai pelbagai nilai gandingan. Semua hasil simulasi diperoleh dengan menggunakan perisian Computer Simulation Technology. Pengukuran parameter-S pengganding berpuntung dan dua siri 2×4 suis alur matrik Nolen diperoleh dengan menggunakan Penganalisa Rangkaian Vektor, manakala pengukuran corak radiasi dilaksanakan dalam kebuk tak bergema. Ketidakseimbangan amplitud dan fasa adalah ± 1 dB dan 5° masing-masing di antara 24.75 GHz dan 27.25 GHz bagi pengganding dan di antara 25.75 GHz dan 26.25 GHz bagi penganjak fasa yang dicadangkan. Sementara, ketidakseimbangan amplitud dan fasa bagi 2×4 suis alur matrik Nolen adalah ± 3.5 dB dan 10° pada julat frekuensi di antara 25.75 GHz dan 26.25 GHz. Sementara itu, di frekuensi tengah 26 GHz, hasil simulasi dan ukuran arah alur utama adalah 10° dan 12° apabila isyarat diberikan pada terminal satu, manakala -31° dan -31.5° pada terminal dua dengan ukuran gandaan sebanyak 10.19 dB dan peratus kecekapan radiasi tertinggi sebanyak 59.98 %.

TABLES OF CONTENTS

CHAPTER	TITLE		PAGE
	DECLARATION		ii
	DEDICATION		iii
	ACKNOWLEDGEMENT		iv
	ABSTRACT		v
	ABSTRAK		vi
	TABLES OF CONTENTS		vii
	LIST OF TABLES		xi
	LIST OF FIGURES		xiii
	LIST OF ABBREVIATIONS		xviii
	LIST OF SYMBOLS		xix
	LIST OF APPENDICES		xxi
1	**INTRODUCTION**		**1**
	1.1	Introduction	1
	1.2	Problem Statement	3
	1.3	Objectives of the Research	5
	1.4	Scope of the Research	6
	1.5	Contributions of the Research	7
	1.6	Thesis Organization	8

2 LITERATURE REVIEW 10

2.1 Introduction 10

2.2 Smart Antenna System 11

2.3 Beamforming Network 13

2.4 Theoretical Concept of Nolen Matrix 39

2.5 Coupler 42

2.5.1 Theoretical Concept of Coupler 41

2.5.2 Recent Works on Coupler Designs 42

2.6 Phase shifter 49

2.6.1 Theoretical Concept of Phase Shifter 50

2.6.2 Recent Works on Phase Shifter Designs 51

2.7 Microstrip Antenna 61

2.8 Summary 62

3 RESEARCH METHODOLOGY 63

3.1 Introduction 63

3.2 Design Methodology and Flowchart 64

3.3 Design Specifications 67

3.4 Substrate Specifications 72

3.5 Measurement Setup 73

3.6 Summary 76

4 T-SHAPED CROSS-SLOTTED SQUARE PATCH COUPLERS 77

4.1 Introduction 77

4.2 Initial Design of Cross-Slotted Square Patch Coupler 78

4.3 The Designs of 1.26 dB, 1.76 dB and 3 dB Couplers with Loaded T-Shaped Stubs 82

4.3.1 Parametric Studies of the Proposed Couplers 84

4.3.1.1 Parametric Studies of Slots' Lengths (L_1, L_2 and L_3) for the Proposed Couplers with Loaded T-Shaped Stubs 85

4.3.1.2 Summary of the Parametric Studies of

Slots' Lengths Variations (L_1, L_2 and L_3) for the 3 dB Coupler. with Loaded T-Shaped Stubs 93
4.3.2 Performance Results of S-Parameters and Phase Differences for the Proposed 3 dB, 1.76 dB and 1.26 dB Couplers with Loaded T-Shaped Stubs 95
4.4 Summary 101

5 DUAL-SERIES 2 × 4 SWITCHED-BEAM NOLEN MATRIX 103
5.1 Introduction 103
5.2 Loaded Stubs and Schiffman Phase Shifters 104
5.3 Chamfered Inset Feeding Microstrip Patch Antenna 108
5.3.1 Performance Results of Inset Feeding Microstrip Patch Antenna 116
5.4 Antenna Array for Dual-series Switched-beam 2 × 4 Nolen Matrix 118
5.5 Dual-series 2 × 4 Switched-beam Nolen Matrix 119
5.5.1 Performance Results of S-Parameters and Phase Differences 120
5.5.2 Performance Results of Radiation Pattern, Gain and Efficiency for the Proposed Dual-Series 2 × 4 Switched-Beam Nolen Matrix. 127
5.6 Summary 135

6 CONCLUSION 136
6.1 Conclusion 136
6.1.1 Couplers with Various Coupling Values and Phase shifters 137

6.1.2 Dual-series 2 × 4 Switched-Beam Nolen Matrix 138
6.2 Recommendations for Future Works 139

REFERENCES **141**

Appendices A-E 149-167

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Qualitative comparison between various configuration designs of beamforming networks.	28
2.2	Coupler parameters and phase shifter design values [25].	39
2.3	Qualitative comparison between configuration designs of couplers.	47
2.4	Qualitative comparison between configuration designs of phase shifters.	56
2.4	Qualitative comparison between configuration designs of phase shifters (continued).	57
3.1	Design parameters and specifications of the proposed components that designed at the center frequency of 26 GHz.	68
3.2	Properties of Rogers RO5880 Substrate [82].	73
4.1	Summarization of the 3dB coupler with loaded T-shaped stubs performances based on the slots' lengths variations between 24.75 GHz and 27.25 GHz, where the symbols of '√' and 'X' denote the achieved and unachieved design specifications, respectively.	93
4.2	Final dimensions of the proposed couplers.	94
4.3	Comparison of the simulated and measured performance results between the proposed couplers with loaded T-shaped stubs that have difference coupling coefficients, *C* across 24.75 GHz to 27.25 GHz.	101
5.1	Initial dimensions of the proposed phase shifters.	107

5.2 Comparison of the simulated and measured performance results between the proposed phase shifters across 25.75 GHz to 26.25 GHz. 112
5.3 Final dimensions of the phase shifters. 113
5.4 Final dimensions of the inset feeding microstrip patch antenna. 115
5.5 Comparison between simulation results and design specifications of the transmission coefficients and differential phase characteristics for the proposed Nolen matrix at between 25.75 GHz and 26.25 GHz. 124
5.6 Summary of comparison between simulation and measurement results of main beam direction, directivity, gain and efficiency for the switched-beam Nolen matrix. 132

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Comparison schemes [2]. (a) Switched-beam antenna. (b) Adaptive antenna array.	12
2.2	Block diagram of the adaptive antenna array system, where RCVR, wM, A/D are receiver, complex weights and analog to digital converter, respectively [2].	12
2.3	Block diagram of the switched-beam antenna array system [40].	12
2.4	Ideal model of Rotman lens with ridge gap waveguides (RGW) [42].	14
2.5	Simulation model of integrated Rotman lens and patch antenna array [43].	15
2.6	Photograph of the fabricated Rotman lens antenna design with fixed feeding lines [43]. (a) Rotman lens. (b) Patch antenna.	15
2.7	Photograph of the fabricated Rotman lens antenna design with switching network [43]. (a) Rotman lens. (b) Patch antenna.	16
2.8	Switched-beam Rotman lens on high resistivity silicon wafer [11]. (a) Geometry structure and design parameters. (b) Layout design. (c) Measurement setup.	17
2.9	Configuration design of compact 4 × 4 Butler Matrix for ISM applications [44]. (a) Block diagram. (b) Layout design.	18
2.10	Configuration design of 2-D switched-beam phased array system based on 4-way Butler matrix [45].	19

2.11 Configuration design of Butler matrix beamforming network for wireless communications in underground mines [35]. (a) Block diagram. (b) Layout design. 21

2.12 Photograph of the proposed SIW planar 4 × 16 Blass matrix [46]. 22

2.13 Blass matrix [9]. (a) Photograph of the Multi-layer SIW 5 × 32 prototype. (b) Schematic design. 23

2.14 Photograph of the modified two-beam Blass matrix [47]. 24

2.15 Photograph of the fabricated planar 4 × 4 SIW Nolen matrix [48]. 25

2.16 Block diagram of the proposed 4 × 4 Nolen Matrix based on coupler delay compensation of broadband substrate integrated waveguide (SIW) [8]. 26

2.17 Configuration design of the s-band Nolen matrix for multiple beam antenna applications [25]. (a) Block diagram. (b) Layout design. 27

2.18 General block diagram of the Nolen matrix [53]. 38

2.19 Circuit symbols and power flow conventions of four ports directional coupler [56]. 42

2.20 Top view of C-band SIW directional coupler [57]. 43

2.21 Folded Lange coupler [58]. (a) Shematic layout. (b) Photograph of the fabricated design. 44

2.22 Physical layout of the microstrip patch-based hybrid coupler [59]. 45

2.23 Physical layouts of the patch cross-slots hybrid couplers [60]. 46

2.24 Block diagram of conventional phase shifter. 50

2.25 Physical layout of the proposed tunable reflection-type phase shifter [62]. 52

2.26 Configuration of the proposed multi-layer phase shifter [63]. 53

2.27 Photograph of the proposed phase shifter [64]. 54

2.28 Photograph with dimensions of the fabricated 90° phase shifter [65]. 54

2.29 A physical layout of 45° phase shifter [66]. 55

2.30 Standard radiation pattern cuts for antenna measurement [54]. 61

3.1 Flowchart of the research project. 64

3.2 Block diagram of the proposed dual-series 2 × 4 switched-beam Nolen matrix, where *C* is the coupling coefficient. 68

3.3 Photograph of the measurement setup for the fabricated prototype of the coupler with loaded T-shaped stubs. 74

3.4 Photograph of the measurement setup for return loss of the fabricated dual-series 2 × 4 switched-beam Nolen matrix prototype. 75

3.5 The setup for radiation pattern and gain measurement. (a) Anechoic chamber room. (b) Control room. 75

4.1 Physical layout of the initial 3 dB cross-slotted square patch coupler, where L_n and W_n (n = 1 and 2) are length and width of the cross slot, accordingly. 78

4.2 Simulation results of S-Parameters and phase difference for initial design of 3 dB coupler. 81

4.3 Physical layout of the proposed loaded T-shaped stubs coupler. 83

4.4 Simulation results for parametric study of parameter L_1 for the loaded T-shaped stubs 3 dB coupler: (a) Reflection coefficient, S_{11} (dB), (b) Transmission coefficients, S_{21} (dB), (c) S_{31} (dB), (d) S_{41} (dB) and (e) Phase difference. 87

4.5 Simulation results for parametric study of parameter L_2 for the loaded T-shaped stubs 3 dB coupler: (a) reflection coefficient, S_{11} (dB), (b) transmission coefficients, S_{21} (dB), (c) S_{31} (dB), (d) S_{41} (dB) and (e) phase difference. 89

4.6 Simulation results for parametric study of parameter L_3 for the loaded T-shaped stubs 3 dB coupler: (a) reflection coefficient, S_{11} (dB), (b) transmission coefficients, S_{21} (dB), (c) S_{31} (dB), (d) S_{41} (dB) and (e) phase difference. 91

4.7 Photograph of the fabricated loaded T-shaped stubs coupler prototype. 95

4.8 Simulation and measurement results of S-Parameters and phase difference for 3 dB coupler with loaded T-shaped stubs. 96

4.9 Simulation and measurement results of S-Parameters and phase difference for 1.76 dB coupler with loaded T-shaped stubs. 98

4.10 Simulation and measurement results of S-parameters and phase difference for 1.26 dB coupler with loaded T-shaped stubs. 99

5.1 Layout of the phase shifters. (a) 0° stub loaded phase shifter (reference line). (b) 45° stub loaded phase shifter. (c) Schiffman phase shifter. 105

5.2 Dimension for chamfering edge at corner of 50 Ω microstrip line [87]. 106

5.3 Simulation results of S-Parameters and phase difference for stub loaded 45° phase shifter. 108

5.4 Simulation results of S-Parameters and phase difference for Schiffman 90° phase shifter. 109

5.5 Simulation results of S-Parameters and phase difference for Schiffman 135° phase shifter. 110

5.6 Simulation results of S-Parameters and phase difference for Schiffman 180° phase shifter. 111

5.7 Geometry of the inset feeding microstrip patch antenna. 114

5.8 Simulated return loss of the rectangular notches patch antenna. 116

5.9 Simulated radiation pattern (phi, φ = 0°) of the rectangular notches patch antenna at 26 GHz. 117

5.10 An antenna array with identical separation distance, *d*. 118

5.11 Photograph of the fabricated dual-series 2 × 4 switched-beam Nolen matrix prototype. 120

5.12 Simulated transmission coefficients of the dual-series 2 × 4 Nolen matrix with port 1 excited. 121

5.13 Simulated transmission coefficients of the dual-series 2 × 4 Nolen matrix with port 2 excited. 122

5.14 Simulated differential phase characteristics of the proposed Nolen matrix. 123

5.15 Simulated and measured return loss responses of the proposed switched-beam Nolen matrix. 125

5.16 Simulated and measured isolations between input ports of the proposed switched-beam Nolen matrix. 126

5.17 Radiation pattern (linear scale) in xz plane at 25.7 GHz when signals are fed at (a) port 1. (b) port 2. 129

5.18 Radiation pattern (linear scale) in xz plane at 26 GHz when signals are fed at (a) port 1. (b) port 2. 130

5.19 Radiation pattern (linear scale) in xz plane at 26.3 GHz when signals are fed at (a) port 1. (b) port 2. 131

5.20 Simulated and measured gain of the dual-series 2 × 4 Nolen matrix with port 1 and port 2 excited. 132

5.21 Simulated and measured efficiency of the dual-series 2 × 4 Nolen matrix with port 1 and port 2 excited. 133

6.1 Photograph of the ferrite bead at end of cable. 140

6.2 Block diagram of 4 × N switched-beam Nolen matrix, where A_N is the number of antenna port. 140

LIST OF ABBREVIATIONS

AUT	-	Antenna Under Test
CST	-	Computer Simulation Technology
dB	-	Decibel
P1	-	Port 1
P2	-	Port 2
P3	-	Port 3
P4	-	Port 4
PC	-	Programmable Controller
PNA	-	Programmable Network Analyzer
RF	-	Radio frequency
RO 5880	-	Rogers 5880
SIW	-	Substrate Integrated Waveguide
S-parameters	-	Scattering parameters
VNA	-	Vector Network Analyzer

LIST OF SYMBOLS

ß$_o$ - Angular wave

f_c - Center frequency

x - Chamfering edge of microstrip line

ε_r - Dielectric constant of the substrate

d_o - Distance between two radiating element

λ - Free space wavelength

h - Height of substrate

X - Length of adjacent

L - Length of coupler structure

R - Length of hypotenuse

Y - Length of opposite

L_t - Length of square patch coupler

$\leq$ - Less than or equal

d - Notch's length

W_n - Notch's width

Ω - Ohm

M - Optimum miter percentage

L_{patch} - Patch's length

W_{patch} - Patch's width

$\Delta\Phi$ - Phase difference

$\Delta\Phi$rad - Phase difference (in radian)

$\Phi\ S_{21}$ - Phase S_{21}

$\Phi\ S_{31}$ - Phase S_{31}

e_r - Radiation efficiency

r - Radius of circular slot

f_r - Resonant frequency

θ_o - Resulting pointing angle

c - Speed of light

λ_g - Guide wavelength

W_t - Width of 50 Ω feeding microstrip line

W - Width of coupler structure

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	List of Author’s Publication	150
B	Datasheet for Rogers Substrate RO5880	151
C	Performances of unloaded T-shaped Stubs 3 dB, 4.77 dB and 6.02 dB Couplers	154
D	Connector loss	160
E	Radiation Patterns for Port 3 and Port 4	162

CHAPTER 1

INTRODUCTION

1.1 Introduction

Up to the present, there are myriad evolvements from the first generation (1G) to fourth generation (4G) in the realm of communication technologies. In order to improve the current generation of technologies with better features concerning fast multi-services to end users, extreme data rates, energy efficient networks, ultra-low latency and large data bandwidth [1], a new evolution is targeted to be deployed beyond 2020 in all over the world by introducing the fifth generation (5G) mobile communication technology that covering all aspects in daily life, which include unlimited communication between humans, machine-to-machine and vehicle-to-vehicle.

In addition, higher capacity, lower power transmission and larger system coverage that expected to be offered by 5G technology can be achieved by using smart antenna systems such as switched-beam antenna and adaptive antenna array [2]. The switched-beam antenna and the adaptive antenna array are consisting of a beamforming network as a key component of multiple-input and multiple-output (MIMO) system, which provides the multiple beams looking in various directions. However, the adaptive antenna array has a more complex design because an individual RF transceiver chain at end of each antenna element and a precise real-time calibration are required [3]. Moreover, the adaptive antenna array has more extortionate price than the switched-beam antenna due to the presence of a sophisticated digital signal processing algorithm [2]. Therefore, the beamforming network of the switched-beam antenna system is more frugal to be developed because no device is required for downconverting the received signal to a baseband [2]. There are myriad examples of these beamforming networks [4] such as Butler matrix [5], [6], Nolen matrix [7], [8], Blass matrix [9], [10] and Rotman lens [11], [12].

The configuration circuit of Butler matrix consists of passive components such as couplers, crossovers and phase shifters. As stated in [13], the Butler matrix has N input (beam) and N output (antenna) ports according to a standard squared number of integer ($N = 2^n$) and generates orthogonal beams, whereas the Blass and Nolen matrices have distinct M input and N output ports. In term of loss, the Blass matrix becomes lossy when matched loads are connected at the end port of every transmission line [13]. Besides that, the presence of power loss due to the non-perfect pointing of the rays limits the performance of the Rotman lens [14]. In contrast with the Butler matrix, the planar realization of the serial Nolen matrix becomes more interesting since the crossovers are eliminated. Moreover, flexibility in deciding the number of ports enables the Nolen matrix to be easily matched with any specific application [15].

By comparing to the other aforementioned beamforming networks, the serial configuration of output ports facilitates the Nolen matrix to be easily connected to the antenna array to develop switched-beam beamforming network. Therefore, the best configuration design of the beamforming networks to be selected in this research project is the Nolen matrix.

1.2 Problem Statement

The innovation of mobile and wireless communication applications towards 5G technology requires a higher frequency range compared to 4G technology. The World Radiocommunication Conference 2015 (WRC-15) [16] decides to invite the International Telecommunication Union Radiocommunication Sector (ITU-R) to investigate the spectrum requirements for International Mobile Communication (IMT) between 24.25 GHz and 86.0 GHz. The European Conference of Postal and Telecommunications Administrations (CEPT) supports compatibility studies at 26 GHz [17]. Owing to the relatively small wavelength at super high frequency towards 5 G [7], [8], the adjacent ports of the couplers, phase shifters, antenna array and switched-beam matrix designs must be fixed with suitable distance to ensure easy connection of RF cables between the ports. Therefore, the appropriate type of configuration design needs to be taken into account due to this issue.

In addition, the appropriate beamforming configuration with low hardware complexity and ease fabrication will be the vital design keys. The crossovers are required in Butler and Blass matrices except in Nolen matrix [7], [8] and Rotman lens [11], [12]. The crossovers in Butler matrix suffers from mismatch loss, cross-coupling and high path loss [15]. The Rotman lens provides multiple beam directions, broad beam scanning and wideband operation due to a true time delay (TTD) characteristic, which develops frequency independent beam steering [18], however, it suffers from presence of phase error across the aperture, power loss within the lens [19] and high ohmic loss [20]. Meanwhile, the Blass matrix becomes lossy due to inherent loss when matched loads are connected to the ports [13]. Therefore, Nolen matrix is the most suitable beamforming network to be chosen as no crossovers are needed [15].

Another arising issue is flexibility on a standard number of beam ports. The Butler matrix requires a standard number of beam ports to be equal to a power of two, whereas the Nolen and Blass matrices flexible in deciding the number of beam ports [15]. Furthermore, both Butler and Nolen matrices develop orthogonal beams that are not couple to each other wherein other beams are at the trough while one beam reaches a certain highest point [21]. The orthogonal beams have limitations on the beam shape, beam direction and sidelobe level [22]–[24] but provide lossless characteristic. The Blass matrix has flexibility in the number of non-orthogonal beams but has higher insertion loss [15]. The Nolen matrix can be developed by altering the diagonal couplers with some simple bent lines of the Blass matrix [25].

The suitable layer topology either a single layer or multi-layer technique needs to be considered to develop simple designs of the couplers, phase shifters and Nolen matrix. The recent reported beamforming networks in [11], [26]–[35] have been developed using the multi-layer technique at less than 14 GHz. The multi-layer technique enhances the bandwidth of the basic beamforming network configurations such as Butler matrix that eliminates the crossovers [36], which consequently reduce the insertion loss, mismatched junctions and size. However, it needs much attention in aligning the two substrate layers since the fabrication tolerance between each layer is difficult to handle. The existence of air gap [37] between substrate layers will yield degradation in the performance. Therefore, a single layer technique is chosen in this research project to avoid the air gap between the substrate layers.

Besides, the antenna array is required to be integrated with the beamforming network. The antenna array maximizes gain and directivity in the required signal direction [38]. The antenna gain is directly proportional to the number of antennas, N when the spacing between the antennas, d is unchanged [2]. Meanwhile, the distance of the inter-element antenna array should be in the range of $\lambda/2 \leq d < \lambda$ to improve the array spatial resolution as well as to prevent aliasing when d is greater than $\lambda/2$ [38] and grating lobe when $d_{\max}$ less than λ [2].

In order to circumvent these arising issues towards achieving the requirements of 5G technology at the super high frequency, the most suitable beamforming network without crossover to be proposed is Nolen matrix that has the flexible number of standard beam ports using single layer technique. In this research project, the number of antennas, $N = 4$ and spacing between the antennas, $d = 0.67\ \lambda$ are taken into account in order to develop high gain, good beam-shaping, narrow main lobe and reduce sidelobes of the antenna array. A suitable configuration of an antenna array is developed and integrated with the Nolen matrix to implement the switched-beam Nolen matrix.

1.3 Objectives of the Research

The works undertaken in this research are aiming on the following objectives:

i) To design the couplers with loaded T-shaped stubs and, loaded stubs and Schiffman phase shifters that can operate at center frequency of 26 GHz.

ii) To design a Nolen matrix that formed by the designed couplers with loaded T-shaped stubs and, loaded stubs and Schiffman phase shifters at center frequency of 26 GHz.

iii) To integrate Nolen matrix with antenna array to perform switchable beams at center frequency of 26 GHz.

1.4 Scope of the Research

This research emphasizes on the designs of cross-slotted couplers with loaded T-shaped stubs, loaded stubs and Schiffman phase shifters, four elements inset feeding microstrip patch antenna array as well as the switched-beam Nolen matrix that can operate at the center frequency of 26 GHz. The selected type of couplers, phase shifters and antenna array are designed using single layer technique. The Nolen matrix is developed by interconnecting the designed couplers and phase shifters. The traditional 4 × 4 Nolen matrix architecture is reduced to the dual-series 2 × 4 switched-beam Nolen matrix due to a limitation of additional path loss which is attributed by extending the lengths of the feed lines for the proposed couplers. The dual-series 2 × 4 switched-beam Nolen matrix is developed by integrating the antenna array to the output ports of the designed Nolen matrix in order to produce radiation pattern with two beam directions.

The individual components and the Nolen matrix are simulated and optimized using Computer Simulation Technology (CST) Microwave Studio software. The design is fabricated onto a Rogers RO5880 board with thickness, h of 0.254 mm and dielectric constant, ε_r of 2.2. The measurement process is carried out using a vector network analyzer (VNA). The performance results of the designed Nolen matrix are studied and analyzed at the center frequency of 26 GHz. The radiation patterns of the switched-beam Nolen matrix are measured at 26 GHz in anechoic chamber to investigate the beam directions.

1.5 Contributions of the Research

One of the contributions in this research is the design of compact coupling tuning based T-shaped stubs-loaded patch couplers as a new approach of coupling tuning for the cross-slotted patch couplers to achieve the required coupling values, S_{31} such as 1.26 dB, 1.76 dB and 3 dB. The T-shaped stubs are introduced at every side of the microstrip lines nearby the square patch coupler. This approach has the ability to exchange the values of S_{21} and S_{31} for the cross-slotted patch couplers at the super high frequency. The performance effects of the microstrip cross slot, rectangular shaped patch slots, circularly slots and T-shaped stubs around the square patch of the coupler are investigated. The parametric studies regarding length variations on performances of scattering parameters and phase differences between the output ports are studied and discussed for each coupler.

The second contribution is the topology of the dual-series 2 × 4 switched-beam Nolen matrix. An additional 0° phase delay is added in the first row of the Nolen matrix configuration to maintain the flatness of phase differences between the output ports across the designated frequency range. The dual-series 2 × 4 switched-beam Nolen matrix which consists of loaded T-shaped stubs couplers (1.76 dB, 1.26 dB and 3.00 dB), loaded stubs (0° and 45°) and Schiffman phase shifters (0°, 90°, 135°, 180°) as well as an additional 0° phase delay are designed. In this research work, the phase shifters ranging from 45°, 90°, 135°, 180° are set as main lines, whereas the 0° loaded stubs and 0° Schiffman phase shifters are set as reference lines. The performance of S-Parameters, phase differences and radiation pattern of the dual-series 2 × 4 switched-beam Nolen matrix is investigated and analyzed. The dual-series 2 × 4 switched-beam Nolen matrix demonstrates good performance in terms of S-Parameters, phase differences and radiation pattern with low phase imbalance and small deviations of transmission coefficients. The highest deviation of the simulated transmission coefficients, phase differences and main beam directions (when the signal is fed at port 1 and port 2) compared to the theoretical values at the center frequency of 26 GHz are ± 3.46 dB, ± 2.86° and ± 3.36°, respectively.

1.6 Thesis Organization

Basically, the entire content of this thesis is divided into six main chapters. The contents of Chapter 1 are concerning the research project overview, problem statement, research objectives, research scope, contributions of the research and last but not least, the thesis organization.

Chapter 2 covers the relevant theoretical background involved in this research project. The literature review describes the related previous works that have been carried out by other researchers. It also contains all relevant terms, theories and equations regarding the smart antenna system, beamforming network, coupler and phase shifter. The qualitative comparisons between various configuration designs of the beamforming network, coupler as well as phase shifter are well described.

Meanwhile, Chapter 3 emphasizes the methodology of the research project, which constitutes a research flowchart to represent graphically the logical decisions and progression of each step involved while completing this research project. The design specifications of the proposed couplers, Nolen matrix and antenna array are discussed in details. The substrate specifications and measurement setups of the proposed couplers and switched-beam Nolen matrix are described in this chapter.

In Chapter 4, the designed couplers with respect to various coupling values for this research are presented. The design parameters and requirements of the couplers are also introduced. The operation and performance results of the designed couplers are analyzed. The simulation software, Computer Simulation Technology (CST) Microwave Studio is utilized to get a comprehensible visualization of the entire design. The performance results of the proposed couplers are verified by the experimental validation between 24.75 GHz and 27.25 GHz.

Chapter 5 presents the proposed antenna array and Nolen matrix. The design parameters and requirements of the antenna are also introduced. The performance results for the designed switched-beam Nolen matrix are further discussed and analyzed. The simulation results are performed by CST software. The performance of scattering parameters and radiation pattern results of the dual-series 2 × 4 switched-beam Nolen matrix are verified by the experimental validation between 25.75 GHz and 26.25 GHz.

Last but not least, the conclusion of the overall progress in this research project is drawn in Chapter 6. Several future works are recommended and described in this chapter.

REFERENCES

[1] S. Kumar, G. Gupta, and K. R. Singh, “5G: Revolution of future communication technology,” in *International Conference on Green Computing and Internet of Things, (ICGCIoT)*, 2015, pp. 143–147.

[2] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd Ed. United State: John Wiley & Sons, 2005.

[3] H. Hourani, “An Overview of Adaptive Antenna Systems,” *Antenna*, pp. 1–5, 2005.

[4] A. Rahimian, “Microwave Beamforming Networks for Intelligent Transportation Systems,” *Intelligent Transportation Systems*, pp. 123–142, 2012.

[5] Q. Yang, Y. Ban, Q. Zhou, M. Li, and A. H. Coupler, “Butler Matrix Beamforming Network Based on Substrate Integrated Technology for 5G Mobile Devices,” *IEEE 5th Asia-Pacific Conference on Antennas and Propagation (APCAP)*, pp. 413–414, 2016.

[6] J. S. Néron and G. Y. Delisle, “Microstrip EHF butler matrix design and realization,” *ETRI Journal*, vol. 27, no. 6, pp. 788–797, 2005.

[7] A. Rahimian, “Investigation of Nolen Matrix Beamformer Usability for Capacity Analysis in Wireless MIMO Systems,” in *19th Asia-Pacific Conference on Communications (APCC)*, 2013, pp. 622–623.

[8] T. Djerafi, N. J. G. Fonseca, and K. Wu, “Broadband substrate integrated waveguide 4 × 4 Nolen matrix based on coupler delay compensation,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 7, pp. 1740–1745, 2011.

[9] F. Casini, R. V. Gatti, L. Marcaccioli, and R. Sorrentino, “A novel design method for Blass matrix beam-forming networks,” *Proceedings of the 37th European Microwave Conference, EuMA*, pp. 1512–1514, 2007.

[10] S. Mosca and F. Bilotti, “A novel design method for Blass matrix beam-forming networks,” *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 2, pp. 225–232, 2002.

[11] W. Lee, J. Kim, C. S. Cho, and Y. J. Yoon, “Beamforming lens antenna on a high resistivity silicon wafer for 60 GHz WPAN,” *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 3, pp. 706–713, 2010.

[12] Y. Zhang, S. Christie, V. Fusco, R. Cahill, G. Goussetis, and D. Linton, “Reconfigurable beam forming using phase-aligned Rotman lens,” *IET Microwaves, Antennas & Propagation*, vol. 6, no. 3, pp. 326–330, 2012.

[13] E. Iannone, *MICROWAVE and RF ENGINEERING E & CE 671-493*, vol. 2. John Wiley & Sons, 2010.

[14] D. Lundberg, “Flow Conditioners,” U. S. Patent No. 7,728,772, 2006.

[15] T. Djerafi, N. J. G. Fonseca, and K. Wu, “Planar K u -band 4×4 Nolen matrix in SIW technology,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 2, pp. 259–266, 2010.

[16] “RESOLUTION 238 (WRC-15). Studies on Frequency-Related Matters for International Mobile Telecommunications Identification Including Possible Additional Allocations to the Mobile Services on a Primary Basis In Portion(s) of the Frequency Range Between 24.25,” 2015. .

[17] “Mandate to CEPT to develop harmonised technical conditions for spectrum use in support of the introduction of next-generation (5G) terrestrial wireless systems in the Union,” 2016. [Online]. Available: https://cept.org/Documents/ecc-pt1/34326/ecc-pt1-17-055_5g-mandate. [Accessed: 01-Jan-2017].

[18] S. Vashist, M. K. Soni, and P. K. Singhal, “A Review on the Development of Rotman Lens Antenna,” *Chinese Journal of Engineering*, vol. 2014, no. 11, pp. 1–9, 2014.

[19] T. Katagi, S. Mano, and S. I. Sato, “An Improved Design Method of Rotman Lens Antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 32, no. 5, pp. 524–527, 1984.

[20] J. J. Lee and G. W. Valentine, “Multibeam array using Rotman lens and {RF} heterodyne,” *Antennas and Propagation Society International Symposium*, vol. 3, pp. 1612–1615 vol.3, 1996.

[21] A. K. Bhattacharyya, *Phased Array Antennas: Floquet Analysis, Sythesis, BFNs, and Active Array Systems*. John Wiley & Sons, 2006.

[22] J. L. Allen, “A Theoretical Limitation on the Formation of Lossless Multiple Beams in Linear Arrays,” *IRE Transactions on Antennas and Propagation*, vol. 9, no. 4, pp. 350–352, 1961.

[23] W. D. White, “Pattern limitations in multiple-beam antennas,” *RE Transactions on Antennas and Propagation*, vol. 10, no. 4, pp. 430–436, 1962.

[24] S. Stein, “On cross coupling in multiple-beam antennas,” *IRE Transactions on Antennas and Propagation*, vol. 10, no. 5, pp. 548–557, 1962.

[25] N. J. G. Fonseca, “Printed S-band 4x4 Nolen matrix for multiple beam antenna

applications," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 6, pp. 1673–1678, 2009.

[26] D. N. A. Zaidel, S. K. A. Rahim, and N. Seman, "4x4 Ultra Wideband Butler Matrix for Switched Beam Array," *Wireless Personal Communications*, vol. 82, no. 4, pp. 2471–2480, 2015.

[27] A. Talbi, M. L. Seddiki, and F. Ghanem, "A Compact 4x4 Butler Matrix for UWB Applications," *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, pp. 1010–1011, 2013.

[28] S. Gruszczynski and K. Wincza, "Broadband 4×4 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*, vol. 57, no. 1, pp. 1–9, 2009.

[29] M. Ben Kilani, M. Nedil, N. Kandil, and T. A. Denidni, "Novel wideband multilayer Butler matrix using CPW technology," in *Proceedings of the IEEE International Symposium on Antennas and Propagation*, 2012, no. 1, pp. 7–8.

[30] O. M. Haraz, "Two-Layer Butterfly-Shaped Microstrip 4×4 Butler Matrix for Ultra- Wideband Beam-Forming Applications," in *IEEE International Conference on Ultra-Wideband (ICUWB)*, 2013, pp. 2–7.

[31] O. M. Haraz, A. R. Sebak, and S. A. Alshebeili, "Ultra-Wideband 4x4 Butler Matrix Employing Trapezoidal-Shaped Microstrip-Slot Technique," *Wireless Personal Communications*, vol. 82, no. 2, pp. 709–721, 2015.

[32] Y. C. Su, M. E. Bialkowski, F. C. E. Tsai, and K. H. Cheng, "UWB switched-beam array antenna employing UWB butler matrix," in *Proceedings of IEEE International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials (iWAT)*, 2008, pp. 199–202.

[33] S. Z. Ibrahim and M. E. Bialkowski, "Wideband butler matrix in microstrip-slot technology," in *APMC 2009 - Asia Pacific Microwave Conference 2009*, 2009, pp. 2104–2107.

[34] L. Abdelghani, T. A. Denidni, and M. Nedil, "Design of a new Ultra-wideband 4x4 Butler matrix for beamforming antenna applications," in *Proceedings of the IEEE International Symposium on Antennas and Propagation*, 2012, pp. 2–3.

[35] M. Nedil, "A New Ultra-Wideband Beamforming for Wireless Communications in Underground Mines," *Progress In Electromagnetics Research*, vol. 4, pp. 1–21, 2008.

[36] M. Nedil, T. A. Denidni, and L. Talbi, "Novel butler matrix using CPW multi-layer technology," *IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*, vol. 3 A, no. 1, pp. 299–302, 2005.

[37] N. S. Binti Muklas, S. K. A. Rahim, N. Seman, D. N. A. Zaidel, K. G. Tan, and A. W. Reza, "A design of compact ultra wideband coupler for butler matrix," *Wireless Personal Communications*, vol. 70, no. 2, pp. 915–926, 2013.

[38] S. C. Swales, M. A. Beach, D. J. Edwards, and J. P. Mcgeehan, “Perfomance enhancemnet of multibeam adaptive abase station for cellular mobile radio systems,” *IEEE Transactions on Vehicular Technology*, vol. 39, no. I, pp. 56–67, 1990.

[39] R. I. Desourdis, *Emerging Public Safety Wireless Communication Systems*. Norwood, MA: Artech House, 2002.

[40] D. Lingaiah, *Software radio: A modern approach to radio engineering [Book Review]*, vol. 20, no. 4. Prentice Hall, 2003.

[41] A. Osseiran, *5G mobile and wireless communications technology*. Cambridge University Press, 2016.

[42] L. F. Carrera-Suarez, D. V Navarro-Mendez, M. Baquero-Escudero, and A. Valero-Nogueira, “Rotman lens with Ridge-Gap Waveguides, implemented in LTCC technology, for 60GHz applications,” *2015 9th European Conference on Antennas and Propagation, EuCAP 2015*, 2015.

[43] J. Säily, M. Pokorný, M. Kaunisto, A. Lamminen, J. Aurinsalo, and and Z. Raida, “Millimetre-wave beam-switching rotman lens antenna designs on multi-layered LCP substrates,” in *10th European Conference on Antennas and Propagation (EuCAP)*, 2016, pp. 1–5.

[44] M. Traii, M. Nedil, A. Gharsallah, and T. A. Denidni, “A New Design of Compact 4x4 Butler Matrix for ISM Applications,” *International Journal of Microwave Science and Technology*, vol. 2008, pp. 1–7, 2008.

[45] Y. R. H. W. Y. Chen, C. C. Tsai, Y. M. Chen, C. C. Chang, and S. F. Chang, “A Compact Two-Dimensional Phased Array Using Grounded Coplanar-Waveguides Butler Matrices,” in *Proceeding of the 42nd European Microwave Conference*, 2012, pp. 747–750.

[46] P. Chen, W. Hong, Z. Kuai, and J. Xu, “A double layer substrate integrated waveguide blass matrix for beamforming applications,” *IEEE Microwave and Wireless Components Letters*, vol. 19, no. 6, pp. 374–376, 2009.

[47] W. Y. Lim and K. K. Chan, “Generation of multiple simultaneous beams with a modified blass matrix,” *APMC 2009 - Asia Pacific Microwave Conference 2009*, pp. 1557–1560, 2009.

[48] T. Djerafi, N. J. G. Fonseca, and K. Wu, “Architecture and implementation of planar 4 ??4 Ku-Band nolen matrix using SIW technology,” *Asia Pacific Microwave Conference, APMC*, 2008.

[49] T. Djerafi and K. Wu, “Super-compact substrate integrated waveguide cruciform directional coupler,” *IEEE Microwave and Wireless Components Letters*, vol. 17, no. 11, pp. 757–759, 2007.

[50] F. Y. Zulkifli, N. Chasanah, and T. Rahardjo, “Design of Butler Matrix Integrated with Antenna Array for Beam Forming,” *International Symposium on Antennas and Propagation (ISAP)*, pp. 1–4, 2015.

[51] Y. M. Cheng, P. Chen, W. Hong, T. Djerafi, and K. Wu, “Substrate-integrated-waveguide beamforming networks and multibeam antenna arrays for low-cost satellite and mobile systems,” *IEEE Antennas and Propagation Magazine*, vol. 53, no. 6, pp. 18–30, 2011.

[52] P. S. Hall and S. J. Vetterlein, “Review of radio frequency beamforming techniques for scanned and multiple beam antennas,” *IEE Proceedings H Microwaves, Antennas and Propagation*, vol. 137, no. 5, p. 293, 1990.

[53] R. C. Hansen, *Phased Array Antennas*. New York: Wiley, 1998.

[54] “IEEE Standard Test Procedures for Antennas.,” *ANSI/IEEE Std 149-1979*.

[55] W. L. Stutzman and G. A. Theile, *Antenna Theory and Design*, 2nd ed. JOHN WILEY & SONS, INC, 1998.

[56] D. M. Pozar, *Microwave Engineering*, 4th Ed. New York: Wiley, 2012.

[57] B. Veadesh, S. Aswin, and K. Shambavi, “Design and analysis of C-band SIW directional coupler,” in *International conference on Microelectronic Devices, Circuits and Systems (ICMDCS)*, 2017.

[58] Q. Xu and Y. E. Wang, “Design and realization of compact folded Lange coupler,” in *IEEE MTT-S International Microwave Symposium Digest*, 2012, pp. 1–3.

[59] X. Jing and S. Sun, “Design of Impedance Transforming 90 Degree Patch Hybrid Couplers,” in *Proceedings of Asia-Pacific Microwave Conference*, 2014, no. 1, pp. 25–27.

[60] S. Sun and L. Zhu, “Miniaturised patch hybrid couplers using asymmetrically loaded cross slots,” *IET Microwaves, Antennas & Propagation*, vol. 4, no. 9, p. 1427, 2010.

[61] B. W. Xu, S. Y. Zheng, Y. M. Pan, and Y. H. Huang, “A Universal Reference Line-Based Differential Phase Shifter Structure with Simple Design Formulas,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 7, no. 1, pp. 123–130, 2017.

[62] W. J. Liu, S. Y. Zheng, Y. M. Pan, Y. X. Li, and Y. L. Long, “A Wideband Tunable Reflection-Type Phase Shifter with Wide Relative Phase Shift,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 64, no. 12, pp. 1442–1446, 2017.

[63] D. N. A. Zaidel, S. K. A. Rahim, R. Dewan, S. F. Ausordin, and B. M. Saad, “Square-shaped phase shifter using multilayer technology for ultra wideband application,” *RFM 2013 - 2013 IEEE International RF and Microwave Conference, Proceedings*, pp. 22–25, 2013.

[64] S. Y. Zheng, W. S. Chan, and K. F. Man, “Broadband phase shifter using loaded transmission line,” *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 9, pp. 498–500, 2010.

[65] Y. Liu, H. Liu, and Q. Liu, “Compact ultra-wideband 90° phase shifter using

short-circuited stub and weak coupled line," *Electronics Letters*, vol. 50, no. 20, pp. 1454–1456, 2014.

[66] K. Y. Kapusuz and U. Oguz, "Millimeter wave phased array antenna for modern wireless communication systems," *2016 10th European Conference on Antennas and Propagation (EuCAP)*, no. 1, pp. 1–4, 2016.

[67] W. Bengal, "Microstrip Patch Antenna ' s Limitation and Some Remedies," *International Journal of Electronics & Communication Technology (IJECT)*, vol. 7109, no. 1, pp. 38–39, 2013.

[68] C. K. Ghosh, S. K. Parui, J. Road, and B. Engineering, "Design , Analysis and Optimization of A Slotted Microstrip Patch Antenna Array at Frequency 5 . 25 GHz for WLAN-SDMA System," vol. 2, no. 2, pp. 102–112, 2010.

[69] J. Kaur and R. Khanna, "Co-axial Fed Rectangular Microstrip Patch Antenna for 5.2 GHz WLAN Application," *Universal Journal of Electrical and Electronic Engineering (UJEEE)*, vol. 1, no. 3, pp. 94–98, 2013.

[70] P. Upadhyay, V. Sharma, and R. Sharma, "Design of Microstrip Patch Antenna Array for WLAN Application," *International Journal of Emerging Technology and Advanced Engineering*, vol. 2, no. 1, pp. 2008–2010, 2012.

[71] S. Koshevaya, "Individual Patch Antenna and Antenna Patch Array for Wi-Fi Communication," *Antenna*, vol. 2, no. 1, pp. 164–177, 2009.

[72] A. Majumder, "Design of an H-shaped Microstrip Patch Antenna for Bluetooth Applications," *International Journal of Innovation and Applied Studies*, vol. 3, no. 4, pp. 987–994, 2013.

[73] G. V. Devi, K. P. Kumar, and V. R. Krishna, "Design of a simple slotted Rectangular Microstrip Patch Antenna for Bluetooth Applications," *International Research Journal of Engineering and Technology (IRJET)*, vol. 4, no. 3, pp. 207–210, 2017.

[74] M. Sontakke, V. Savairam, S. Masram, and P. P. Gundewar, "Microstrip Patch Antenna with DGS for Bluetooth Application," *International Journal of Engineering & Technology (IJERT)*, vol. 6, no. 3, pp. 524–527, 2017.

[75] T. S. Bird, "Fundamentals of aperture antennas and arrays: From theory to design, fabrication and testing," in *Fundamentals of Aperture Antennas and Arrays: From Theory to Design, Fabrication and Testing*, John Wiley & Sons, Ltd., 2015, pp. 1–430.

[76] A. Zaidi, A. Baghdad, A. Ballouk, and A. Badri, "Design and optimization of an inset fed circular microstrip patch antenna using DGS structure for applications in the millimeter wave band," *Proceedings - 2016 International Conference on Wireless Networks and Mobile Communications, WINCOM 2016: Green Communications and Networking*, pp. 99–103, 2016.

[77] B. S. Yan, L. Wang, Z. Q. Luo, D. M. Deng, L. Y. Feng, and H. X. Zheng, "Dual-band microstrip antenna fed by coaxial probe," *ISAPE 2016 - Proceedings of the 11th International Symposium on Antennas, Propagation and EM Theory*, no. 1,

pp. 228–230, 2017.

[78] A. S. Emhemmed, N. A. Ahmed, and K. Elgaid, "Reconfigurable Proximity Coupled Elevated Patch Antenna," *4th International Conference on Control Engineering & Information Technology (CEIT)*, pp. 3213–3215, 2013.

[79] V. Balusa, V. S. K. P. Kumar, and B. T. P. Madhav, "Aperture coupled feed circularly polarized antenna," *International Conference on Signal Processing and Communication Engineering Systems - Proceedings of SPACES 2015, in Association with IEEE*, pp. 240–244, 2015.

[80] T. M. Macnamara, *Introduction to Antenna Placement and Installation*. John Wiley & Sons, L td, 2010.

[81] F. E. Fakoukakis and G. A. Kyriacou, "Novel Nolen Matrix Based Beamforming Networks for Series-Fed Low Sll Multibeam Antennas," *Progress In Electromagnetics Research B*, vol. 51, pp. 33–64, 2013.

[82] S. R. Avenue, *RT/duroid ® 5870 /5880*. Rogers Corporation, 2016.

[83] R. Coccioli, F. R. Yang, K. P. Ma, and T. Itoh, "Aperture-coupled patch antenna on uc-pbg substrate," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 11, pp. 2123–2130, 1999.

[84] A. Rahman, M. T. Islam, M. J. Singh, S. Kibria, and M. Akhtaruzzaman, "Electromagnetic Performances Analysis of an Ultra-wideband and Flexible Material Antenna in Microwave Breast Imaging: To Implement A Wearable Medical Bra," *Scientific Reports*, vol. 6, no. December, pp. 1–11, 2016.

[85] A. Eroglu, *Wave propagation and radiation in gyrotropic and anisotropic media*. New York: Springer, 2010.

[86] C. H. Ho, L. Fan, and K. Chang, "A Broad-Band Uniplanar Branch-Line Coupler Using a Coupled Rectangular Slotline Ring," *IEEE Microwave and Guided Wave Letters*, vol. 3, no. 6, pp. 175–176, 1993.

[87] N. S. and M. E. Bialkowski, *Microstrip-slot transitions and its applications in multilayer microwave circuits*. InTech, 2010.

[88] N. Seman and S. N. A. M. Ghazali, "Design of Multilayer Microstrip-Slot In-Phase Power Divider with Tuning Stubs for Wideband Wireless Communication Applications," *Wireless Personal Communications*, vol. 83, no. 4, pp. 2859–2867, 2015.

[89] R. J. P. Douville and D. S. James, "Experimental Study of Symmetric Microstrip Bends and Their Compensation," *IEEE Transactions on Microwave Theory and Techniques*, vol. 26, no. 3, pp. 175–182, 1978.

[90] A. Arora, A. Khemchandani, Y. Rawat, S. Singhai, and G. Chaitanya, "Comparative study of different feeding techniques for rectangular microstrip patch antenna," *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, vol. 3, no. 5, pp. 32–35, 2015.

[91] M. Ramesh and K. Yip, "Design formula for inset fed microstrip patch antenna," *Journal of Microwaves and Optoelectronics*, vol. 3, no. 3, pp. 5–10, 2003.

[92] T. Haynes, *A Primer on Digital Beamforming*. 1998.

[93] H. Boutayeb and T. A. Denidni, "Gain enhancement of a microstrip patch antenna using a cylindrical electromagnetic crystal substrate," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 11 II, pp. 3140–3145, 2007.

[94] A. E. I. Lamminen, J. Säily, and A. R. Vimpari, "60-GHz patch antennas and arrays on LTCC with embedded-cavity substrates," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 9, pp. 2865–2874, 2008.

[95] J. Navarro, "Wide-band, low-profile millimeter-wave antenna array," *Microwave and Optical Technology Letters*, vol. 34, no. 4, pp. 253–255, 2002.

[96] J. Anguera, G. Font, C. Puente, C. Borja, and J. Soler, "Multifrequency microstrip path antenna using multiple stacked elements," *IEEE Microwave and Wireless Components Letters*, vol. 13, no. 3, pp. 123–124, 2003.

[97] G. M. Rebeiz, "Millimeter-Wave and Terahertz Integrated Circuit Antennas," *Proceedings of the IEEE*, vol. 80, no. 11, pp. 1748–1770, 1992.

[98] C. Y. H. and H. R.-C. S. S. Hsu, K. C. Wei, "A 60-GHz Millimeter-Wave CPW-Fed Yagi Antenna Fabricated by Using 0.18-µm CMOS Technology," *IEEE Electron Device Letters*, vol. 29, no. 6, pp. 625–627, 2008.

[99] P. J. Massey and K. R. Boyle, "Controlling the Effects of Feed Cable in Small Antenna Measurements," *The Institute of Electrical Engineers*, pp. 561–564, 2003.

[100] C. R. White and G. M. Rebeiz, "Single- and Dual-Polarized Tunable Slot-Ring Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 1, pp. 19–26, 2009.