WAVEGUIDE-BASED BUTLER MATRIX BEAMFORMING NETWORK FOR MILLIMETERWAVE APPLICATIONS

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DEDICATION

To My Precious Mother "Aliyah" May Your Soul Rest in Peace

Your love and YOU Always Live Inside Me

Our Family Dedicates This Work for You as Your Wish Comes

True

In Heaven, We Meet Insha'Allah

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ABSTRACT

The current wireless cellular system may suffer from congestion and spectrum shortage issue. Thus, higher frequency spectrum is introduced for wireless cellular system. However, at high frequencies, a higher propagation loss is expected. With smaller antenna element at millimeterwave band, more elements can be packed creating arrays making beamforming possible by controlling the signal phase. The Butler matrix beamforming network is adopted in this thesis due to its simplicity with capability to form the beam in desired direction by having different phases at the outputs. However, at millimeterwave the massive network can introduce significant losses on the components as well as the interconnections. Therefore, this thesis proposes a low loss waveguide-based structure where the signal is governed within the walls. Components of Butler matrix beamforming circuit are designed using waveguide structure prior to the integration with the antenna. The components are the 3-dB coupler, 0-dB crossover, and 45° phase shifter. The components are implemented using rectangular cavity resonators with iris coupling *k*-value control method. This iris coupling *k*-value controls the coupling and the phase shift of the Butler matrix components. By using the analytic technique of tuning *k*-value, the required coupling and phase difference at outputs can be obtained. The antenna is basically a very directive waveguide slots antenna. The slots are symmetrically distributed on both sides of the broad wall of the waveguide structure. This enables a dual-beam property. The structures are simulated using CST microwave software before fabricated using direct metal laser melting (DMLM) and selective laser melting (SLM) 3-dimensional (3D) printing techniques and measured using standard vector network analyser (VNA). The printed 4 × 4 Butler matrix has been measured and analysed. The measured reflection and isolation coefficients are observed to be less than -10 dB, with transmission coefficients ranging between -7 to -9 dB. The phase differences of - 42.02°, 42.02°, -130.95°, and 133.3° are observed at the outputs. The matrix has been integrated with four waveguide slots antennas. The measured results show the highest gain of 15.21 dB with scanning angles between 20° to 30°. Overall, the waveguide Butler matrix beamforming network shows good performance and has great potential for millimeterwave wireless systems applications.

ABSTRAK

Sistem selular tanpa wayar semasa mungkin mengalami kesesakan dan masalah kekurangan spektrum. Oleh itu, spektrum frekuensi tinggi diperkenalkan untuk sistem selular tanpa wayar. Walau bagaimanapun, pada frekuensi tinggi, jangkaan bagi kehilangan adalah lebih tinggi. Dengan elemen antena yang lebih kecil pada jalur gelombang milimeter, lebih banyak elemen boleh diletakkan dalam ruangan yang terhad bagi membolehkan pembentukan alur dengan mengawal fasa isyarat. Rangkaian matrik Butler diadaptasi dalam tesis ini kerana kesederhanaannya dan keupayaan untuk membentuk alur isyarat pancaran pada arah yang dikehendaki dengan anjakan fasa pada keluaran. Walau bagaimanapun, pada gelombang milimeter rangkaian besar boleh membawa kepada kehilangan isyarat yang ketara pada komponen dan juga pada penyambungan. Oleh itu, tesis ini mencadangkan struktur berasaskan pandu gelombang berkehilangan rendah yang baru di mana isyarat terkawal di antara dinding. Komponen litar matrik Butler direka bentuk menggunakan struktur pandu gelombang sebelum diintegrasikan dengan antena. Komponennya adalah pengganding 3-dB, litar lintas 0-dB, dan penganjak fasa 45°. Komponen tersebut diimplementasi menggunakan penyalun rongga segiempat tepat dengan nilai *k* gandingan iris sebagai elemen kawalan. Nilai *k* gandingan iris akan mengawal gandingan dan anjakan fasa komponen matrik Butler. Dengan menggunakan teknik analitik penalaan nilai *k*, gandingan dan anjak fasa yang diperlukan pada keluaran boleh diperolehi. Antena pada dasarnya adalah antena gelombang slot pandu yang sangat terarahan. Slot ini diagihkan secara simetrik pada kedua-dua belah dinding luas struktur pandu gelombang. Ini membolehkan sifat dwi alur. Struktur tersebut disimulasikan menggunakan perisian gelombang mikro CST sebelum difabrikasi menggunakan teknik percetakan tiga-dimensi (3D) secara peleburan logam dengan laser secara terus (DMLM) dan peleburan laser secara pilihan (SLM) serta diukur menggunakan analisa rangkaian vektor (VNA). Matrik Butler 4 × 4 yang dicetak telah diukur dan dianalisis. Pekali balikan dan pengasingan yang diukur adalah kurang daripada -10 dB, dengan pekali penghantaran antara -7 hingga -9 dB. Perbezaan fasa sebanyak - 42.02°, 42.02°, -130.95°, dan 133.3° didapati pada keluaran. Matrik telah diintegrasikan dengan empat antena slot pandu gelombang. Hasil pengukuran menunjukkan gandaan maksima 15.21 dB dengan sudut pengimbasan antara 20° hingga 30°. Secara keseluruhan, rangkaian matrik Butler menunjukkan prestasi yang baik dan mempunyai potensi besar untuk aplikasi sistem tanpa wayar gelombang milimeter.

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LIST OF ABBREVIATIONS

AM	-	Additive Manufacturing
BFNs	-	Beamforming Networks
BM	-	Butler Matrix
CA	-	Carrier Aggregation
COMP	-	Coordinated Multipoint
CPW		Coplanar waveguide
CST-MWS	-	Computer Simulation Technology-Microwave Studio
DMLM	-	Direct Metal Laser Melting
DOA	-	Direction of Arrival
DSP	-	Digital Signal Processing
EBM	-	Electron Beam Melting
FDM	-	Fused Deposition Modelling
ITU	-	International Telecommunication Union
mm-Wave	-	Millimetre Wave
M2M	-	Machine to Machine
P2P	-	Point to Point
RF	-	Radio Frequency
SAS	-	Smart Antenna System
SBSA	-	Switched Beam Smart Antenna Systems
SIW	-	Substrate Integrated Waveguide
SLM	-	Selective Laser Melting
4G	-	Fourth Generation
5G		Fifth Generation

LIST OF SYMBOLS

λ	-	Wavelength of the waveguide
d	-	Cavity Length
b	-	Width of the Waveguide
v	-	Velocity of light
x	-	Offset from centre line
L	-	Length of the Butler Matrix
W	-	Width of the slots
a	-`	Length of the waveguide
λg	-	Guided wavelength
g	-	conductance value
t	-	Thickness of walls
μ	-	Permeability
ε	-	Permittivity

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The increasing demands for higher traffic capacity, higher data rates, and higher gain in the wireless communication systems have been addressed in this past few decades [1]. Wireless communication systems use electromagnetic field that transverses in certain frequency bands to broadcast data over air. The higher the frequency, the wider the bandwidth. Hence, the International Telecommunication Union (ITU) stated that by the year of 2020 the wireless communication traffic would increases from 25 to 100-fold growth ratio compared to the year 2010 [1]. Millimeter wave (mm-wave) spectrum is proposed to accommodate these demands. A mm-wave spectrum has the capability of achieving tens to hundreds bandwidth compared to the lower bands. For example, let us consider the latest cellular standards, the fourth-generation cellular network (4G). The 4G operates in 2.6 GHz spectrum and suffers from congestion of frequency bandwidth at the lower band. However, some research efforts are presented in [2-5] to increase the data rates and improving the spectrum efficiency such as multiple inputs multiple output (MIMO), Carrier aggregation (CA), coordinated multipoint (COMP), and Hetnets methods. Yet, it is not a valuable solution to support the need of more traffic capacity for 2020 and beyond. Therefore, fifth generation cellular network (5G) is proposed to be implemented using mm-wave spectrum [6].

The 5G and mm-wave technology are expected to provide huge transmission rate up to Gbps, and more than 100 times peak data rate than 4G. Moreover, 5G and mm-Wave technology are also expected to enable point to point (P2P) and machine to machine (M2M) communication systems that will affect both consumers, and industry [7, 8]. However, to achieve a reliable P2P and M2M communication systems at mm-wave and 5G technology, a high data rates, high gain, high directivity beams are needed. In such systems smart antenna systems (SAS), is vastly recommended for high gain, high directivity beams, and high data rates wireless in mm-wave technology [9, 10]. In SAS, a tracing system is needed to continuously follow the targets and then adjust the radiation pattern beams of the antenna to deliver several narrow beams of the switched beam smart antenna systems (SBSA) to the desired targets and eliminates the interference causes.

At mm-wave frequency, the problem of free space loss is addressed and smart antenna systems (SAS) is proposed to overcome this problem. SAS uses antenna array, radio frequency (RF), and beamforming networks (BFNs) to increase the sensitivity in the desired direction with strong signal strength received as the user mobiles throughout the track-point [9]. It offers various benefits of less complexity and expensive [10]. Additionally, adaptive array uses digital signal processing (DSP) and direction of arrival (DOA) to enhance the sensitivity and steer the beam toward desired direction, still more cost and complexity is considered in these systems. The SBSA performance relies on the accurate design of the beamformer circuit which delivers fixed beam directions. Various BFNs topologies are introduced such as Rotmans Lens [11], Blass Matrix [12], and Butler matrix [13]. Butler matrix (BM) is received significant attention [14, 15] due to its easy to design, simplicity, and can support one dimensional (1-D) beam switching at ±45° and ±135° [16]. It is chosen for this research work and will focus on realising a 1-D beam switching based on BM BFNs. However, this BM BFN may suffer from high loss transmission lines and fabrication tolerance at mm-wave technology. Different transmission lines such as microstrip, stripline, coaxial line, and waveguide-based structured are studied for low loss transmission line in mm-wave frequency [17-20]. Waveguide-based structures are good candidate for implementation of BM beamformer due to its property of low loss transmission line.

The traditional manufacturing techniques in mm-wave technology are considered high cost with high fabrication tolerance, which degrades the performance of the fabricated devices at mm-wave frequencies [21]. Additive manufacturing (AM) namely three-dimensional (3D) printing technology [22, 23] is proposed to overcome these problems due to its advantages of low-cost fabrication, short time process, and exactable fabrication tolerance at mm-wave technology [24, 25]. A different types of 3D printing techniques are introduced with features and drawbacks based on build speed, cost, resolution, geometry limitations, and surface finishing [25, 26]. The commonly types of 3D printer are Fused Deposition Modelling (FDM) in term of dielectric material and Electronic Beam Melting (EBM), Direct Metal Laser Sintering/Melting (DMLS/M), and Selective Laser Melting (SLM), in term of metal material. 3D printing applications are found in the fabrication of passive devices such as waveguides, horn antennas, and cavity-based components. The 3D printing technology uses powder or liquid based materials. 3D printing technology has several advantages of consuming lower energy, efficient material utilization, lower labour costs, capability of realizing complex structure, and shorter processing cycle. However, some of 3D printing techniques are reported with surface roughness and dimensional tolerance [26]. In this work, full waveguide Butler matrix antenna beamforming network are designed and fabricated using 3D print technology. The performance is studied over the ability of the structures to work accordingly.

1.2 Problem Statement

Beamforming networks can be realized using fixed network circuits such as Blass matrix, and Butler matrix. The Butler matrix is received significant attention due to its simplicity with capability to form high gain-narrow beam signal by various phase shift characteristic at the output [9, 13]. The BM consists of hybrid coupler, crossover, and phase shifter. The hybrid coupler or branch line coupler (BLC) is a four-port network device with quarter-wavelength transmission line between two coupled ports which gives 90 degrees phase difference. Therefore, overall dimension of the coupler is basically inversely proportional to the frequency in order to maintain the quarter-wavelength line. At millimeter wave frequencies the size of a planar BLC would be comparably small and distance between adjacent lines would be closer. Hence, crosstalk between the BLC sections is expected. A microstrip BLC at 28 GHz is presented in [27, 28]. The BLC sections have very small separation (0.1 mm and 1 mm) which produces crosstalk between the lines, resulting in phase difference errors at output ports. More losses and phase errors are expected if the component is to be integrated to form a BM network. In other work, conventional BMs are designed at 30 GHz and 60 GHz in [29, 30]. The structure exhibits a high insertion loss of 9 dB and phase difference error of greater than ±5°. Thus, it is a challenge to design low loss network circuit at millimeter wave frequency band such as Butler matrix to feed the antenna so that the beam can be formed in the desired direction. Therefore, waveguide technology is proposed to overcome the challenges. The circuit including the antenna is proposed to be designed using waveguide-based structure to overcome components losses and crosstalk where signals are confined within the walls of the waveguide structure. However, it is not easy to control the phase by having common direct coupling in waveguide design [31, 32], especially for BLC, crossover and phase shifter as the basic components in BM network. Therefore, a cavity resonator with iris coupling control is proposed in this work.

1.3 Research Aim and Objectives

The aim of this research is to design a low loss butler matrix beamforming network at millimetre wave frequency band. The following are the main objectives of this research.

1. To design and develop a low loss Butler matrix network including hybrid coupler, 0-dB crossover, and 45° phase shifter using iris coupling control method in waveguide-based technology at 28 GHz.

2. To design and develop a high gain directive dual-beam waveguide slot antenna at 28 GHz to be integrated to the waveguide-based Butler matrix beamforming network.

3. To analyse the performance of the antenna beamforming network at 28 GHz that would benefit the antenna beamforming system for millimetre wave application.

1.4 Scope of Work

This research focuses on developing a low loss Butler matrix antenna beamforming at 28 GHz frequency based on waveguide technology. The Butler matrix consists of couplers, crossovers, and phase shifter. The components are designed and analysed individually before integrated to form Butler matrix beamforming network. The Butler matrix network is to be integrated with a high gain waveguide slotted antenna. The structures are designed based on theoretical calculations before simulated and optimized using Computer Simulation Technology (CST) Microwave Studio (MWS). All the designs are implemented using waveguide-based structure technology. The designed components are fabricated using 3D printing techniques namely Direct Metal Laser Melting (DMLM) and Selective Laser Melting (SLM). The surface roughness and fabrication tolerance of the fabricated waveguide slots antenna is studied in correlation to the performances. Figure 1.1 shows the research scope of this work. The coloured boxes are indicated the chapters where the designs are discussed, and the arrows present the workflow. The green box content is presented in Chapter 2. The pink box component is discussed in Chapter 4. The yellow boxes components are introduced in Chapter 5, and blue boxes in Chapter 6.

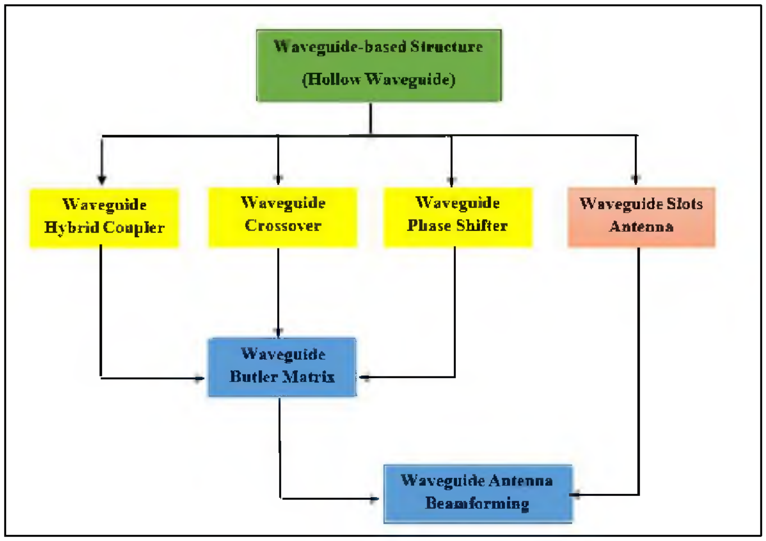

Figure 1.1 The research scope flow.

1.5 Research Contributions

In this research, three main contributions are claimed. These are:

1. Waveguide based Butler matrix network components including hybrid coupler, 0-dB crossover, and 45° phase shifter are developed using cavity resonator based on iris coupling control *k*-value methods at 28 GHz.

2. A highly directive dual-beam radiation pattern of a waveguide slotted antenna at 28 GHz is achieved by having slots on two broad-walls.

3. Fully waveguide Butler matrix network is developed with ± 42°, ± 133° phase difference.

1.6 Thesis layout

This thesis is prepared in seven chapters.

Chapter 1 introduces the overview of research background, followed by the problem statement, research objectives, and the scope of work. The research contributions to knowledge and the thesis outlines are highlighted at the end of the chapter.

Chapter 2 presents a literature on Butler matrix beamforming network in mm-wave technology. Planar transmission lines and waveguide-based structures are presented in the beginning, followed by Butler matrix beamforming network and its components. Then, waveguide slot antenna fundamentals are presented. Related works on waveguide slot antenna, branch line coupler, crossover, phase shifter, Butler matrix beamforming networks are critically reviewed in this chapter.

Chapter 3 focuses on the methodology used to achieve the proposed designs. The methodology steps are simplified in the form of a flowchart. The design specifications are justified based on related published work and standards requirement as guidance. The design parameters and equations are discussed and the fabrications as well as the measurement procedures are presented.

Chapter 4 focuses on the Butler matrix components; from the design to the fabrication and measurement. The parametric studies of all the components are studied and discussed before the optimized design is finalized. The optimized designs are fabricated using 3D printing technology before it is measured, and the performances are analysed.

Chapter 5 presents the design of the waveguide slots antenna. Longitude slot type is chosen and thus the design; simulation and optimization are presented. The antenna is fabricated using 3D printing technology and the performance is discussed, as well as the effect of the fabrication tolerance on the performance.

Chapter 6 discusses the integration of the Butler matrix circuit and the designed antenna with the ability of one-dimensional beam switching. The simulated and measured results are analysed.

Chapter 7 concludes the finding of this research. The recommendation for future work on the antenna beamforming networks for millimeterwave technology is listed.

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Appendix A

LIST OF PUBLICATIONS

Indexed Journal

1. Sabri, M.W., Murad, N.A. and Rahim, M.K.A**.** Highly directive 3D-printed dual-beam waveguide slotted antennas for millimeter-wave applications. *Microwave and Optical Technology Letters*. 2019. 61(6): 1566-1573. **(ISI indexed)**
2. Sabri, M.W., Murad, N.A. Rahim, M.K.A., Zubir, F. 3D Printed Horn Antenna Using Direct Metal Laser Melting Technique for Millimetre Wave Applications. *Indonesian Journal Of Electrical Engineering And Informatics*. 2019.7(2): 323-330. **(Indexed by SCOPUS)**
3. Sabri, M.W., Murad, N.A. and Rahim, M.K.A. Bi-Directional Beams Waveguide Slotted Antenna At Millimeter Wave. *Telkomnika*. 2018. 16 (4): 1515-1521. **(Indexed by SCOPUS)**
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