SWITCHABLE DIELECTRIC RESONATOR ANTENNA ARRAY FOR FIFTH GENERATION APPLICATIONS

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Dedicated and thankful appreciation to,

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ABSTRACT

A new generation in telecommunication technology has evolved into 5G. Due to its shorter wavelength compared to the previous generation, this technology requires a wide bandwidth and high gain antenna to compensate for the added losses at a higher frequency. Therefore, a phased array capable of steering the direction of beam with high gain can be used to recover any additional losses. A dielectric resonator (DR) with a dielectric constant of 10 is used in the phased array antenna design and integrated on Rogers/RT Duroid 5880 with a conductor coating of 17.5 µm, a thickness of 0.254 mm, dielectric constant, ε_s of 2.2 and loss tangent, δ_{tan} of 0.001. All designs are simulated using Ansoft High Frequency Structural Simulator (HFSS) and the numerical analysis involved is done by using MATLAB. The performance of the reflection coefficient and the bandwidth of the fabricated antenna are verified using Vector Network Analyzer (VNA) while the radiation pattern and the antenna gain are tested in an anechoic chamber. The proposed switchable dielectric resonator antenna (DRA) array at 15 GHz is formed through three design stages. The first stage is formed by a single element DRA placed on the ground plane and fed through a narrow aperture. The impedance bandwidth achievable is 2.5 GHz for DRA excited in $TE^{y}_{1\delta3}$ mode compared to 1.8 GHz for DRA excited in $TE^{y}_{1\delta1}$ mode. Besides, the gain of the antenna has improved approximately by 10 dBi in comparison to 5.6 dBi when it was excited in $TE^{y}_{1\delta1}$ mode. Then, a design is formed using three elements of DR named as DRA sub-array design. The driven DR at port 1 is fed by radio frequency (RF) source and the parasitic DRs at port 2 and 3 are excited by the driven DR through mutual coupling effect. A steerable beam is achieved by switching the termination capacitor on the parasitic elements. Then, two DRA sub-array configurations are designed and named as configuration A and configuration B, respectively. Both configurations are excited by a driven DR in $TE^{y}_{1\delta3}$ mode while the parasitic DRs for configurations A and B are excited in the $TE^{y}_{1\delta3}$ mode and $TE^{y}_{1\delta1}$ mode, respectively. From the observation, configuration B demonstrates improved performance with $\pm 32°$ steering angle and maximum gain of 9.63 dBi. Furthermore, configuration B has a narrower beamwidth compared to configuration A. The final stage design is formed by incorporating configuration B with a combination of two driven DRs using power divider and phase switching. The switchable DRA array achieved a maximum gain and bandwidth of 12.8 dBi and 3.1 GHz, respectively. Moreover, the switchable DRA array is able to steer at three various steering angles which are 0°, -30° and +30° with 3 dB beamwidth around 24° by using only 2 ports. Hence, the switchable DRA array is capable to cover 60° sector which is considered suitable for 5G applications.

ABSTRAK

Generasi baharu teknologi telekomunikasi telah berkembang kepada 5G. Disebabkan panjang gelombang yang lebih pendek berbanding generasi sebelumnya, teknologi ini memerlukan lebar jalur yang luas dan gandaan antena yang tinggi untuk mengimbangi penambahan kehilangan kuasa pada frekuensi tinggi. Oleh itu, tatasusunan berfasa yang berkebolehan untuk memandu arah alur dengan gandaan yang tinggi boleh digunakan untuk memulih sebarang kehilangan kuasa tambahan. Dielektrik resonator (DR) dengan pemalar dielektrik bernilai 10 digunakan di dalam rekabentuk tatasusunan antena berfasa dan disepadukan pada Rogers/RT Duroid 5880 dengan salutan pengalir 17.5 µm, ketebalan 0.254 mm, pemalar dielektrik, ε_s 2.2 dan tangen kehilangan, δ_{tan} 0.001. Kesemua rekabentuk disimulasi dengan menggunakan *Ansoft High Frequency Structural Simulator* (HFSS) dan analisis berangka yang terlibat dilaksanakan menggunakan MATLAB. Prestasi pekali pantulan dan lebar jalur fabrikasi antena ditentusahkan menggunakan Penganalisis Rangkaian Vektor (VNA) manakala corak radiasi dan gandaan antena diuji di dalam kebuk tak bergema. Tatasusunan dielektrik resonator antena (DRA) bolehubah yang dicadangkan pada 15 GHz terbentuk melalui tiga peringkat rekabentuk. Peringkat pertama dibentuk daripada elemen tunggal DRA yang diletakkan disisi satah bumi dan disuap melalui bukaan sempit. Galangan lebar jalur boleh capai ialah 2.5 GHz untuk DRA yang diuja dalam mod $TE^{y}_{1\delta3}$ berbanding 1.8 GHz untuk DRA yang diuja dalam mod $TE^{y}_{1\delta1}$. Selain itu, gandaan antena telah diperbaiki lebih kurang 10 dBi berbanding 5.6 dBi apabila diuja dalam mod $TE^{y}_{1\delta1}$. Kemudian, rekabentuk dibentuk menggunakan tiga elemen DR yang dinamakan rekabentuk subtatasusunan DRA. Pemacu DR di terminal 1 disuap oleh sumber frekuensi radio (RF) dan parasit-parasit DR di terminal 2 dan 3 diuja oleh pemacu DR melalui kesan gandingan bersama. Bolehpandu alur tercapai dengan mengubah kapasitor penamatan pada elemen-elemen parasit. Setelah itu, dua konfigurasi subtatasusunan antena direkabentuk dan dinamakan sebagai konfigurasi A dan konfigurasi B. Kedua-dua konfigurasi diuja oleh pemacu DR dalam mod $TE^{y}_{1\delta3}$ manakala parasit DR untuk konfigurasi A dan konfigurasi B diuja dalam mod $TE^{y}_{1\delta3}$ dan mod $TE^{y}_{1\delta1}$, masing-masing. Daripada pemerhatian, konfigurasi B menunjukkan prestasi yang lebih baik dengan sudut pandu $\pm 32°$ dan gandaan maksimum 9.63 dBi. Tambahan pula, konfigurasi B mempunyai lebar alur yang lebih sempit berbanding konfigurasi A. Peringkat rekabentuk terakhir dibentuk dengan menggunakan konfigurasi B yang menggabungkan dua pemacu DR dan digunakan bersama kuasa pembahagi dan fasa bolehubah. Tatasusunan DRA bolehubah telah mencapai gandaan maksimum dan lebar jalur masing-masing pada 12.8 dBi dan 3.1 GHz. Selain itu, tatasusususunan DRA bolehubah mampu untuk memandu pada tiga sudut pandu iaitu 0°, -30° dan +30° dengan lebar alur 3 dB sekitar 24° dengan menggunakan hanya 2 terminal. Oleh itu, tatasusunan DRA bolehubah mampu untuk meliputi sektor 60° yang dianggap sesuai untuk aplikasi 5G.

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LIST OF ABBREVIATIONS

HFSS - High Frequency Structural Simulator
VNA - Vector Network Analyzer
DRA - Dielectric Resonator Antenna
DR - Dielectric Resonator
RF - Radio Frequency
AMPS - Advance Mobile Phone Service
GSM - Global System for Mobile
WCDMA - Wideband Code Division Multiple Access
LTE - Long Term Evaluation
LTE-A - Long Term Evaluation-Advanced
3GPP - 3rd Generation Partnership Project
1G - First Generation
2G - Second Generation
3G - Third Generation
4G - Fourth Generation
5G - Fifth Generation
LMDS - Local Multipoint Distribution Services
PCB - Printed Circuit Board
ESPAR - Electronically Steerable Passive Array Radiator
ML - Microstrip Line
MSA - Microstrip Slot Aperture
OECPW - Open-end Coplanar Waveguide
CPW - Coplanar Waveguide
HPBW - Half Power Beamwidth
mmW - Millimeter Wave
CSPA - Circular Switched Parasitic Array
PTFE - Polytetrafluoroethylene

EP - Element Pattern

AF - Array Factor

LIST OF SYMBOLS

$\%$ - Percentage

μ_0 - Permeability of freespace

ω - Angular frequency

k_0 - Wavenumber

θ - Angle

β - progressive phase shift

η - Efficiency

t_s - Thickness of substrate

c - Velocity of light

ε_s - Dieletric constant/Relative permittivity of substrate

ε_r - Dielectric constant/Relative permittivity of DR

ε_{eff} - Effective dielectric constant

ε_e - Slot effective permittivity

λ - Wavelength

λ_g - Guided Wavelength

$\mathit{\Omega}$ - Ohm

δ - Loss tangent/Dissipation factor

Γ - Reflection Coefficient

$\triangle\phi$ - Differential phase shift

χ - Coupling amount

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Telecommunication innovation has advanced quickly from the original (1G) to the fifth generation (5G). The 1^{st} generation (1G) was pioneered for voice service in early 1980's, where almost all of them were using analog systems in the frequency band 824-894 MHz. It was based on a technology known as Advance Mobile Phone Service (AMPS) [1]. Then, the 2^{nd} generation (2G) was accomplished in 1990's in the frequency band 850-1900 MHz intended for Global System for Mobile (GSM) technology. In the frequency band 1.8 - 2.5 GHz, 3^{rd} generation (3G) based on Wideband Code Division Multiple Access (WCDMA) technologies was introduced to offer high speed wireless internet access in addition to the conventional voice service. Although the 3G technologies deliver significantly higher bit rates than 2G technologies, consumers and business professionals keep demanding for the high quality services, low latency, and the improved system capacity and coverage. Hence, the solution is Long Term Evolution (LTE) that was standardized by the 3^{rd} Generation Partnership Project (3GPP), the next generation network beyond 3G. The LTE operates over different frequency bands from 400 MHz up to 4 GHz with bandwidth from 1.4 to 20 MHz [2]. The 4^{th} generation (4G) usually refers to the successor of the 3G and 2G standards. The LTE release 10, also known to as LTE-Advanced (LTE-A), is claimed to be the true 4G evolution step with the frequency band from 2 GHz to 8 GHz [3].

Presently, telecommunication technology has significantly changed everyday life of individuals with expanding interest in boundless access to data and information sharing [4]. Considering the path ahead, there are a few patterns that will debilitate the abilities of existing media transmission, for example, explosive development of data traffic, a massive increase in the number of interconnected devices and the consistent rise of new services and application scenarios. To coordinate the patterns, 5G is expected to penetrate into every aspect of the future society to create a user-centric information ecosystem. The 5G technology is expected to complete the 4G technology and provide solutions to the shortage arising from 4G technologies. It includes all kinds of advanced features which make it most forceful and immense request in the near future. Consequently, the increase in usage and the demand for simultaneous communication between devices cause interference, especially at higher frequencies in 5G. Therefore, as a 5G requirements, a smart device embedded with a bandwidth more than 1 GHz [5] and the antenna gain more than 12 dBi [6] is required to encounter the increasing traffic demands and to address the interference problems [7][8].

Subsequently, this technology has drawn attention to millimeter-wave bands in a frequency spectrum from 3-300 GHz with reduced wavelengths ranging from 100 mm to 1 mm [5]. Meanwhile, the Federal Communications Commission (FCC) has allocated the entire spectrum for different services and auctioned the spectrum for Local Multipoint Distribution Services (LMDS) [9]. The LMDS operating on frequencies from 28 to 30 GHz was conceived as a broadband, fixed wireless and point-to-multipoint technology. Apart from that, Ofcom has stated that the spectrum above 6 GHz has gained so much attention for future networks and 15 GHz is one of the potential 5G spectrum bands as mentioned by Ericsson [10]. Hence, this frequency has been attracted the interest of researchers to conduct research towards 5G applications [11][12][13][14].

Based on Friss formula, it is often assumed that higher frequencies propagate poorly in free space compared to the lower frequencies. The reason for this misconception is the underlying assumption often used in equation (1.1) that the path loss is calculated at a specific frequency between two isotropic antennas [9]

$$L_{FSL} = 92.4 + 20\, log_{10}\, f + 20\, log_{10}\, R \tag{1.1}$$

where f = frequency (GHz) and R = distance between two isotropic antennas (km). The $20\, log_{10}\, f$ indicates that the loss is frequency dependent due to losses exist in the spreading beam from point to point at the speed of light.

Consequently, the antenna gain needs to be increased to compensate the anticipated incremental loss. In addition, a directional antenna is also indispensable to satisfy the necessities of a long distance communication [15]. Therefore, the case of directional transmit antenna with transmission gain, G_t are considered as stated in equation (1.2) [16][17] .

$$G_t = \frac{4\pi A_{eff}}{\lambda^2} \tag{1.2}$$

For the same antenna aperture areas (A_{eff}), shorter wavelengths (higher frequencies), λ should not have any inherent disadvantage compared to longer wavelengths (lower frequencies) in terms of free space loss. However, with shorter wavelengths more antennas can be packed into the same area [18].

Accordingly, in order to fulfill the 5G requirements as stated previously, multiple antennas in the phased array that is capable of steering the direction beam with the gain more than 12 dBi [6] can be used to recover the additional loss as well as to support the required access and the reconfigurable backhaul link [19]. Backhaul can be reconfigured to allow transmission between point to point and point to multipoint applications. In addition, more than 1 GHz of the antenna bandwidth is needed to meet the requirements [5]. Thereby, in this thesis, antenna array designed with phased shift capability is presented. The following section highlights the motivation towards this research study.

1.2 Problem Statement

The complex phased array design that incorporates power distribution network, phase shifter and bias component has produced a larger overall dimension [20][21]. Meanwhile, phase shifters are expensive and require intricate feeding networks that will introduce more losses at higher frequencies [20][22]. Thus, to solve the problem, new phased arrays need to be developed by using different techniques. The switchable antenna array can be constructed by using a linear array which consists of only one driven element and the remaining are of parasitic elements. In this light, the phase shift between elements is adjustable by switching the capacitive loading of the parasitic elements. In the interest to have the switchable antenna array that fulfills the 5G requirements, there are crucial issues need to be concerned starting with the single element design.

Microstrip patch antennas built on printed circuit board (PCB) substrate, are attractive due to their various features such as, light weight, low cost and easy fabrication. However, the microstrip element is affected by the inherent limitation of narrow impedance bandwidth causing poor performance due to high substrate loses and low radiation efficiency at mm-wave frequencies [23][24][25][26]. Recent studies also indicated that DRAs have an intriguing advantages as a promising candidate to replace traditional radiating elements at high frequencies, especially at millimeter waves and beyond [27][28][29][30][31]. This is mainly attributed to the fact that DRAs do not suffer from conduction losses and are characterized by high radiation efficiency when excited properly [24][32][33]. In addition, single element DRAs are normally excited in the fundamental mode with an ordinary gain of about 5 dBi, when employed on a large ground plane [34]. Several approaches in [35], [36], [37], [38] and [39] are suggested to increase the gain of the DRAs. In some of these cases, it can also improve the impedance bandwidth of the antenna. Nevertheless, most of these methods caused a significant increase in surface area, complexity and costs. Altering the single element DRA by utilizing higher-order radiation modes is another technique to increase the gain [40]. However, the impedance bandwidth decreases as the height of the dielectric resonator (DR) is increased. This is due to the larger ratio of volume (V) to surface (S) in the higher-order mode compared to the fundamental mode that can also cause the Q-factor to increase.

Past researchers had conducted electronically steerable passive array radiator (ESPAR) investigations on patch elements [41] and wire [42] to steer the antenna beam without using any phase shifters. However, the microstrip ESPAR had a limited steer angle at the boresight direction, while the steerable beam in [22] just achieved the angle of ±20° and in [43], it achieved ±15°. Besides that, the microstrip ESPAR has produced a narrow impedance bandwidth and the performance of antenna gain was less than 8.0 dBi [44][45][46]. Thus, in comparison to the microstrip antennas, the DRA have shown various benefits, such as wider bandwidth and low loss. In recent years, the dielectric resonator antenna (DRA) ESPAR was fed through the microstrip line [47], which is typically excited in the fundamental mode without considering the effect of mutual impedance by the different distance between the DR and the effect of H-field distribution inside the DR. Despite that, the impedance bandwidth between DRA ESPAR in [47] and microstrip ESPAR in [43] was more or less the same. Thus, this research proposes a new concept of DRA ESPAR by using higher-order mode excitation that have never been studied in ESPAR design. This will significantly result in a higher gain, wider bandwidth and better of steering capability.

By taking the 5G's specification requirements into consideration, the antenna design should achieve the gain of more than 12 dBi [6]. With that, related work has been done in [48], [49] , and [50] in determining potential frequency of 5G and meet the specifications. Consequently, it has increased the antenna elements and the number of phase controls, resulted in increase of cost and complexity of the design.

Based on these concerns, to secure a high-gain DRA array that is capable of switching the direction beam, new high-gain DRA array design will be proposed with a goal to steer the direction beam without using any external phase shifter. The implementation of a new concept DRA ESPAR resulted in reducing the number of antenna elements and phase controls.

1.3 Objective of the Research

This research is based on the following accompanying objectives:

1. To design and analyze a single element DRA by improving the gain (more than 5 dBi) and bandwidth (more than 1 GHz) that will be used to form a DRA subarray.
2. To apply the selected most practicable design of single element DRA in constructing the DRA subarray with switchable beam capability operating at 15 GHz.
3. To design high-gain (more than 12 dBi) switchable DRA array that consists of the incorporated DRA subarray at 15 GHz.

By achieving the stated objectives with good performance results, the proposed high-gain switchable DRA arrray can be a potential design solutions for 5G applications.

1.4 Scope of the Research

This research focuses on the design of high-gain switchable DRA array that is suitable for 5G applications requirement as stated in section 1.1. A high-gain switchable DRA array, consists of switchable DRA subarray and power divider network that is being integrated with switched-line phase shifter. In order to develop a high-gain switchable DRA array, the scope of this research is divided into three parts, which is single element DRA, switchable DRA subarray and high-gain switchable DRA array. Prior to that, various investigation on different feeding techniques of the single element DRA excited in the higher-order mode are studied at frequency 28 GHz. However, when the DRA is mounted on a ground plane, only odd mode can exist in the z-direction of DR. Therefore, mode 5 $(TE^y_{1\delta 5})$ in the z-direction is used to investigate the different feeding technique for DRA after considering mode 3 is nearly to the fundamental mode $(TE^y_{1\delta 1})$. Three techniques of the feeding structures, which is microstrip line (ML), microstrip slot aperture (MSA) and open-end coplanar waveguide (OECPW) are designed, simulated and optimized. The studies are carried out in order to identify the best feeding technique that is most appropriate for 5G requirements in terms of bandwidth, radiation pattern and gain of the single element DRA especially those excited in the higher-order mode. The design, simulation and optimization process are performed using Ansoft High Frequency Structural Simulator (HFSS) ver. 16.0.

Next, based on the best feeding technique chosen, the single element DRA is designed at 15 GHz for the realization of the fabrication and measurement process. This is due to the limited range of the measurement facilities that up to 20 GHz. According to research done in [51] and [52], there is not much difference in radiation pattern behavior between the 28 GHz and 15 GHz antennas. However, the antenna dimension at 15 GHz is slightly larger than 28 GHz due to its wavelength. The analytical study of the single element which involved the DRA excited in the fundamental mode $(TE^y_{1\delta 1})$ and higher-order mode $(TE^y_{1\delta 3})$ will be performed to observe and compare the behavior in 5G performance. Then, the determining factors of the coupling amount that can reduce the Q-factor and increased the bandwidth of the antenna in the higher-order mode $(TE^y_{1\delta 3})$ will be established. In this regard, the higher-order mode is stipulated with an index numbers m = 1 and n = 3 at 15GHz. With the excitation index number, n more than 3, it will increase the height of DRA and resulted in very limited practical applications at 15 GHz.

Subsequently, the best performance of the single element DRA will be promoted as a driven element in the construction of DRA subarray. In order to steer the beam, a phased array with analog beam steering capability will be designed. It will conveniently be adjustable by changing the reactance of capacitors on the parasitic elements. The investigation with regards to the beam steering in theory and based on the simulation, as well as the six controlling ideal switches embedded in the feed line of the parasitic elements are explained to manage the beam switching.

Lastly, the DRA subarray design is used and incorporated into a high-gain DRA array by using power divider network. While, the phase shift between the DRA subarray will be achieved by integrating the switched-line phase shifter at one of the transmission line in the power divider network. The performance of high-gain DRA array will be analyzed and investigated at 15 GHz. All fabricated design are verified and experimentally tested by using a vector network analyzer (VNA) and measured in an Anechoic Chamber. The simulated and measured results, including reflection coefficients, bandwidth, gain and switching angle, are then analyzed and discussed.

1.5 Contribution of the Research

In this thesis, four major contributions are presented. The first contribution is the determination of microstrip slot aperture (MSA) as the best feeding technique of the single element DRA excited in the higher-order mode, $TE^{y}_{1\delta5}$ at 28 GHz compared to microstrip line (ML) and open-end coplanar waveguide (OECPW). This investigation neither being done nor reported by other researchers and publications.

The second contribution is a design of higher-order mode DRA with enhanced bandwidth and gain at 15 GHz. The higher-order, $TE^{y}_{1\delta3}$ mode has been utilized by increasing the dimension of DR in normal to ground plane directions with the spacing between the short magnetic dipole corresponds to 0.46λ. It has achieved the antenna gain at 9.76 dBi in comparison to 5.6 dBi for the fundamental mode. Then, the amount of coupling involving the slot width (Ws), the stub lengths (S), and the microstrip line widths (W) is altered to reduce the Q-factor of the higher-order mode DRA. This causes significant impact to the impedance bandwidth such that it achieved 2.5 GHz for the single element DRA excited in the $TE^{y}_{1\delta3}$ mode compared to 1.8 GHz for DRA excited in $TE^{y}_{1\delta1}$ mode.

The third contribution is a new design and analysis of DRA subarray that consists of one driven DR and two parasitic DRs. The implementation of higher-order mode ($TE^y_{1\delta3}$) DR as a driven element while fundamental mode ($TE^y_{1\delta1}$) DR as the parasitic element has successfully achieved a strong mutual impedance between the elements that improved the switching angle. In addition, the design has produced a narrower half-power beamwidth (HPBW) particularly when the beam is switched due to no degeneration occurs between the driven DR ($TE^y_{1\delta3}$ mode) and the parasitic DRs ($TE^y_{1\delta1}$ mode).

Then, the last contribution is concerning the new design of high-gain switchable DRA array. The design is formed by incorporating two switchable DRA subarray with power divider network. Meanwhile, the phase shift between the DRA subarray is achieved by integrating the switched-line phase shifter at one of the transmission line in the power divider network. Apart from using external phase shifter, the design contributes in reducing the number of antenna and control elements with the best switching angle at ± 30 degrees that is capable in covering 60° sector. Accordingly, with specifications accomplished from the proposed design, it can be considered as a great potential for 5G applications.

1.6 Thesis Outline

This section discusses the thesis outline which is divided into seven chapters. Chapter 1, which discusses the overview of the whole project, comprises research background, problem statement, objectives of the research, scope of the research, contributions of the research, and lastly, thesis outline.

Meanwhile in Chapter 2, it focuses on the literature reviews, where the basic concept of dielectric resonator antenna with bandwidth and gain enhancement, antenna array and beam steering techniques are elaborated. Furthermore, previous works are reviewed, which mainly focus on beam steering techniques by using parasitic elements and related work for 5G applications.

In Chapter 3, the methodology of this research is discussed. The research work flows of the whole research are presented, which includes design specifications, research method framework, selection of substrate and the process of antenna fabrication, testing and measurement.

Next, in Chapter 4, design of single element DRA with different excitation mode are presented and described. Initially, the performance of single element DRA excited in the $TE^{y}_{1\delta5}$ mode with three different feeding techniques which are ML feed, MSA feed and OECPW feed are investigated at 28 GHz. Then, the best feeding technique is selected and used to determine the best thickness of the RT/Duroid 5880 substrate for the optimum antenna performance. Subsequently, the single element DRA excited in the fundamental mode, $TE^{y}_{1\delta1}$ with the best feeding technique is designed at 15 GHz for realization of the fabrication and measurement process. Correspondingly, the higher-order, $TE^{y}_{1\delta3}$ mode DRA is designed and analyzed to enhance the gain and bandwidth. The Q-factor is further reduced by controlling the amount of coupling that involves the slot width (W_s), the stub lengths (S), and the microstrip line widths(W).

In Chapter 5, two types of switchable DRA subarray configuration designs are proposed by utilizing the higher-order, $TE^{y}_{1\delta3}$ mode DR as a driven element. Performance of the both configuration are observed and compared especially in terms of gain, bandwidth, angle of switching and HPBW. The analysis and performance of the designed switchable DRA subarray are described and discussed thoroughly in this chapter. The best configuration is selected to be incorporated in the construction of the high-gain switchable DRA array in Chapter 6.

In Chapter 6, the high-gain switchable DRA array are designed and presented. The design consist of the DRA subarray integrated with the power divider network and switched-line phase shifter. The results of the power divider network and switched-line phase shifter are elaborated and analyzed. Also, comparison of various designs' performances with the other related work is further explained in this chapter.

Lastly, in Chapter 7, the conclusion is drawn. The findings of the research, contributions and recommendations for future works are proposed and described. Additionally, the list of references and appendices are provided at the end of this thesis.

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