A MILLIMETER WAVE REFLECTARRAY ANTENNA WITH TILTED SIDE PATCH ELEMENTS FOR FIFTH GENERATION COMMUNICATION SYSTEMS

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DEDICATION

Sincerely dedicated to my beloved mother and late father

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ABSTRACT

A flat surface reflectarray antenna is becoming an impending competitor for fifth generation (5G) communications among the generally known conventional antenna systems. Its narrow bandwidth and high loss performance lead to restrict its gain and efficiency at millimeter wave frequencies. Additionally, high design sensitivity is also an issue at millimeter waves that can trigger the problem of imperfect fabrications. Therefore, a simple design of reflectarray patch element is required with wide reflection phase range to achieve wideband and high gain performance. Efficiency of reflectarray antenna is also needed to be formulated properly to acquire polarization diversity. In this work, a new reflectarray patch element with a tilted side is recommended for a wideband dual resonance operation within 24 GHz to 28 GHz frequency range. Dual resonance of the tilted side patch element offers a reflection phase range of more than 600° and a reflection loss of 1.6 dB with a novel design. Simulated results of the patch element have been verified by the scattering parameter measurements using a waveguide simulator. Additionally, a mathematical relationship has been formulated to predict the efficiency of the reflectarray antenna based on its aperture shape and feed distance. It has been found that, a circular aperture reflectarray attains 21.46% higher efficiency than its equivalent square aperture reflectarray of the same feed distance. Consequently, a circular aperture reflectarray consisting of 332 variable size tilted side patch elements has been designed and tested at 26 GHz with various possible configurations. The high cross polarization issue due to the asymmetric design of the tilted side patch element has been tackled by mirroring the orientations of the elements on the surface of reflectarray. Moreover, circular ring slots with variable radius have been embedded in reflectarray ground plane for gain improvement. Experimental results show that, the slotted ground reflectarray antenna offers a 3.5 dB higher gain with 22.9% higher efficiency and 3% wider bandwidth than a full grounded reflectarray antenna. A maximum of 26.1 dB gain with 41.3% efficiency and 11.5% (3 GHz) bandwidth has been acquired with the slotted ground reflectarray antenna. The tilted side patch reflectarray has offered dual linear polarization when its elements are mirrored to each other and dual circular polarization when its elements are not mirrored to each other. Its main beam has been numerically steered up to ±20° by a progressive phase shift of 80°. The acquired parameters of the tilted side patch reflectarray antenna fit within the requirements of the 5G communication systems.

ABSTRAK

Antena *reflectarray* yang mempunyai permukaan yang rata menjadi pesaing untuk komunikasi generasi kelima (5G) di antara sistem antena konvensional yang diketahui umum. Lebar jalurnya yang sempit dan prestasi kehilangannya yang tinggi menjurus kepada kekangan gandaan dan kecekapan pada frekuensi gelombang milimeter. Di samping itu, kepekaan reka bentuk yang tinggi merupakan masalah pada gelombang millimeter yang akan mencetuskan masalah pada ketidak sempurnaan fabrikasi. Oleh itu, reka bentuk yang ringkas pada elemen tampalan *reflectarray* diperlukan dengan pelbagai julat fasa pantulan yang luas dan prestasi gandaan yang tinggi. Kecekapan untuk antena *reflectarray* juga diperlukan untuk dirumus dengan baik untuk memperolehi kepelbagaian polarisasi. Di dalam kerja ini, elemen tampalan *reflectarray* baru dengan sisi condong disyorkan untuk dual operasi jalur lebar dari julat frekuensi 24 GHz sehingga 28 GHz. Dual resonans bagi elemen tampalan sisi condong memberikan pelbagai fasa pantulan lebih daripada 600° dan 1.6 dB kehilangan pantulan dengan reka bentuk yang novel. Hasil simulasi bagi elemen tampalan telah disahkan oleh pengukuran parameter berselerak menggunakan simulator pandu gelombang. Di samping itu, hubungan matematik telah dirumuskan untuk menjangkakan kecekapan antena *reflectarray* berdasarkan bentuk bukaan dan jarak masukan. Telah diperolehi bahawa bukaan bulatan *reflectarray* mencapai kecekapan yang tinggi iaitu 21.46% berbanding dengan bukaan empat segi *reflectarray* pada jarak masukan yang sama. Oleh itu, bukaan bulatan *reflectarray* terdiri daripada 332 kepelbagaian saiz tampalan elemen condong direka bentu dan diuji pada 26 GHz dengan pelbagai konfigurasi. Isu polarisasi menyilang yang tinggi disebabkan oleh reka bentuk asimetri elemen tampalan sisi yang condong telah ditangani dengan pencerminan orientasi elemen pada permukaan *reflectarray*. Selain itu, slot cincin bulatan dengan pelbagai radius sudah dibenamkan pada satah bumi *reflectarray* untuk meningkatkan gandaan. Keputusan eksperimen menunjukkan bahawa, antena *reflectarray* yang mempunyai satah bumi memberikan gandaan 3.5 dB dengan 22.9% kecekapan dan 3% lebar jalur yang lebih tingi berbanding antena *reflectarray* yang tiada slot. Gandaan maksimum 26.1 dB dengan 41.3% kecekapan dan 11.5% (3 GHz) lebar jalur telah diperolehi dengan antena *reflectarray* yang mempunyai berslot. Pada sisi *reflectarray* tampalan condong menawarkan polarisasi dua linear apabila unsur-unsurnya dicerminkan antara satu sama lain, manakala dua bulatan diperolehi apabila unsur-unsurnya tidak dicerminkan pada satu sama lain. Alur utamanya telah dikemukakan secara berperingkat sehingga ±20° oleh pergerakan fasa progresif sebanyak 80°. Parameter-parameter yang diperolehi daripada antena *reflectarray* sisi condong adalah sangat bersesuaian dengan apa yang diperlukan untuk sistem komunikasi 5G.

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LIST OF ABBREVIATIONS

5G	–	Fifth Generation
AF	–	Array Factor
AR	–	Axial Ratio
AUT	–	Antenna Under Test
CST	–	Computer Simulation Technology
dB	–	Decibel
DR	–	Dual Resonance
EF	–	Element Factor
FBR	–	Front to Back Ratio
FEM	–	Finite Element Method
FIM	–	Finite Integral Method
GHz	–	Giga Hertz
HFSS	–	High Frequency Structure Simulator
HP	–	Horizontal Polarization
LHCP	–	Left Hand Circular Polarization
LP	–	Linear Polarization
RHCP	–	Right Hand Circular Polarization
SNR	–	Signal to Noise Ratio
SR	–	Single Resonance
TE	–	Transverse Electric
VNA	–	Vector Network Analyzer
VP	–	Vertical Polarization
	–	

LIST OF SYMBOLS

f – Frequency

c – Speed of Light

λ – Wavelength

φ – Reflection Phase

S – Element Spacing

G – Gain

D – Directivity

E – Electric Field

A – Area

η – Efficiency

q – Exponent of Feed Pattern Function

L – Length

d – Diagonal

ε – Dielectric Constant

J – Surface Current

k – Wave Number

σ – Conductivity

β – Progressive Phase Shift

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CHAPTER 1

INTRODUCTION

Fifth Generation (5G) communications are currently represented as a future technology, which is supposed to meet the high data rate goals, roughly 1000 times faster than the current systems. The peak data rate in the order of Gbps will require fast switching mechanism which is possible at short wavelengths of millimeter waves (mm-waves). The mm-waves are considered with the wavelengths ranging from 1 mm to 100 mm, occupying the frequency range from 3 GHz to 300 GHz [1]. However, due to congested frequency spectrum at lower frequencies, the frequencies over 20 GHz have a good potential to be considered for 5G communications [2]. Consequently, different frequency bands were proposed for 5G starting from 24.25 GHz up to 86 GHz in World Radiocommunication Conference (WRC-15) [3]. The data rate requirements of 5G can be met by enhancing the bandwidth and efficiency of the antenna systems at mm-waves [2, 4]. However, the mm-wave frequencies have some propagation limitations in terms of high path loss and very short communication distances. Massive improvements in the architecture of current communication systems are desperately required in order to adopt 5G technology [1].

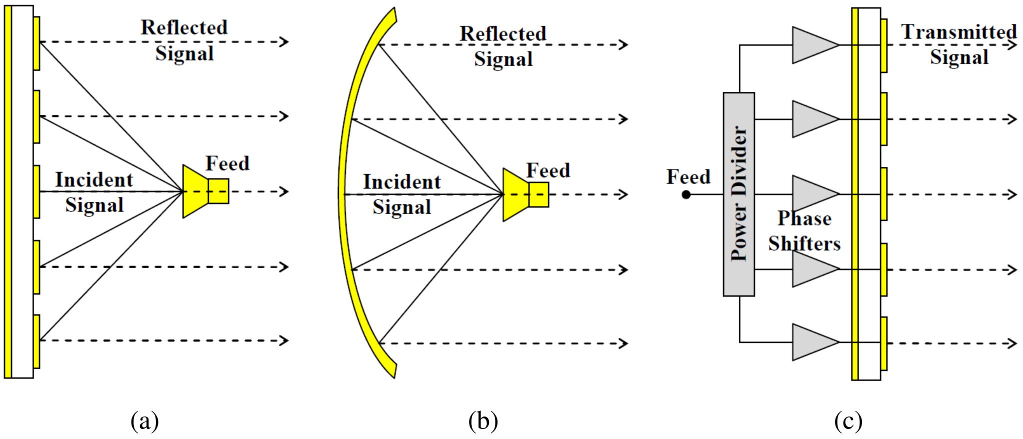
The propagation issues related with mm-waves can be avoided by selecting a suitable type of antenna for 5G systems. Array antennas are considered as a good candidate to compensate the issues regarding path loss for short range communications [5]. Two dimensional planar arrays with large electrical apertures can provide narrow beamwidth, which is essential for 5G base station operations [1]. Large electrical aperture at mm-waves for 5G, does not affect the physical profile of the antenna due to short wavelengths. Massive MIMO systems have also been suggested for 5G due to their possible integrity with small cells [1, 6]. However, as compared to array antennas massive MIMO are not the potential candidate for 5G systems due to their design complexity and less adaptability with shorter wavelengths [1, 2]. There are many other types of antennas, which can be found in the literature for proposed 5G operation

[7, 8, 9]. Their main purpose is to achieve wide bandwidth to support high throughput of 5G systems [10]. The operation of antenna systems for 5G compatibility largely depends on the enhancement of its bandwidth performance. A massive bandwidth is required in mm-wave range to support high data requirements [11]. Bandwidth of the order of GHz is attainable at mm-wave frequency range, but some extra design efforts are still required to fully utilize it with other requirements.

However, by just enhancing the bandwidth of proposed antenna does not solve all issues regarding 5G compatibility. Significant improvements in some other parameters like gain, efficiency, polarization diversity and adaptive beamsteering are also considered as a need of time [11, 12, 1]. It is because, the antenna performance for 5G can directly depend on the mode of antenna operation. Antenna used for transmission or reception can significantly affect its required parameters for 5G operation. It is widely believed that the requirement of improvement in antenna parameters for transmission is higher than the same parameters for reception. An improved gain performance can ensure the strong transmission capabilities for antenna [11]. In the case of 5G, when antenna systems are required to work at mm-waves, their communication distances significantly decrease due to the short wavelength. In this case, a high gain antenna can radically improve the path loss performance, without disturbing its original power consumption [7].

A high aperture efficiency of antenna systems ensures the best utilization of maximum gain value for the reduction of path loss [12]. On the other hand, the data rate can also be increased by enhancing the spectral efficiency of antenna systems [2]. Polarization diversity can be achieved when a single antenna is used with two or more different polarizations [13]. The concept of frequency reuse also emerges from polarization diversity, where a single frequency can be dually utilized with different polarizations of the signal. Frequency reuse is useful for 5G systems, where wide bandwidth is essentially required. The mm-wave antennas support fixed narrow beam operation for high gain performance, which enables the need of adaptive beamsteering [1]. Moreover, the highly directional nature of mm-waves can produce blockage of signals, which can be countered by performing adaptive beamsteering [2]. These described parameters of a potential 5G antenna, are attainable with a reflectarray antenna.

The array of elements combined together on a flat dielectric surface to reflect the incidence signals coming from a properly distant feed defines the main architecture of a reflectarray antenna [14]. Figure 1.1 distinguishes between the basic operational characteristics of a reflectarray antenna, parabolic reflector and phased array antenna. As demonstrated in Figure 1.1, the reflection of the signals can be directed like a parabolic reflector with an additional advantage of a plane and light weighted surface. Moreover, reflectarray can also perform beam scanning like a phased array antenna, but without the aid of any power divider or additional phase shifters [15]. The less complex design of reflectarray makes it more cost effective and competitive, especially for beam scanning applications. The bulky and curvy design of parabolic antenna is not a good candidate for high frequency applications [14]. Alternatively a reflectarray antenna can easily be designed from as low as Microwave [16] to as high as Terahertz frequency range [17]. The adaptability of reflectarray to high frequencies makes it suitable for high gain and high bandwidth operation.



(a) (b) (c)

Figure 1.1 Operational layout of (a) Reflectarray antenna (b) Parabolic reflector (c) Phased array antenna

Phased array antenna is the nearest possible competitor of reflectarray antenna for 5G operation, but it faces efficiency lacking problems at mm-waves due to its additional loss performance at high frequencies [18]. Moreover, its design complexity and power consumption are also major issues at mm-wave frequencies. On the other hand, the discussed antenna parameters for possible 5G application are inevitable with reflectarray antenna. Its bandwidth can be enhanced by optimizing its unit cell designs with different substrate thicknesses [19]. The high gain performance can be obtained by increasing the size of the reflectarray, which can produce sharp beams [14]. Its reflection loss performance along with its feeding mechanism can be optimized for efficiency enhancement. Different design configuration of patch elements can be utilized for various polarization combinations. Furthermore, the incident signal from feed or the reflection phase of the reflectarray can be dynamically tuned to get adaptive beamsteering [20].

There are a lot of techniques mentioned in the literature for the enhancement of each discussed parameters of reflectarray. In this work, the emphasis has been given specially on the design configuration needed for reflectarray bandwidth and gain enhancement as a 5G base station antenna. Improvement in the bandwidth performance surely reduces the gain of the reflectarray antenna. Therefore, various techniques have been implemented in the reflectarray comprised of the proposed elements for high gain and high efficiency performance. The finalized design of the reflectarray antenna has also been realized for the possibility of acquiring polarization diversity and electronic beamsteering at mm-wave frequency range.

1.1 Problem Statement

High reflection loss and narrow bandwidth are the two main performance degradation of reflectarray antenna, which also limit its gain and efficiency. The losses in the reflectarray are associated with the design of its unit cell element and the material used to construct it. A wide patch element, such as a square patch, reflects back most of the incident signals and offers low loss performance. However, it also provides narrow bandwidth performance due to its limited reflection phase range. In order to coincide with the 5G high data rate requirements, a wide bandwidth reflectarray antenna is required with high gain and high efficiency at mm-wave frequency range. The main problem associated with mm-wave is its high design sensitivity due to shorter wavelengths. It means that, a slight change in the dimension of reflectarray element would drastically affect its performance. This slight change in the dimension is unavoidable in the case of an imperfect fabrication. Alternatively, the high performance parameters of 5G reflectarray antenna come with increasing design complexity. The high design complexity also increases the chances of imperfect fabrication at mm-wave frequencies due to very short physical dimensions. The bandwidth of the reflectarray antenna can be improved by introducing extra resonances at its unit cell level. However, this may trigger extra losses with a possibility of mutual coupling between the elements and degradation in gain performance. This effect of mutual coupling can alter the resonant behavior, increase the cross polarization level and limit the efficiency of reflectarray antenna. Gain and efficiency of the reflectarray antenna are largely dependent on its aperture size and feeding mechanism. The spillover and illumination efficiencies can be optimized by selecting a proper feed distance in front of the reflectarray. A suitable feed distance also eliminates the chances of high side lobe formation that limits the gain performance. The mm-wave array antennas produce highly directional narrow beams, which shrink down their coverage area and limit the full bandwidth utilization by introducing signal blockage problem. The signal blockage can be avoided by introducing electronic beamsteering, whereas the diversity in the polarization can be utilized as an efficient tool for frequency reuse. Therefore in this work, a novel reflectarray unit cell with simple design and extended reflection phase range has been proposed to avoid the design complexity issue at mm-waves. The mutual coupling and hence the high cross polarization issue of the proposed unit cells has been tackled by selecting the proper orientation of the elements on the surface of constructed reflectarray. The gain and efficiency of the constructed reflectarray have been optimized by a suitable aperture size with a proper feed distance. The reflectarray antenna comprising the new unit cells has also been realized with the available possibilities of polarization diversity and beamsteering.

1.2 Research Objectives

There are four main research objectives of this work, which are listed below;

1. To design and investigate the performance of a wideband tilted side reflectarray patch element with wide reflection phase range.
2. To numerically analyze the relationship between the efficiency, aperture size and feeding mechanism of the reflectarray antenna.
3. To develop a wideband reflectarray antenna with improved gain and reduced cross polarization.
4. To implement a technique for the realization of polarization diversity and beamsteering in the reflectarray antenna.

1.3 Research Scope

The main scope of this research work comprises of the designing of a reflectarray antenna that could satisfy the requirements for the 5G communications systems. Unit cell patch element of the reflectarray antenna has been characterized in order to obtain dual resonance response operating at 26 GHz for bandwidth enhancement. The unit cell simulations has been performed using CST MWS and Ansys HFSS simulations tools, while measurements have been done by waveguide simulator approach. Rogers 5880 material has been selected as the substrate for the reflectarray antenna with 0.254 mm thickness. A full reflection phase span of 720° and 360° is selected for the realization of a proper full reflectarray antenna design. Far-field measurements of the full reflectarray antenna have been performed in anechoic chamber. Three different horn feeds with different gains are used to analyze the effect of variable feed distance on the performance of the reflectarray antenna. A mathematical relation has been derived to estimate the efficiency of the reflectarray antenna by considering its aperture shape and feeding mechanism characteristics within the frequency range of 24 GHz to 28 GHz. Gain enhancement in the reflectarray antenna is characterized by embedding circular ring slots in its ground plane. Reduction in the cross polarization of the reflectarray antenna has been optimized by selecting different element orientations on its surface. Different polarization operation of the reflectarray antenna has been tested by 90° rotating its aperture, while keeping the same feed orientation. Finally, Matlab software is used to numerically obtain the maximum possible beamsteering by the finalized reflectarray antenna design.

1.4 Thesis Organization

The second chapter of the thesis discusses the main techniques available in the literature for the performance enhancement of reflectarray antenna. The performance parameters of reflectarray antenna in terms of its bandwidth, gain, efficiency, polarization diversity and adaptive beamsteering are thoroughly analyzed in this chapter. Importance of each of these parameters is also explored for their plausible compatibility with 5G communication systems.

The conventional tactics and procedures involving the design and analysis of a reflectarray antenna are provided in the third chapter. Detailed design analyses of a unit cell element with its proper boundary conditions and excitation is included. The step by step process involving the design of a full reflectarray antenna is mentioned in this chapter. The methods of performing simulations, fabrication and measurements of the reflectarray antenna are also thoroughly discussed.

Chapter four studied the efficiency characteristics of reflectarray antenna in conjunction with its feeding mechanism. Mathematical equations for the aperture efficiency of reflectarray antenna are formulated and analyzed by performing far-field simulations and measurements of a square path reflectarray antenna. Total efficiency of the reflectarray antenna is also estimated by the developed equations and the results are validated by the conventional gain-directivity relation.

The tilted side patch element and its full reflectarray configuration are thoroughly analyzed in chapter five. Process of the evaluation of the tilted side patch element from a square patch element is defined in this chapter. The wide reflection phase range of the tilted side patch element is then utilized to study different configurations of the reflectarray antenna for its performance improvement. The main techniques for the enhancement of bandwidth and gain, and reduction of the cross polarization of developed reflectarray antenna are also provided in this chapter. The

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