CIRCULARLY POLARIZED AND RECONFIGURABLE FREQUENCY SELECTIVE SURFACE BASED TRANSMIT ARRAY ANTENNA FOR X-BAND APPLICATIONS

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ABSTRACT

Transmitarray (TA) antennas have attracted much attention in recent years due to their number of applications. These include the 5G/6G mobile networks and satellite communication systems for the microwave frequency range. The various satellite applications require high-gain antennas with polarization agility. Also, the state-of-the-art smart communication systems require reconfigurable antennas allowing the frequency and beam switching according to the application requirements. In this research, three different TA antennas have been studied and designed for X-band applications which are high gain and wideband TA antenna, circularly polarized TA antenna, frequency and beam reconfigurable TA antenna. For the first design, two Frequency-Selective Surface (FSS) unit cells which include Double Square Ring with Center Patch (DSR-CP) and Split Ring Resonator (SRR), have been applied to increase the antenna gain and bandwidth. The optimized unit cell structure shows that a four-layer configuration could provide maximum phase range with low insertion losses. The complete DSR-CP TA consisting of 121 elements has produced an impedance bandwidth of 33.3% with a peak gain value of 20.4 dBi and 1-dB gain for bandwidth of 10%. SRR-based TA achieved the impedance bandwidth of 35% with a peak gain value of 21.9 dBi and 11.6% 1-dB gain bandwidth. A circularly polarized TA using a Meander Line Polarizer (MLP) superstrate has been studied and presented. The MLP unit cell was simulated and optimized at 12 GHz, having 90^0 phase difference between the two orthogonal E-field components, Ex and Ey. The final prototype measurement results show that a low axial ratio of 1.89 and 20.17 dBi gain at 11.2 GHz has been obtained. Finally, the last part of the research focused on the frequency and beam reconfigurable TA antenna. A U-shape superstrate layer has been added to introduce frequency selectivity in front of the horn antenna that acts as a bandpass filter. Then, by varying the strip length of the U-shape unit cell, the antenna frequency can be reconfigured from 8.5 GHz to 11.2 GHz. On the other hand, a new active TA unit cell equipped with four switchable strips using Positive Intrinsic Negative (PIN) diodes has been employed to achieve beam reconfigurable TA antenna. Thus, the antenna beam can be tilted by controlling the PIN diodes ON and OFF switching states. Results show that a full-beam switching range of 43.2^0 has been obtained. In conclusion, this research has successfully presented three new TA antenna designs, which are highly potential for the X-band applications.

ABSTRAK

Antena Transmitarray (TA) telah menarik banyak minat sejak beberapa tahun kebelakangan ini kerana pelbagai kegunaanya. Ini termasuklah rangkaian mudah alih 5G/6G dan sistem komunikasi satelit dalam julat frekuensi mikrogelombang. Aplikasi satelit memerlukan antena gandaan tinggi disamping kebolehan untuk menukar jenis polarisasi. Selain itu, sistem komunikasi pintar yang terkini juga memerlukan antena yang boleh dikonfigurasikan semula bagi membolehkan penukaran frekuensi dan pensuisan alur mengikut keperluan aplikasi. Di dalam penyelidikan ini, terdapat tiga jenis TA antenna yang berlainan telah dikaji dan direkabentuk untuk aplikasi jalur-X iaitu antena TA dengan jalur lebar dan gandaan tinggi, antenna TA dengan jenis polarisasi bulat dan antena TA yang boleh dikonfigurasi secara frekuensi atau alur. Di awal kajian, dua unit sel permukaan memilih frekuensi (FSS), iaitu gelang persegi berganda dengan tampalan tengah (DSR-CP) dan penyalun gelang terbelah (SRR) telah digunakan bagi meningkatkan gandaan dan lebar jalur antena. Kajian menunjukkan reka bentuk unit sel adalah optimum dengan menggunakan empat lapisan tatarajah yang dapat menghasilkan julat fasa yang maksimum berserta kehilangan sisipan yang rendah. Konfigurasi antena TA berasaskan DSR-CP yang lengkap pula mengandungi 121 elemen, telah berjaya menghasilkan galangan lebar jalur sebanyak 33.3% dengan nilai gandaan puncak 20.4 dBi dan 10% gandaan lebar jalur 1-dB. Manakala, antenna TA berasaskan SRR menunjukkan lebar jalur galangan sebanyak 35% dengan nilai gandaan puncak 21.9 dBi, dan 11.6% gandaan lebar jalur 1-dB telah diperolehi. Seterusnya, antena TA terkutub membulat menggunakan super-strata pengutub garis liku (MLP) telah dikaji dan dibentangkan. MLP unit sel disimulasi secara optimum pada 12 GHz supaya mempunyai perbezaan fasa sebanyak 90^0 di antara dua komponen ortogen medan elektrik, E_x dan E_y. Hasil pengukuran prototaip akhir menunjukkan antena dengan nisbah paksian yang rendah sebanyak 1.89 dan gandaan 20.17 dBi pada 11.2 GHz telah didapati. Kajian terakhir pula memfokuskan kepada rekabentuk antena TA lapisan superstrate yang boleh dikonfigurasi semula melalui frekuensi dan alur. Unit sel dengan bentuk U telah ditambah dihadapan antena hon supaya bertindak sebagai penapis lulus jalur bagi membolehkan pemilihan frekuensi. Seterusnya, dengan menggubah panjang jalur bentuk U unit sel tersebut, frekuensi antena boleh dikonfigurasi daripada 8.5 GHz sehingga 12 GHz. Disamping itu, unit sel antena TA baru yang mengandungi empat jalur suis boleh ubah menggunakan positif intrinsik negatif (PIN) diod telah digunapakai bagi mengubah alur antena. Dengan itu, alur antena dapat dikonfigurasi dengan mengawal keadaan pensuisan buka dan tutup PIN diod tersebut. Keputusan kajian menunjukkan julat pensuisan alur penuh sebanyak 43.2^0 telah berjaya dikawal. Sebagai kesimpulan, keseluruhan kajian ini telah berjaya merekabentuk tiga jenis TA antena yang baru dan berpontensi untuk digunakan dalam aplikasi jalur-X.

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LIST OF ABBREVIATIONS

5G	-	Fifth Generation
6G	-	Sixth Generation
AUT	-	Antenna Under Test
AR	-	Axial Ratio
CP	-	Circularly Polarized
CPW	-	Coplanar waveguide
DSR	-	Double Square Ring
DSR-CP	-	Double Square Ring with Center Patch
FSS	-	Frequency-selective Surface
F/D	-	Focal distance to diameter ratio
LHCP	-	Left-handed Circular Polarization
MEMS	-	Micro-electromechanical systems
MLP	-	Meander line polarizer
mmW	-	Millimeter-wave
PBG	-	Photonic Band Gap
PIN	-	Positive Intrinsic Negative
RA	-	Reflectarray
RADAR	-	Radio Detection and Ranging
RHCP	-	Right-handed Circular Polarization
SRR	-	Split Ring Resonator
TA	-	Transmitarray
UUT	-	Unit Cell Under Test
VNA	-	Vector Network Analyzer

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Antennas are essential electronic devices that work on the principle of electromagnetics. They have many applications, including wireless communication systems, radars, space exploration, broadcasting, and remote sensing. Although antennas have more than 100 years of history, new concepts have emerged in antenna design techniques. This is due to exploring new frequency bands like Terahertz bands, advanced computational capabilities, new materials and advanced fabrication facilities.

High gain, wideband, and compact TA antennas can be used in many wireless communication systems at microwave frequencies (Luo et al., 2018; Mei et al., 2020). This family of antennas requires high gain values greater than 20dB. Low-cost and lightweight TA antennas can be used in Ka and Ku-bands for satellite communication systems (Li et al., 2020; Naseri, Matos, et al., 2017). TA antennas in 5G mobile networks can be used in front haul and backhaul applications at Ka, V and S-band, respectively (Diaby et al., 2018).

The research on TA antennas has increased due to lightweight, low profile and simple planar fabrication methods (Xu et al., 2017; Yang et al., 2020). The TA antennas do not suffer from feed blockage due to highly transmissive layers. Moreover, feed losses and complex beamforming networks can be avoided due to spatial feeding techniques. TA antennas thus effectively combine the attractive features of microstrip arrays and the lens-type antennas (Hsu et al., 2018).

There are three different design configurations used in TA antennas. The most commonly used design approach is the “receiver-transmitter” configuration. Due to high insertion losses by radiating elements, overall TA bandwidth (Luo et al., 2018) and aperture efficiency are reduced (Cai et al., 2018). The inclusion of active devices and vias for layer interconnection increase the complexity of TA antennas. The other two design types include the FSS and the metamaterial configurations for the TA antennas. FSS has been attractive due to its bandpass filtering capability. Including FSS in TA designs can produce wider bandwidths (Hsu et al., 2018). Moreover, high transmission coefficient magnitudes and a complete 360^0 phase range can be achieved using multilayer designs. The FSS-based TA antennas can increase antenna efficiency due to lower insertion losses (Cai et al., 2018).

1.2 Research Background

High gain, low profile and wideband antennas have been used widely in long-range communication systems. The conventional parabolic type antennas are an example of an optical approach with large size reflectors and heavyweight (Kalra et al., 2018). The second approach for designing high gain antennas uses the antenna array theory. Microstrip patch antenna arrays and waveguide slot arrays are examples of the second approach. The phased array antennas also use this design approach providing high gain and beam reconfigurability(Guan et al., 2018). However, the feeding and power division circuit makes these antennas complex. The RA antennas are highly directive with planar configuration. However, due to the placement of the feed source in the main beam direction, the RA antenna suffers from blockage of the main beam due to the feed source (Mohammadi et al., 2018). In recent years, TA antennas have gained much attraction. By combining lens and array antenna features, TA antennas (X. Zhang et al., 2020) can be designed with high gain and pencil beam radiation patterns (Cai et al., 2018). The feed blockage problem can be avoided in TA antennas by the source placement behind TA layers (An et al., 2018; Pham et al., 2020). The spatial feeding technique can reduce insertion losses in feeding and power division circuits (Clemente et al., 2013; Feng, Qu, & Yang, 2020).

Circularly polarized TA antennas are required in many applications to increase the probability of reception (Veljovic & Skrivervik, 2020). This results in avoiding the problem of aligning the transmitting and receiving antennas. Moreover, the frequency bands have been congested with the development of several wireless communication applications. Depending on the system requirements, the antenna must reconfigure or tune the frequency for reliable communication systems (Guo et al., 2018). Meanwhile, the necessity of beam reconfigurable antennas has been widespread in applications like RADARs, satellite communications and vehicles on the move (Aziz et al., 2020; Farzami et al., 2017).

1.3 Problem Statement

The TA unit cell designs suffer from the problem of narrow bandwidth (Clemente et al., 2020) and low aperture efficiency (Cai et al., 2018). In addition, the FSS TA antennas have the problem of complex unit cell designs (Wu et al., 2019) and use many active devices in big-sized arrays (Tuloti et al., 2018). The FSS unit cell needs a wider phase range and high transmission coefficient magnitude. The techniques can be applied for a wider phase range, such as multilayer configurations and multi-resonant structures. However, increasing the number of layers will also increase the transmission losses and reduce the antenna gain. Meanwhile, multi-resonant structures can make the unit cell more complex and difficult to fabricate. Thus, in this thesis, we proposed a new unit cell design with wider phase range and high transmission coefficient to increase the bandwidth and improve the gain while having a compact array size.

A few techniques have been presented to convert the polarization from linear to circular. These include the reconfigurable polarization source (Tewari et al., 2017b) or sequential rotation of elements in complex configurations due to layer interconnections (Pham et al., 2020); (Diaby et al., 2018; F. Zhang et al., 2020). However, these techniques are complex or require many active devices. Therefore, we try to implement an MLP superstrate to convert the linear polarization to circular. This technique will provide less complexity, wider bandwidth and more straightforward implementation (Nakajima et al., 2018).

The frequency of the TA antenna can be reconfigured by using different techniques. The reconfigurable feeding sources use active switching devices like PIN diodes, varactors and MEMS (Janisha et al., 2020). However, these techniques show narrow bandwidth and complex configuration with many active devices for a complete TA antenna. Therefore, we applied the superstrate layer that can be included as a spatial bandpass filter in the TA designs to reconfigure the frequency (Wu et al., 2019). Such designs have the advantage of low profile, wide bandwidth and can be incorporated into existing TA designs (Chatterjee et al., 2018).

Beam switching can be implemented for TA antenna design using the few techniques presented. For reconfigurable feeding source-based designs, various devices like MEMS switches, ferrites, liquid crystals and pin diodes (Frank et al., 2019; Vilenskiy et al., 2020) have been used. The phase shifters-based TA designs have used the receiver-transmitter configuration (Clemente et al., 2020; Di Palma et al., 2017). However, these techniques have drawbacks of large size, complex configuration and layer interconnection issues. Therefore, we propose an active FSS-based TA design using PIN diodes with compact size, wider bandwidth and wide beam tilting range.

1.4 Research Objectives

The research on FSS TA is required for applications requiring compact, wideband and high gain antennas. Many applications, including satellite communication systems, require circularly polarized high-gain antennas. The reconfigurable antenna is essential to suit the long-range communication systems like satellites and radar with added features. This research work will focus on the following objectives:

(a) To design, fabricate and measure an FSS TA unit cell at X-band with a high transmission coefficient magnitude and wide phase range.

(b) To design, fabricate and measure linearly polarized, wideband and high gain FSS TA antennas at X-band using the proposed FSS unit cell designs.

(c) To design, fabricate and measure circularly polarized TA antenna using an MLP superstrate.

(d) To design, fabricate and measure frequency and beam reconfigurable TA antenna by using the FSS superstrate and active unit cell design.

1.5 Scope of the work

This research will focus on designing a wideband and high gain TA antenna at 12GHz. Different FSS-based unit cells will be analyzed in the CST studio. The parametric analysis will optimize the transmission coefficient magnitude and phase. The effect of incrementing the number of FSS unit cell layers will also be studied. Fabricating unit cell array patches will validate the unit cell simulation results. The unit cell prototype will be tested using rectangular to square waveguide transitions. Also, the FSS-based TA designs will be analyzed using different unit cell designs. The phase distribution table for TA design will be calculated for the three different TA designs. Complete TA design will be performed in CST studio. The parametric analysis will optimize the focal distance to diameter ratio for maximum gain and bandwidth. The fabrications of TA layers will be performed using a low-cost FR4 substrate. Measurements of the TA antenna will include the return loss measurements using a vector network analyzer (VNA), radiation pattern and peak gain measurement in the anechoic chamber.

Different types of metasurface used for linear to circular polarization will be reviewed and analyzed using simulations. The Meander line unit cell will be simulated in the CST studio for the perpendicular incidence of E-field components. The circularly polarized TA will be designed using the MLP layer with FSS layers. In addition, the parametric analysis by variations in the position of the polarizer superstrate will be carried out to obtain a low return loss, wide bandwidth, high gain, and low axial ratio. Finally, the polarizer superstrate will be fabricated and tested for return loss, radiation pattern, peak gain and axial ratio measurements.

The frequency reconfigurable TA design will be implemented using a dual-band FSS superstrate layer. FSS unit cell will be designed in CST using sequential rotations of U-structure. Unit cell simulations will achieve the dual-passband properties that can be tuned by changing specific parameter lengths. The superstrate array layer will be designed and placed in front of the horn antenna along with FSS

TA layers. The analysis will validate the frequency shifting results with the complete TA design. Different tuning states will be considered to tune the frequency of TA over the range of 9GHz to 12GHz. Results will be validated by fabricating dual-band FSS superstrate layers for different parameter lengths. The shift in design frequency will be confirmed by measurements, including return loss, peak gain and radiation patterns.

Finally, different unit cell designs for the beam reconfigurable TA design will be reviewed and analyzed using CST studio to find suitable structures with wide phase-shifting capability. Active unit cell design with multiple layers will be designed using CST studio. Switching the active devices on transmission coefficient magnitude and phase will be observed. Complete TA design using active unit cell array will be implemented in CST studio. Simulations will be performed to find the properties of active beam reconfigurable TA, including the return loss, peak gain and radiation pattern. A passive TA model will be designed for validation by replacing the PIN diodes with open and short circuits. The fabrication of passive TA layers for five switching states will be carried out. Measurements will be performed to verify the simulation results and determine the maximum beam tilting range.

1.6 Significance of research

Modern long-range communication systems require the antenna to have high gain and wide bandwidth. FSS TA antennas can achieve high gain and wide bandwidth, keeping the profile low. The reception probability increases with circularly polarized antennas on both the transmitter and receiver ends. The meander line superstrate-based CP TA has a compact design with polarization reconfigurability as the original FSS TA layers remain intact in this design. The frequency tuning feature introduced in the FSS TA using a superstrate layer can shift the design frequency depending on the unit cell strip length. An antenna beam must be switched in some applications like satellite on-the-move communication systems. This research will result in a new active FSS-based unit cell design with the PIN diodes required for phase shifting. The complete active TA design can scan the beam over a wide angular range.

1.7 Thesis Outline

Chapter 1 briefly introduces long-range communication systems and the significance of the TA antennas. The different configurations of TA antennas are discussed briefly. The problems faced in high gain antennas for long-range applications will be addressed. The objectives are focused on the solution to identified research gaps.

Chapter 2 includes the literature review on the TA unit cell, its primary structure, the design configurations, linear to circular polarizers, frequency and beam reconfigurable TA antennas. TA designs are compared in all sections to find the best suitable techniques.

Chapter 3 shows the flow chart of the research project and the different stages involved in implementing the research. The TA unit cell design will be presented using FSS and a complete TA design. A brief overview of designing the linear to circular polarizer unit cell and complete layer is shown. Finally, the frequency and beam tuning methods used to reconfigure the TA will be discussed.

Chapter 4 covers the FSS unit cell and complete TA design, transmission coefficient magnitude & phase results, complete TA reflection coefficient, radiation pattern, and peak gain plot. Wideband and high gain linearly polarized TA antennas are designed to investigate the results.

Chapter 5 illustrates the linear to circular polarizer design and results. The meander line unit cell and superstrate layer design are described. Finally, the circularly polarized TA is designed, and the results are presented.

Chapter 6 shows the frequency and beam reconfigurable TA design. The results are shown in the two sections to illustrate the performance and characteristics of the proposed designs.

Chapter 7 concludes the thesis report and presents the research outputs and future recommendations.

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3) Iqbal, M. N., Yusoff, M. F. M., Rahim, M. K. A., Hamid, M. R. B., Johari, Z., & Rahman, H. U. (2021b). Circularly Polarized TA Antenna Design Using Meander Line Polarizer for Ku-Band Applications. IEEE Access. (Q2, IF=3.367)

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1) Iqbal, M. N., Yusoff, M. F. M., Rahim, M. K. A., Hamid, M. R., & Johari, Z. (2019). X-band Rectangular to Square Waveguide Transition for TA Unit Cell Characterization. Paper presented at the 2019 IEEE Conference on Antenna Measurements & Applications (CAMA).
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