DESIGN OF REFLECTARRAY ANTENNA INTEGRATED WITH FSS TEXTURED CONFIGURATIONS FOR WIRELESS COMMUNICATION APPLICATIONS

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Sincerely dedicated to my parents, family and friends whom constant encouragement, love and support have made all of this possible.

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ABSTRACT

Modern communication systems require intelligent antenna arrays to achieve increased phase range for the performance improvement. Moreover the design requirements of spacecraft antennas for satellite communications and telecommunication missions require multifunction antennas to prevent the propagation of electromagnetic waves in certain frequency bands. This project investigates the feasibility of employing reflectarray antenna integrated with FSS textured configurations to combat the scan blindness problem. Performance investigation of different strategic resonant elements has been carried out in X-band frequency range by using commercially available computer models of CST MWS and Ansoft HFSS based on Finite Integral Method (FIM) and Finite Element Method (FEM) respectively. Frequency Selective characteristics are also exploited by embedding the dipole, square loop and triangular loop resonant elements on top of the groundless substrate. Integrated FSS Reflectarray (FSS-RA) configurations based on iterative loop length approach are than implemented for operation in both X and Ku-band to improve the static phase range for the reduction of phase errors resulting in scan blindness. It has been demonstrated that the maximum static phase range of 540° can be obtained with the loop length variation of 6.8mm. Moreover novel algorithms based on mathematical models have been developed for the calculation of progressive phase distribution depicted by each individual resonant element and resonant frequency estimation of FSS reflectarrays. In order to validate the authenticity of numerical results waveguide scattering parameter measurements have been carried out by fabricating two patch unit cells for each reflectarray resonant element. Measured results demonstrated that reduction in reflection area of resonant elements from 105.74mm^2 to 7.33mm^2 tends to increase the reflection loss values from 2.63dB to 20.25dB. Moreover, an increased measured static phase range of 290° offering the reduction in phase errors is also shown by employing the triangular loop element.

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RESEARCH ACCOMPLISHMENTS (PUBLICATIONS/AWARDS)

Following is the list of publications and awards achieved in result of the research work presented in this thesis.

International Refereed Journals

[1] M. Y. Ismail and Arslan Kiyani, "*Characterization of Printed Reflectarray Elements on Variable Substrate Thicknesses,*" International Journal of Electrical, Electronic Science and Engineering, Vol. 8, No. 2, pp. 208-212, 2014.

[2] Arslan Kiyani and M. Y. Ismail, "*Design and Analysis of High Performance Reflectarray Resonant Elements*," Procedia Engineering, Vol. 53, pp. 248-254, 2013.

Proceeding Papers

International Conferences

[3] M. Y. Ismail and Arslan Kiyani, "*Characterization of Printed Reflectarray Elements on Variable Substrate Thicknesses*," International Conference on Communication and Information Technology (ICCIT 2014), February 2014, Rio de Janerio, Brazil.

[4] M. Y. Ismail and Arslan Kiyani, "*Investigation of Reflection Area on Strategic Reflectarray Resonant Elements*," IEEE International Symposium on Wireless Technology and Applications (ISWTA 2013), September 2013, Kuching, Malaysia.

[5] Arslan Kiyani and M. Y. Ismail, "*Numerical Model for Phase Distribution Characterization of Reflectarray Elements*," IEEE International Symposium on Telecommunication Technologies (ISTT 2012), November 2012, Kuala Lumpur, Malaysia

Local Conferences

[6] Arslan Kiyani and M. Y. Ismail, "*Integrated Reflectarray Antenna with FSS Resonant Elements for Scan Blindness Reduction*," Malaysian Technical Universities Conference on Engineering and Technology (MUCET 2013), December 2013, Pahang, Malaysia.

[7] Arslan Kiyani and M. Y. Ismail, "*Design and Analysis of High Performance Reflectarray Resonant Elements*," Malaysian Technical Universities Conference on Engineering and Technology (MUCET 2012), November 2012, Perlis, Malaysia.

Awards

International Recognition

[1] Semi-Grand Prize (Gold Medal & Special Trophy) awarded by Korean Invention Promotion Association (KIPA) for the product "*Frequency Selective Reflector for Radio Communications*," at Seoul International Invention Fair (SIIF 2013), November 2013, South Korea.

[2] Gold Medal for the product "*Frequency Selective Reflector for Radio Communications*," under Telecommunications category at 24th International Invention, Innovation and Technology Exhibition (ITEX 2013), May 2013, KLCC, Malaysia.

Local Recognition

[3] Gold Medal for the product "*Frequency Selective Reflector for Radio Communications*," under Electrical, Electronics and Communications category at Research and Innovation Festival (R&I 2012), November 2012, UTHM, Malaysia.

Patents

[1] M. Y. Ismail and Arslan Kiyani, "*Frequency Selective Reflector for Radio Communications*," applied for Patent Filing with Application Number PI 2013003946 *(Patent Pending)*.

CHAPTER 1

INTRODUCTION AND BACKGROUND

With recent boom in wireless communication technology, the need for high-gain microwave antennas with wide beam scanning and low cost production has emerged in many applications such as radars, direct broadcasting, radio astronomy, deep-space explorations and earth remote sensing. Previously parabolic reflector antennas have been employed for these applications. However the reflector antenna possesses curved structure which leads to the manufacturing difficulty especially at millimeters wave. It occupies more space because of its bulky size and is heavier than a planar antenna (Huang & Encinar 2007). Furthermore wide-angle electronic beam scanning cannot be achieved using parabolic reflector because of its limited scan angle (Encinar et al. 2006). To overcome this weakness high gain phased array antenna took place of parabolic antenna consisting of multiple fixed elements which are capable of achieving wide-angle beam scanning electronically when equipped with the controllable phase shifters (Bialkowski & Encinar 2007). Amplifier modules need to be integrated with the phased arrays to combat the power inefficiency problem, thus making it an expensive solution for long distance communications. Therefore, in order to eliminate these problems a new way has been found by introducing a flat low-profile reflector known as reflectarray. Microstrip reflectarrays has emerged as a future candidate for high-gain antenna and promises higher efficiency at reduced cost by combining many benefits of reflector antennas and planar phased arrays since they are hybrid design of both types as shown in Figure 1.1.

(a) (b) (c)

Figure 1. 1. (a) Parabolic antenna (b) Phased array antenna (c) Reflectarray Antenna

The design requirements of spacecraft antennas for satellite communications and telecommunication missions are becoming extremely stringent. A variety of military systems employ multiple antenna apertures on a single platform such as a ship or an aircraft. In order to reduce cost and improve performance characteristics, it is desirable to combine multiple functions into a single aperture. Wide bandwidth, low cost and light weight reflectarrays with frequency selectivity properties are needed to accomplish this goal. As a consequence, another field of interest is the integration of reflectarrays with Frequency Selective Surfaces (FSSs). FSSs compromise of an array of periodically arranged patches or apertures on a dielectric substrate. They provide different characteristics over different frequency bands hence regarded as filters of electromagnetic waves. The frequency selective properties can be exploited to make a reflectarray antenna much more efficient. The design of such array responds to the more and more demanding requirements on modern antenna arrays with purpose of improving antenna performance such as widening of scan region (increased phase range) for the reduction of scan blindness.

X and Ku frequency bands have been targeted for the operation of proposed reflectarray configurations. X-band is most often used in modern radars applications. X-band radar frequency sub-bands are used in civil, military, and government institutions for weather monitoring, air traffic control, maritime vessel traffic control, defense tracking, and vehicle speed detection for law enforcement. Whereas, Ku-band is primarily used for satellite communications, most notably for fixed and broadcast services, and for specific applications such as NASA's Tracking Data Relay Satellite used for both space shuttle and International Space Station (ISS) communications.

1.1. Problem statement

Despite significant advantages of reflectarrays such as flat structure, low profile and high gain, the major shortcoming of most of the printed reflectarrays is their narrow band operation and limited phase range. One of the main shortfalls of the conventional reflectarrays is that they have no ability of providing constant paths for the ray from feed to the aperture plane, known as progressive phase distribution. Thus there is a difficulty to convert spherical wave generated by the feed into a plane wave resulting in phase errors. Moreover, scan blindness is one of the known effects resulting due to the limited phase range. It degrades the reflectivity performance, limits the scan range and lowers the antenna efficiency. It is an undesirable feature which results in a decrease in gain at some specific frequencies causing antenna array to stop function. In this regard a complete understanding of this phenomenon and an accurate method for the prognosis of scan blindness is of great practical interest.

1.2. Objectives of the research work

This research provides a comprehensive analysis for the performance optimization of reflectarrays. The key objectives of this research work are as follow:

1. To investigate X-band (8-12GHz) reflectarray antenna by employing strategic resonant elements.
2. To design Frequency Selective Reflectarrays (FSS-RA) in order to achieve an increased static phase range for the optimization of scan blindness.
3. To demonstrate the functionality of the predicted reflectarrays with optimized performance by carrying out the scattering parameter measurements.

1.3. Scopes of the research work

This research work focuses on the study of various factors that can affect the performance of reflectarray antennas within the X-band and Ku-band frequency range. Theory of operation including the variable substrate thickness, material properties and different resonant element configurations has been investigated thoroughly. In this work the feasibility of reflectarray antenna integrating with FSS has been investigated. Moreover, the FSS reflectarray configurations have also been shown for performance improvement in both X-band and Ku-Band. Analytical investigations and numerical characterization of designed reflectarray antennas were carried out using commercially available computer models of CST Microwave Studio, Ansoft HFSS and MATLAB. Scattering parameter measurements using waveguide simulator technique have also been carried out in order to validate the theoretical analysis by comparing the simulated and measured results.

1.4. Operation principle of reflectarray antenna

Reflectarray antenna consists of a number of resonant elements printed above a grounded dielectric substrate as depicted in Figure 1.2. The array which is space fed by a primary feed horn operates in reflection mode. The feed is placed either at a symmetrical location as in center-fed reflector or at an offset location, as in off-set reflector. This feeding method eliminates the complexity and losses of the feeding network used in planar arrays. The path length from the feed to all patch elements is different. A reference plane has been defined in order to observe the behavior of reflected fields at a particular point as shown in Figure 1.2. The array elements cancel out the quadratic phase error of the incident fields emanating from the primary feed. This phase adjustment results in the planar phase distribution at the reference plane for the reflected fields.

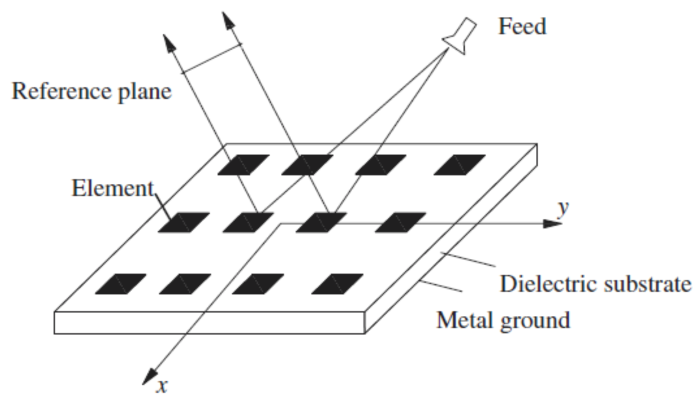
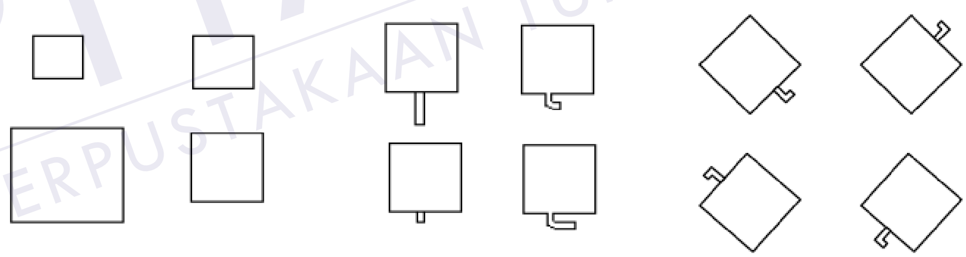


Figure 1. 2. Geometry of reflectarray antenna

Various techniques including identical patches of variable-length stub (Javor et al. 1995), square patches of variable size (Pozar & Metzler 1993) and identical planar elements of variable rotation angle (Huang & Pogorzelski 1998) have been reported for the phasing of reflectarray elements as given in Figure 1.3.



(a) (b) (c)

Figure 1. 3. (a) Variable size patches (b) Identical patches with phase delay line (c) Identical planar elements with variable angular rotation

These methods can implement in order to introduce a small change in the resonant frequency of each element which has the effect of changing the phase of the reflected field.

1.5. Advantages of reflectarray antenna

Reflectarray antenna offers the best characteristics and eliminates the poor features of parabolic reflector and phased array antennas. Several advantages of reflectarray antennas are discussed by (Huang 1995), (Bialkowski & Encinar 2007), (Encinar 2008) as below:

1. The reflectarray antenna can achieve more than 50% in terms of antenna efficiency because power divider is no longer necessary. This fact can be accepted for very large apertures as very little resistive insertion loss has been detected.

2. For the wide-angle beam scanning capabilities, similar to phased-array antenna, the reflectarray meet the specification which the main beam can tilt at a large angle, more than 50° from its broadside direction. Therefore, the complicated high-loss beam-forming network and high-cost transmit/receive amplifier modules is not necessary anymore.

3. Under certain circumstances, especially in the situations where a large aperture spacecraft antenna needed a deployment mechanism, the physical structure of the reflectarray provide a simpler easy handling folding mechanism compared to the parabolic antenna.

4. The flat structure of the reflectarray is convenient when mounting the new antenna to the existing one without adding extra weight or volume to the overall structure.

5. It can be easily fabricated with a simple and low-cost chemical etching process particularly when produced in large numbers.

6. With a large number of radiating elements being used on the reflectarray surface, the antenna is capable for elemental phase adjustment. Consequently, it can achieve very precisely contour beam shape based on the phase synthesis.

7. By locating multiple feed elements at the focal area of the antenna, it can achieve multiple-beam of the antenna radiation pattern.

8. Reflectarrays have demonstrated their capability to produce fixed focused and contoured beams, using simple photo-etching techniques. Reconfigurable-beam reflectarrays have been developed by introducing control devices on the reflecting elements; also some potential applications of reflectarrays in space have been researched such as contoured beam antennas for Direct Broadcast Satellites (DBS) and very large inflatable antennas.

1.6. Disadvantages of reflectarray antenna

Despite all the advantages mentioned above, the major shortcoming of most of the printed reflectarrays is their narrow-band operation and scan blindness (Li *et al.* 2011).

1.6.1 Bandwidth performance

The bandwidth performance of reflectarray antenna can be limited by four factors which are as follows (Huang 1995):

- Microstrip patch element
- Array element spacing
- Feed Antenna bandwidth
- Differential spatial phase delay

Microstrip patch element can generally achieve a bandwidth of only 3% because of its thin cavity. Techniques such as stacked dual patch or the patch with a thicker substrate can be employed for the bandwidth enhancement. The array element spacing factor limits the performance of reflectarray antenna depending upon the frequency. Therefore an optimum value is required in order to avoid the grating lobes and mutual coupling effects. It has been reported that element spacing effect will not be detrimental until the frequency variation is more than 30% (Huang 1995). Third factor affecting the bandwidth of reflectarray antenna is the feed antenna which can be designed to operate over a bandwidth of at least 10% while maintaining a relatively constant beam shape and input impedance. Cavity-backed dipoles and waveguide horns are the possible candidates to be used as feed antennas (Huang 1995).

The fourth important factor that limits the reflectarray bandwidth is the spatial phase delay (ΔS) which is described as the difference between the electrical paths of the two elements in the array. It can be seen from Figure 1 .4 ΔS, is the difference between the electrical paths S1 and S2. This will be maximum when the delay is calculated comparing the element in the centre of the array to the one at the edge. This ΔS can be many multiples of the wavelengths at the center operating frequency and cause phase errors (Huang 1995). Spatial phase delay needs to be minimized by obtaining a planar wavefront in order to reduce the phase errors.

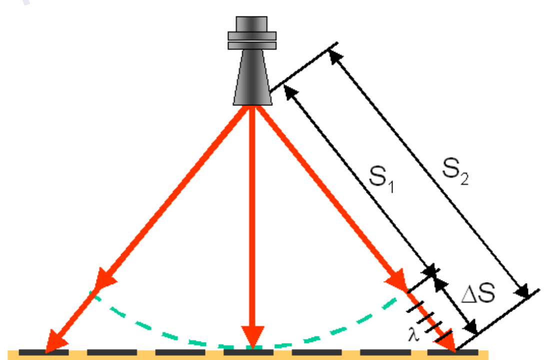


Figure 1. 4. Differential spatial phase delay of reflectarray

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