

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

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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 then 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 Janeiro, 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.

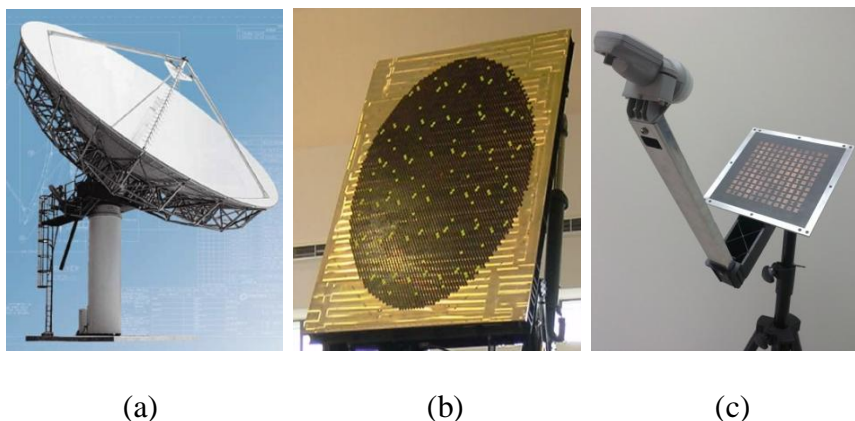


Figure 1. 1. (a) Parabolic antenna (b) Phased array antenna (c) Reflectarray Antenna

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 comprise 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.

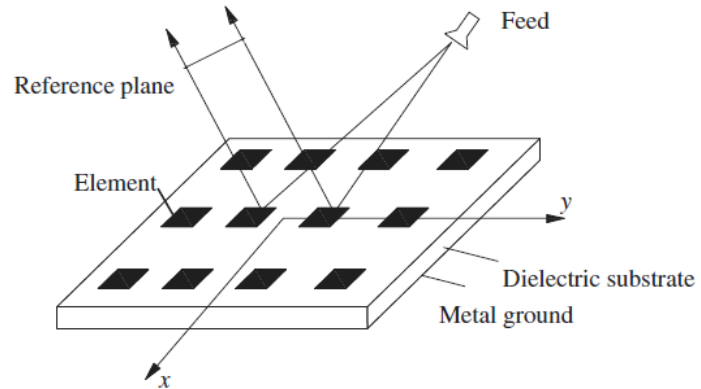


Figure 1. 2. Geometry of reflectarray antenna

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.

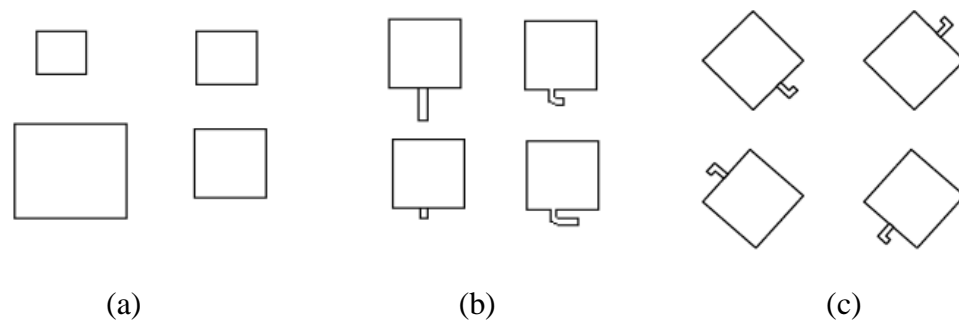


Figure 1. 3. (a) Variable size patches (b) Identical patches with phase delay line (c) Identical planar elements with variable angular rotation

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 S_1 and S_2 . 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.

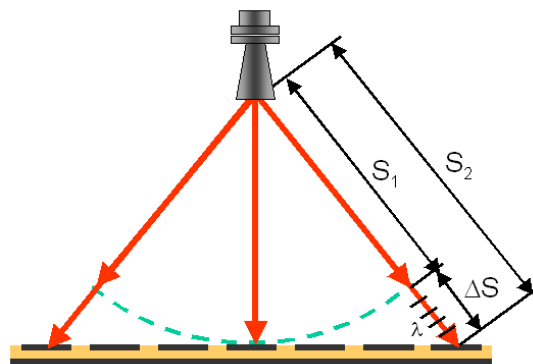


Figure 1. 4. Differential spatial phase delay of reflectarray

1.6.2 Phase error compensation considerations

The main shortfall of reflectarrays is that they have no ability of providing constant paths for the ray from feed to the aperture plane, which is inherently offered by a parabolic reflector. Thus there is a difficulty to convert spherical wave generated by the feed into a plane wave resulting in phase errors that reduce its gain as the frequency departs from the resonant frequency. For typical reflectarrays being of many wavelengths in size, the required phase shift can be many multiples of 360° . The actual value depends upon the focal length and diameter in terms of wavelength (Sayidmarie & Bialkowski 2008). In order to counter this problem more recent approaches involve the use of different resonant size elements such as concentric rings, double square rings, double cross loops or more advance shapes such as windmill, compound cross loop or double-petal loop (Misran et al. 2010), (Chaharmir et al. 2006), (Hua Li et al. 2007), (Ren et al. 2011). The use of such elements provides not only the phase range of greater than 360° .

1.6.3 Scan blindness

Scan blindness is one of the known effects which degrades the reflectivity performance, limits the scan range and lowers the antenna efficiency (Debatosh Guha 2011). It is an undesirable feature which results in a decrease in gain at some specific frequencies causing antenna array to stop function. It arises due to strong mutual couplings among reflectarray resonant elements. Inter-element spacing between the elements cause the change in scan impedance, as frequency is decreased the electrical element spacing becomes small and excessive mutual coupling effects start to degrade the array performance. As frequency is increased, the electrical element spacing becomes large, and undesirable grating lobes begin to appear. Therefore an optimum value of inter-element spacing is required to avoid grating lobes and mutual coupling effects. Another approach to reduce scan blindness is to enhance the static phase range resulting in less phase errors.

1.7. Frequency Selective Surfaces (FSSs)

A Frequency Selective Surface (FSS) is an array of periodically arranged patches or apertures on a dielectric substrate that provide different characteristics over different frequency bands regarded as filters of electromagnetic waves. Such structure shows total reflection or transmission in the resonance region. Frequency behavior of an FSS is entirely determined by the geometry of the surface in one period i.e. unit cell (Munk 2000). FSSs found many application areas such as antenna radomes, antenna polarizers, dichroic reflectors, artificial magnetic conductors and waveguide or cavity controlled coupling (Yan et al. 2014), (Bayatpur & Sarabandi 2008).

1.8. Reflectarray integration with FSS

FSS's can be used to shape the frequency or angular response of an antenna. The integration of reflectarray antennas with FSS is convenient from the structural point of view, since it results in a more compact configuration and in performance enhancement. Another advantage is that the FSS can be used as an Electronic Band Gap material, to enlarge the bandwidth of printed array antennas (Erdemli et al. 2002). FSS-Baked reflectarray structure is different from a conventional reflectarray as it implements FSS elements for the backing of reflectarray structure. FSS layer provides a good isolation between the reflectarray elements of different bands. Second there is more freedom for the selection of the element type compared to conventional methods. Experimental investigations on arrays of elements of different shapes like Jerusalem cross, circular ring and the square loop have been carried out by (Munk 2000).

Following are the main factors which affect the performance and behavior of FSS structure including selection of appropriate unit cell geometry, electrical properties of different dielectric materials, FSSs, thickness and periodicity of the array (Gianvittorio et al. 2003). The dimensions of the elements must be about half of the electromagnetic wave-length at the frequency of operation. On the other hand, one can

intuitively deduce that a smaller periodicity in a periodic array leads to less variability in the induced electric current distribution, which in turn results in a reflectivity response less sensitivity to the overall dimensions.

1.9. Progress towards FSS planar reflector antennas

An overview of performance comparison of reflectarrays with parabolic reflectors and phased array antennas along with the feasibility of employing FSS-RA is provided in Figure 1.5. As shown in Figure 1.5 the parabolic reflectors have bulky structure with very huge size. They give the highest bandwidth ($>30\%$) and high gain of (30-40dB). Use of motors is required to mechanically rotate the whole structure for beam steering purpose which is quite slow. Whereas, phased arrays have low planar profile as compared to parabolic reflectors and provide moderate bandwidth ($>25\%$) with high gain (30-40dB). Beam steering can be obtained electronically by using phase shifters. However, amplifier modules need to be integrated in order to combat the power inefficiency. On the other hand reflectarrays combine certain best features of both parabolic reflectors and phased arrays. They have low weight planar structure which gives moderate bandwidth ($<20\%$) and gain (20-30dB). In case of reflectarrays the beam steering can be done electronically without utilizing any external equipment. FSSs share almost similar properties with the reflectarrays in terms of bandwidth and gain respectively. The main difference in the characteristics is the filtration effect. FSSs can be utilized as pass-band or stop-band structures in order to either reflect or transmit the incident fields according to the requirement. Therefore, the possibility of integrating reflectarrays with FSS is of great practical interest as it can result in various combinations that can enhance the reflectivity performance of the reflectarrays. It also includes the feasibility of employing the integrated FSS-RA to achieve an increased static phase range for the possible reduction of scan blindness.

	Parabolic Reflectors	Phased Arrays	Reflect Arrays	Frequency Selective Surfaces (FSS)	Reflectarrays Integration With FSS Textured Configurations
Year of Invention	1888	1905	1987	1966	
Structure	Bulky, Paraboloid	Low Profile, Planar	Low Weight, Planar	Low Weight, Planar	
Design Complexity	High	High	Low	Low	
Bandwidth	High, > 30%	Moderate, > 25%	Low, > 20%	Low, > 20%	
Gain	High (30-40dB)	High (30-40dB)	Moderate (20-30dB)	Moderate (20-30dB)	
Beam Steering	Mechanical, Slow, < 360	Electrical, Fast, 360	Electrical, Fast, 360	Electrical, Fast, 360	
Filtering Effect	No	No	No	Possess Band-stop and Band-Pass behavior	
Interfacing	Use of Motors for Mechanical Movement	Phase Shifters and Power amplifiers for Sectorial Scanning	Different Reflectarray Elements printed on top of grounded substrate	Various Combinations of FSS Elements mounted on top of groundless substrate	This research work aims to study the feasibility of integrating Reflectarrays with Frequency Selective Surfaces (FSS) for the performance improvement (<i>Static phase range enhancement for the reduction of scan blindness</i>). Different possible techniques will be investigated thoroughly to make reflector much more efficient. Numerical analysis will also be carried out for the proposed FSS-RA structure.
Drawbacks	Heavy weight, Wind Loading, Slow Physical antenna rotation	Mutual Coupling Effects, Scan Blindness	Surface Wave Excitation, Scan Blindness, Limited Bandwidth	Mutual Coupling Effects	

Figure 1.5. Progress towards FSS reflector antennas

1.10. Flow of thesis

Chapter 1 explains the basic introduction and background on the evolution of reflectarrays from conventional parabolic reflectors and phased array antennas. It provides the operation principle of reflectarrays and its various advantages and limitations. This chapter also explains the means for the integration of reflectarrays with FSS configurations for the performance improvement.

Chapter 2 presents the detailed theoretical overview of reflectarrays and FSS along with the implementation of critical design configurations that have been used in the past by the renowned researchers and experts. It thoroughly elaborates the reflectarray analysis techniques and various performance parameters required to analyze the reflectivity of reflectarrays.

Chapter 3 provides a brief outline of the research methodology by explaining the different phases and flow that have been opted during the whole research work. It also provides a comparison of commercially available computer models of CST Microwave Studio and Ansoft HFSS that have been rigorously utilized for the analysis of infinite reflectarrays and FSS-RA.

Chapter 4 starts with the validation work of multilayer reflectarrays by using CST microwave Studio and miniaturized FSS by utilizing Ansoft HFSS. After finalizing the settings of both the computer simulation tools, infinite array model has been designed to investigate the different factors affecting the reflectarray performance. Moreover, the detailed analysis of strategic reflectarray resonant elements, FSS-RA's and stacked layer is presented respectively.

In Chapter 5, the fabrication of unit cell reflectarrays, dimension measurements using digital vernier caliper and complete measurement setup for the scattering parameter measurements is presented. It also provides the comparison of simulated and measured results by incorporating the fabrication discrepancies.

Chapter 6 concludes the thesis with the outcomes of this research work and proposes some recommendations for the future work.

CHAPTER 2

THEORETICAL BACKGROUND AND LITREATURE REVIEW

Literature study is one of the most crucial parts of the research work. Reliable sources of related research papers and books by renowned researchers have been utilized in order to thoroughly understand the basic fundamentals of the reflectarrays. A detailed background of reflectarray antennas is presented in accordance with the limitations mentioned in the Section 1.6. This chapter further elaborates various analysis techniques, number of critical configurations and advance investigations being carried out by different researchers for the performance improvement of reflectarrays.

2.1. Reflectarray cell element configurations

Reflectarrays are “quasi-periodic” structures composed of different cell elements that are mounted on top of a flat dielectric substrate as shown in Figure 2.1, where F is the feed horn antenna, h is the height of the dielectric substrate, G is the ground plane at the bottom of the substrate, O and A are the incident fields and r_{out} is the reflected field. A typical stub loaded reflectarray cell element was used at the early stages of reflectarray research as shown in the Figure 2.2. The incident field on the patch is re-radiated with a phase shift determined by the patch stub’s length, assuming the stub to be a microstrip transmission line (Javor & Chang 1994).

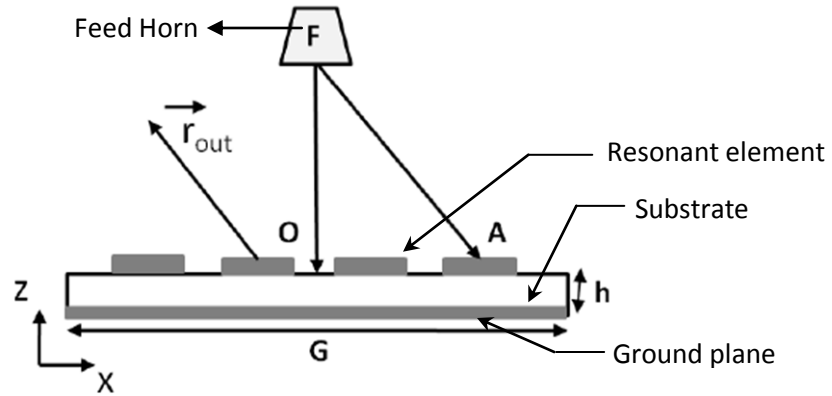


Figure 2. 1. Reflectarray configuration

As the length of patch is parallel with the polarization of incident wave, hence phase is realized by changing the length of the resonating patch while keeping the width constant. The φ_{patch} of the field reflected from a rectangular patch in the reflectarray be chosen so that the total phase delay from the feed to the fixed aperture plane in front of the reflectarray is constant for all elements. Required phase (φ_{patch}) that ought to be contributed by the patch can be calculated by using equation 2.1. The notation for the equation given below is defined in Figure 2.1.

$$K_o(FA - FO \cdot r_{out}) - \varphi_{patch} = 2\pi N \quad (2.1)$$

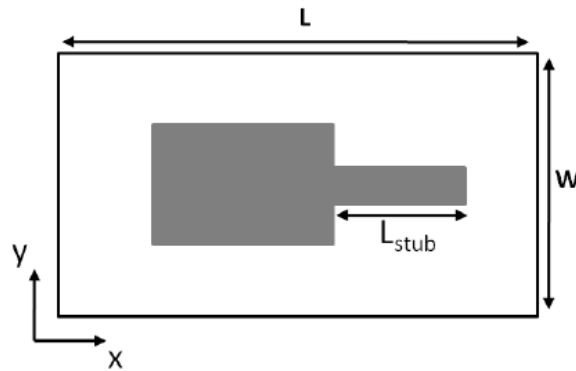


Figure 2. 2. Stub-loaded reflectarray cell element

However stub-loaded patch element demonstrated the generation of spurious radiations which can alter the required phase and degrade the cross-polarization level. Rectangular patch is the most common type of cell element that has been used widely in some previous literatures by (Pozar *et al.* 1997), (Leberer & Menzel 2005). Pozar presented microstrip patch elements of variable size and also discussed that polarization selectivity can be achieved by using rectangular patches for linear polarization, and square patches, circular patches or cross dipoles for dual/circular polarization (Pozar *et al.* 1997). Reflectarray with variable size patches have been implemented to address the issues related with stub-loaded patches as shown in Figure 2.3 (Huang & Encinar 2007).

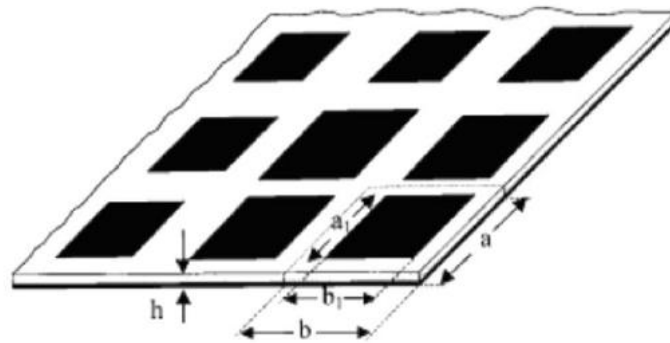


Figure 2. 3. Reflectarray with variable size patch elements (Huang & Encinar 2007)

2.2. Reflectarray analysis techniques

The reflectarray is considered as relatively complex antenna as compared to the conventional microstrip antennas. Therefore, an accurate analysis technique is required for precise prediction of the radiation features such as reflection loss, reflection phase, bandwidth, gain, efficiency and radiation patterns. The critical part in the design of reflectarray antenna is to consider the criteria for element specification. Selection of appropriate unit cell elements plays an important role in the performance of reflectarrays. Therefore, four techniques have been presented and compared for the analysis of reflectarrays.

2.2.1 Full wave analysis

A full-wave analysis technique such as Method of Moment (MoM), Finite Integral Method (FIM) and Finite Element (FEM) must be utilized to compute the losses and phase-shift produced by the reflected field of each element. Usually, in reflectarrays mutual coupling can degrade the reflectivity performance thus it cannot be neglected especially in the case of varying-sized patches. In varying-sized patch reflectarray the dimensions of some of the patches are larger than half-wavelength (0.5λ) in the dielectric and the separation between the patches is usually small (less than 0.25λ). Therefore, the effect of mutual coupling can be stronger in this case. (Huang & Encinar 2007) summarized some of the important considerations that are generally needed to be taken into account for analyzing reflectarray antenna using full-wave analysis method.

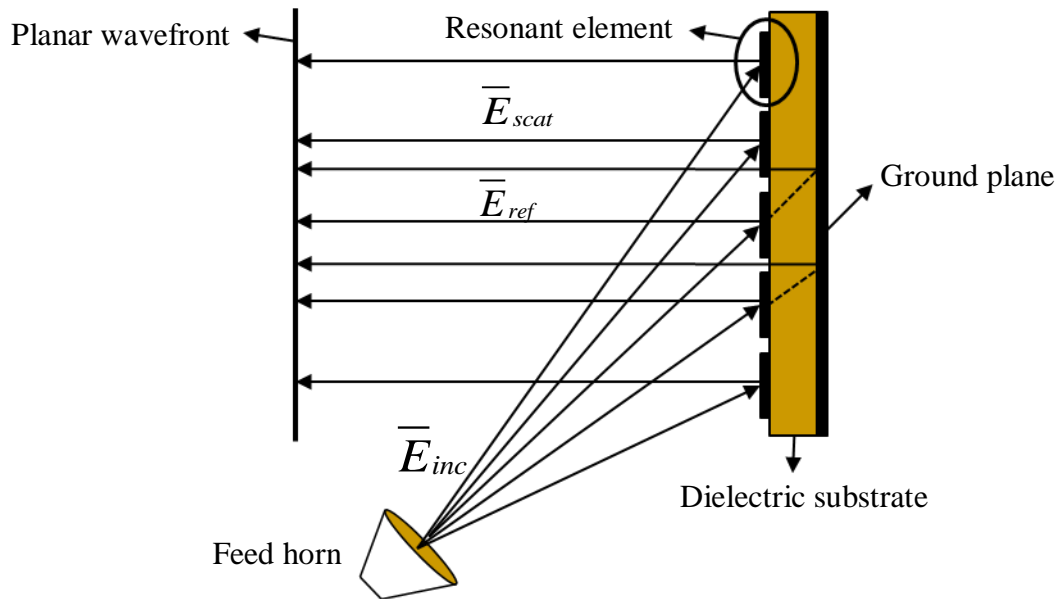


Figure 2. 4. Total electric field for a unit cell resonant element reflectarray

When the electric field impinges on the resonant elements from a feed horn, some of the incident energy is reradiated by the resonant patches and remaining is reflected by the ground plane as shown in the above Figure 2.4. Therefore the total electric field can be given by equation 2.2 as:

$$\vec{E}_{tot} = \vec{E}_{inc} + \vec{E}_{ref} + \vec{E}_{scat} \quad (2.2)$$

2.2.2 Infinite array analysis

The infinite array model can be used in case of reflectarrays having a large number of elements by applying Floquet's theorem. In this way the analysis is reduced to only one periodic cell. Moreover, this technique provides the good prediction of each individual element of the array by automatically taking into account the mutual coupling effect. Any type of phase shifter element can be analyzed by using infinite array approach. For elements with stub of different length (attached or aperture-coupled), all the radiating patches are exactly the same and only the stub length varies from one element to the next element. In this case, the infinite array approach will be very accurate, because the coupling produced by the stubs is less significant, assuming a minimum of separation between stubs and other metallic lines or patches (Encinar 2008).

For multilayer reflectarrays consisting of aperture-coupled patches or stacked patches of variable size, a modular approach based on Spectral-Domain (SMoM) has been used in a periodical environment as described and used by (Wan & Encinar 1995), (Gay-Balmaz *et al.* 2000). Spectral domain Method of Moment is very appropriate and numerically efficient for full-wave analysis of periodical structures, assuming planar arrays of patches or apertures in a single or multilayer configuration.

2.2.3 Local periodicity (LP) approach

An efficient analysis technique for the improved modeling and characterization of reflectarrays based on a periodic approach has also been used. The reflectarray is analyzed by assuming local periodicity (LP) i.e. the individual array element is embedded in an infinite array of identical elements (Encinar 2010). This approach is accurate for reflectarray with smooth patch dimensions from one cell to the next, because it takes into account all mutual coupling between the patches. However, the local periodicity approach is not applicable in case of reflectarrays where surrounding patches are of very different dimensions.

2.2.4 Extended local periodicity (ELP) approach

Reflectarrays are inherently aperiodic due to the need to compensate the spatial phase delay from the feed. Therefore an infinite approach where periodicity is applied on an extended unit cell, which includes the actual surrounding elements is proposed by (Zhou *et al.* 2011). This technique is known as the Extended Local Periodicity (ELP) approach. Each cell is increased to include the nearest eight surrounding elements in a rectangular grid. Whereas, for the non-edge elements the extended unit cell consists of nine elements with the element under consideration as the central one as shown in Figure 2.5. The surrounding elements are the actual neighboring elements in the reflectarray.

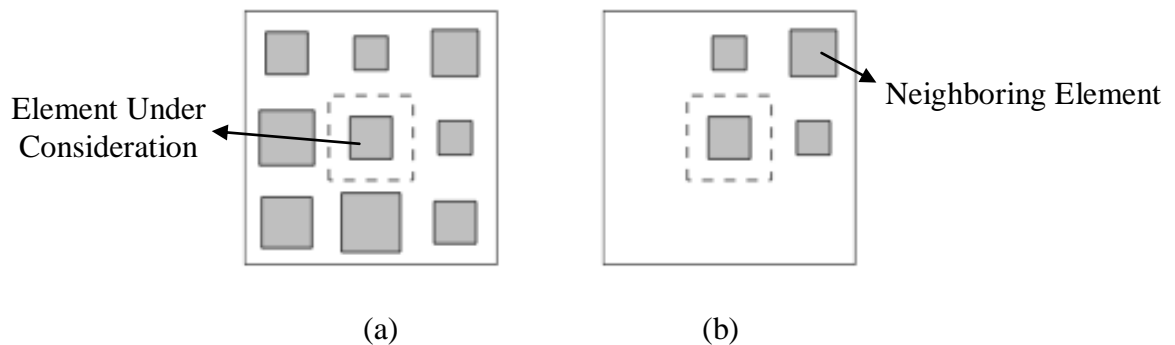


Figure 2. 5. Extended unit cells for (a) non-edge elements (b) corner elements the element under consideration is the central element indicated by the dashed lines (Zhou et al. 2011)

It can be concluded that among all the techniques mentioned above, full wave and infinite array analysis technique are commonly used. Full wave modeling of reflectarrays plays an important role by taking into account all the physical aspects of interests such as finiteness of radiating patch elements on top of the dielectric substrate, mutual coupling effect among the patch elements, estimation of surface currents and also complex multilayered structures. Whereas infinite array analysis is the best basis for the design of a very large finite array and the inter-element spacing can be kept constant for the ease of the design.

2.3. Performance parameters of reflectarray

One of the most important aspects of the reflectarray design and analysis is the accurate characterization of the resonant element. Once the unit cell has been fully characterized, the performance of reflectarray antenna can be carried out on the basis of reflection loss, 10% bandwidth, reflection phase and Figure of Merit (FoM). A reflectarray unit cell has been shown in the Figure 2.6. It can be seen that the port excitation (feed) is impinging the electric fields on the reflectarray resonant element. Some of the incident microwave energy is being absorbed in the substrate region and remaining is reflected back with a particular phase depending on the design of the resonant element. This reflected field consists of scattered energy from the resonant element and the reflected energy from the ground plane.

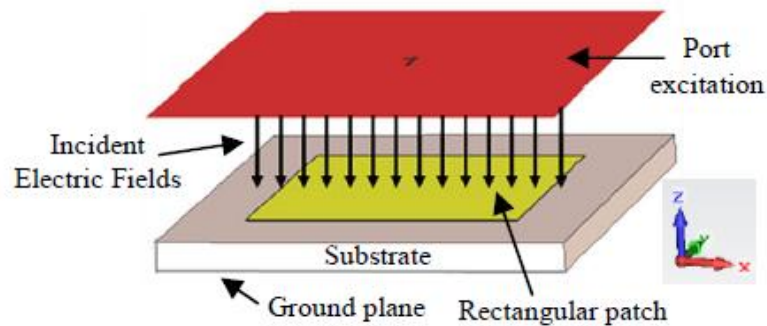


Figure 2. 6. Unit cell reflectarray resonant element (Ismail & Kiyani 2013)

2.3.1 Reflection loss and 10% bandwidth

Reflection loss is considered to be an important parameter in the analysis of loss performance of reflectarrays. Figure 2.7 shows the resonant frequency of 10GHz with the reflection loss value of 0.23dB. Reflectarray antennas require maximum reflection of the incident electric fields to undergo lowest possible reflection loss. Therefore, the ideal value of the reflection loss for a reflectarray antenna is 0dB (maximum reflection) at resonance.

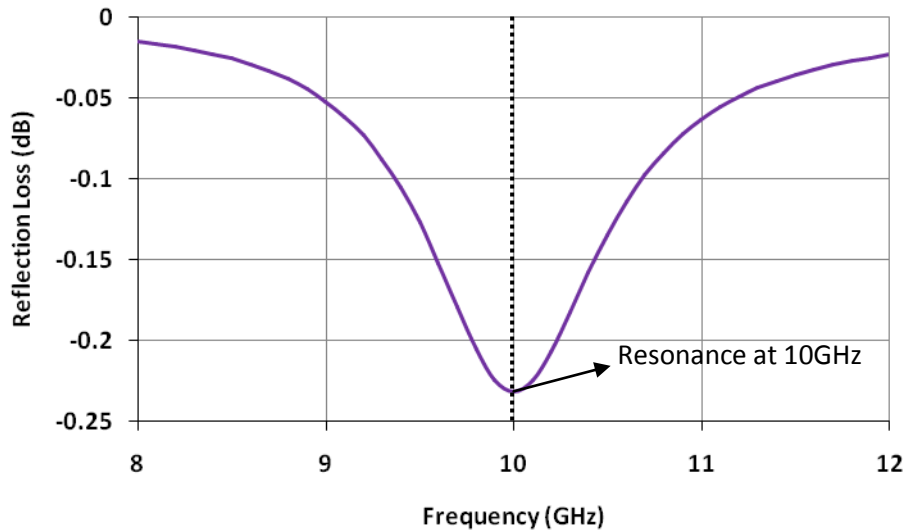


Figure 2. 7. Reflection loss curve at 10GHz

The bandwidth of the reflectarray antenna can be represented by the reflection loss curve. In order to analyze the bandwidth performance, the ratio of the bandwidth is defined by moving 10% above the maximum reflection loss value at the resonance. Reflectarrays attribute dielectric loss due to the dielectric absorption in the substrate and conductor losses due to the conductivity of the conducting material utilized for the design of reflectarray resonant elements (Pozar *et al.* 1997), (Ismail & Inam 2010). The dielectric loss occurs due to the strong electric fields in the substrate region and copper loss occurs due to high current generated on the top surface of the patch element. The incident electric field generates electric current densities (J) on the conducting surfaces of the resonating elements. These fields are maximum at the resonant frequency. This is because at resonant frequency the reflectivity of reflectarrays is at its maximum level, which is the reason of the highest loss at the resonant frequency (Kiyani & Ismail 2012). Thus the reflection loss performance of the reflectarrays depends on the material properties and thickness of the dielectric substrate. The reflection loss can be given by equation 2.3 as:

$$R_L = \alpha_d + \alpha_c \quad (2.3)$$

where, R_L is the reflection loss and α_d and α_c are the attenuation due to the dielectric substrate and conductor loss respectively which can be calculated using equations 2.4 and 2.5 as:

$$\alpha_d = \frac{\omega}{2} \sqrt{(\mu_o \epsilon_o \epsilon_r)} \tan \delta \quad (2.4)$$

$$\alpha_c = \frac{8.68}{WZ_m} \sqrt{\frac{\omega \mu_o}{2\sigma_c}} (db/cm) \quad (2.5)$$

Where ω is the angular frequency, μ_o is the permeability of free space, ϵ_o is the permittivity of free space, ϵ_r is the relative permittivity, Z_m is the input impedance and σ_c is the conductivity. Moreover, the dielectric absorption into the substrate region of reflectarray antenna is depicted in Figure 2.8. It can be seen that the port excitation is placed at a distance of $\lambda_g/4$ to incident the electric fields on the reflectarray resonant element and the dielectric substrate t , where λ_g is the guided wavelength. These incident fields are being absorbed by the substrate region resulting in multiple bounces phenomenon. Thus the intensity of dielectric absorption in a particular substrate determines the reflection loss performance. For thinner substrates, a number of rapid multiple bounces will occur due to higher dielectric absorption which contributes the higher reflection loss performance. Whereas, the number of multiple bounces can be decreased in order to obtain low reflection loss performance by increasing the substrate thickness.

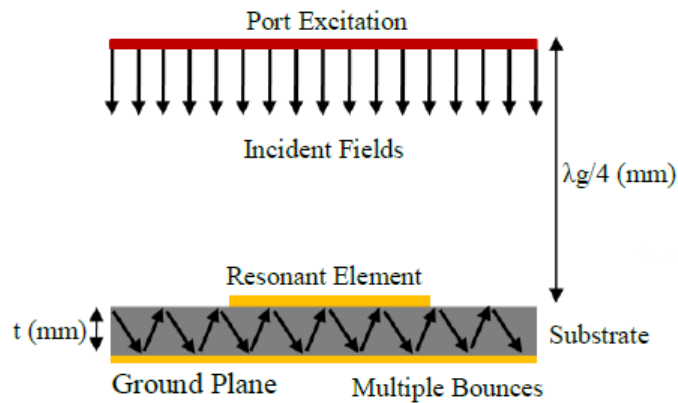


Figure 2. 8. Dielectric absorption in the substrate region of reflectarray (Ismail & Kiyani 2014)

2.3.2 Reflection phase and Figure of Merit (FoM)

Reflection phase is another important parameter that is used to analyze the reflectivity and bandwidth of reflectarrays. Moreover phase errors can also be observed using phase plots. Figure 2.9 shows the S-shaped reflection phase curve for the reflectarray antenna resonating at 10GHz. For the minimum amount of phase errors the reflection phase curve of reflectarray should cover the whole 360° phase range keeping the reflection phase to be 180° at resonance, where the maximum reflection of the signals occurs. The bandwidth performance of reflectarray antennas can also be realized by using reflection phase curves. Generally, the bandwidth is calculated based on the slope of the phase curve. Steeper the slope of reflection phase curve, lesser will be the bandwidth. Another factor that can be used to analyze the reflection phase curve is the Figure of Merit (FoM) and the static phase range, which shows the linearity of the phase curve. FoM is defined by (Ismail & Inam 2012) as the ratio of change in reflection phase to the change in the frequency and it can be expressed as:

$$FoM = \frac{\Delta\varphi}{\Delta f} (\text{°/MHz}) \quad (2.6)$$

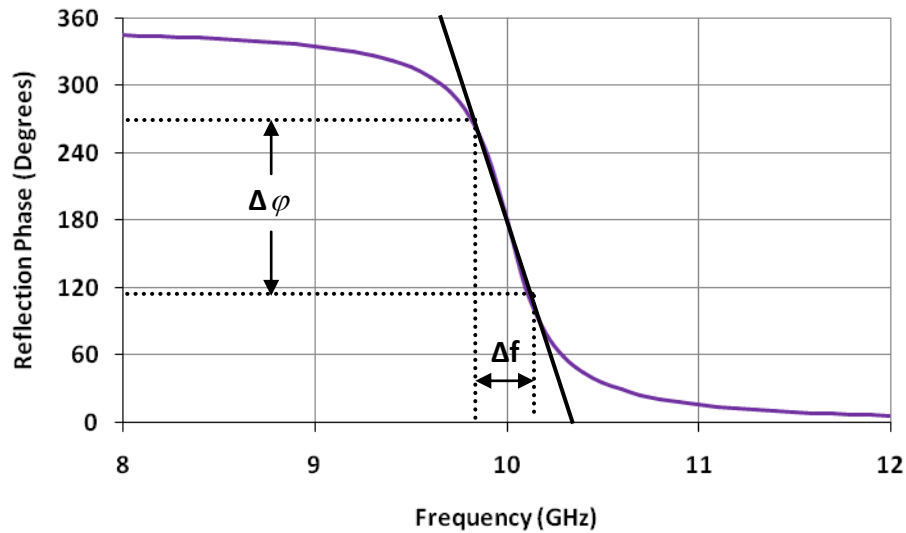


Figure 2. 9. Reflection phase curve at 10GHz

2.4. Reflectarray bandwidth limitations

The main disadvantage of reflectarray is the limitation on the available bandwidth, which has been taken into account by explaining the three main factors responsible for the reflectarray phasing errors resulting in the gain reduction. Three main factors affecting the reflectarray bandwidth are considered. First factor is the phase compensation requires dealing with the non-equal path lengths from feed to the aperture i.e. conversion of spherical wave front into planar wave front. Ray-tracing approach is used to show that the phase compensation depends upon the position of the element across the array. Second factor is related to the limited phase range of typical microstrip reflectarrays. Truncation of compensation phase is accomplished by subtracting an integer multiple of 2π from the exceeding phase values and final the third factor deals with the phase shift generated by the array elements as a function of frequency (Sayidmarie & Bialkowski 2008). Nonlinear nature of the phase response of the unit cell as a function of the size of its geometrical features restricts the bandwidth of conventional reflectarray antennas to about 4% (Poazar 2003). Thick substrate has been proposed in the past as a method to reduce the slope of the phase response which would in turn broadens the bandwidth. Unfortunately, the smaller attainable phase range in such cases has an adverse effect on gain and overall radiation efficiency (Poazar *et al.* 1997).

2.5. Multilayer reflectarray configurations

Multilayer reflectarray structures have been suggested as an alternative to overcome bandwidth limitations of the single layer reflectarrays. Such as, the element bandwidth is provided to be improved by the appropriate design of phase shifter (Carrasco *et al.* 2007). The proposed radiating element is shown in Fig. 2.10 consists of a fixed-sized rectangular patch printed on a dielectric slab, a variable length rectangular slot in a ground plane and a variable length microstrip line separated by a substrate on the other side.

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