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DYNAMIC TUNABILITY ENHANCEMENT OF REFLECTARRAY ANTENNA USING NON-HOMOGENEOUS DIELECTRIC MATERIALS

MUHAMMAD HASHIM DAHRI

A thesis submitted in
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Faculty of Electrical and Electronics Engineering
Universiti Tun Hussein Onn Malaysia

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ABSTRACT

The conventional antenna systems require the mechanical movement of beam scanning antenna to meet the demands of emerging field of communications. To overcome the flaw of the mechanical movement an electronically tunable reflectarray antenna based on non-homogeneous properties of substrate materials has been introduced. This research study provides a thorough investigation on the tunability performance of reflectarrays designed in X-band frequency range. The objective of this work is to demonstrate the functionality of an active reflectarray antenna with optimized loss performance and enhanced dynamic phase range. Different types of reflectarray resonant elements such as rectangular, dipole and ring are discussed here with different design configurations based on their ability of frequency tunability and dynamic phase range. Commercially available computer models of CST Microwave Studio and Ansoft HFSS have been used to investigate the phase agility characteristics of reflectarray resonant elements printed above various non-homogeneous materials ($0.17 \leq \Delta\varepsilon \leq 0.45$). The analytical approach has been used to develop equations for progressive phase distribution and frequency tunability of individual reflectarray element which is validated by CST simulations. The results obtained from theoretical investigations have been further validated by experimental implementations. An optimized configuration of non-homogeneous Liquid Crystal (LC) material with 0.5 mm thickness below the resonant element has been designed and tested by waveguide scattering parameter measurements. An external bias voltage of 0V to 20V has been applied across the LC substrate of individual resonant elements in order to obtain the electronic tunability. The three resonant elements namely rectangular, dipole and ring offer a measured dynamic phase range of 95°, 153° and 197° respectively at 10 GHz using the proposed design configuration. Moreover, the ring element attains a 107% higher dynamic tunability with a 56% reduction in the reflective area as compared to rectangular element.

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Journals:

(i) M. Y. Ismail and M. Hashim Dahri, "Tunability Performance of Reflectarrays Based on Non-Linear Material Properties", American Journal of Engineering and Applied Sciences, 2013, Volume 6, Issue 1, Pages 25-30.

(ii) M. Hashim Dahri and M. Y. Ismail, "Performance Analysis of Reflectarray Resonant Elements based on Dielectric Anisotropic Materials", in Procedia Engineering, Volume 53, 2013, Pages 203–207.

(iii) M. Y. Ismail and M. Hashim Dahri, "Tunable Reflectarray Resonant Elements based on Non-linear Liquid Crystals", in Journal of Advanced Materials Research, Volume 746, 2013, Pages 357-362.

(iv) M. Y. Ismail, M. Inam and M. H. Dahri, "Phase Characterization of Reconfigurable Reflectarray Antennas", in International Journal on Electrical Engineering and Informatics, Volume 5, Number 4, December 2013.

(v) M. Y. Ismail and M. Hashim Dahri, "Microwave Absorption Analysis of Passive and Active Reflectarray Resonant Elements", accepted for publication in International Journal of Electrical Engineering and Informatics.

Proceedings:

(i) M. Y. Ismail and M. Hashim Dahri, "Tunable Reflectarray Resonant Elements based on Non-linear Liquid Crystals", in International Conference on Material Science and Technology (ICMST 13), Hong Kong, 2013.

(ii) M. Y. Ismail, M. Hashim Dahri and W. N. Zaihasra, "Characterization of Material Properties for Tunable Reflectarray Antenna Design", in 2012 National Conference on Physics (PERFIK 2012), published in American Institute of Physics (AIP) Conference Proceedings 1528, pages 237-242.

(iii) M. Yusof Ismail and M. Hashim Dahri, "Analytical Investigation of Phase Agile Reflectarray Elements Based on Non-Linear Materials", in International Conference on Electrical, Computer, Electronics and Communication Engineering ICECECE 2012, Bali, Indonesia October 24-25, 2012.

(iv) M. Hashim Dahri and M. Y. Ismail, "Phase Distribution Analysis of Reflectarray Resonant Elements based on Linear and Non-linear Materials", in International Symposium on Telecommunication Technologies (ISTT2012), 26-28 November 2012 in Kuala Lumpur, Malaysia.

(v) M. Hashim Dahri and M. Y. Ismail, "Performance Analysis of Reflectarray Resonant Elements based on Dielectric Anisotropic Materials", in Malaysian Technical Universities Conference on Engineering & Technology (MUCET 2012), November 2012.

(vi) M. Y. Ismail and M. Hashim Dahri, "Microwave Absorption Analysis of Reflectarray Resonant Elements Based on Non-Homogeneous Substrate", 15th International Symposium of Antenna Technology and applied Electromagnetics (ANTEM) 25–28 June 2012 – Toulouse France.

(vii) M. Hashim Dahri and M. Yusof Ismail, "Performance Analysis of Reflectarray Antenna Elements Printed on Non-linear Dielectric Materials," Progress in Electromagnetic Research Symposium (PIERS 2012), Malaysia, March 2012.

(viii) M.Y. Ismail, M. Inam and M. Hashim Dahri, "Reconfigurable Reflectarray

Antennas: An Alternative Novel Solution for Satellite Communication Systems". Invited talk in 9th International Conference on Frontiers of Information Technology (FIT), December 2011, Islamabad, Pakistan.

(ix) M. Hashim Dahri and M.Yusof Ismail, "Phase Distribution Analysis of Reflectarrays based on Variable Material Properties," IEEE Student Conference on Research and Development (SCORED 2011), Malaysia, December 2011.

(x) M. Hashim Dahri and M. Yusof Ismail, "Tunability Performance of Reflectarray Elements based on Anisotropic Substrates," International Seminar on the Application of Science & Mathematics (ISASM 2011), November 2011.

(xi) M. Hashim Dahri and M. Yusof Ismail, "Phase Distribution Analysis of Reflectarrays Based on Isotropic and Anisotropic Substrate Materials," Malaysian Technical Universities International Conference on Engineering & Technology (MUiCET 2011), November 2011.

LIST OF AWARDS

(i) Silver Medal, "Tunable Microwave Absorber for Wireless Systems", International Technology Invention and Innovation Exhibition (ITEX 2012), May 2012, Kuala Lumpur Malaysia.

(ii) Silver Medal, "Non-Resonant Microwave Absorber for Mobile Radio Environment", Malaysia Technology Expo (MTE 2012), February 2012, Kuala Lumpur Malaysia.

(iii) Consolation Prize, "Non-Resonant Microwave Absorber for Mobile Radio Environment" Research and Innovation Compete, November 2011, UTHM.

(iv) Gold Medal, "Multi-function dynamic Steerable Flat Antenna", International Conference and Exposition on Invention of institutions of Higher Learning (PECIPTA 2011), September 2011, Kuala Lumpur, Malaysia.

CHAPTER 1

INTRODUCTION

Throughout the time, one thing that has distinguished humans from other creatures is their ability to exchange ideas and other information. That is, humans can communicate and share the information between each other. In ancient times, fire was first used as a communication tool by Chinese. Ancient Egyptians and Romans were able to use some sound making instruments to convey their messages at a distance. It is this capability that has played a big part in the development of human civilization. In fact, as our civilization continues to grow, the advancement in our communication capacity is required. The one of the first application of the new field of electricity was to extend our communication range. This was accomplished through the use of wires and telegraphy. Messages were sent by turning electrical currents on and off in accordance with a telegraph code. This system gradually evolved into the telephone system where the electrical currents are varied at audio rate. Thus the spoken word can be conveyed between two distant points. However, the telephone system still required wires, which limited its capabilities. Thus, the next development was to move towards "wireless" communications in the form of radio waves. This greatly extended the communication range, which was useful to communicate with ships at sea and remote areas of the world. Wireless or radio communications represented a significant advancement. The signals were brought to send into the free space without using any wired media with the help of a device called "Antenna".

Antenna is a device which converts electrical signals into the radio waves and make them capable to propagate into the free space (Balanis 2005). The idea of an antenna was first introduced by Heinrich Hertz in 1886, during his work to prove the existence of electromagnetic field which was first predicted by James Clerk Maxwell in 1873 (Pozar 2005). But it was Guglielmo Marconi who was able to send microwave signals across Atlantic by an antenna consisting of 50 vertical wires. Marconi's inception led scientists to enter into the modern antenna technology during World War II. Some new elements such as waveguides, horns, reflectors along with microwave sources like Klystron and Magnetron, were invented in this period (Balanis 2005). The invention of parabolic reflector starts a new era of communication for radar, remote sensing and deep space communication.

According to the geometry of optics when a beam of parallel rays is incident upon a parabola, the reflection will converge at a spot which is called focal point. In the same way if a source is placed at the focal point, the reflected rays will appear as a parallel beam (planar wavefront) in front of the reflector, as shown in Figure 1.1. This is a form of reciprocity principle which demonstrates the functionality of a parabolic antenna. Parabolic antennas are widely used as large aperture ground based antennas with narrow beamwidth and high directivity. A pyramidal or a conical horn is widely used as a feed of parabolic reflector. Most common applications of parabolic reflector are in radio astronomy, satellite communications and radar systems (Skolnik 2008). The beam scanning capability is required in satellite and radar systems for tracking the path of the satellite or target during communications. In this regard mechanical motors were widely used to rotate a parabolic reflector up to 360° (Zhang et al. 2011; Xie et al. 2010). The bulky structure of parabolic reflector with mechanically rotating parts led a new technology called phased arrays, come into existence with much faster scanning rates by electronic beam steering (Fowler 1998).

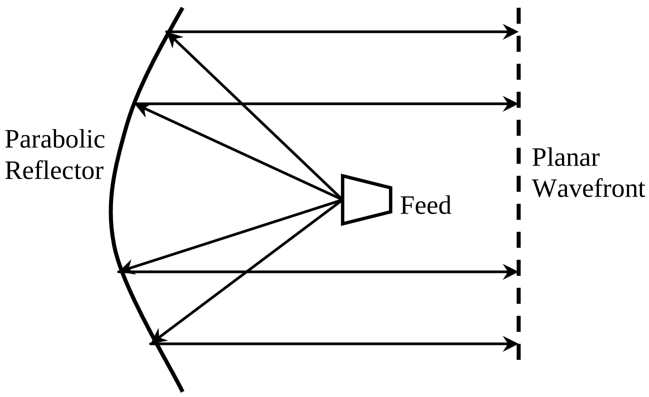


Figure 1.1: A parabolic reflector antenna with centre feed point

Phased array antennas are formed by the combination of individual radiated elements such as slots, dipoles and patches. The antenna characteristics are defined by the geometric position of the element, amplitude and phase of the excitation. Figure 1.2 shows the operation of phased arrays where RF input is applied to different phase shifter elements and amplifiers are used to boost up the outgoing signal for desired purpose. As shown in Figure 1.2, a large number of phase shifters are used to control the individual phase response of each element. Due to electronic beam steering it can move its beam to a new location within the fraction of time without using any mechanically rotating part (Skolnik 2008). Phased arrays are commonly used in radar systems to track multiple targets at a time. The beamwidth and operating frequency of phased arrays changed, depending on the direction of excitation of the signal. The direction of the excited wave depends on the phase and amplitude of the individual element used in phased array antenna. The individual elements are combined to form large aperture phased arrays for high gain applications. Apart from the advantages of phased arrays they are very expensive with complex design configurations. Furthermore a very large system is required to electronically control the amplitude and phase of all individual elements.

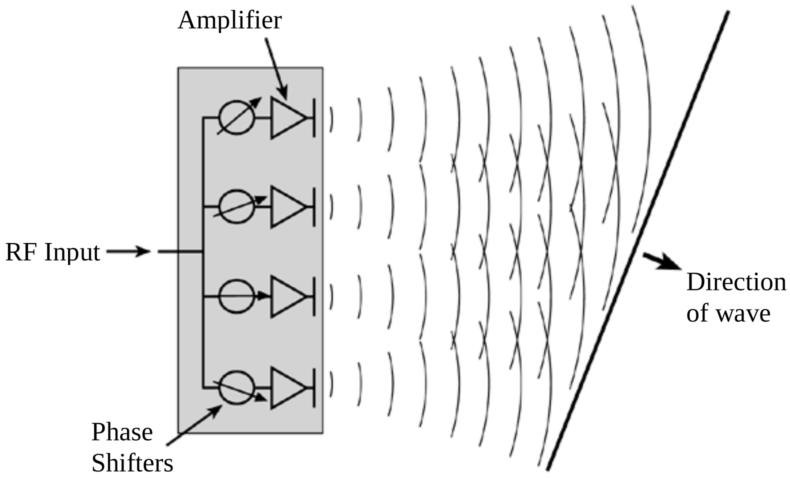


Figure 1.2: Operation of phased arrays

At the high microwave frequencies the parabolic reflector is also difficult to design due to its curved surface and large size. Therefore a planar reflectarray antenna was introduced by (Berry et al. 1963) to overcome the flaws of conventionally used antenna systems. Reflectarray antenna has been acknowledged as a potential alternative to the traditionally used high gain antennas (parabolic reflectors and phased arrays). The printed reflectarray combines some of the best features of microstrip array antenna and the traditional parabolic reflector antenna. It can be designed to have a very high gain with relatively good efficiency, as well as to have its main beam tilted/scanned to large angles from its broadside direction (Huang et al. 2007). Such an antenna would be an attractive option for mobile communications, satellite communication and terrestrial systems (Huang & Encinar 2007).

This chapter provides the introduction about the research work that has been carried out throughout this thesis. Problem statement is defined based on some conventionally used systems to justify the purpose of this research work. Then the objectives of this work are discussed to solve the stated problems. Scope of the research provides a thoroughly described way of the work and steps that have been taken into account to achieve the stated objectives. Flow of this thesis report is stated at the end of the chapter which includes the brief introduction about each chapter of the thesis.

1.1 Problem statement

The limited bandwidth and high loss performance of reflectarray antenna are considered as its main performance limitations. The narrow bandwidth is generally due to the differential spatial phase delays, which are occurred due to the limited phase range of individual reflectarray element. The high loss performance of reflectarray antenna is associated with dissipation of incident microwave signals in the dielectric substrate region. Moreover, the conventional parabolic reflectors require mechanical movement of entire antenna structure for the beam scanning applications. In radar and satellite communication systems, the electric motors are used to turn the parabolic reflectors up to 360° of rotation for the detection of desired moving objects. Furthermore in phased array antennas the phase of individual element is electronically controlled by a number of complex phase shifter devices to produce a directive beam pattern. Therefore an electronically controlled reflectarray antenna based on non-homogeneous dielectric materials is proposed here with optimized loss performance to overcome the flaws of conventionally used antenna systems. The dielectric non-linear properties of non-homogeneous materials are used to control the phase and frequency of reflectarray antenna electronically. The effect of non-linear material properties on frequency tunability and dynamic phase range of reflectarray antenna is investigated in X-band frequency range. Different design configurations for various reflectarray antenna elements are analyzed by numerical equations and computer simulations. Formulated and simulated results are then experimentally validated by scattering parameter measurements based on waveguide simulator technique.

1.2 Objectives of the study

This research work focuses on the tunability performance of reflectarray antenna based on non-linear material properties. The main objectives of this research work are defined here based on the problems that have been stated in the previous section. The objectives are;

(i) To investigate the feasibility of realizing an active reconfigurable reflectarray antenna system electronically with enhanced dynamic tunability.

(ii) To construct an analytical formulation for dynamic phase distribution of tunable reflectarray antenna.

(iii) To demonstrate the functionality of an active reflectarray antenna for beam scanning application.

1.3 Scopes of the study

The performance investigation of active reflectarray antenna elements printed on non-homogeneous dielectric materials is thoroughly discussed in this research work. The main scopes of this work are as follows;

(i) The non-homogeneous dielectric materials and their properties are utilized for the designing of an electronically tunable reflectarray antenna.

(ii) Different reflectarray resonant elements such as rectangular, dipole and ring printed on non-homogeneous substrates are designed to investigate their performance for different possible applications.

(iii) Computer Simulation Technology (CST) Microwave Studio^{2012} and Ansoft HFSS^{13} software are used to model infinite reflectarray unit cells.

(iv) The analytical technique has been introduced to generate a formulation for progressive phase distribution and frequency tunability of individual reflectarray element based on non-linear material properties.

(v) At the final stage reflectarray antenna elements are fabricated and scattering parameters measurements are carried out by Vector Network Analyzer (VNA) using waveguide simulator technique.

1.4 Introduction to reflectarray antenna

Reflectarray antenna consists of printed reflecting elements on a grounded flat dielectric surface, illuminated by a feed antenna (Huang & Encinar 2007). The overall operation of the reflectarray antenna is similar to the curved surface parabolic reflector. Figure 1.3 compares the function of reflectarray antenna with parabolic reflector, where offset feed horns are used to illuminate the antenna systems. As shown in Figure 1.3, the individual elements of the array are designed to scatter the incident field with a proper phase required to form a planar phase surface in front of the aperture (Pozar et al. 1997).

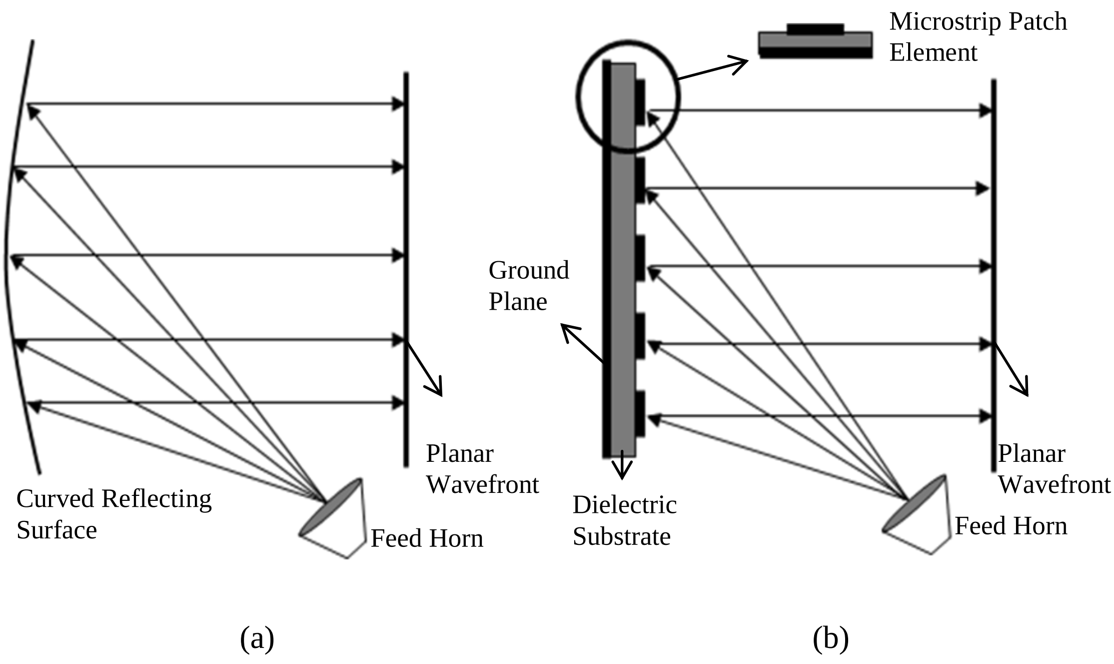


Figure 1.3: Operation of (a) parabolic reflector (b) reflectarray antenna

The phases of elements are associated with different path lengths covered by the incident signal. One of the key features of microstrip reflectarray implementation is how the individual elements are made to scatter with the desired phases. There are two most commonly used techniques to achieve the planar wave front. One is to use identical patches with variable phase delay lines to compensate for the phase delays over the different paths of incident signal (Huang & Encinar 2007). Another technique is to use variable size patches to have different scattering impedances and different phases to compensate the different path delays (Pozar & Metzler 1993). A detailed discussion based on the selection of patch elements for optimized reflectarray antenna performance can be found in Chapter 2.

Since the microstrip reflectarray does not require any power divider therefore its efficiency in a large array system is much higher than a conventional array with the same aperture size. One possible drawback of reflectarray is that, in addition to the reradiated fields from the patches, there will also be scattered field from the patches, reflected field from the ground plane (especially away from the resonant frequency of the patch), scattered field from the phase delay lines, and diffracted field from the edge of the reflectarray. These backscattered fields may increase the side lobe level and possibly distort the main beam shape of antenna. But this backscattered energy is generally small relative to the desired main beam. In other words, the microstrip reflectarray can be an efficient antenna system if it has a large number of array elements (500 or more) (Huang 1995).

The patches of reflectarray that are located in front of main feed have both incident and reflected waves in the same direction. Whereas the patches that are located close to the edges of reflectarray have reflected wave directed away from the main beam. Therefore the spacing between the patches or elements, which is denoted by *d*, should be defined according to the position of elements on reflectarray surface (Huang & Encinar 2007) as given in Equation (1.1) and (1.2).

$$d > 0.9\lambda \qquad \text{(for center element)} \qquad (1.1)$$

$$d \leq \frac{\lambda}{1+\sin\theta} \qquad \text{(for edge element)} \qquad (1.2)$$

Where, d is element spacing

λ is free space wavelength

θ is angle of feed or main beam tilt angle

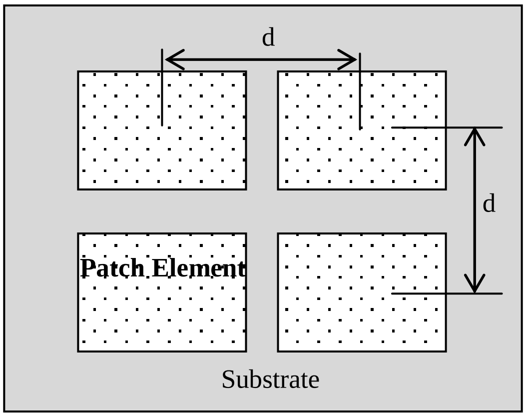


Figure 1.4: A 2 X 2 rectangular patch reflectarray antenna with proper element spacing

It has been shown from Equation (1.1) and (1.2) that the spacing between the adjacent elements of reflectarray antenna depends on the position of the element and free space wavelength. Figure 1.4 depicts a four patch rectangular element reflectarray antenna, where *d* shows the proper element spacing measured from the center of the adjacent elements to avoid the mutual coupling effects. The mutual coupling can cause a distorted radiation from reflectarray antenna which leads to form grating lobes in radiation pattern of the antenna (Huang & Encinar 2007).

1.4.1 Advantages and disadvantages of reflectarrays

Reflectarray antennas are used with low surface profile, small in size and low manufacturing cost. Since the antenna's reflecting surface is a thin, flat structure, it can be mounted onto the surface of any planar structure. The flat panel folding technique has been commonly used in the deployment of solar panels and has shown excellent reliability. The flat structure of reflectarray antenna makes it more reliable and more flexible than parabolic reflectors. The antenna also can be cost effective due to low-cost etching process, especially when it is produced in large quantities. The main beam of the microstrip reflectarray can be designed to point at a large fixed angle (up to 60°) from the broadside direction, while a parabolic reflector can only have a very limited beam tilt. The reflectarray can achieve as good efficiency as a large array antenna system because no power divider mechanism is needed for the excitation of signal from different patch elements (Huang & Encinar 2007; Huang 1995). Table 1.1 summarizes the main pros and cons of reflectarray antenna.

Table 1.1: Advantages and disadvantages of reflectarray antenna

Advantages	Disadvantages
Easily accumulate with the surface of structures	High loss performance
Flexible design	Limited bandwidth performance
Lower cost	Narrow phase range
Beam steering	Mutual coupling of adjacent elements
Integratable with solar panels	Differential spatial phase delays
Large array with high efficiency	

Apart from these advantages there are some disadvantages of reflectarrays which have been mentioned in Table 1.1. The high loss performance of reflectarray antenna is due to the absorption of incident energy into the dielectric substrate. Additionally, the conducting material which is used for patch elements is also attributed for generating conductor losses in the reflectarray antenna. A printed microstrip reflectarray can only achieve a bandwidth of about 5% due to its relatively thin dielectric substrate. To achieve wider bandwidths, techniques such as using different thick substrates, stacking multiple patches and using sequentially rotated sub-array elements are employed. The limited phase range of reflectarray antenna causes to generate phase errors in the performance of antenna. The phase errors are defined as, the difference between the ideal (360°) and the actual phase range of reflectarray antenna. At higher frequencies, the element spacing becomes large relative to the frequency of operation, which leads to generate side lobes in the main antenna pattern. The proper inter element spacing is required for good pattern generation, as previously has been discussed in section 1.4. The differential special phase delays are also a main reason behind the limited frequency bandwidth of reflectarray antenna. This is due to the different path lengths of incident signal coming from feed horn antenna, which causes a non-planar wavefront and full energy cannot be reflected back to the desired direction (Huang & Encinar 2007). More details on the techniques to overcome the stated drawbacks of reflectarray antenna are discussed in Chapter 2.

1.4.2 Potential applications of reflectarray antenna

The recent developments in reflectarray antenna technology in past few decades make it prominent for present and future applications. Reflectarray antenna has been evolved as a possible alternative for some conventionally used antenna systems such as parabolic reflectors and phased arrays. The reconfigurable nature of reflectarray antenna makes it flexible to be used for the wide range of frequencies (Huang & Encinar 2007). Figure 1.5 depicts some common fields of applications for reflectarray antenna. It has been shown in Figure 1.5 that, reflectarray antennas covers the major areas of communication technology. The sector antennas used in mobile communication systems can be replaced by a flat surface reflectarray antenna. The high gain reflectarray antennas can also be used to communicate between BTS (Base Transceiver Station) and MSC (Mobile Switching Centre) in a very progressive manner. Direct broadcast satellite (DBS) services or home TV services can utilize a reflectarray antenna as an alternative of parabolic dish antenna, planar structure and small size of reflectarray antenna makes it more eminent for home use.

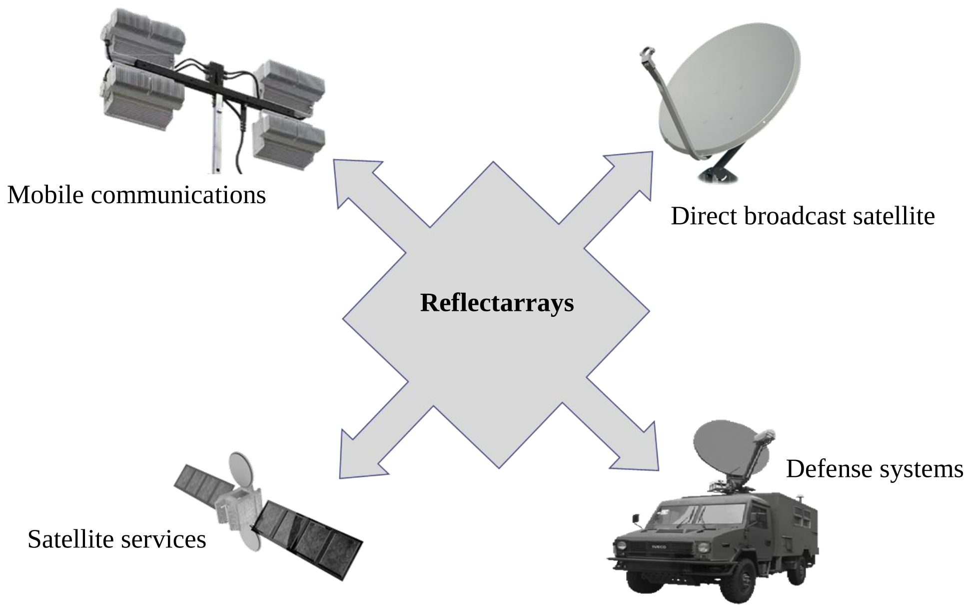


Figure 1.5: Applications of reflectarrays

The radar technology can count as a base-line for the military and defense purposes. The military vehicles are also using antenna technology to communicate from the remote areas. Reflectarray antennas can be used in radar communication systems due to their scannable beam characteristic. The small size and planar structure of reflectarray antenna is useful to mount it over the roof of military vehicles. The satellite services with deep space communications play an important role in remote sensing technology. The planar solar panel of satellite system is a very good platform to hold a reflectarray antenna instead of an additional bulky structure antenna system. The enhanced deep space communication can only be possible with reduced size spacecraft systems, which can easily go beyond the limits of human reach. An efficient and smaller size reflectarray antenna can make it possible for the betterment of mankind and extends the boundaries of human space-research (Huang 1995).

1.5 Thesis statement

Chapter 1 contains the information about the conventionally used antenna systems and discusses the major problems in their operation. The objectives and scopes of the research work are explained here in conjunction with the introduction of reflectarray antennas.

The detailed theoretical studies regarding this research work are summarized in Chapter 2. The design analysis of reflectarray antenna with its dielectric material properties is thoroughly explained. The non-homogeneous materials and their variable dielectric properties are discussed based on their molecular composition. Furthermore some basic applications of non-homogeneous materials have also been discussed in this chapter.

Chapter 3 provides the materials and methods for the design and implementation of tunable reflectarray antenna. Three main stages based on simulations, numerical analyses and measurements have been mentioned here.

In Chapter 4, the detailed investigation of reconfigurable reflectarray antenna has been presented based on the reflection loss and reflection phase analysis. Some possible design configurations for tunable reflectarray antenna have been proposed and designed by commercially available simulation tools. CST Microwave studio and Ansoft HFSS are widely used here for the study of different factors affecting the tunability performance of reflectarrays. Finally numerical analysis has been provided based on the prediction of various reflectarray parameter by using non-linear material properties.

The design and fabrication process of encapsulated LC based reflectarray unit cell elements is thoroughly explained in Chapter 5. The waveguide simulator measurements of passive and active reflectarray unit cell elements by vector network analyzer are provided. The detailed analysis and comparison between measured and simulated results is also provided in terms of dynamic phase range and frequency tunability.

Chapter 6 summarizes and concludes the overall findings and achievements of the research work. Finally some recommendations for expected future work are provided.

CHAPTER 2

THEORETICAL OVERVIEW

This chapter contains detailed literature studies regarding reflectarray antenna design. The historical background of reflectarray antenna is thoroughly discussed and some previous design techniques to improve the performance of reflectarray antenna are provided. Moreover, the design of a unit cell reflectarray element in an infinite array approach has been discussed in this chapter. Furthermore, the dielectric properties of substrate materials, containing homogeneous and non-homogeneous materials have been analyzed. Factors affecting on the dielectric non-linear properties of substrate materials have been thoroughly discussed. Finally some applications of non-homogeneous materials in tunable microwave devices are explained.

2.1 History and background of reflectarray antenna

Since the time of reflectarray introduction by (Berry et al. 1963), it has passed through different evolving periods. It started from the bulky size, large arrays of open-ended waveguide reflectors for low microwave frequencies, and now it has become a low profile antenna with printed microstrip patches, to operate until millimeter wavelength. Reflectarrays are manufactured on a flat substrate by printed circuit technology and attain the capability of beam steering (Huang & Encinar 2007). In early 90s some new tactics in reflectarray antenna design have been introduced to compensate the inconsistent phasing behavior of printed patches. This inconsistent phasing behavior of patches can cause different additional time delays in reflected signals, which considerably limits the bandwidth performance of reflectarrays. To solve this problem, the microstrip patches were proposed, either with different electrical lengths or with open-ended microstrip stubs (Huang 1991;

Huang & Encinar 2007). However the described techniques exhibit the cross-polarization problem due to the lack of leakage radiation which limits the radiation efficiency of reflectarray antenna. Recent studies in reflectarray antenna design provided some new tactics to improve its loss and bandwidth performance. These strategies have been discussed later in this chapter.

A microwave system can be analyzed by its frequency range of operation over which it is considered to provide acceptable performance characteristics. The frequency ranges are further divided into different frequency bands of operation. In recent years the applications of reflectarray antenna in X, K, Ka and Ku bands have been noticed (Huang et al. 2007; Encinar & Barba 2008). Table 2.1 summarizes the main possible applications of each frequency band that can be used for reflectarray antenna operation.

Table 2.1: Different frequency bands and their applications (Skolnik 2008; Rappaport 2003)

Name of Frequency band	Range of Frequencies	Applications
S-band	2-4 GHz	Mobile Satellite Services (MSS), NASA and deep space research
C-band	4-8 GHz	Fixed Satellite Services (FSS), fixed service terrestrial microwave
X-band	8-12.4 GHz	FSS, military communications, Fixed service terrestrial microwave, earth exploration and meteorological satellites
Ku-band	12.4-18 GHz	FSS, Broadcast Satellite Service (BSS), Fixed service terrestrial microwave
K-band	18-26.5 GHz	FSS, BSS, Fixed service terrestrial microwave
Ka-band	26.5-31 GHz	FSS, Fixed service terrestrial microwave, Local multi-channel distribution service (LMDS)

It has been analyzed from Table 2.1 that, most of the applications of different frequency bands belong to satellite and terrestrial systems. Moreover the mobile communication systems are the most important feature of S-band frequency range. The applications of reflectarray antenna that have been described in section 1.4.2, can completely tally with those which are mentioned in Table 2.1 for different frequency bands.

2.2 Design and analysis of microstrip reflectarray antenna

The basic step of reflectarray antenna is to design and characterize the single microstrip element in an infinite array approach. Where a single element can be tested and analyzed as a part of entire reflectarray antenna. The commonly used method is H-wall waveguide where top and bottom surface of waveguide are electric conducting walls, while the right and left sides are magnetic walls.

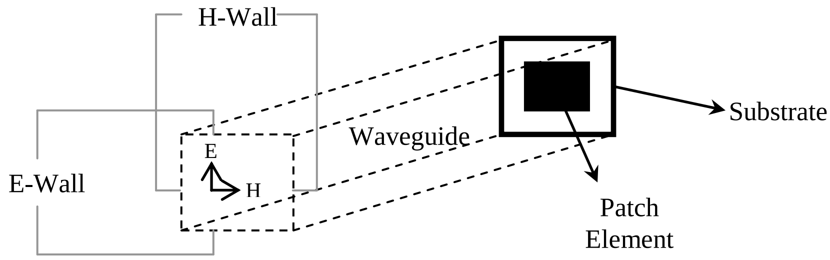


Figure 2.1: A reflectarray element placed in an infinite array approach

In result of this step a vertically polarized wave is used to resonate the element which is placed at the end of the waveguide (Huang & Encinar 2007) as shown in the Figure 2.1. This technique is used to analyze a single reflectarray element in terms of reflection loss and reflection phase performance. Moreover the phase versus element change curve based on the element size can be derived which is essential in the design of microstrip reflectarray (Huang & Encinar 2007; Balanis 2005).

In order to fully analyze the performance of reflectarray antenna there are different methods which have been used by researchers, such as Finite Integral Method (FIM), Finite Element Method (FEM) and Method of Moment (MoM) (Huang & Encinar 2007). The single patch element can be analyzed as a reflective element printed on a grounded dielectric substrate. The patch element can be treated as a single isolated element or in an array environment. The overall radiated field from the reflectarray element is the sum of the two main components; the field scattered by the conductive patch element (E_s) and the field reflected (E_r) by the ground plane (Huang 1991), as shown in Figure 2.2. It can be observed from Figure 2.2 that, the total electric field of the system is the sum of E_i, E_s and E_r components.

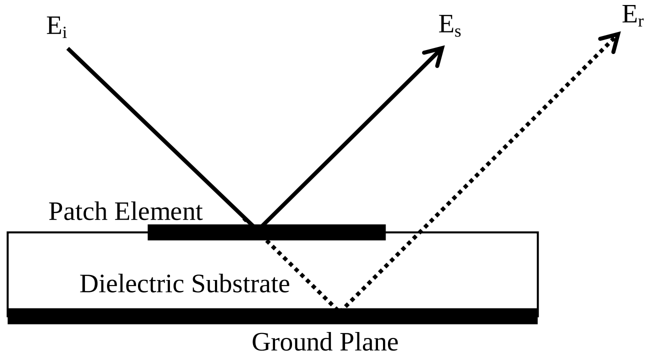


Figure 2.2: Incident and reflected E-fields of a reflectarray element

The full wave analysis of reflectarray antenna is based on the complete investigation of the total E-field present in the system. The full wave analysis can be performed by either MoM, FIM or FEM techniques (Huang & Encinar 2007; Inam & Ismail 2011b). MoM technique is fully based on the spectral domain analysis of single or multi-layered periodic structures. On the other hand FIM and FEM techniques are used for a single reflectarray element with proper boundary conditions suitable for an infinite array analysis. Usually zero thickness is used for patch and ground conductors in MoM technique, whereas FIM and FEM allow the real thicknesses for the analysis. The analysis of reflectarray antenna by Maxwell's equations in integral form is done by FIM technique, where E-field based integral equations are solved in either time or frequency domain. FEM is used to solve the partial differential equations by full wave analysis of total E-fields of single reflectarray element in an infinite array approach. MoM is a fast technique especially when it is used for the periodicity or mutual coupling effects between the adjacent elements of reflectarray antenna. On the other hand FIM and FEM have slower CPU timings for the calculations as compared to MoM technique (Huang & Encinar 2007; Pozar 2005).

2.2.1 Selection of the substrate material

Different types of dielectric substrates are used to design a reflectarray antenna, their dielectric constants are usually in the range of $2.2 \leq \varepsilon \leq 12$ (Balanis 2005). The thickness of substrate also plays an important role for reflectarray analysis. A thinner substrate causes multiple bounces of incident energy which affects the surface wave excitation. Therefore more energy is dissipated the substrate region and reflection loss is increased (Inam & Ismail 2011a). The most desirable for good antenna performance are thicker substrates with low dielectric constant values because they provide better efficiency and wide bandwidth, but at the cost of larger element size (Balanis 2005). The effect of material properties on the performance of reflectarray antenna is described in details, later in this chapter.

2.2.2 Selection of the patch element

The radiating patch elements are printed by photoetching process on the surface of dielectric substrate. Different types of radiating patch element configurations like rectangular, square, circular, dipole, elliptical, triangular, ring etc can be used based on their performance characteristics (Balanis 2005). Some reflectarray patch elements are shown in Figure 2.3.

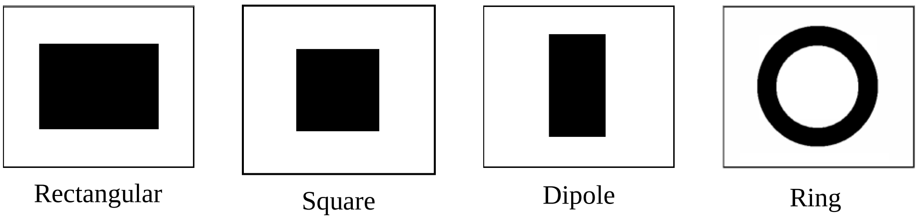


Figure 2.3: Different types of reflectarray patch elements

Rectangular and square elements occupy large bandwidth but on the account of larger element size and narrower phase range. Whereas elements having smaller sizes like dipole and ring occupy wider phase ranges but with the drawback of high reflection losses (Balanis 2005; Ismail et al. 2009). Selection of the patch element can affect the performance of reflectarray antenna, a detailed investigation is provided later in this chapter.

2.2.3 Reflection loss and bandwidth of reflectarray antenna

The amount of energy that is not fully reflected back from reflectarray antenna during the reflection process is called reflection loss. In addition to losses in directivity due to spillover, amplitude taper, and phase errors, reflectarrays also suffer potentially significant loss due to dielectric loss, copper loss, and surface wave excitation. Dielectric loss is strongly dependent on the thickness and loss tangent of the reflectarray substrate (Balanis 2005). The maximum loss occurs at the resonant frequency because the surface current density on the patch element and concentration of electric fields inside the substrate are maximum at the point of resonance (Rajagopalan & Rahmat-Samii 2010). The maximum surface current density occurs at the center of the patch element whereas the maximum electric field occurs at the edges of the patch element inside the dielectric substrate (Ismail & Inam 2010b; Rajagopalan & Rahmat-Samii 2008b) as shown in Figure 2.4. It has been shown in Figure 2.4 (a) that current follows the path along the length of the patch element therefore it is maximum at the center of the patch element and minimum around the edges of the patch element.

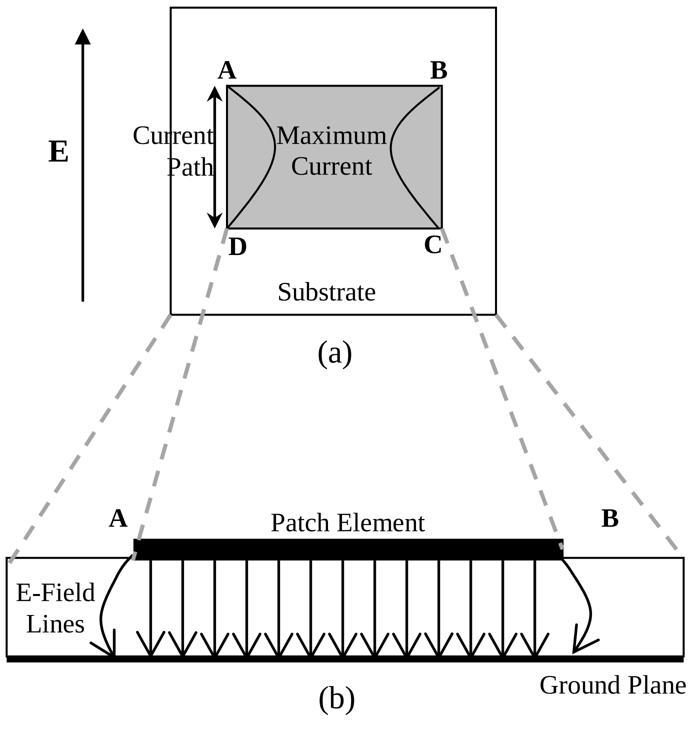


Figure 2.4: (a) Surface current on the patch element (b) E-fields inside the substrate material

Surface current mainly depends on the conductivity of the electric conductor used for patch and ground plane whereas electric field corresponds to the dielectric constant of the substrate material as shown in Equation (2.1) and (2.2) respectively (Pozar 2005).

$$\overline{J} = \sigma\overline{E} \tag{2.1}$$

$$\overline{D} = \varepsilon\overline{E} \tag{2.2}$$

Where

σ is conductivity of patch element

ε is dielectric constant of substrate material

J is surface current density

D is electric flux density

The surface current density (*J*) of patch element is responsible for the high conductive dissipation of the incident energy. On the other hand, (*D*) is the flux density and its value depends on the number of electric field lines inside the dielectric substrate, which corresponds to the dielectric dissipation of the incident energy. The reflection loss of the patch element can be categorized into conductor loss and dielectric loss (Ismail & Inam 2010a). The dielectric loss occurs due to the strong E-fields in the substrate region as shown in Figure 2.4 (b), whereas the conductor loss occurs due to the high currents on the top surface of the patch at resonance as shown in Figure 2.4 (a). These losses also depend on the thickness of the substrate material and decrease by increasing the substrate thickness. The ratio of conductor loss to dielectric loss is not same for different substrate thicknesses (Ismail & Inam 2010a; Rajagopalan & Rahmat-Samii 2008a). The conductor and dielectric losses (Pozar 2005; Ismail et al. 2010) of reflectarray antenna are given, as shown in Equation (2.3) and (2.4) respectively.

$$\alpha_c = \frac{8.68}{WZ_m}\sqrt{\frac{\omega\mu_0}{2\sigma_c}}\,(dB/cm) \quad \text{(Conductor Loss)} \tag{2.3}$$

$$\alpha_d = \frac{\omega}{2}\sqrt{(\mu_0\varepsilon_0\varepsilon_r)}\,\tan\delta\,(dB/cm) \quad \text{(Dielectric Loss)} \tag{2.4}$$

$$R.L = \alpha_c + \alpha_d \qquad \text{(Total Reflection Loss)} \quad (2.5)$$

Where

W is the width of patch element

Z_m is the characteristic impedance

σ_c is conductivity of patch element

$tan\delta$ is Dissipation factor

and $\omega=2\pi f_r$

Equation (2.5) provides the total reflection loss of reflectarray antenna, which is the sum of the dissipated energies, occurred due to conductor and dielectric losses.

Bandwidth is defined as "the range of frequencies within which the performance of the antenna with respect to some characteristics conforms to a specified standard" (Balanis 2005). The bandwidth of a reflectarray antenna can be evaluated by its reflection loss curve and it can be defined in terms of 10% or 20% bandwidth (Ismail & Inam 2010a). The 20% bandwidth is calculated by moving 20% above the maximum reflection loss value and 10% bandwidth is calculated by moving 10% above the maximum reflection loss value, which is at the resonance frequency. Figure 2.5 shows the total reflection loss of a reflectarray element along with the 10% and 20% bandwidth performance where f_r is the resonant frequency of the reflectarray.

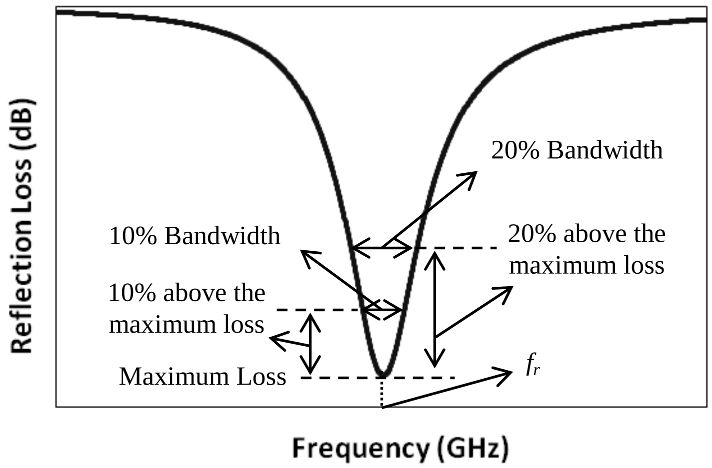


Figure 2.5: Reflection loss and bandwidth of reflectarray antenna

It has been shown in Figure 2.5 that, 20% bandwidth is wider than the 10% bandwidth of reflectarray antenna because it lies at a point where loss curve has a wide frequency range. The 20% and 10% bandwidths can be used for the characterization of performance of unit cell reflectarray elements.

2.2.4 Reflection phase and FoM

Another important parameter that can be used to analyze the reflectivity of reflectarrays is its reflection phase performance. Reflectarray patch element has an S shaped phase curve. The slope of the reflection phase versus reflection frequency curve is a measure of the bandwidth of reflectarrays (Inam & Ismail 2011a). As the slope of reflection phase increases the phase becomes steeper, as a results a rapid change in reflection phase occur at the resonant frequency, hence the bandwidth performance of reflectarray decreases (Pozar et al. 1995). For comparison of bandwidth performances in terms of reflection phase curves a Figure of Merit (FoM) has been defined as the ratio of the change in reflection phase ($\Delta\varphi$) to the change in the frequency (Δf) and can be expressed as given in Equation 2.6.

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

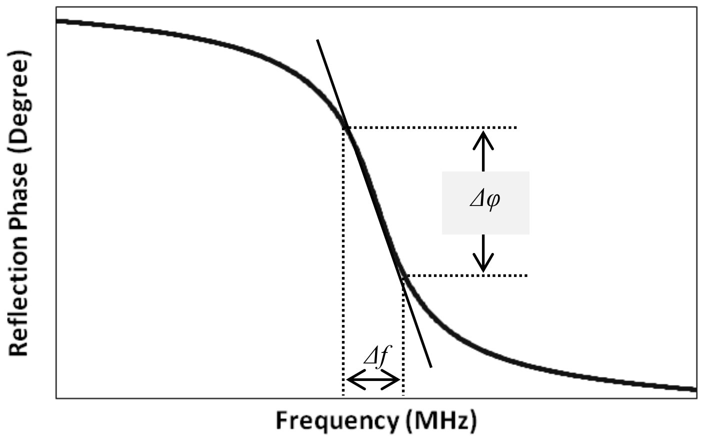


Figure 2.6: Reflection phase of reflectarray antenna

Figure 2.6 shows the reflection phase curve of a reflectarray antenna. As shown in Figure 2.6, the range of frequency (Δf) at which the reflection phase shows linearity is called static phase range ($\Delta\varphi$) of the reflectarray element. Reflection phase also depends on the thickness of the substrate of reflectarray. For a thinner substrate the number of multiple bounces of incident energy inside substrate region increase hence more energy is dissipated in the substrate and as a result phase becomes steeper. Therefore low dielectric constant materials have smoother phase curves with low static phase range whereas high dielectric constant materials have steeper phase curves with wide static phase range (Ismail et al. 2010).

2.3 Performance enhancement of reflectarray antenna using different optimization techniques

It has been identified that, the narrow bandwidth and high reflection losses are the main performance limitations of reflectarray antenna. Limited bandwidth is mainly due to the differential spatial phase delays, which means that by controlling the phase of individual reflectarray patch element, the bandwidth performance can also be improved. On the other hand properties of substrate material and radiating patch element are equally responsible for the high loss performance of reflectarray antenna. This shows that the proper selection of substrate material and resonating patch element plays an important role in the optimized design of reflectarray antenna. A substrate material can be taken based on its dielectric properties and thickness, whereas a patch element can be selected based on its design configurations. Many researchers have been working on the design optimization of reflectarray antenna based on various dielectric materials with different resonant patch elements. In this section a thorough investigation has been performed on the studies that have been carried out for performance enhancement of reflectarray antenna.

2.3.1 Optimization of loss and bandwidth performance by material properties

The performance of reflectarray antenna based on dielectric material properties was investigated by (Ismail et al. 2010). The reflectivity of a rectangular reflectarray patch element was analyzed at 10 GHz printed on different dielectric substrates using

FIM technique. Capacitive losses occurred in dielectric substrates were thoroughly investigated. It was shown that the occurred capacitance is directly proportional to the area of the conducting plates (patch and ground plane) and inversely proportional to distance between them, as shown in Equation (2.7).

$$C = \varepsilon \frac{A}{d} \tag{2.7}$$

Where:
C is the capacitance of a reflectarray antenna
A is the area of the patch and ground plane
ε is the dielectric constant of the substrate material
d is the separation between patch and ground plane (substrate thickness)

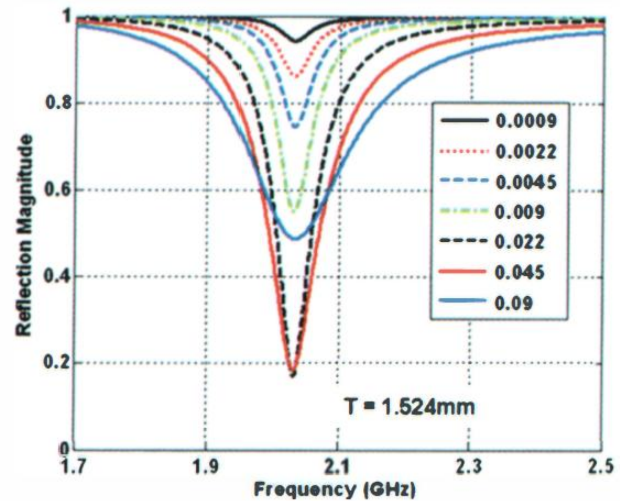
This explanation shows that a thin substrate possesses high losses due to high capacitive dissipation inside the substrate region. It has been observed from Equation (2.7) that, the dielectric constant of substrate material also plays an important role in the loss performance of reflectarray antenna. The relationship between dielectric constant value and capacitance of different dielectric substrates was observed for different substrate material at a constant substrate thickness of 1 mm. It was analyzed that as the dielectric constant value increases from 2.08 to 13, the capacitance of reflectarray substrate was also increased from 160 pF to 310 pF. A high value of capacitance also boosts up the reflection loss performance of reflectarray antenna. It was shown that, dielectric material Teflon with a dielectric constant of 2.08 offers a lower reflection loss of 0.179 dB as compared to Gallium arsenide (ε=13) which offers 4.326 dB. It was concluded from this work that, low dielectric constant materials are required for optimized loss performance of reflectarray antenna but on the cost of large sized reflectarray element.

Another important work based on the relationship between dielectric material properties and reflectarray bandwidth performance was done by (Ismail & Inam 2010a). A rectangular patch reflectarray antenna with different dielectric materials was analyzed with an infinite array approach. It was shown that the Teflon (ε=2.08, tanδ=0.0004) attains a maximum bandwidth performance of 540 MHz, whereas

Gallium Arsenide (ε=13, tanδ=0.006) which offers a minimum bandwidth of 126 MHz. Furthermore, different substrate thicknesses of 1, 1.4 and 2 mm were used to analyze the FoM performance of reflectarray antenna. It was observed from this work that, a thicker substrate attains a smoother reflection phase curve with wide bandwidth performance as compared to a thinner substrate which offers steeper reflection phase curves. It was concluded that, steeper the slope of the reflection phase curve the lesser will be the bandwidth of the reflectarrays which shows a drawback between bandwidth and static phase range performance of reflectarrays.

I. Reflectivity analysis of high loss and low loss substrates

The investigation of high loss and low loss substrate materials for the performance improvement of reflectarray antenna was carried out by (Rajagopalan & Rahmat-Samii 2010). A square patch reflectarray antenna was used to resonate in S-band frequency range for a substrate with dielectric constant of 2.2 with thickness ranging from 0.381 mm to 6.096 mm. The different loss tangent values of substrate material were selected from 0.0009 to 0.09 in order to characterize a lossy dielectric substrate. This work particularly described the effect of dielectric loss on the reflection magnitude and phase range performance of reflectarray antenna.



$\tan\delta$	Minimum $\lvert\Gamma\rvert$
0.0009	0.94
0.0022	0.86
0.0045	0.75
0.009	0.55
0.022	0.17
0.045	0.19
0.09	0.49

Figure 2.7: Paper results of different reflection magnitudes at various loss tangent values (Rajagopalan & Rahmat-Samii 2010)

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