DESIGN AND CHARACTERIZATION OF FLAT LENS ANTENNA USING APERTURE-COUPLED MICROSTRIP PATCHES

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Especially dedicated to my beloved parents, my wife and my siblings who supported and inspired me throughout my journey of education

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ABSTRACT

A planar discrete lens antenna is a low profile, light weight and cost effective solution to conventional and curved dielectric lenses. The basic theory of operation of flat lens antenna unit cell is to collimate the feed spherical electromagnetic incident wave into planar wavefront at the back of the aperture. Therefore, the array unit cell must be designed to establish the required phase adjustment. Flat lens antenna elements which are based on aperture-coupled microstrip patches are presented. The lens contains 7×7 elements with a diameter of 71 mm and operates in the X-band frequency range. The lens was experimentally validated and good agreement between simulation and measurement results were obtained. The achieved measured peak gain is 15.85 dB. This gives 6 dB gain enhancement for the system. The antenna 1-dB gain bandwidth and power efficiency are 7.8% and 58% respectively. A very good transmission phase shift of 340° is achieved with transmission coefficient of better than 2.25 dB. In addition, the measured radiation pattern results show that the antenna system has good symmetry between E and H plane with a half-power beamwidth of 16.2° and 16.6° in E-plane and H-plane respectively. Moreover, the proposed lens element employs a simple and less fabrication complexity mechanism for phase shift correction. Finally, the obtained results show that the proposed flat lens antenna is an attractive choice for the applications of wireless airborne systems such as VSAT (Very Small Aperture Terminal).

ABSTRAK

Antena kanta rata merupakan sebuah antena kanta berprofil rendah, ringan dan kos efektif berbanding dengan kanta dwi elektrik konvensional yang berbentuk melengkung. Ianya terdiri dari susunan unit-unit sel diskrit yang direkabentuk dan disusun secara bersistematik bagi menerima dan memancarkan gelombang electromagnet pada kadaran fasa yang seolah-olah mewakili sebuah kanta dwi elektrik konvensional melengkung. Perwakilan ini membolehkannya direkabentuk pada permukaan rata di atas papan jalur mikro. Dalam penyelidikan ini, unit sel yang di rekabantuk adalah berdasarkan teknik gandingan bukaan. Kanta rata yang telah direkabentuk mempunyai 7×7 bilangan elemen unit sel dengan diameter keseluruhan sebesar 71 mm, untuk beroperasi pada frekuensi jalur-X. Antena kanta rata yang direkabentuk ini telah dibina dan di tentu ukur bagi membandingkan prestasinya dengan rekaan simulasi. Secara keseluruhan, keputusan-keputusan dari pengukuran dan simulasi telah menunjukkan keputusan yang sama dengan sedikit perbezaan yang tidak begitu signifikan. Gandaan puncak secara pengukuran telah menunjukkan yang antenna kanta rata ini mampu mencapai bacaan setinggi 15.85 dB. Secara perbandingan, ini sebenarnya telah memberikan penambahan gandaan sebanyak 6 dB jika dibandingkan dengan sistem tanpa kanta (iaitu hanya antenna hon digunakan bersendirian). Lebarjalur gandaan (merujuk pada 1-dB) diukur untuk antenna ini adalah pada 7.8%, manakala kecekapan kuasanya adalah 58%. Pacuan anjakan fasa yang diperolehi adalah sebanyak 340º dengan pekali pacuannya berada pada kadar yang lebih baik daripada 2.25 dB. Corak radiasi yang ditunjukkan oleh antena kanta rata ini menunjukkan corak radiasi simetri pada kedua-dua satah-E dan -H, dengan ukuran lebar sinaran separuh kuasanya berada pada 16.2º di satah-E dan 16.6º di satah-H. Secara keseluruhannya, penyelidikan ini telah berjaya merekabentuk dan mencadangkan sebuah sistem antena kanta rata yang ringkas dan mudah untuk dibangunkan. Dari segi aplikasi, rekabantuk ini sangat sesuai digunakan bagi beberapa tujuan telekomunikasi jarak jauh termasuklah untuk sistem VSAT (*Very Small Aperture Terminal*), satelit television dan telekomunikasi data tanpa wayar.

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LIST OF ABBREVIATIONS

PCB	Printed Circuit Board
CST	Computer Simulation Technology
MWS	Microwave Studio
EM	Electromagnetic
dB	Decibel
BW	Bandwidth
HPBW	Half Power Beamwidth
FR4	Fire-retardant 4
UTHM	University Tun Hussien Onn Malaysia
AR	Axial Ratio
MIC	Microwave Integrated Circuits
FSS	Frequency Selective Surface
WR	Waveguide Rectangular
GHz	Giga Hertz
IEEE	Institute of Electrical and Electronics Engineers
RHC	Right-hand-circularization
LHC	Left-hand-circularization
CP	Circular Polarization
LP	Linear Polarization
F/D	Focal Length to Diameter Ratio
AFA	Antenna-Filter-Antenna
CPW	Coplanar Waveguide

LIST OF APPENDICES

LIST OF PUBLICATIONS

Journals:

(i) Abdisamad A. Awaleh and Samsul H. Dahlan, "A compact and wideband flat lens antenna based on aperture coupled patches for X-band applications," Jurnal Teknologi, Universiti Teknologi Malaysia, pp. 1-5, 2015.

(ii) Abdisamad A. Awaleh and Samsul H. Dahlan "A circularly polarized aperture coupled patch element for flat lens antennas," ARPN Journal of Engineering and Applied Sciences, pp. 9038-9042, 2015.

(iii) Abdisamad A. Awaleh and Samsul H. Dahlan "Design and modeling of planar lens antenna element in X-band applications," ARPN Journal of Engineering and Applied Sciences, pp. 8807-8811, 2015.

Proceedings:

(i) Abdisamad A. Awaleh, Samsul H. Dahlan, M. Zarar M. Jenu, "Equivalent electrical lumped component modeling of E-shaped patch flat lens antenna unit cell," IEEE Asia-Pacific Conference on Applied Electromagnetics, APACE 2014, Johor Bahru, Malaysia, pp. 39–42, 2014.

(ii) Abdisamad A. Awaleh, Samsul H. Dahlan, M. Zarar M. Jenu, "A compact flat lens antenna with aperture coupled patch elements," IEEE Asia-Pacific Conference on Applied Electromagnetics, APACE 2014, Johor Bahru, Malaysia, pp. 23–26, 2014.

(iii) Abdisamad A. Awaleh, Samsul H. Dahlan, M. Zarar M. Jenu, “Measurement of flat lens antenna unit cell using waveguide simulators”, Malaysian Technical Universities Conference on Engineering & Technology (MUCET), pp. 10-11 2014.

(iv) Abdisamad A. Awaleh, Samsul H. Dahlan, “Evaluation of slot patch unit cell for discrete lens antenna applications,” The 4th International Conference on Engineering Technology and Technopreneuship, ICE2T 2014, Kuala Lumpur, Malaysia, pp. 199-203, 2014.

LIST OF AWARDS

(i) **Silver Medal in International Invention, Innovation and Technology Exhibition [ITEX 2015]:** Samsul H. Dahlan, Abdisamad Ali Awaleh. “A Compact Flat Lens for Microwave Applications.”

CHAPTER 1

INTRODUCTION

1.1 Background

Antennas are key components of any wireless communication or sensing system and transmit and/or receive electromagnetic waves. Antennas have developed into different sorts of shapes and sizes and implanted commonly everyday applications, such as personal communications, home electronics, warfare electronics and transportation [1]. The vast variety of antennas might be grouped into low gain antennas (<10 dBi), middle gain antennas (10 dBi ~ 20 dBi), and high gain antennas (>20 dBi) [2]. Flat lens antenna also known as discrete lens antenna fits to the high gain antenna group.

Classification of lens antennas are done on the basis of their shape and material from which they are developed [3]. Therefore, flat lens antenna is a discretized lens and it consists of a dual array structure. This antenna configuration comprises of an illuminating feed antenna and a flat array lens, which is designed to convert the spherical incident wavefront into a planar radiated wavefront in the far-field distance without too much transmission loss. Thus, a focused radiation beam can be achieved with a high gain.

A planar discrete lens antenna is a low profile, light weight and cost effective solution to conventional and curved dielectric lenses. These benefits, especially weight and packed volume made this antenna an attractive choice for space-born communication systems [4]. However, the design of a suitable unit cell element to obtain a good performance flat lens antenna is not straight forward and many difficulties appear due to the fact of the phase adjustment needed at each antenna element.

For the last decade, a considerable effort has been made in developing high performance discrete lens antennas. The major difference among the designs of the antennas is the phase correction technique used to compensate the incoming wavefront errors. The three most significant design considerations of flat lens antenna are its phase range, insertion loss and bandwidth. Motivated by these factors, a research is carried out to develop a compact and less fabrication complexity flat lens antenna for X-band applications. A phase shift technique based on aperture coupled microstrip patches is proposed in this study. The phase control approach used in this design has the potential ease of fabrication with a phase tuning range capability of up to 340° and low insertion loss.

1.2 Problems statement

Some of the most potential application spheres of flat lens antenna are satellite and point-to-point communications in which the transmitted power is required to be more concentrated in to a specific direction. For this reason, antenna with high directivity and gain are needed. To our best knowledge, most of the high performance antenna designs reported recently consist of coupled patch antennas, using transmission delay lines [5] – [8] and element rotation [9] – [11] to realize the required phase shift. However, the most challenging task is to place the phase delay line inside the structure or between the radiating patches, because of the limited space available [12]. The use of metallic vias to connect the two radiating interfaces of the element rotation technique adds another complexity to the design and creates construction limitations. Therefore, one of the most serious challenges of flat lens antenna systems is making a compromise between design complexity and performance.

Fundamentally, lens antenna must collimate the incident wave from the feeding source so as to achieve high gain and directivity. The amount of phase correction needed at each unit cell depends on the location of the element on the array surface. However, for a large antenna size, elements must demonstrate the capability of providing a phase range of 360°. Therefore, a unit cell equivalent circuit modelling is proposed, in order to systematically investigate how the phase range changes with the physical parameters of the antenna structure. This modelling approach was applied as an optimization technique for the structure to gain additional control of the antenna performance outcomes.

On the other hand, even though a lot of efforts have been made to enhance the performance of lens arrays, however, most of the time the size of the antenna becomes inevitably large and complex to fabricate. For such problems, the major concern is to investigate the capabilities of reduced size flat lens antenna with high quality performance and competence.

1.3 Research motivation

Flat lens antenna is a promising potential technology for applications where broadband, beam shaping, sidelobe suppression and beam steering in space are required to realize in a single compact and inexpensive structure. In addition to these characteristics, discrete lenses have narrow beamwidth and high gain which made them an attractive choice for the applications of the ongoing development of wireless communications and digital radar system for remote sensing.

Compared to other conventional high gain antenna apertures, flat lens antenna exhibits the benefit of eliminating aperture blockage by the feed and supporting rods. As a result, flat lens antenna can achieve low distortions and cross-polarization. Moreover, reducing the antenna weight and packed volume is very significant especially during antenna launching. Therefore, in this research, a compact and aperture coupled antenna configuration is proposed. This design approach makes a compromise between design complexity and performance.

1.4 Research objectives

The objective of the research is:

1. To design and develop a suitable element that has less fabrication complexity for flat lens antenna using slot technique for phase shift adjustment.
2. To model the antenna unit cell structure using equivalent lumped element circuit.
3. To design, analyze and fabricate full array flat lens antenna using printed circuit technology.

1.5 Scopes of study

The scope of this study is limited to the following areas:

1. A flat lens antenna element design based on aperture coupled patches with a common ground plane coupling has been developed and simulated using Computer Simulation Technology (CST). The element operates at X-band frequency range (8-12 GHz) and was fabricated using microstrip technology (substrate type: FR4 with relative permittivity $\varepsilon_r = 4.3$).

2. An equivalent circuit for the antenna element have been modelled and simulated to investigate its performance using Multisim^{v13} software.
3. Full array prototype which contains 7×7 elements was designed, analyzed and measured.

1.6 Significance of research contribution

This thesis has made several significant contributions to the field of antenna engineering. Specifically, these are included antenna design, antenna modeling, analytical derivations and antenna miniaturization technique. To validate this research outcome experimentally, full array lens antenna have been prototyped and measured. Each contribution presented in this thesis has also been published in journals and conference proceedings. In summary, the major contributions are as follows:

1. A simple and less fabrication complexity lens element is proposed and published in. This element design eliminates the floating antenna structures created by transmission delay lines and air gap between the lens layers. It demonstrates that the element can achieve phase shift by varying embedded slot length. In this thesis it is presented in section 4.2.
2. To obtain the physical insight of the element, an equivalent circuit model was designed.
3. A prototype of flat lens antenna with high gain and directive beam was developed.
4. A comprehensive study and comparison among several feeding sources for lens antenna were carried out in order to enhance the antenna performance.
5. A second flat lens antenna design from an FSS perspective which has the feasibility of circular polarization properties has also been contributed.
6. A circularly polarized aperture coupled patch element has been proposed.

1.7 Organization of the thesis

This thesis is divided into 6 main chapters. Chapter 1 presents the research introduction, problem statement, objectives, scope, research motivations and significance research contribution of this project.

In chapter 2, an extensive literature review on flat lens antenna, transmission phase controlling techniques, antenna modeling and lens antenna feeding methods are discussed.

Chapter 3 discusses the methodology of the research and describes the instruments and procedures used in this study. The obtained results and discussions of this study are highlighted in Chapter 4 and Chapter 5.

Finally, Chapter 6 discusses about the conclusions and recommendations as well as suggested future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the theoretical background that was used to design and analyze flat lens antenna. A passive flat lens antenna array design with various feeding techniques will be elaborated. And lastly, results and proposed designs in literature which are relevant to this thesis were reviewed.

A planar discrete lens antenna is a low profile, light weight and cost effective solution to conventional and curved dielectric lenses. For this antenna system the radiation characteristics of a feed antenna are modified by using a flat lens. A feeding source usually horn antenna, open-ended waveguide or patch antenna is usually used to illuminate one side of the array, and for passive discrete lenses, either side of the array can be either a transmitter or a receiver (or vice versa). Flat lens antenna is an attractive candidate for the ongoing development of wireless communications and digital radar system for remote sensing, because of its narrow beamwidth and high gain.

The basic theory of operation of flat lens antenna elements is to collimate or convert the spherical electromagnetic incident wave from the source into a planar radiated wave at the back of the antenna structure [13] - [14]. The easiest design technique for any focusing lens can be achieved by using geometric optics or ray tracing. Hence, the electrical patch length of the constituent elements of the flat array lens must be equal for each unit cell.

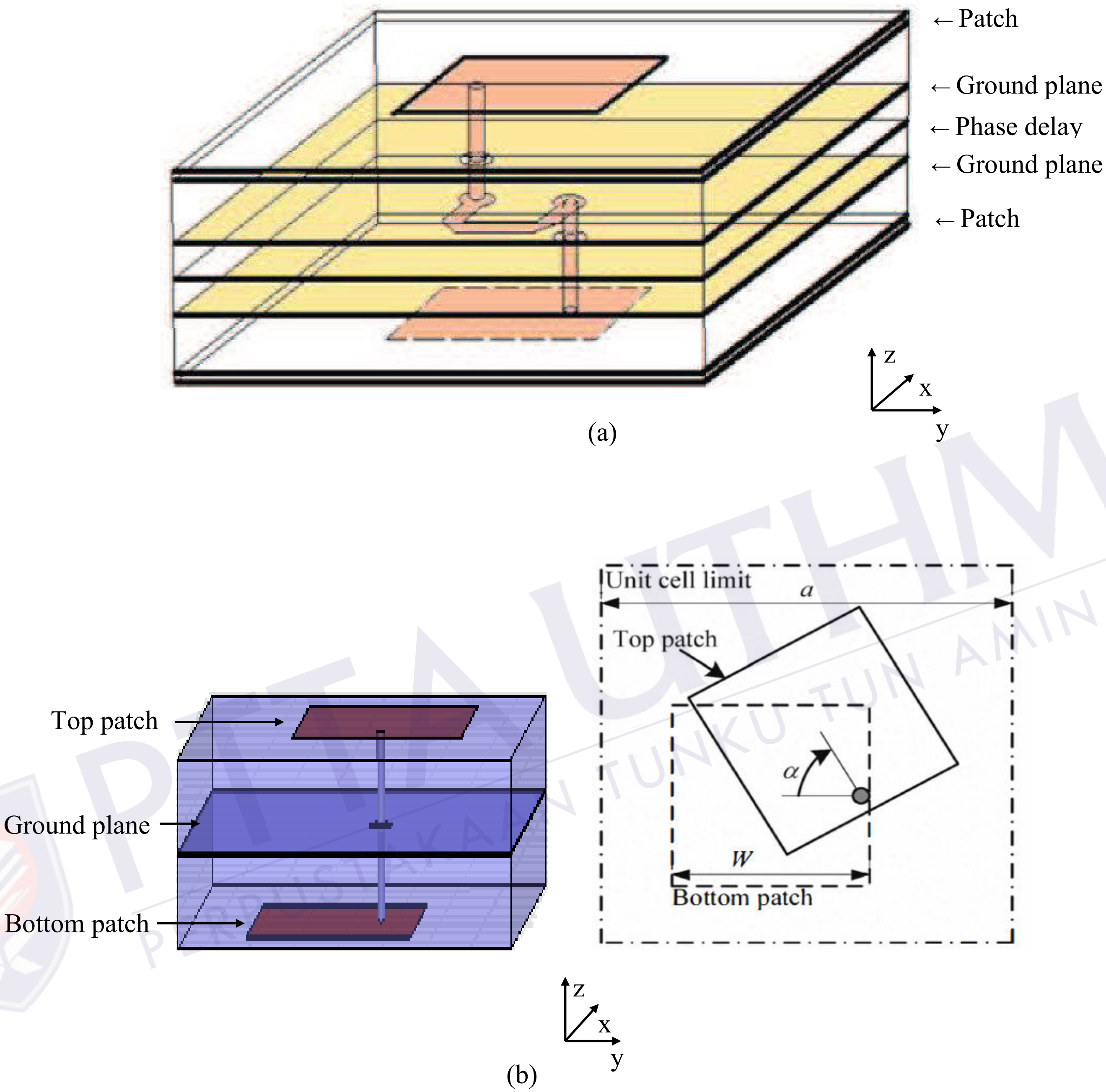
2.2 Passive flat lens antenna array

In recent years a new generation of antenna known as flat lens antenna (transmitarray) has emerged for space communications. This advanced technology is rapidly improving, thanks to the printed circuit board technology (PCB). Flat lens antenna are grouped into active (reconfigurable) lenses (if external control signal is utilized from inner circuit configuration) [15] – [20] or passive (non-reconfigurable) lenses on the actuality [21] – [27].

Fundamentally, a flat lens antenna is analogous to the traditional dielectric lenses, while the bulky and spherical shaped lens is replaced with a planar array configuration. The main function of lens antenna is to shape or focus an electromagnetic radition from a feed antenna into the desired pattern. The most prominent feature and basic operation of this antenna is to control the phase of each unit cell in the array. And by utilizing this unique feature of phase compensation, has to collimate the feed spherical electromagnetic incident wave into a planar wave front. Depending on the nature of emitted source, there are three types of wavefronts which are planar, cylindrical and spherical. Compared to other types, a planar wave is a travelling wave in which the energy density or concentration is constant and as a result the wave amplitude remains constant with no attenuation [28].

As mentioned, flat lens antenna array radiating elements must be designed into a geometrical pattern where the phase of each unit element can be controlled. The unit cell approach which is to simulate and analyze the frequency response of unit cell rather than full array is adopted in most designs. A waveguide simulator technique can be used to measure the scattering paramters of the unit cell elements [29]. By using this method, the significant point of designing a unit cell for flat lens antenna is to obtain the essential requirement phase shift range of up to 360º.

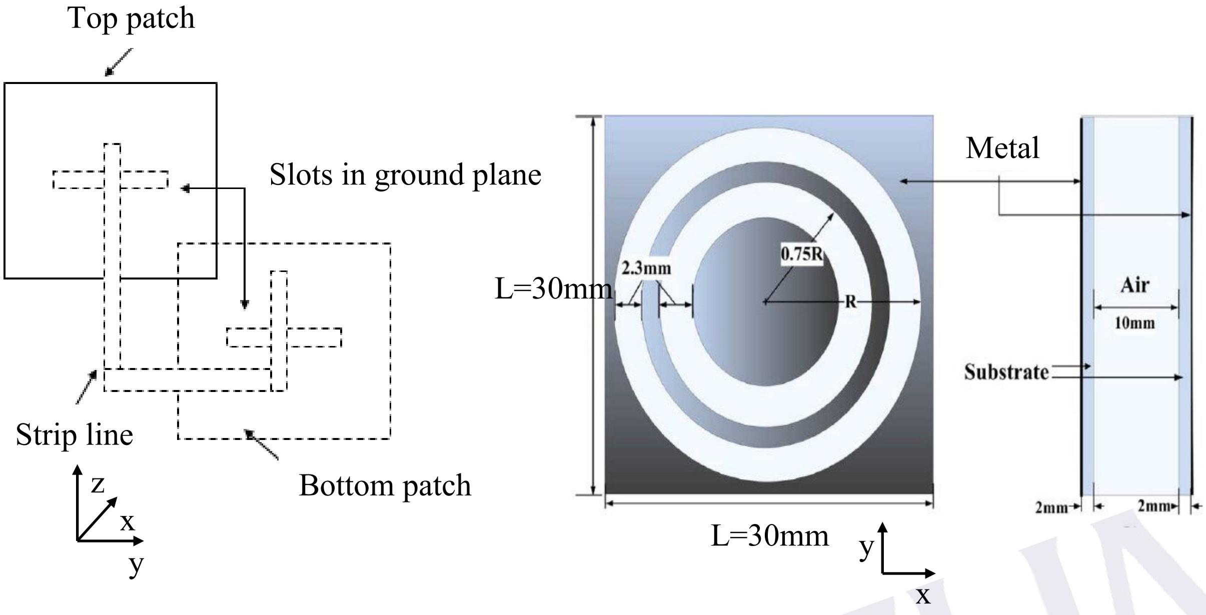
For the last decade a considerable effort has been made in developing high performance flat lens antennas. Regardless of the several existing design approaches, these studies have tried to demonstrate high directivity flat lens arrays design with very low transmission losses and large bandwidths at many different frequencies. Most of the designs structure and techniques deployed are microstrip delay line [25], element rotation [23], aperture coupled patches [21], and multi-resonance behavior [24] to realize phase shift compensations. In the following, a number of prototypes (Figure 2.1 and Figure 2.2) of passive flat lens array antennas, demonstrating the phase shift surfaces and design layout will be illustrated and elaborated in the next sections.



(a)

(b)

Figure 2.1 : Different passive flat lens antenna design configurations (a) using phase delay lines [25] and (b) element rotation concept [23]



(c) (b)

Figure 2.2 : Different passive flat lens antenna design configurations (a) aperture coupled patches [22] and (b) using multi-resonance behaviour technique [24]

2.2.1 Characteristics of flat lens antenna

In order to describe the performance of this antenna design, the most fundamental antenna parameters must be understood to fully characterize the antenna. There are various interrelated parameters, however, the most significant parameteters in this study are scattering parameters, radiation pattern, gain and polarization.

(a) Scattering parameters

The reflection and transmission coefficients of flat lens antenna elements can be represented as a scattering matrix. The antenna array has two ports and for passive lenses either side can be a transmitter or a receiver (and vice versa). For instance, if the array is in the xy-plane, wave travels in the -z direction as illustrated in Figure 2.3. That means if the incoming wave from port 1 is E_1^+ the scattering parameters can be achieved from the following relations:

Reflection (S_{11}) = (E_1^-/E_1^+). (2.1)

Transmission (S_{21}) = (E_2^-/E_1^+). (2.2)

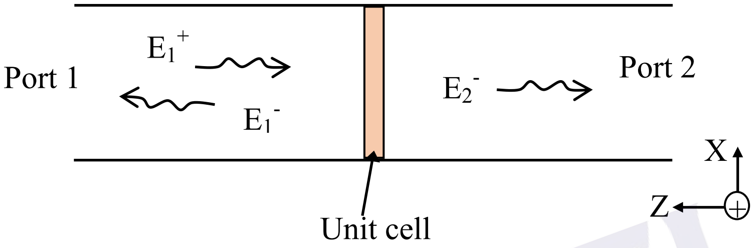


Figure 2.3: Electric field waves across unit cell inside waveguide simulator [30]

Reflection coefficient indicates the amount of signal reflected compared to the amount transmitted. It also specifies the antenna impedance bandwidth along its frequency range. Reflection coefficient also measures the antenna proper matching and matching will be appropriate if the reflection coefficient is less than -10 dB [3]. On the other hand, transmission phase and transmission coefficient magnitude basically measure the lens antenna performance. A high transmission coefficient magnitude and wider phase range with a slower and linear slope will lead to wider bandwidth, high gain, high efficiency and low sidelobes [24].

(b) Radiation pattern

According to the IEEE Standard Definitions, an antenna radiation pattern is defined as a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates [31]. It can be plotted in terms of field strength, power density, or decibels. The shape of the antenna radiation pattern indicates how the antenna concentrates its power; hence determines the application in which the antenna will be used. For example, lens antenna has an optimum airborne application which requires highly directive unidirectional radiation pattern.

(c) Gain

Antenna gain is defined as the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically [32]. The gain of the antenna is closely related to the directivity.

$$\text{Gain} = 4\pi\ (\text{Radiation intensity/Total input accepted power}) = 4\pi\ (U(\theta,\varphi/P_{in})) \qquad (2.3)$$

The maximum directivity of the antenna can also be determined as follows [33]:

$$D_{th} = 4\pi A_e/\lambda^2 \qquad (2.4)$$

Where A_e is the total array area and λ is the design frequency wavelength.

The main functions of lens antenna are gain enhancement and beam shaping. Therefore, it might be grouped into the high gain antennas (>20 dBi). High gain is recommended for more directive beam antennas and it is one of the objectives to be fulfilled in this study.

(d) Polarization

Polarization is an electromagnetic radiation property that describes the shape and orientation of the locus of the extremity of the field vectors of single frequency [32]. It is very important property to consider when choosing antenna applications. Polarization is classified as linear, circular or elliptical. The electric field determines the polarization or orientation of the radio wave. For instance, if the vector that describes the electric field at a point in space as a function of time is always directed along a line, the field is said to be linearly polarized. In this case, the antenna can be said vertically polarized (linear) when its electric fields are perpendicular to the Earth's surface and horizontally polarized (linear) if their electric fields are parallel to the Earth's surface.

In a circularly polarized antenna, the plane of orientation rotates in a circle making one complete revolution during one period of the wave. If the rotation is clockwise looking in the direction of propagation, the sense is called right-hand-circular (RHC). If the rotation is counterclockwise, the sense is called left-hand-circular (LHC) [31]. A circular polarized wave radiates energy in both the horizontal and vertical planes and all planes in between. The difference, if any, between the maximum and the minimum peaks as the antenna is rotated through all angles, is called the axial ratio and is usually specified in decibels (dB). If the axial ratio is near 0 dB, the antenna is said to be circular polarized. However, still an axial ratio of less than 3 dB can be accepted for circular polarization.

Circular polarization (CP) is very essential for space-borne communication systems as it trivializes the Faraday rotation effect in the ionosphere. The fundamental advantage of circular polarization is that all reflections change the direction of polarization, precluding the usual addition or subtraction of main and reflected signals. Therefore, there is far less fading and flutter when circular polarization is used at each end of the link. The work in this thesis concerns both linear (LP) and circular (CP) polarizations. The proposed planar lens designs use controllable aperture coupled patches to provide the required phase shift. The shape and orientation of the coupling slot determines whether the antenna works linear or circular polarizations. Therefore, two lenses are designed with different slot coupling shapes for linear and circular polarizations. To accommodate circular polarization, square patches with two identical and orthogonal cross slot apertures are used. Details about the unit cell designs and slot length adjustments are presented in sub-sections 3.5.1 and 3.5.3.

2.2.2 Equivalent circuit model

Flat lens antenna can be appropriately represented in equivalent circuit form, derived from the basic cavity model concept of patch antenna as shown in Figure 2.4 [3]. This is to potentially obtain the physical insight of the antenna elements. A coupled-resonator approach which models the antenna element structure using resonators was reported in [20]. Before evaluating the circuit, component parameters such as R, L and C must be determined using analytical expressions considering the physical structure of the unit cell. Analytical circuit parameters determination and derivations are elaborated in chapter 5 of this thesis.

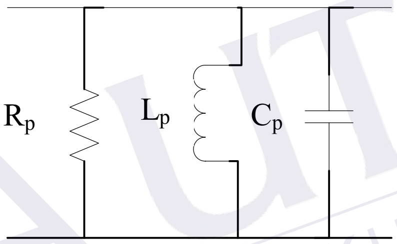


Figure 2.4: Basic equivalent circuit for patch antenna [3]

In this project the proposed equivalent circuit model consists of two resonators connected by a coupling transformer model. Equivalent circuit representation can conveniently model a single element from the antenna array. However, the limitation is that, it cannot model the interaction between the adjacent cells.

2.3 Review of relevant literature

The ongoing development of wireless and space-borne communications systems lead lens antenna to gain bigger research interest during the last decade. The relevant recent studies of flat lens antenna employing different phasing techniques have been compared to this project work. The major difference among these works is the design approaches or phasing mechanism used to realise the desired phase error corrections of the antenna array. There are four phasing techniques used in these recent works of flat lens antenna. Table 2.1 summarizes the characteristics and performances of previous relevant flat lens antenna works.

Table 2.1: Performance and characteristics of previous works

Publication	Year	Frequency (GHz)	No. of Elements	Phasing Technique*	Gain (dB)	Polarization	Efficiency (%)	Array Thickness (mm)
[5]	2010	12	36	LT	16	Linear	_	5.255
[24]	2013	6	49	MR	16.7	_	23.4	14.07
[34]	2010	30	225	MR	28.59	Linear	47	10.308
[35]	2011	12.9	349	ER	27.9	Circular	48	11.588
[36]	2011	60	400	ER	23	Linear & Circular	63	0.532

*Phase shift mechanism: Length of transmission line (TL), element rotation (ER), multi-resonance behavior (MR) or aperture-coupled patches (AC)

─ No data available

It can be seen from Table 2.1, that some of the antennas performances are quite high; however, these designs experience fabrication complexity and high quantization error [25]. For example the most upsetting task for varying length transmission line phase shift technique as in [5] is to place the delay lines inside the structure or between the radiating patches, because of the space available [37], [38]. The use of metallic vias to connect the two radiating interfaces of [36] adds another complexity to the design and creates construction limitations. The third phasing technique proposed in [24], [34] utilizes multi-resonance behavior to compensate the wavefront error. However, an air gap was inserted between the lower and upper substrates on the receiving and transmitting patches of the antenna. Hence, creates floating antenna structure.

A conceptually compact and simple element design with less fabrication complexity based on aperture-coupled patches is presented in this thesis work. The power efficiency (58%), its cross-polarization performance and achieved gain (15.85 dB) are comparable to other array lenses. However, antenna fabrication simplicity, the -3 dB bandwidth (33%) and array thickness (3.305 mm) of this work are better than those of the entire relevant flat lens antenna array published in literature and discussed in Table 2.1. Further comparisons between the recent works of flat lens antenna are shown in Table 2.2.

Table 2.2: Scopes of previous works related to this thesis

Publication	Freq. range (GHz)	Equivalent circuit model	Feeding technique analysis	Fabrication simplicity	Compact structure	Software simulation	Experimental measurement
[5]	12-18	-	-	-	-	√	√
[24]	4-8	-	-	-	-	√	√
[34]	28-32	-	-	-	-	√	√
[35]	11-14	-	-	-	-	√	√
[36]	40-75	√	-	-	√	√	√

2.4 Applicable theoretical concepts

A number of applicable antenna theories have been considered to design and analyze the flat lens antenna proposed in this thesis. Space-fed antenna array, aperture-coupled patches and the power loss that spills over the antenna aperture and affects its efficiency are discussed. The theories referred and presented here can be found in antenna textbooks including: [3], [39], and [40].

2.4.1 Spatial feed antenna array

Basically, antenna array consists of a number of conducting elements designed and arranged in a systematic pattern. Each unit cell in the array is a practical antenna itself; hence, distributing power to each element is crucial. Therefore, a spatial feeding network is more recommended for planar lens antennas. This is because; it is both simple and efficient as well as distributes energy equally to all antenna array elements.

Typically, the power is generated by a single moderate gain antenna such as horn or microstrip patch array. The feed antenna must be designed for the intention of good radiation efficiency. That means, the major lobe of the antenna radiation pattern must direct and transfer most of the energy on to the array. However, space feeding technique has the limitation of antenna gain reduction, specifically as spillover and taper losses. But it is important to note that spatial feed losses are unlike and less than those associated with transmission line feed. Therefore, one notable advantage of using spatial feed is that losses do not increase with antenna array size and it is more beneficial for very large antenna array designs.

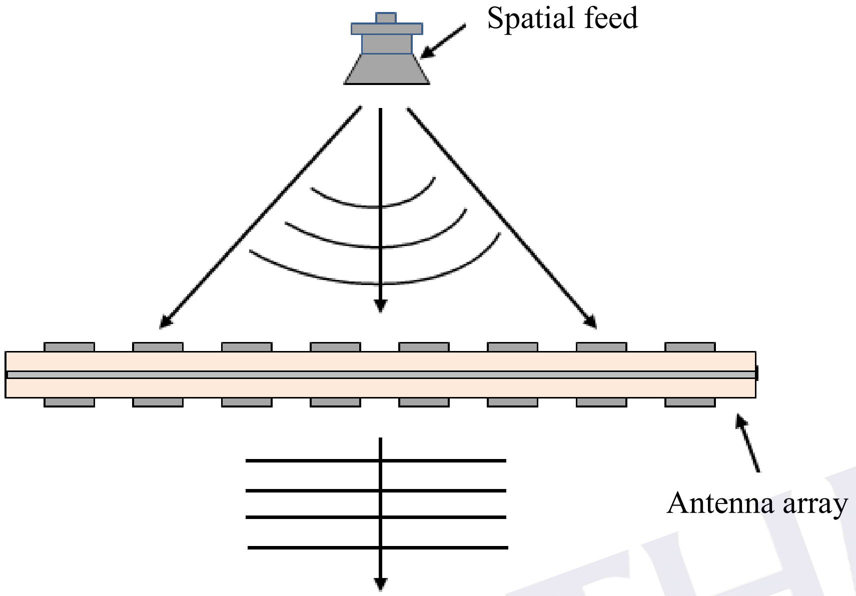


Figure 2.5: Space fed planar lens antenna array (Horn antenna feed) [36]

2.4.2 Array losses

Lens antenna array experiences many different losses which can be determined from simulated or measured data. Array losses include resistive loss, specular reflection and back-scatter. An element s-parameter value (S^{mn} of the cell mn) measures the specular reflection and back-scatter ($|S_{11}^{mn}|$) of the cell which is the power reflected from the array. The s-parameters values depend on the tuning of the cell. Therefore, fractional resistive loss of each cell can be calculated by summing the reflected and transmitted power as,

$$\text{Resistive loss} = |S_{11}^{mn}|^2 + |S_{21}^{mn}|^2 \qquad (2.5)$$

The resistive loss in above equation is the proportion of power that is not dissipated by the antenna array elements. However, to determine the overall array loss, individual unit cell losses must be weighed, considering how much incident power it receives from the feed antenna. This is because if an element receives small amount of power from the source, it will have a small effect on the overall loss. The feed antenna illumination impact is illustrated in Figure 2.6.

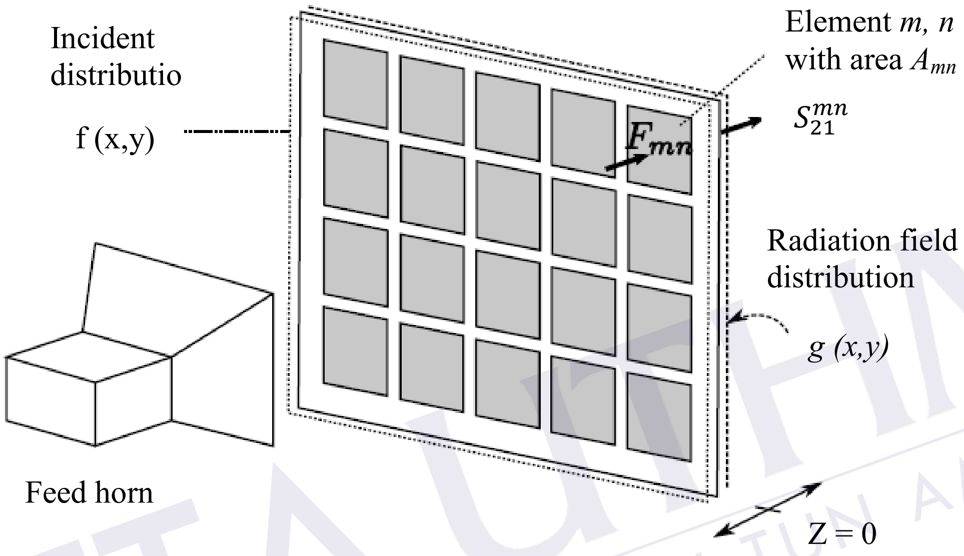


Figure 2.6: Flat lens antenna array setup [20]

2.4.3 Spill-over loss and taper efficiency

The spillover loss is the power radiated by the feed antenna which does not illuminate any element of the antenna array and is considered to be lost. On the other hand, taper efficiency is the reduction in antenna gain and directivity due to inconstant magnitudes of currents or fields on the radiating aperture. In simple terms, the feed antenna should have a radiating pattern that illuminates the entire array aperture while minimizing the power that spills over the aperture.

Both spillover and taper efficiencies depend on the feed antenna radiation pattern and F/D ratio. For instance, the taper efficiency increases as the feed antenna moves away from the array aperture. However, moving the feed antenna away from the aperture decreases the spillover efficiency (More spillover loss). This compromise is sketched in Figure 2.7.

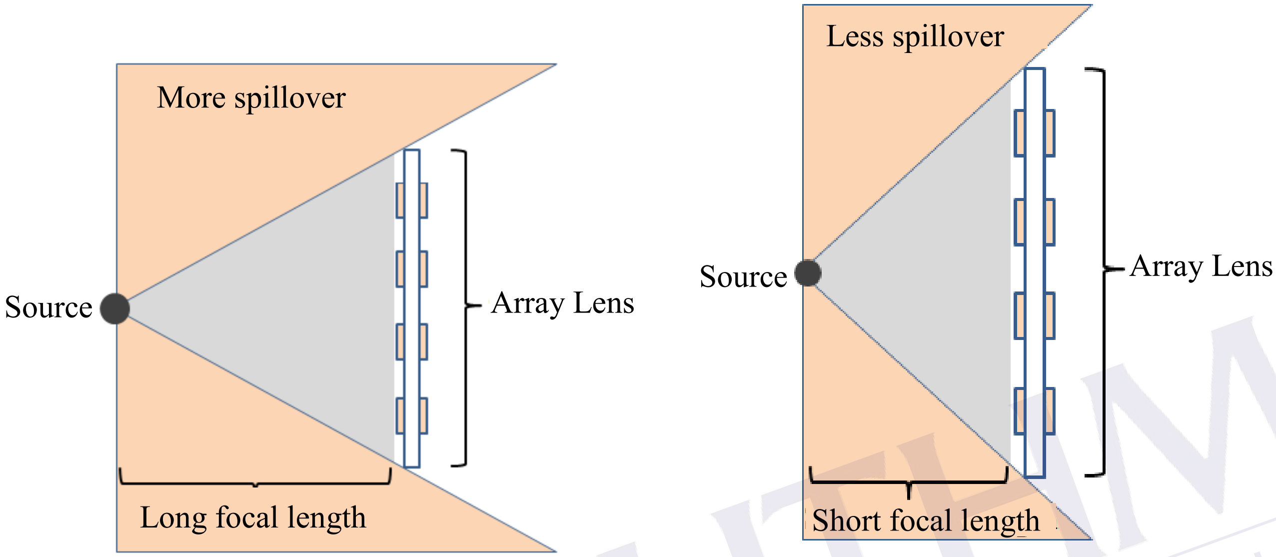


Figure 2.7: The trade-off between spillover loss and taper efficiency, the triangles in the illustration depict the angular magnitude of the spillover [20]

Referring to Figure 2.6, the spillover loss can be calculated by the ratio of the total incident power on the array lens, and the total power radiated by the feed antenna.

$$\text{Spillover loss} = \frac{\int\int_A f(x,y)dxdy}{P_{feed}} \tag{2.6}$$

Where A in the equation is the surface area of the array lens and P_{feed} is the total power radiated by the feed antenna. So, assuming that the feed antenna is a directive horn and the backward radiation of the horn is significant, then the power radiated from the feed can be determined as:

$$\text{P}_{\text{feed}} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)dxdy \tag{2.7}$$

To calculate the taper efficient of the antenna aperture, Figure 2.6 is referred again. And as illustrated in Figure 2.6, $g_{\mathrm{mn}}(x, y)$ is the fields on the radiating surface of the antenna array produced by unit cell m, n. The magnitude of $g_{\mathrm{mn}}(x, y)$ is depending on both the transmission coefficient S_{21}^{mn} and the illumination F_{mn} of each unit cell.

$$g_{\mathrm{mn}}(x, y) \propto \sqrt{F_{mn}}|S_{21}^{mn}| \tag{2.8}$$

Therefore, the total field on the radiating surface of the antenna array is the sum total $g_{mn}(x, y) = \Sigma_{mn} g_{\mathrm{mn}}(x, y)$. The value of $g(x, y)$ can be estimated from f(x, y) and S_{21}^{mn}. Hence, the directivity of a broadside beam with constant phase can be calculated as:

$$D = \frac{4\pi}{\lambda^2} \frac{\left(\int_S |g(x,y)| dxdy\right)^2}{\int_S |g(x,y)|^2 dxdy} \tag{2.9}$$

And finally, the taper efficiency can be determined as follows:

$$\text{taper efficiency} = \frac{D}{D_{ideal}} = \frac{(\int_S |g(x,y)| dxdy)^2}{(\int_S dxdy)(\int_S |g(x,y)|^2 dxdy)} \tag{2.10}$$

Where D_{ideal} is the maximum directivity in which a rectangular aperture (with dimensions $a \times b$) can achieve.

$$D_{\max} = \frac{4\pi ab}{\lambda^2} \tag{2.11}$$

In this thesis, since all elements of the array lens have very similar transmission coefficients, the power efficiency of the flat lens antenna depends only on the focal length to diameter ratio (F/D) which determines the spillover losses. Moreover, antenna gain and directivity performances of different F/D ratio were thoroughly investigated. Therefore, the optimal F/D ratio range can easily be determined.

2.4.4 Aperture coupled patch elements

Microstrip patch antenna consists of a radiating patch printed on one side of a substrate and patterned a ground plane on the other side. Different feeding methods of microstrip patch antenna are reported in literature including probe-feed, microstrip feed, proximity-coupled feed and aperture coupled feed. Aperture coupled technique for space-fed flat lens antenna is employed in this thesis work. Because, it is both simple to fabricate and makes the antenna more compact. Flat lens antenna concept based on aperture coupled microstrip patch elements with stripline delay lines was first reported in [22] as shown in Figure 2.8.

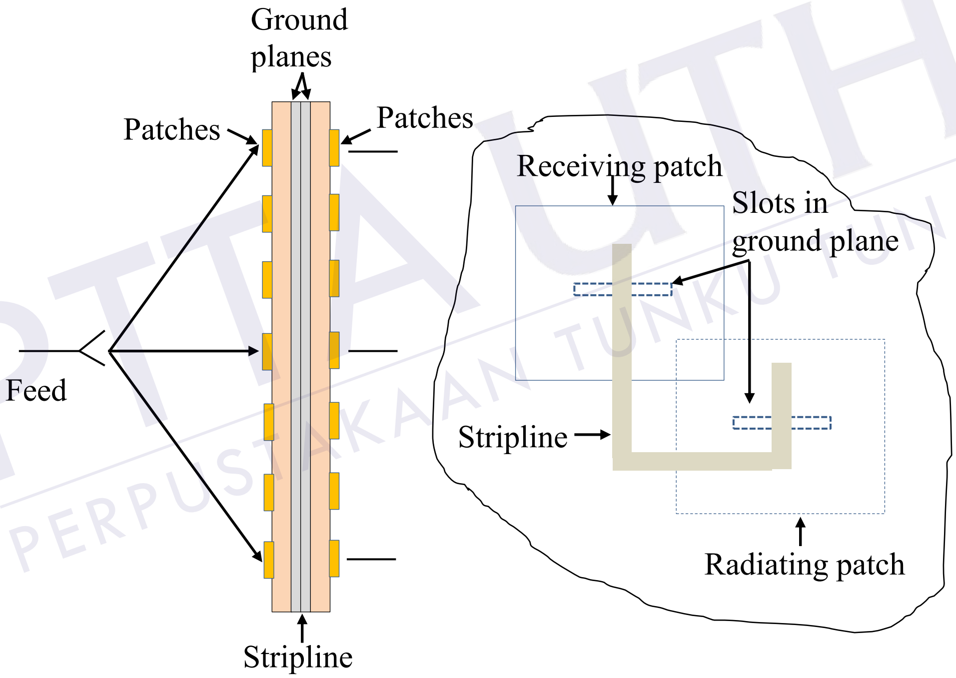


Figure 2.8: Cross section and top views of flat lens using two parallel aperture coupled microstrip patches via stripline delay lines [22]

However, stripline delay lines increase the antenna array weight and sometimes produce unwanted radiations. Therefore, to make the antenna simpler to manufacture, the stripline delay lines are eliminated in this study. A back-to-back patch element with slotted common ground plane coupling is presented in this thesis.

Conceptually, the elements operate as follows:

1. First, the receiving patch of the element receives the incident wave from the source.
2. Next, the signal couples through the aperture (slots on the ground plane) and onto the transmitting side of the element.
3. Then, the slots on the ground plane alter the magnitude and phase of the wave
4. Finally, the wave couples through the aperture, excites the transmitting patch and radiates.

2.5 Feeds for flat lens antennas

The feeding techniques of flat lens antenna can be any medium gain antenna including: horns, microstrip patch, dipoles and even arrays of antenna elements. In practice horn antennas, open ended waveguides and patches are most commonly used, or, in some cases, arrays of such elements [39].

2.5.1 Microstrip patch feeds

Some of the most important advantages of microstrip patch antennas are their ease and low cost of fabrications, light weight, ease of integration with other microwave printed circuits and robustness in nature. However, while considering these positive properties, some of the drawbacks of patch antenna as a primary feed for flat lens antenna must be highlighted as well. For example, the low profile property of patch antennas help to avoid the headroom intrusion which would be created by horn or waveguide feeds. On the other hand, one common disadvantage of patch antenna is the ohmic loss caused by both conductors and substrate layers. This effect increases dramatically with frequency.

REFERENCES

1. Tin Komljenovic, “Lens Antenna – Analysis and Synthesis at mm waves,”http://www.fer.hr/download/repository/kvalifikas cijski rad komljenvic.pdf
2. Abdelrahman, A. H., Elsherbeni, A. Z.,Yang, F., “Transmission phase limit of multilayer frequency selective surfaces for transmitarray designs,” IEEE Trans. on Antennas and Propagat., vol. 62, no. 2, pp. 690-697, 2014.
3. Balanis, C. A., “Antenna theory: analysis and design,” Third edition, John Wiley & Sons, pp. 7-8, 2005.
4. Phillion, R. H., “Flat lenses for circularly polarized electromagnetic waves,” PhD dissertation, University of Calgary, 2010.
5. Padilla, P., Munoz-Acevedo, A., Castaner, M. S., Perez, M. S., “Electronically reconfigurable transmitarray at Ku band for microwave applications,” IEEE Trans. on Antennas Propagat., vol. 58, no. 8, pp. 2571-2579, 2010.
6. Lau J., and Hum, S., “A wideband reconfigurable transmitarray element,” IEEE Trans. on Antennas Propagat., vol. 60, no. 3, pp. 1303–1311, 2012.
7. Bialkowski M. E. and Song, H. J., “A Ku-band active transmit-array module with a horn or patch array as a signal launching/receiving device,” IEEE Trans. Antennas Propag., vol. 49, no. 4, pp. 535–541, 2001.
8. Delisio M. P. and York, R. A., “Quasi-optical and spatial power combining,” IEEE Trans. Microw. Theory Tech., vol. 50, no. 3, pp. 929–936, 2002.
9. Kaouach, H., Dussopt, L., Sauleau, R., and Koleck, T., “Design and demonstration of 1-bit and 2-bit transmitarrays at X-band frequencies,” Proceedings of the 39th European Microwave Conference, pp. 918–921, 2009.
10. Phillion R. H and Okoniewski, M., "Array lens antenna using element rotation," in Proc. 13th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM), 2009.
11. Yu, A., Yang, F., Elsherbeni, A. and Huang, J.,“An x-band circularly polarized reflectarray using split square ring elements and the modified element rotation

technique," in Proc. IEEE Antennas and Propagation Society International Symposium AP-S 2008, 2008, pp. 1–4.

12. Ryan, C. G. M., Chaharmir, M. R., Shaker, J., Bray, J. R., Antar, Y. M. M., Ittipiboon, A., "A wideband transmitarray using dual-resonant double square rings," IEEE Trans. on Antennas Propagat., vol. 58, no. 5, pp. 1486–1493, 2010.
13. Kaouach, H., Dussopt, L., Sauleau, R., and Koleck, T., "Design and demonstration of an x-band transmitarray," in European Conf. Antennas and Propag. 1191-1195, 2009.
14. McGrath, D., "Planar three-dimensional constrained lenses," IEEE Trans. on Antenna and Propag., vol. 34, no. 1, pp. 46-50, 1986.
15. Lafond, O., Fuchs, B., Palud, Caillet, S. M., Himdi, M., Rondineau, S. and Le coq, L., "Reconfigurable antenna in mm-waves based on strati- fied lens and sources array," in Proc. 3rd Eur. Conf. Antennas Propag., Berlin, Germany, 2009, pp. 2838–2841.
16. Lau, J. Y., Hum, S. V., "Reconfigurable transmitarray design approaches for beamforming applications," vol. 60, no. 12, pp. 5679–5689, 2012.
17. Clemente, A., Dussopt, L., Reig, B., Sauleau, R., Potier, P., Pouliguen, P., "Reconfigurable unit-cells for beam-scanning transmitarrays in X-band ," 7th European conference on Antennas and Propag. (Eucap), pp. 1783–1787, 2013.
18. Clemente, A., Dussopt, L., Sauleau, R., Potier, P., and Pouliguen, P., "1-Bit reconfigurable unit cell based on PIN diodes for transmitarray applications in V-band," IEEE Trans. on Antenna and Propag., vol. 60, no. 5, pp. 2260–2269, 2012.
19. Hum, S. V., and Carrier, J. P., "Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review," IEEE Trans. on Antenna and Propag., vol. 62, issue. 1, pp. 183-198, 2014.
20. Lau, J. Y., "Reconfigurable transmitarray antennas, "PhD dissertation, University of Toronto, 2012.
21. Phillion R. and Okoniewski, M., "Analysis of a transmit-array antenna for circular polarization," in Proc. 26th International Review of Progress in Applied Computational Electromagnetics, pp. 1–4, 2010.

22. Pozar, D. M., “Flat lens antenna concept using aperture coupled microstrip patches,” IEE Electronics Letters, vol.32, no. 23, 2109–2111, 1996.

23. Clemente, A., Dussopt, L., Sauleau, R., Potier, P., Pouliguen, P., and Leti, C. E. A., “Design and characterization of 2-bit passive unit cells and transmitarrays in X-band,” 6Th Eur. Conf. on Antennas Propag., EuCAP ., pp. 1484–1487, 2011.

24. Chen, Y., Chen, L., Yu, J., Shi, X., “A C -band flat lens antenna with double-ring slot elements,” IEEE Antennas and Wirel. Propag. Lett., vol. 12, pp. 341–344, 2013.

25. Padilla, P., Acevedo, A. M., Sierra-Castaner, A. M., “Passive microstrip transmitarray lens for Ku band,” in Proc. 4th European Conference on Antennas and Propagation EuCAP., pp. 2–4, 2010.

26. Perotoni, M. B., Rondineau, S., Lee, R., Consonni, D. and Popovi, Z., “X-band discrete lens array for a satellite communication ground station antenna,” IEEE Trans. On Antennas Prop., pp. 197–200, 2005.

27. Padilla, P., Sierra-Castañer, M., “Transmitarray for Ku band”, European Conference on Antennas and Propagation (EuCAP 2007), pp.1-5, 2007.

28. Easton, R., “Basic principles of imaging science II,” Chester F. Carlson Centre for Imaging Science, 2005.

29. Hannan P. and Balfour, M., “Simulation of a phased-array antenna in waveguide,” IEEE Trans. on Antennas Propagat., vol. 13, pp. 342–353, 1965.

30. Storer, J. E., Sheingold, L. S., Stein, S.,“A simple graphical analysis of a two-port waveguide junction,” Proceeding of the IRE, vol. 41, no. 8, pp. 1004-1013, 2007.

31. IEEE standard test procedures for antennas, IEEE Standard 149TM, 1979, Reaffirmed December 10, 2008.

32. Booker, H. G., Rumsey, V. H., Deschamps, G. A., Kales, M. I. and Bohnert, J. I., “Techniques for handling elliptically polarized waves with special reference to antennas,” Proceedings of the IRE, vol 39, pp 533–52, 1951.

33. Kaouach, H., Dussopt, L., Sauleau, R., and Koleck, T., “X-band transmitarrays with linear and circular polarization,” in Proc. 4th European Conference on Antennas and Propagation EuCAP., pp. 1–5, 2010.

34. Ryan, C. G. M., Chaharmir, M. R., Shaker, J., Bray, J. R., Antar, Y. M. M., and Ittipiboon, A., "A wideband transmitarray using dual-resonant double square rings," IEEE Trans. on Antennas Propag, vol. 58, no. 5, pp. 1486 –1493, 2010.
35. Phillion, R. H., and Okoniewski, M., "Lenses for circular polarization using planar arrays of rotated passive elements," IEEE Trans. on Antenna and Propag., vol. 59, no. 4, pp. 1217–1227, 2011.
36. Kaouach, H., Dussopt, L., Lanteri, J., Koleck, T., and Sauleau, R., "Wideband low-loss linear and circular polarization transmitarrays in V-band," IEEE Trans. Antennas Propag., pp.2513-2523, 2011.
37. Padilla, P., Sierra-Castañer, M., "Design and prototype of a 12 GHz Transmitarray," Microw. Opt. Technol. Lett., vol. 49, no. 12, pp. 2152–2155, 2007.
38. Barba, M., Carrasco, E., Encinar, J. A., "Suitable planar transmit-arrays in X-band", European Conference on Antennas and Propagation (EuCAP 2006), pp. 1-6, 2006.
39. Thornton, J., Huang, K. C., "Modern lens antenna for communications engineering," IEEE Press, pp. 18-44, 2012.
40. Kin- Lu Wong, "Compact and broadband microstrip antennas," John Wiley & Sons, Inc., pp. 23-52, 2002.
41. Barba, M., Carrasco, E., Encinar, J. A., "An X-band planar transmitarray," 30th ESA Workshop on Antennas for Earth observation, Science, Telecommunication and Navigation Space Missions, pp. 236-239, 2008.
42. Rajaraman, R., "Design of wideband Vivaldi antenna array for the snow radar", Master's thesis, Coimbatore, India.
43. Abdelrahman, A. H., Elsherbeni, A. Z., and Yang, F., "Transmitarray antenna design using cross-slot elements with no dielectric substrate," IEEE Antennas and Wirel. Propag. Lett., vol. 13, pp. 177–180, 2014.
44. Abbaspour-Tamijani, A., Sarabandi, K., Rebeiz, G. M., "A millimetre-wave bandpass filter–lens array," IET Microw. Antennas Propag., Vol. 1, No. 2, 388 – 395, April 2007.

45. Abbas Abbaspour-Tamijani, “Novel Components for Integrated Millimeter-Wave Front-Ends,” PhD dissertation, The University of Michigan, 2004.
46. Padilla P., De La Torre, “Contribution to analysis and design of transmitarray lenses,” PhD dissertation, Technical university of Madrid, 2009.
47. Datthanasombat, S., Prata, A., Amaro, L. R., Harrell, J. A., Spitz, S., and Perret, J., “Layered lens antennas,” IEEE Antennas Propagat. Symp. Digest, Vol.2, pp.777-780, 2001.
48. Rajagopalan, H., Xu, S., and Samii, Y. R., “Reflectarray reflection phase diagnostics,” IEEE International Symposium on Antennas and Propagation (APS/URSI), Washington,USA, pp. 1636-1638, 2011.
49. CST, 2013, http: //www.cst.com.
50. Zubir, F., Rahim, M. K. A., Ayop, O., Wahid, A., Majid, H. A., “Design and analysis of microstrip reflectarray antenna with minkowski shape radiating element,” Progress In Electromagnetics Research B, Vol. 24, pp.317 – 331, 2010.
51. Rectangular waveguide dimensions, http: //www.microwaves101.com.
52. Tin Komljenovic, “Lens antenna analysis and synthesis at mm-waves,” http://www.fer.hr/download/repository/kvalifikas cijski rad komljenvic.pdf.
53. Wahid, A., Rahim, M. K. A., Zubira, F., Ismaila, M. F., “Dual layer microstrip reflectarray composed of two stacked arrays with minkowski and square shaped radiating element,” Jurnal Teknologi, Vol 58, pp. 13-18, 2012.
54. Stockmann J., and Hodges, R., “The use of waveguide simulators to measure the resonant frequency of Ku-band microstrip arrays,” IEEE Antennas Propag. Soc. Int. Symp., vol. 1A, no. 1, pp. 417–420, 2005.
55. http://www.measurementest.com/2010/09/how-to-measure-antenna-gain-part-1-gain_08.html.
56. Godi, G., Sauleau, R., Le Coq, L. and Thouroude, D., “Design and optimization of three dimensional integrated lens antennas with genetic algorithm,” IEEE Trans. on Antennas Propagat., vol. 55, no. 3, pp. 770-775, 2007.
57. Kida, S., Awai, I., “Flat lens antenna with antireflection layers based on artificial dielectrics,” China-Japan Joint Microwave Conference, pp. 415-418, 2008.

58. Foegelle, M. D., “Antenna pattern measurement: concepts and techniques,” Compliance Engineering, Compliance Engineering 19, No. 3, pp. 22-33, 2002.

59. Awai, I., Kida S., and Mizue, O., "Very thin and flat lens antenna made of artificial dielectrics," Proc. Korea-Japan Microwave Conference, pp.177-180, 2007.

60. Volman, V., “Wide band flat antenna for mobile microwave terminals,” Satellite Systems for Mobile Communications and Navigation, Conference Publication No. 424 lEE, 1996.

61. Multisim, 2013, http: //www.ni.com/multisim.

62. Kaouach, H., Dussopt, L., Sauleau, R., “Modeling, design and demonstration for discrete lens antenna with circular polarization in the 60 GHz Band” Int. J. of Res. in Wireless Syst., Vol.1, Issue 1, pp.7-15, 2012.

63. Hum, S. V., Okoniewski, M., and Davies, R. J., “Modeling and design of electronically tunable reflectarrays,” IEEE Trans., on Antennas and Propag., vol. 55, no. 8, pp. 2200–2210, 2007.

64. Lau J. Y., and Hum, S. V., “Analysis and characterization of a multipole reconfigurable transmitarray element,” IEEE Trans., on Antennas and Propag., vol. 59, no. 1, pp.70 -79 2011.

65. Garg, R., Bhartia, P., Bahl, I., Ittipiboon, A., “Microstrip antenna design handbook,” Artech house Boston, MA, 2001.

66. Orban D., and Moernaut G. J. K., “The Basics of Patch Antennas, Updated,” Edition of the RF Globalnet (www.rfglobalnet.com) newsletter, 2009.

67. Panday V. K., and Vishvakarma, B. R., “Analysis of an E-shaped patch antenna,” Microwave and Opt. Technol. Lett. Vol.49, no 1, pp.4-7, 2007**.**

68. Zhang X. X. and Yang, F., “Study of a slit cut on a microstrip antenna and its applications,” Microwave Opt. Tech. Lett., vol.18, pp.297-300, 1998.

69. Bahl, I., “Lumped elements for RF and microwave circuits,” Artech House, Boston, pp.456-459, 2003.

70. Terman, F. E., “Electronic and radio engineering, Tokyo, pp.10-80, 1955.

71. Liu, L., Ghassemlooy, Z., Sambell, A., Danaher, S., Lu, Q. and Korolkiewicz E., “Investigation of transformers’ turn ratios and design procedure for an aperture

coupled slot antenna". IEEE Proceedings on Microwaves Antennas and Propagation, pp. 61-65, 2006.

72. Wai-Kai Chen, "The circuits and filters handbook," CRC Press, 2002.
73. Hum, S. V., Okoniewski, M., and Davies, R. J., "Modeling and design of electronically tunable reflectarrays," IEEE Trans. on Antennas and Propag., vol. 55, no. 8, pp. 2200– 2210, 2007.
74. Pous R., and Pozar, D. M., "A frequency selective surface using aperture couples microstrip patches," IEEE Trans. on Antennas and Propag., vol. 39, pp. 1763–1769, Dec. 1991.
75. Ben A. Munk, "Frequency selective surfaces: Theory and design," John Wiley & Sons, 2000.
76. Singh, D., Kumar, A., Meena, S., Agarwala, V., "Analysis of frequency selective surfaces for radar absorbing materials," Progress In Electromagnetics Research B, Vol. 38, 297 - 314, 2012.
77. Stutzman, W. L., "Antenna Theory and Design," 2nd Edition, John Wiley and Sons, Hoboken, NJ.1997.
78. Kaouach, H., Dussopt, L., Lanteri, J., Koleck, T., Sauleau, R., "Circularly-polarized discrete lens antennas in the 60-GHz band," ICECom, Conference Proceedings, vol., no., pp.1-4, 20-23, 2010.
79. Iwasaki, H., "A circularly polarized small-size microstrip antenna with a cross slot," IEEE Trans. on Antennas and Propag., vol. 44, no. 10, pp.1399 -1401 1996.
80. Huang, C. Y., Wu, J. Y., and Wong, K. L., "Cross-slot-coupled microstrip antenna and dielectric resonator antenna for circular polarization," IEEE Trans. on Antennas and Propagat., vol. 47, pp.605 -609 1999.
81. Sohail, I., Ranga, M. Y., Esselle K. P. and Hay, S. G., "A linear to circular polarization converter based on jerusalem cross frequency selective surface," 7Th European Conference on Antenna and Propagation, (EuCAP), pp.2141-2143, 2013.