Design of a Novel Flat Array Antenna for Radio Communications

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ABSTRACT

In mobile microwave communication, reflector antennas have widely been used for very long time. Flat array antennas which have very rigid structure are being used in satellite communication, radar and airborne applications. These antennas are relatively smart in size and have more rigid structure than reflector antennas. The $32 \times 32$ elements vertical polarized slotted waveguide flat array antenna is presented in this thesis, The sub-array and feed waveguide network are set up and simulated by 3D-Electromagnetic Software HFSS. This array can have over 4.3% reflection and radiation bandwidth, low side lobe and back lobe. So it has potential application value in radio communication.
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All praises to ALLAH, the cherisher and the sustainer of the universe, the most gracious and the most merciful, who bestowed us with health and abilities to complete this project successfully.

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CHAPTER 1

1 INTRODUCTION

With recent development in the field of telecommunication, wireless communication became an important part of today’s communication system. In the past decades, huge research has been made on this particular area. After evolution of cellular systems, an important aspect of the research became cheap and reliable communication.

Electromagnetic spectrum is divided into sub frequency bands. Frequency band between 7GHz to 40 GHz is known as microwave frequencies. This microwave spectrum is divided into sub frequency bands. Frequency band between 12GHz to 18GHz is known as Ku band that is mostly used in cellular networks for point-to-point transmission.

Antenna is fundamental part of wireless communication. From the past decades, various types of antennas are being used for point-to-point transmission in cellular networks. Among them, reflector antennas are more common in wireless networks because of certain features it has.

Reflector antennas are used widely in microwave transmission stations at the moment. The structure of this kind of antenna is simple, usually composed with two parts, the feed horn and the reflector plate. It can be produced rapidly and easily in telecommunication system, the performances of reflector antenna must follow the ETSI (European Telecommunication Standards Institute) or the others, depending on the different
application areas. These standards regulate the radiation pattern envelopes of telecommunication antennas in different frequency bands.

Another type of antenna known as flat array antenna, which was developed for microwave frequency band. But till now, this antenna is being used in satellite and radar communication. A study has been made in this thesis report, to use flat array antenna in microwave transmission of cellular systems.

Flat array antennas are composed of amount of antenna units. There are many forms of antenna units, horn waveguide, slotted waveguide, micro-strip patch, dipoles and so on. By using array antenna, you can get arbitrary gain and antenna area freely. Slotted-waveguide antenna arrays are attractive for many millimeter-wave radar and communication applications because of their low loss, high efficiency and flatness. These antennas may be either standing-wave or travelling-wave arrays of various radiating slots. Standing-wave arrays have a broadside beam at the centre frequency but a narrow reflection and gain bandwidth, while travelling arrays produce a broad reflection/gain bandwidth. They have a tilted beam from the broadside at the off-centre frequency. In both arrays, the beam directions are frequency dependent [6]. Because we need the main beam toward the stable direction, the standing-wave array form is chosen. For all these advantages, we want to make a design of this kind of antenna and show the possibility of applying it in microwave transmission of cellular networks.

The microwave transmission of mobile application have more than 10 sub-frequency bands, from 7GHz to 40 GHz as usual, nowadays, even much higher frequency bands. In this thesis we take 15GHz sub-frequency band to analyze. Our target is to form an array antenna to work in 14.7-15.35 GHz with the gain of 37 dB, and the low side lobe and back lobe. To fit all these important parameters, the array size needs to be $32 \times 32$ elements at least. This antenna is composed of 8 elements sub-array and a feed waveguide network, which offers every sub-array the equal amplitudes and phases. The sub-array is a radiation waveguide with 8 slots and all the $32 \times 4$ sub-array lay on the first
layer and the second layer is the feed waveguide network. Between these two layers, there is the couple slot.

In this thesis we have set the model of sub-array and the feed waveguide network in HFSS, and then simulated the structure and parameters. Radiation pattern envelops of sub-array and full array are shown. From those graphs, the values of directivity at various angles are determined. Another area of our research was finding the values of voltage standing wave ratio (VSWR) of the newly designed antenna. This is one of important parameters to be determined in order to evaluate the exact performance of an antenna. The simulation results tell us that the proposed model of slotted waveguide array antenna has an acceptable value of VSWR which motivates its use in mobile microwave transmission.

The rest of report is organized as follows. In Review of state of art, the brief development of conventional antennas being used in mobile microwave transmission is introduced. This chapter contains the description of these antennas as well as brief operational principles. The development in design and principles of Flat array antennas is also included in this chapter. In the last chapter of Conclusion, we have concluded the work we have done and its significance. Also recommendations about future work have been made in this chapter.

In Chapter 2, we analyzed the features of reflector antennas being used in mobile microwave transmission. Specifically Cassegrain and Sputtering antennas are considered because of their wide usage. Their configuration and parameters at various bands are analyzed. The research work on Slotted Wave guide Array Antennas is important part of this section. Different applications developed by Slotted Wave guide array antennas are also presented in this part.

In Chapter 3, we presented the design part of our antenna waveguide. HFSS is used to build our model. All the simulation results are presented in this section. We mainly discussed the gain and voltage standing wave ratio as performance parameters.
In Chapter 4, we concluded what we have done. The qualities and drawback of our proposed model is written in this chapter. Some recommendations for improvement of the results are also given there.
CHAPTER 2

2 REVIEW OF STATE OF THE ART

With the increasing demands of communication, microwave communication has been accepted as one of significant part in today’s communication systems. Advantages like wide bandwidth, availability of multiple channels and wireless has made microwave communication popular in wireless environment. One of the limitations of microwave transmission is the need of line-of-sight (LOS) for effective communication.

The electromagnetic spectrum in microwave frequency range is divided into sub-bands. The frequency band we are going to consider is Ku band which lies just below the K band. According to IEEE Standard 521-2002, it ranges from 12 GHz to 18 GHz. Earlier application of this band was in satellite communication such as in NASA’s Tracking Data Relay Satellite. The International Telecommunication Union (ITU) has divided this band into multiple segments depending on geographical area. National Broadcasting Company (NBC) from America is the first company which uplink its feeds using Ku band in 1983.

Ku band has certain advantages which compel its use in mobile microwave transmission. For example in C band one must need to reduce the power to decrease interference. But in Ku band reducing power is not the only way of decreasing interference. So keeping a fix threshold of interference, we can increase power that will result in size reduction of antennas [1]. Comparing Ku with Ka band, Ku is less vulnerable to fading due to rain fall than Ka band.
One of the fundamental requirements of microwave transmission is the need of a suitable antenna. Different antennas have been designed for microwave transmission such as twist Cassegrain antennas, shaped-reflector antennas, micro strip antennas, slotted-waveguide array antennas, omni-directional antennas, electronically steered-array antennas and flat array antennas. The applications of these antennas include communication in radar, satellite, ground, navel, airborne and space environments. The requirements such as high gain, front to back ratio, voltage standing wave ratio etc. has made R&D work a major challenge for researchers. A brief description of a few microwave antennas is mentioned here.

2.1 Reflector Antenna

Many kinds of reflector antennas have been in use since 1888. They are developed from World War II when the radar applications spread. The spectacular process in development of analytical and experimental techniques for reflector shaping and optimization of illumination over reflector’s aperture so that the gain can be maximized, was the result of demands that arose in field of radio astronomy, microwave and satellite communication. In the 1960’s, the use of reflector antennas in space programs, especially its successful deployment on surface of moon, made this a very well known antenna type. Reflector antennas are developed with different geometrical configurations like plane, curved and corner reflectors as shown in Figure 2.1. Huge research has been made about design and their analysis by researchers [11, 15].
Huge utilization of Cassegrain is being made in low noise applications, e.g. radio astronomy. As this antenna provides a good tradeoff between cost and performance, so its use is being made in very diverse applications. One must understand these tradeoffs while design process in order to achieve a cost-effective solution. For designing large reflectors not only huge budget is required, but also a complex structure needs to be addressed [13].

2.1.1 Cassegrain Antenna

In Cassegrain antenna there is a special arrangement in which the incident rays are focused to one point using two reflectors instead of one. To design such arrangement primary reflector must be of parabolic shape and the sub-reflector must be hyperbolic shaped. The feed or head unit is placed along the axis of parabolic reflector near to the vertex. This arrangement is known as back feed. Figure 2.2 illustrates this arrangement. This unique combination of main parabola reflector and secondary hyperbola reflector...
was used in the construction of telescopes and was later adopted for radio frequency systems. The rays reach the primary reflector after deflecting from the sub-reflector which is illuminated by them before the reflection. If the point of origination of these rays happens to be the focal point of the primary reflector, then these rays are converted to parallel rays after reflection. Of course the primary condition of primary parabola and the secondary hyperbola reflector need to be met [13].

![Figure 2.2 The arrangement of Cassegrain antenna [21].](image)

Because of the secondary reflector, the designs of said antennas have very bulky and complex feeds such as those used in satellite communication. The mechanism of complex feeds can be placed behind the primary reflector. Another advantage of secondary reflector is flexibility in beam shaping. We can shape the beam by modifying the design of secondary reflector. The main dish (primary reflector) is the most costly part of this antenna which is made of metal. Plastic made reflectors are available but are more venerable to climate and need complex design technology.

A lot of research work has been done on design issues of Cassegrain antenna. A parametric study of shaped Cassegrain antenna is made by R.A. Kennedy [2]. Numerical analysis is made on both shaped reflector and classical paraboloid/hyperboloid geometry Cassegrain antennas. Main focus of the study is to achieve desired value of gain and beam shape by moving the feed and sub-reflector on axis of reflector system. For the best performance of reflector at lower frequencies, higher feed offsets are needed. So adjusting only the sub-reflector is not sufficient to achieve the desirable directivity and
beam shape. Kennedy came out with some useful rules for designing shaped Cassegrain antennas mentioned here [2].

Over wide range of frequencies, the optimum results can be achieved by positioning the feed with frequency dependent manner, not on geometrical focus. This can be done by performing numerical analysis. Instead of fixed reflector, there must be a movable reflector that is present in most of reflector systems. Reflector geometry must be considered for sub-reflector illumination [2].

Another key feature to be considered during design is the VSWR. Research has been done in the past to maximize efficiency and simultaneously decreasing VSWR. One way of achieving desired standards is sub-reflector shaping. In [3], it is proved that improvements can be made appropriate designing the sub-reflector without making change in the main reflector. In smaller antennas, the feed and sub-reflector are very close imposing two effects. VSWR gets increased as the power from sub-reflector re-enters to the feed. Secondly, the overall radiation pattern also gets distorted.

Potter attempted to resolve this issue by designing sub-reflector using spherical wave expansion techniques. In this way, a null is produced on axis of far field of sub-reflector. This accompanies two flaws. First, the feed is located at sub-reflectors near field. So the substantial on axis fields may exist in this region. Secondly, from practical point of view that seems to be difficult because of design complexity of both feed and sub-reflector [4].

G.T. Poulton has come up with solution free from above mentioned flaws. A naval design has been introduced that is optimal in terms of maximized gain and limited VSWR. Since two parameters are involved, there must be a tradeoff for the final or optimal solution. After theoretical work and empirical results done by Poulton, the idea about finding optimum solution considering maximized gain and reduced VSWR is possible. Figures 2.3 and 2.4 illustrate the empirical test performed by him to achieve high gain and low VSWR [5].
Figure 2.3 VSWR plots of the Cassegrain antenna presented in [5].

Figure 2.4 Radiation pattern of Cassegrain antenna presented in [5].
The Cassegrain arrangement is not without its limitations. One of the most common is diffractions which mostly occur at the edges of the secondary and primary reflectors. The system's overall response is greatly affected by the diffractions occurring around the edges of both the reflectors. Though the system's response in low intensity regions is more susceptible to errors caused by diffraction, great care should be taken at regions of high intensity too, if fine ripple pattern is required. To make the Cassegrain arrangement relatively more desirable and easy to use, the transmitting and reflecting arrangement consisting of waveguides and 'front 'electronics can be mounted behind the primary reflector. This in turn also increases the aperture efficiency [13].

The reflector having a parabolic shape can be of two different forms. The first form has the configuration of a parabolic right cylinder as shown in Figure 2.5. The energy in this form is concentrated parallel to the axis of the cylinder, through the focal point of the parabolic reflector. Linear array, linear dipole or slotted waveguide are usually considered feed for this form of the reflector [13].

Figure 2.5 Parabolic right cylinder [13].
The second form has the configuration of a paraboloid also known as parabola of revolution. This configuration is shown in the Figure 2.6. This arrangement is formed by rotating the parabola around its axis. Mostly, this configuration uses a pyramidal or a conical horn as its feed. Among large aperture ground-based antennas paraboloidal reflectors are the most widely used [10]. At the time of its construction, the world’s largest fully steerable reflector was the 100m diameter radio telescope [11] of the Max Planck Institute for Radio Astronomy at Effelsberg, Germany, while the largest in the United States was the 64m diameter [12] reflector at Goldstone, California built primarily for deep-space applications.

When used effectively, i.e. fed from its focal point, these reflectors produce a high-gain with narrow beam having low side lobes. This type of antenna finds its application in
low-noise fields for instance radio astronomy. Moreover, it provides a good compromise between effectiveness and cost. Owing to the severe weather conditions that an antenna withstands plus its huge structure requires a large financial budget for its erection and assembly. Cassegrain designs have efficiencies of 65–80%. With their dual-reflector surfaces, their use in satellite ground-based systems where pattern control is essential is widely increasing. The use of dual reflector makes them superior to the single reflector front fed arrangement by about 10%. The unique Cassegrain configuration consisting of a paraboloid and a hyperboloid, is designed to achieve a uniform phase front in the aperture of the paraboloid. Spill over can be reduced and uniform illumination of the reflector can be achieved by applying good feed designs. A uniform amplitude and phase with a substantial enhancement in gain can be achieved by slight modification in the shape of the reflectors [10]. Reflectors with modified shape are called shaped reflectors and they find their applications in satellite earth-stations.

By utilizing two-reflector system, the performance of large ground-based microwave reflector antennas for satellite tracking and communication can be improved considerably. For the utilization of Cassegrain dual-reflector system in optical telescopes, the required collimation characteristics must be achieved, the main reflector must be a paraboloid and the smaller must be a hyperboloid. The use of sub-reflector in the arrangement gives the additional edge of achieving goals in number of versatile applications. Without considering the diffraction techniques, its performance can never be accurately examined.

Few of the generally known benefits of the Cassegrain arrangements are as follows:

1. The place of the feed can be easily altered.
3. A focal length much shorter than the physical length can be obtained.
4. By moving the reflecting surfaces beam can be broadened and scanning can be achieved.

The sub-reflector must be a few wavelengths in diameter, if good radiation characteristics are to be achieved. However, it cannot be used as a microwave antenna as its presence
introduces shadowing. The gain of the system is degraded by shadowing, unless the main reflector is several wavelengths in diameter. The applications which require gain of 40dB or more usually use the Cassegrain. However, aperture blocking by the sub-reflector can be minimized by a variety of techniques. Some of these techniques are:

1. Minimum blocking with simple Cassegrain.
2. Twisting Cassegrains for least blocking.

![Diagram of virtual-feed concept](image)

**Figure 2.7** Virtual-feed concept [19].

### 2.1.2 Sputtering reflector antenna

There is also another special form of parabolic antenna sputtering reflector which is widely used in microwave transmission. Sputtering reflector antenna is one kind of two
reflector surface antenna. The main reflector surface does not modify the shape of the beam; the work was done by medium surface.

It is composed of three parts, the feed, sputtering board and medium, shown in the Figure 2.8. Commonly, engineers applied circle waveguide as the feed for this kind of antenna. The sputtering board is made of flat metal board as usual. The medium can uphold the feed and the sputtering board, through the selecting of the dielectric constant; we can modify the medium surface to make the refraction wave fill the distribution requirements when it is reflected to the aperture of the antenna.

![Configuration for Sputtering reflector antenna.](image)

Comparing with the other reflector antenna, sputtering reflector antenna has some advantages:

1. It turns the front feed to back feed.
2. Using medium surface as upholder and sputtering board as sub-reflector, the overall structure is reduced.
3. The electromagnetic waves which are off the illumination angle of the feed refract inside surface of the medium, and then illuminate the sputtering board.
After several reflections and refractions, at last they arrive at the main reflector. In this way, the feed illumination efficiency is increased.

4. We can modify the sub-reflector and the medium to control the phase and amplitude distribution on the aperture of the antenna.

5. Because sputtering reflector antenna uses the standard parabolic shape main reflector, it can be easy produced and lower the cost.

6. Comparing with Cassegrain, Gregorian Antenna, it does not need sub-reflector strut, easy for installation, transportation.

2.1.3 Slotted Waveguide Array Antenna

Slotted waveguide array antennas are being widely used in high frequency systems like radars and navigation systems. They have advantages like simple fabrication, high efficiency and they radiate linear polarization with relatively small cross polarization. These type of antennas are very popular in aircraft applications because of their conformance to the type of surface on which they are mounted.

The width of the slots is made as narrow as possible. It is because to control cross polarization. For thin slots the fractional bandwidth is approximately between 3 to 5 percent while the wide slots may have fractional bandwidth up to 75 percent.
Figure 2.9 shows the structure of a slotted waveguide array antenna (SWAA). Length is given by parameter ‘a’ while width is shown by ‘b’. Each slot in this waveguide array could be fed independently through a suitable voltage source but practically that is not possible to do for large arrays.

A lot of research has been made on SWAA for different applications. A. K. Singh investigated for low cost, low side lobe and high efficiency non-orthogonally coupled slotted waveguide array antenna for monopulse radar tracking. The antenna requirements for modern airborne tracking radar system are analyzed. One of the critical things to consider in such case is that the side lobes must be very low. Considering the power consumption requirements it demands higher efficiency too. The SWAA can be a good choice for such case as such waveguide system is really low medium. Such demands, i.e. low side lobe and high gain at higher frequencies, exist both in military and non-military applications. In military applications, it includes missile technology and unmanned aerial vehicle (UAV). Weather radars and collision avoidance radars are included in non-
military applications of such antennas. Advantages like rugged and compact structure, high power handling and better radiation efficiency mechanically scanned SWAA has made them more useful in different radar application [14].

A. K. Singh has investigated a new manufacturing technique for non-orthogonally coupled resonant SWAA for monopulse tracking radar. A successful realization of diagonally coupled SWAA has been performed. The new idea presented in this paper is diagonal coupled quadrant division of radiation aperture. To couple the power from monopulse comparator output ports to array feed input ports, use of non-orthogonal slot coupler is made. A new joining process in antenna manufacturing is also presented which helps in fewer defections [14].

Also radiation pattern is divided into four quadrants diagonally. This is so to achieve monopulse capabilities and also to reduce mechanical complexities. A planar monopulse comparator network which is made of magic T junctions is used here. Figures 2.10 and 2.11 depict the hardware of the designed antenna [14].

![Figure 2.10 Back view of SWAA designed in [14].](image)
Figure 2.11 Front view of the SWAA designed in [14].

Figure 2.12 Radiation pattern envelop of the designed antenna in [14].
Figure 2.12 depicts the radiation pattern envelop of the designed antenna. The gain is greater than 29dB and peak side lobe level (SLL) is less than -28dB at 500MHz.

Figure 2.13 depicts the return loss in dB of the designed antenna. The VSWR of this antenna is less than 1.5.

SWAA in airborne and space borne synthetic-aperture radar (SAR) applications at higher frequencies is discussed in [15]. The authors presented a broadband dual polarized slotted waveguide array antenna. To obtain compact cross section of two linear polarized arrays, the use of ridged waveguide dividers is made. The design and process is done in Ansoft HFSS simulator which is considered as one of best antenna simulators.

A design has been made for dual-polarized slot array which consists of two sub-arrays i.e. horizontal polarized (HP) and vertical polarized (VP). HP is Untitled edge-slotted waveguide array antenna while VP is ridged slotted waveguide array. A dual polarized
sub-array can be obtained by development of linear VP and HP arrays. On each of the
arrays, there are 16 slots which are divided into group of two and then fed by a
waveguide divider. As ridge waveguide is used for VP linear array, the array has
achieved a compact cross section. The thickness of HP linear array is double of the width
of waveguide.

Several configurations for HP waveguide arrays are made. Figure 2.14 a and b shows the
dual ridged and single ridged waveguides instead of rectangular waveguides. Replacement of radiating waveguide with ridged waveguide is shown that is resulting
more compact ratio. Overlapping of radiating waveguide and feed waveguide finally
resulted in low profile of the array.

A dual polarized slotted antenna sub-array is formed by combining two linear arrays. To
achieve vertical polarization, a back-to-back ridged waveguide is used to feed broadband
ridged slotted antenna array. Also an asymmetric ridged waveguide is used to feed
asymmetric ridge waveguide array. The proposed HP and VP linear arrays are shown in
Figure 2.15.
The testing results by using Agilent 8722ES network analyzer shows the voltage standing wave ratio is less than 2. The input impedance bandwidth of VP linear array is 12% while it is 10% for HP linear array. In Figure 2.16, the testing results of VP linear array are shown.
The radiation patterns for both HP and VP linear arrays are measured in indoor near-field environment. It is observed that there is no significant impact on radiation patterns by changing frequencies. The measured radiation pattern and cross polarization plots are shown in Figures 2.17 and 2.18, respectively.
For HP linear array, the maximum side lobe level is -10.5dB and it is -12.2dB for VP linear array. The cross polarization level for HP linear array is 41dB below the main lobe and it is 40dB for VP linear array.

**Figure 2.17** Measured radiation pattern envelope plot [15].

**Figure 2.18** Measured cross polarization plot [15].
Figure 2.18 is showing excellent compression of cross polarized component. Henry and others [16] presents new idea in the design of antenna. This new concept is to use single photo-image-able (Figure 2.19) thick film combined with waveguide antenna in a multi-layer arrangement.

![Diagram of photo-image-able process steps]

Figure 2.19 Printing of photo-image-able process steps (a) printing; (b) exposure; (c) developing; (d) firing [16].

At high frequencies and high degree of repeatability this new antenna provides best performance and fine geometry. They also present new technique to fabricate the antenna as well as experimental results at 70 GHz frequency. 18 layers of photo-image-able substance are used in this antenna. They study and analyze the radiation pattern and calculate the losses in the substrate (Figure 2.20).
The concept of fabricating 3D integrated waveguides in the planar circuit verified successfully.

The beam antenna for low radar cross-section (RCS) applications is investigated in [17] presenting the design and testing of an offset. Its simulation and optimization is done by using HFSS s/w considering different parameters. It is characterized by the measurements of scattered and radiated parameters. The achieved measured results are pretty close to theoretical predictions and simulated results.

As slotted waveguide antennas are compact with rugged construction, reduced losses and high power handling capability, they are very popular for radar and communication applications. They attain less volume and are light weight leads to airborne applications. The technique used in radar tracking technique is Frequency Selective Surface (FSS) as radiomen over the antenna. FSS help to reduce the antenna RCS.

Another technique to reduce antenna RCS is use of offset beam.
Antenna slotted waveguides can be resonant or wave type. For resonant slotted waveguide antennas, the main beam is always pointed at normal to antenna aperture as the elements are spaced at half the guide wavelength. While for travelling wave, it must be positioned as the main beam at the desired angle. Slots are not required to be in half the guide wavelength for this case [17].

Array of antennas in this paper is simulated in HFSS. Simulation model is shown in Figure 2.21.

An offset-beam antenna 16.5GHz is simulated and fabricated at Ku-band. It is manufactured by using CNC milling machine. It is tested and assembled for S-parameters using Vector Network Analyzer.
Figure 2.22 depicts the radiation pattern envelope of 18 element linear array. Results achieved through this are discussed in [17] with the consideration of different parameters. At the end it is also concluded that the offset beam linear and planar slotted waveguide array can be used for low RCS applications.

Normally used radiator in antenna system is slot. Certain number of slots cut into the walls of a waveguide that forms an array. These arrays are highly efficient, mechanical simple, robust and highly reliable. L.P. Oliveira represented the simulation and measured results of slotted waveguide novel type antenna operating in X-band with vertical polarization [18].

This is an advantage in using slotted waveguide that slots integrated easily into an array feed system, as waveguide without a special matching network. The main point in [18] is observation that by increasing the width of vertical slot, its radiation level also increases and the vertical polarization remains constant.

For oil leakage monitoring on surface of ocean, engineers have designed a form of antenna. To achieve this application, they have to set some additional requirements. Due
the requirement of high power, the array constructed by using WR90 waveguide and the feed system manufactured using metallic waveguides [18]. In [18], authors ended up with the conclusion that as this kind of antenna exhibit low radiating efficiency due to slot positions, but the radiation power spread out can be controlled by modifying the slot. So frequency bandwidth below -19dB and side lobes below -20dB desired for their project to achieve modulating slots width following a quarter sinusoidal laws.

2.2 European Telecommunication Standards Institute

The SWAA we have modeled is following European Telecommunication Standards Institute (ETSI) standard. One of the major purpose of ETSI standards is the efficient use of the spectrum by radio communication equipment so that harmful interference can be avoided. The antenna is fundamental part of radio communication so these standards must be followed while designing. The specific document being followed in our work is **EN 302 217-4-2 V1.3.1 (2007-10)**. According to this standard the antenna supplier must provide the operating frequency band, the values of gain at edges of band and at mid frequency. Linear polarized wave should be radiated from the antenna. The single polarized antennas must meet radiation pattern envelope (RPE) and cross polarization detect ability (XPD) requirements also, if the frequency coordination is applied [9].

**EN 302 217-4-2 V1.3.1 (2007-10)** mainly focuses on radiation pattern envelope. For sake of simplicity, the RPE is divided into different classes shown in Table 2.1.
Table 2.1 RPE classes against frequencies in GHz [9].

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</tbody>
</table>

We are going to use frequency class 2, as the frequency band which we are going to use is 14.7 -15.35 GHz. The radiation pattern envelopes of three different antenna classes, falling in frequency class 2 are shown below.
Figure 2.23 ETSI radiation pattern envelope of class 2 antennas [9].

Figure 2.23 depicts the radiation pattern envelope of class 2 antennas. The horizontal scale represents angle in degrees relative to main lobe while vertical scale represents gain in dBi. Co-polar pattern is shown with solid black line while cross polar pattern is shown with gray color dashed line.
**Figure 2.24** ETSI radiation pattern envelope of class 3 antennas [9].

Figure 2.24 depicts the radiation pattern envelope of class 3 antennas. The horizontal scale represents angle in degrees relative to main lobe while vertical scale represents gain in dBi. Co-polar pattern is shown with solid black line while cross polar pattern is shown with gray color dashed line.
Figure 2.25 ETSI radiation pattern envelope of class 4 antennas [9].

Figure 2.25 depicts the radiation pattern envelope of class 4 antennas. The horizontal scale represents angle in degrees relative to main lobe while vertical scale represents gain in dBi. Co-polar pattern is shown with solid black line while cross polar pattern is shown with gray color dashed line.
CHAPTER 3

3 PROBLEM SOLUTION

The design frequency band used here is 14.7 - 15.35 GHz as this frequency is commonly used in mobile microwave transmission.

The dimensions of SWAA are defined by

\[ A_e = \frac{G \lambda^2}{4\pi \eta} \]  

(1)

Where \( A_e \) is effective area, \( G \) is gain of antenna in dB and \( \lambda \) is wavelength in free space, \( \eta \) is the efficiency of waveguide array antenna, that is equal to 0.75.

By placing appropriate values it tells us that we need total size 466 \( \times \) 466mm to meet our requirements. So, we have 32 \( \times \) 32 elements and distance between elements is 0.5 \( \lambda_g \).

The equivalent normalized slot admittance \( Y \) can be obtained as follows:

\[ \frac{Y}{Y_0} = \frac{1 - \tau}{1 + \tau} \]  

(2)

where \( Y_0 \) is the waveguide admittance and \( \tau \) is the reflection coefficient, which is obtained from a simulation with the aid of the finite element method tool Ansoft’s HFSS.

3.1 Flat Resonant Array Design

Flat resonant array is composed by several resonant linear arrays. In airborne fire control radar, flat slotted resonant array need to have small cubage, light weight, the lever of side-lobes close the main lobe need to under -25 or -30 dB, high gain and mono-pulse.
Flat resonant usually divide the array to four quadrants, using plus and minus microwave network to connect them, then using plus and minus network to form one plus and two minus signals. The airborne fire control radar usually requires the antenna has 2-6% bandwidth. For fulfilling the requests of the bandwidth, we split every quadrant into several sub-arrays.

In Figure 3.1, the waveguide with long direction slots is called radiation waveguide; the geometrical size of every radiation waveguide is same. The waveguide which feed the radiation waveguide is called couple waveguide. These two kinds of waveguides are orthogonally placed. The feed power depends on the obliquity of the couple slot.

The radiation waveguide usually use standard waveguide, the narrow side wall of two contiguous waveguide is shared. To give the two contiguous waveguide 180 degree phase difference, the couple waveguide usually use un-standard waveguide.

The working bandwidth of slotted resonant flat array is an important parameter. Its bandwidth is related to the number of the slots in total. The solution to deal with this problem is to divide the array into several sub-arrays. When doing the antenna design, if we divide the whole array into more sub-arrays, the margin of bandwidth is bigger. But it will cause the complexity of the feed networks, and larger the cubage and weight of the array. So, to decide right number of the sub-array is also a problem for designers. The classic slotted waveguide array configuration is shown below in Figure 3.1.
3.1.1 The Theoretical Calculation of Antenna

1. If the distance between two contiguous elements and the impulse amplitudes are same, impulse phases are linear, this kind of line array called uniform line array. The array factor is:

\[ |f(\psi)| = \frac{\sin \frac{N\psi}{2}}{\sin \frac{\psi}{2}} \] (3)

In the function, \( \psi = \beta d \cos \theta - \alpha \), \( N \) is elements number, \( d \) is distance between contiguous elements, \( \alpha \) is phase difference between two contiguous elements, \( \theta \) is angle between observation direction and the line array, \( \beta \) is phase shift constant.

2. The position of the side lobe is the angle \( \psi_s \) of the maximum value of side lobe,

\[ \frac{d|f(\psi)|}{d\psi} = 0 \] (4)

\[ N \tan(\frac{\psi}{2}) = \tan(\frac{N\psi}{2}) \]

So, we can get \( \psi_s = \pm (2l + 1)\pi/N \), \( l = 1, 2, 3 \ldots \)
Side lobe level is

\[ SLL = 10 \log \frac{|E_s|}{|E_m|} \]  \hspace{1cm} (5)

In function, \(|E_s|\) and \(|E_m|\) is the maximum value of side lobe and main lobe. After calculating the position of the side lobe, we can get the first side lobe level, -13.5 dB.

\[ \frac{|f(\psi_{s1})|}{F(0)} = \frac{1}{N \sin(3\pi/2N)} \approx \frac{2}{3\pi} \]  \hspace{1cm} (6)

3. The direction coefficient is defined by function

\[ D = 4\pi \frac{s}{\lambda^2} \]  \hspace{1cm} (7)

The efficiency of antenna is

\[ \eta = \frac{G}{D} \]  \hspace{1cm} (8)

4. The resonant array bandwidth has an inverse ratio with the number of the slots, it has a relationship with the SWR and the number of the slots \(N\):

\[ SWR = 1 + \frac{2}{a^2} + \frac{2}{a^2} \sqrt{1 + \frac{1}{a^2}} \]  \hspace{1cm} (9)

where

\[ a = \frac{\frac{1}{\pi NB}^{2}}{\left[ \frac{3 \times 10^4}{\frac{300}{\pi NB}} \right]} \]  \hspace{1cm} (10)

and \(B\) is ratio of bandwidth

5. When \(Nd \gg \lambda\), the half power beam width \(BW_{0.5}\) has a relationship with \(N\) and \(d\),

\[ BW_{0.5} = 50.77 \frac{\lambda}{Nd} \]  \hspace{1cm} (11)

So, with \(BW_{0.5}\) and \(d\), we can get the total number of slots of the array.
3.2 Sub-Array Design

Figure 3.2 shows the geometry structure of 8 elements sub-array. The first layer is the radiation slots. The place of each slot bias from the centre of the radiation waveguide can get a 180° opposite phase, so all radiation slots have equal phases and amplitudes. The centre-feed configuration is used in the second layer to feed the radiation waveguide power. It increases the reflection bandwidth [8]. The terminal feed waveguide is \(1/4\lambda_g\) length to form a short circuit. In this study, the slot is round-ended, 2.0mm in width, 1.0mm in thickness, and placed at a quarter guided wave-lengths from the shorted wall. A correction is usually applied for the round-end effects of the slot after the rectangular slot has been modeled [6], but in this study they are included in the simulation. Data for the self-admittance, resonant conductance, and resonant length against slot offset are obtained at several points from the HFSS simulation [6]. Using HFSS to simulate the 3D model; we can get the radiation pattern envelope and reflection bandwidth shown in Figures 3.3 and 3.4. The gain of this sub-array can reach 15 dB in this frequency band, and use VSWR to measure the reflection bandwidth, in 14.7-15.35 GHz, the VSWR is less than 1.5.
Figure 3.2 Geometry of 8 elements sub-array.

Figure 3.3 Radiation pattern envelope of 8 elements sub-array.
3.3 Entire Array Design

By connecting all the sub-array and the feed waveguide network, we can get the profile of the whole array. The profile of the entire array is shown in Figure 3.5. From the simulation data, we can form the RPE of the entire array. In Figure 3.6, we can see that the gain of the array antenna in the RPE, it can reach 37dB, and the side lobe is low enough but the back lobe is not small enough to fit the ETSI standard (-20dB). There are some reasons. First, it’s the software problem that calculates the power level which is too low; it couldn’t calculate the accurate value, but assumable data. From many papers which is about array antenna analysis, we can see, all antenna engineers simulate and test the RPE of array antenna to side lobe region, usually it is $-90^\circ$ to $90^\circ$ in $\theta$ direction. Commonly, array antenna testing is done in this region, to test the accurate value of back lobe is really hard, it needs very rigorous testing condition. Second, today, to reduce research difficulty, we take uniform amplitude and phase array to study, it has higher efficiency and gain, and is a little bit simple to design and analyze. The Array antenna,
which has tailor distribution amplitudes, can lower the back lobe, but reduce the gain efficiency and increase a plenty of design complexity.

Figure 3.5 Geometry of whole32 × 32 array built in HFSS.
3.4 Feed Waveguide Network Design

3.4.1 Waveguide splitter

The waveguide splitter, which is a kind of microwave power divider, splits the microwave energy from the main waveguide to two or several roads. Commonly, there are three forms, E plane T, H plane T, and matching double-T.

3.4.1.1 E-T Splitter

E plane T-splitter has a branch on the main waveguide broadside surface, its axis is parallel to the main waveguide TE10 mode electric field, we call it ET branch. Its
structure and equivalent circuit is shown in Figure 3.7. From the equivalent circuit, ET branch equals to series branch waveguide with the main waveguide.

Figure 3.7 Structure and equivalent circuit E-T network.

When the microwave signal input from port “3”, is divided averagely to port “1, 2”, the two ports have the same amplitude but reverse phase of the TE10 wave. When port “1, 2” have reverse phase impulses, the port “3” combines the maximum output. When there is reverse phase impulses, port “3” there will has no output. The s-matrix of the network is:

\[
[s] = \begin{bmatrix}
\frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\
\frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\
-\frac{1}{\sqrt{2}} & -\sqrt{\frac{1}{2}} & 0 \\
\end{bmatrix}
\]  

(12)
3.4.1.2 H-T Splitter

HT has a branch on the narrow side of the main waveguide surface, its axis is parallel to the magnetic field of the main waveguide TE10 mode, its structure and equivalent circuit are shown in Figure 3.8, H-T circuit equals a parallel branch to the main waveguide.

When microwave signal enters from port "3", the port "1, 2" will output signals with same amplitude and in-phase. When there are in-phase same amplitude signals in ports "1, 2", the port "3" gives combined signal. When there are reverse phase same amplitude signals, port "3" will have no output. H-T scattering matrix is shown in Figure 3.8.

![Figure 3.8](image)

**Figure 3.8** Structure and equivalent circuit of H-T network.

The s-matrix of the network is:
\[ [s] = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \end{bmatrix} \] (13)

As we need to get uniform amplitude distribution for each element of the array, H-T waveguide splitter will be used to construct the entire network.

### 3.4.2 Entire Network Design

The whole feed waveguide network is composed by 31 T-Junctions, each terminal T-Junction feed 8 radiation waveguides and the configuration of the designed T-Junction is shown in Figure 3.9. From Figures 3.10 and 3.11, we can see, in the working frequency band, the splitting unit can get a good characteristic, the VSWR can be less than 1.15, and the splitting ratio is 3.02±0.02dB. The connection between feed network and radiation waveguide is oblique couple slots, the distance between which is 13.8mm, the wide wall 11.8 mm plus 2 thickness of the thin wall. This structure is compact and can prevent the back lobe power dill through. The fabric of the couple slots is shown in Figure 3.12.
Figure 3.9 Configuration of T-Junction.

Figure 3.10 Return loss of T-Junction.
Now 8 roads power splitter is constructed, which can feed a half entire array. It can estimate the return loss of the feed network. The configuration of the 8 roads power
splitter is shown in Figure 3.13. In Figure 3.14, the simulation result for VSWR is shown. Figure 3.15, depicts the power splitting ratio of the splitter. The VSWR of the whole feed network is lower than 1.3 and the splitting ratio is 9.05 ± 0.1.

Figure 3.13 configuration of the 8 roads power splitter.
Figure 3.14 The simulation result for VSWR.

Figure 3.15 Power splitting ratio of splitter.
CHAPTER 4

4 CONCLUSION

A 32×32 element slotted-waveguide array antenna was produced to provide a broad reflection and gain bandwidth. The sub-array concept was introduced and the two-layer compact producible feed network was proposed. Our simulation results indicate a broad gain of 4.3% with variation within 1 dB in vertical plane. The maximum gain is 37.2 dB at 15.35 GHz. The reflection bandwidth is 0.65 GHz based on system VSWR that is less than 2.0, the side lobe levels are less than -13.5 dB, and the 3 dB beam width is 2.2 degree in vertical plane at the desired frequencies. These results demonstrate that the 32×32 slotted-waveguide antenna array with a proposed two-layer feed network has a broad reflection/gain bandwidth. Though the simulation result of back lobe level couldn’t fit the ETSI standard, this problem can be solved by some special structure design on the edge of the array or use tailor amplitude distribution method. In conclusion, it has potential application value in radio communication.
References


