This reference book entitled ‘Design of Corrugated Linearly Tapered Slot Antenna for Wireless Application’ highlights the fundamental concepts, theories, principles, design and application related issues for Corrugated Linearly Tapered Slot Antennas. The graphical, and tabulated results, design equations, design steps, formulae, numerical and mathematical analyses produced here are of high quality and reliable. This book also includes the basic fundamentals of antenna.

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Design of Corrugated Linearly Tapered Slot Antenna for Wireless Apps
Design of Corrugated Linearly Tapered Slot Antenna for Wireless Apps

Theory and Principles
ABSTRACT

The many practical advantages of the Linearly Tapered Slot Antenna (LTSA) are based on its low cost, light weight and relative simplicity. The aim of this thesis is to propose a wide band, higher gain Corrugated linearly tapered slot antenna (CLTSA) with relatively low cross-polarization levels and also to investigate how different patterns of corrugations will affect the radiation characteristic of linearly tapered slot antenna. In the initial study, the design of a conventional TSA with an exponential taper was examined. Previously obtained radiation patterns show that conventional tapered slot antenna suffers from poor directivity in the lower part of band as well as it has poor E-field distribution over the radiating surface. To overcome this shortfall, corrugations will be added on its sides as well as along the tapered length. By comparing performances of the conventional and corrugated TSA it will be demonstrated that by choosing a suitable corrugation pattern the directivity, gain, E-field distribution and beam efficiency can be improved.

Corrugation structures are adopted on both sides of radiating elements to improve the radiation pattern. Current distribution is examined to analyze the effect of corrugation structure. Current distribution exclude tapered section of radiating element is caused radiation of unwanted direction which causes higher sidelobe and cross-polarization. Current path is arranged to be parallel and opposite in direction by placement of corrugation, thus helping them to minimize the radiation toward the undesired direction.

There are mainly three physical parameters that affect the radiation pattern of TSAs. These are antenna length, aperture width and the ground extension. First Microstrip line fed and then Coax line fed tapered slot antenna models are simulated with the use of a commercially available electromagnetic simulation software HFSS by ANSOFT.
ACKNOWLEDGEMENT

Project work, lays the foundation of student’s career today. The satisfaction that comes with successful completion of task would be but incomplete without the mention of the people who made it possible. It gives us immense pleasure to acknowledge all those who have extended their valuable guidance and magnanimous help.

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UNADKAT VIVEK M.
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<td>CLTSA</td>
<td>Corrugated Linearly Tapered Slot Antenna</td>
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<td>FEM</td>
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<td>HFSS</td>
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<td>First Null Beamwidth</td>
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<td>FCPW</td>
<td>Finite-Ground-Width Co-Planar Waveguide</td>
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CHAPTER 1

INTRODUCTION

Antennas have been used in the past for both military and commercial applications. The original use of antennas was confined primarily in communications radio transceivers operating in the MHz range. The antennas for military applications were used for radar systems and peer to peer communications between units. Most of those antennas were bulky (Figure 1) and costly and therefore accessible to a small, specialized category of people. In the last 20 years though, personal and mobile communications networks have developed rapidly, causing an increasing need for affordable, compact and easily integrated antennas. The increasing demand for cellular phone services, wireless internet access, wireless cable television, among others, will force such systems to provide high throughput, and therefore very large bandwidths as well as simultaneous access to different systems through the same device, which can be accomplished with multi-band technology.

![Fig. 1.1](a) circular horn, (b) pyramidal horn

As a result of the increasing need for gradually smaller and more affordable antennas a lot of research has been going on. The major need for commercial antennas concerns miniaturized planar antennas suitable for relatively small
mobile devices like cell phones or portable computers. Patch antennas (Figure 2), printed dipoles and slot antennas fall into that category. A special type of slot antennas, tapered slot antennas (Figure 3) will be the focus of this research project.

![Patch antenna](image1)

**Fig. 1.2 Patch antenna**

![Tapered Slot antenna](image2)

**Fig. 1.3 Tapered Slot antenna on dielectric substrate**

The need of wide operation diversity forces wireless communications systems to use different high frequency bands in the microwave and millimetre wave regions; frequency bands in which slot antennas are often used. However previously designed planner patch antennas are limited in bandwidth and gain. So a technique needed to increase the band width and gain in planner antennas is proposed in this research.
1.1 Aim and Objectives of the thesis

The aim of this thesis is to propose a wide band, higher gain Corrugated linearly tapered slot antenna (CLTSA) with relatively low cross-polarization levels and also to investigate how different patterns of corrugations will affect the radiation characteristic of linearly tapered slot antenna. Aiming to complete the design of this project on schedule is given the highest priority. During the literature survey about TSA, it is found that conventional tapered slot antenna suffers from poor directivity in the lower part of band. Consequently in this thesis, it is aimed to investigate the radiation characteristics of TSA and to explore the possibility of improving the radiation pattern and directivity of TSA. Throughout the course of the thesis, gaining a comprehensive understanding of travelling wave antennas, matching capabilities as well as microstrip and slotline characteristics will definitely provide useful knowledge for the future.

HFSS is a tool introduced due to the need to design and simulate different microwave devices and antennas. Being able to gain knowledge on HFSS will prove to be a useful tool for the present and future. This, together with learning and understanding how basic antennas generally work, are also aims of this project.

1.2 Background

Tapered slot antennas (TSA) are travelling wave antennas. In general, all antennas whose voltage or current distribution can be modeled by one or more travelling waves are called travelling wave (non-resonant) antennas. Unlike standing wave (resonant) antennas, the phase distribution along a traveling wave antenna cannot be assumed to be constant as stated in (Balanis, 1982). The reflected wave in resonant antennas is totally or partially minimized in the traveling wave antennas by proper termination. An example to this phenomenon
is the long wire antenna which is actually a resonant dipole antenna terminated by a matched load.

There are two types of traveling wave antennas: slow wave antennas and fast wave antennas. Slow wave antennas are antennas whose phase velocities are equal to or smaller than the speed of light. For surface wave antennas, a type of slow wave antennas, the radiation takes place at the discontinuities, non-uniformities and curvatures where the bound wave on the antenna surface is interrupted. The travelling wave antennas of this class are endfire or near endfire radiators. Fast wave antennas on the other hand have phase velocities larger than the speed of light. Consequently, leaky wave antennas are considered as fast wave antennas. This type of antenna couples power discretely or continuously through its length. The result is a tilted main beam from the endfire direction.

A tapered slot antenna uses a slot line etched on a dielectric material, which is widening through its length to produce an endfire radiation (Milligan, 2005). An electromagnetic wave propagates through the surface of the antenna substrate with a velocity less than the speed of light which makes TSAs gain slow wave antenna properties. The EM wave moves along the increasingly separated metallization tapers until the separation is such that the wave detaches from the antenna structure and radiates into the free space from the substrate end. The E-plane of the antenna is the plane containing the electric field vectors of the radiated electromagnetic (EM) waves. For TSAs, this is parallel to the substrate since the electric field is established between two conductors that are separated by the tapered slot. The H plane, the plane containing the magnetic component of the radiated EM wave runs perpendicular to the substrate.
TSAs have moderately high directivity (on the order of 10-17 dB) and narrow beamwidth because of the traveling wave properties and almost symmetric E-plane and H-plane radiation patterns over a wide frequency band as long as antenna parameters like shape, total length, dielectric thickness and dielectric constant are chosen properly. Other important advantages of TSAs are that they exhibit broadband operation, low side lobes, planar footprints and ease of fabrication. A TSA can have large bandwidth if it exhibits a good match both at the input side (transition from the feed line to slot line) and the radiation side (transition from the antenna to free space) of the antenna (Amena Kauser Syeda, 2003). The gain of a TSA is proportional to the length of the antenna in terms of wavelength. Tapered slot antennas are also suitable to be used at high operating frequencies (greater than 10 GHz), where a long electrical length corresponds to a considerably short geometrical length. The main disadvantage of the TSA is that only linear polarization can be obtained with conventional geometries.

Most common types are Linearly Tapered Slot Antenna (LTSA), Vivaldi or Exponentially Tapered Slot Antenna and Constant Width Slot Antenna (CWSA).

These three main types of TSAs are compared in (Yngvesson et al., 1989) in terms of beamwidths and sidelobe levels. For a TSA with the same antenna length, aperture width and substrate parameter, CWSA has the narrowest beamwidth, followed by LTSA and then Vivaldi. The sidelobe levels are highest for CWSA, followed by LTSA and then Vivaldi.

TSAs are first introduced in 1979 in the 9th European Microwave Conference by two independent presentations (Gibson, 1979), (Prasad et al., 1979). In (Gibson, 1979), an ETSA (Vivaldi) to be used in a 8-40 GHz video receiver module is proposed. The antenna had a usable bandwidth of 2-20 GHz with a
gain of approximately 10dBi and -20dB sidelobe level. Exponential taper was chosen in this work in order to achieve a wideband performance with an aperiodic continuously scaled structure. It is stated that the energy in the travelling wave on the tapered slot becomes weaker as the separation between the arms of the slot line increases and at last the energy couples to the radiated field.

In (Prasad et al., 1979), an X-band LTSA excited by a microstrip line on alumina substrate is proposed. The antenna was designed to be used in short range radar and phased array systems. The LTSA had a gain of 6dBi and a sidelobe level of -10dB. The antenna had a %5 bandwidth centered at 9 GHz. The slot width at the open end of the slot line was changed while keeping the antenna length constant and the change in the gain and sidelobe levels were observed.

In 1985, CWSA is proposed in (Yngvesson et al., 1985). In this study, the effective thickness value required for compliance with Zucker’s curves for travelling wave antennas are stated. Effects of the parameters of the dielectric substrate and the dimensions of the antenna on the radiation characteristics of the antenna were investigated experimentally for LTSA, Vivaldi and CWSA geometries.

Until 1986, only experimental studies had been conducted for the analysis of TSAs. The numerical analysis of TSAs through the use of Method of Moments (MoM) is first proposed by Janaswamy in his Ph.D. dissertation (Janaswamy, 1986). In 1989, Johansson also demonstrated the MoM analysis of LTSAs to determine the surface currents on the antenna (Johansson, 1989). In (Koksal, 1997), analyses of TSAs are also performed by MoM and the dielectric constant profile of the substrate is optimized to achieve a required radiation pattern.
After the work of (Yngvesson et al., 1989) that emphasizes the easy integration feature of TSAs, they started to be widely used in millimeter-wave and array applications. TSAs operating at millimeter-wave frequency band are designed and studied in (Dong-Sik Woo et al., 2007), (Kim et al., 2006), (Muldavin et al., 1999). In [Dong-Sik Woo et al., 2007], two types of TSAs (LTSA and ETSA) operating at 23-80 GHz band are designed. According to simulation results the input return loss values of both of the antennas are below -10dB within the frequency band. However, when the radiation characteristics of the antennas are investigated, it is observed that the antenna starts to be more directive as the frequency increases. Therefore the gain of the antenna varies between 7-12 dBi for the LTSA and between 8-10 dBi for the ETSA. It is concluded that the radiation pattern bandwidth of the ETSA is wider compared to LTSA. In (Kim et al., 2006), a LTSA operating at 45-75 GHz band is designed on a low temperature cofired ceramic (LTCC) substrate. It is observed that the high dielectric constant of the LTCC substrate degrades the radiation characteristics of the antenna by lowering the gain and distorting the radiation pattern. Therefore an air cavity at the back of the antenna is introduced to lower the effective dielectric constant of the substrate. In this way, the distortions in the radiation pattern of the antenna are eliminated but still a variation of 4.9dBi to 5.9dBi is observed in the gain of the antenna within the frequency band. In (Muldavin et al., 1999), the effective dielectric constant of the substrate is reduced by selectively machining holes in the dielectric substrate. The radiation characteristics of the designed antenna are investigated at 24, 30 and 36 GHz both with and without holes. It is observed that the introduction of the holes lowers the sidelobe levels, significantly decreases 10dB beamwidths and increases the gain of the antenna. However, the dependency of the gain of the antenna on frequency is same as the examples discussed so far.
Chapter 1 • Introduction

Arrays of TSAs can be used to obtain higher directivity and some demonstrative TSA antenna array examples can be found in (Kim et al., 1990), (Ender et al., 2003).

1.3 Organization of the Thesis

This thesis report consists of seven chapters in total. The framework for the thesis is described as follows:

Chapter 1 provides a brief introduction about the Tapered slot antennas and the need for an implementation of this thesis.

Chapter 2 begins with an introduction of a basic Tapered Slot Antenna. Characteristics and design considerations will give a better insight into the operations of the antenna. Most importantly, the effects of the taper profile and two feeding techniques will be discussed.

Chapter 3 begins with the design guidelines for tapered slot antenna. Microstrip design formulas are also included in this chapter to provide useful equations for designing.

Chapter 4 will cover the Design and Simulated Results of the Linearly Tapered Slot Antenna. Both Microstrip line fed and coaxial line fed tapered slot antenna has been designed and simulated.

Chapter 5 introduces two new designs for tapered slot antenna, which includes corrugations and known as corrugated linearly tapered slot antenna (CLTSA). Here one can observe the effect of corrugations in tapered slot antenna, and how the overall result is improved from the previous case.
Chapter 1 • Introduction

Chapter 6 includes the fabricated model of CLTSA and also the measurement results for the same. From which measured and simulated results are compared.

Chapter 7 will give an overall Conclusion by summarizing all the work done during the course of it and future prospects for the linearly tapered slot antenna.

1.4 Simulation Tool: HFSS

HFSS is a high-performance full-wave electromagnetic (EM) field simulator for arbitrary 3D volumetric passive device modeling that takes advantage of the familiar Microsoft Windows graphical user interface. It integrates simulation, visualization, solid modeling, and automation in an easy-to-learn environment where solutions to your 3D EM problems are quickly and accurately obtained.

Ansoft HFSS employs the Finite Element Method (FEM), adaptive meshing, and brilliant graphics to give you unparalleled performance and insight to all of your 3D EM problems. Ansoft HFSS can be used to calculate parameters such as S-Parameters, Resonant Frequency, and Fields. Typical uses include:

Antennas/Mobile Communications – Patches, Dipoles, Horns, Conformal Cell Phone Antennas, Specific Absorption Rate (SAR), Infinite Arrays, Radar Cross Section (RCS), Frequency Selective Surfaces (FSS)
Connectors – Coax, Backplane, Transitions
Waveguide – Filters, Resonators, Transitions, Couplers
Filters – Cavity Filters, Microstrip, Dielectric

HFSS is an interactive simulation system whose basic mesh element is a tetrahedron. This allows you to solve any arbitrary 3D geometry, especially those with complex curves and shapes, in a fraction of the time it would take using other techniques.
The name HFSS stands for High Frequency Structure Simulator. Ansoft pioneered the use of the Finite Element Method (FEM) for EM simulation by developing/implementing technologies such as tangential vector finite elements and adaptive meshing. Ansoft HFSS has evolved over a period of years with input from many users and industries. In industry, Ansoft HFSS is the tool of choice for high-productivity research, development, and virtual prototyping.

The above description of the simulation program HFSS is a summarized version obtained from the User Manual of HFSS. For more detailed information on HFSS, this manual is recommended.
CHAPTER 2

TAPERED SLOT ANTENNA

The chapter begins with a review on some characteristics of the Tapered Slot Antenna. This is followed by design aspects to be taken into consideration in the process of constructing the antenna. In general, designs differ only in the taper profile of the slot and the feeding technique. Some of the common taper profiles and feeding techniques will be presented in this chapter.

2.1 Characteristics of a Tapered Slot Antenna

The tapered slot antenna (TSA) belong to the general class of end-fire travelling wave antennas and consist of a tapered slot etched onto a thin film of metal. This is done either with or without a dielectric substrate on one side of the film. Besides being efficient and lightweight, the more attractive features of TSAs are that they can work over a large frequency bandwidth and produce a symmetrical end-fire beam with appreciable gain and low side lobes (Wang et al., 1997). An important step in the design of the antenna is to find suitable feeding techniques for a slotline excited TSA. Understanding the characteristics of the TSA is fundamental and would help a great deal in designing the antenna. From research journals on the TSA, we can confirm that TSAs generally have wider bandwidth, higher directivity and are able to produce symmetrical radiation patterns (Janaswarmy et al., 1987).

2.1.1 Radiation Characteristics

As the TSA is a travelling wave antenna, the phase velocity and the guide wavelength, $\lambda_g$, varies with the change in thickness, dielectric constant and taper shape. Having the gain proportional to $L/\lambda_g$, parameters such as length, width and taper profiles also have direct impact on the radiation patterns, directivity and cross-polarization level of the antenna. The radiation characteristics of the
antenna are also affected by the substrate thickness and ground plane. (Lee et al., 1997)

2.1.2 Bandwidth Characteristics

The TSA is capable of having an operating bandwidth within a frequency range of 2 GHz to 90 GHz. To achieve a wider bandwidth, it is ideal for the TSA to have a perfect impedance match at both the feed transition and the slot termination. Different methods for bandwidth broadening depend on the feed methods chosen. This will be described further in section 2.4. The bandwidth is normally proportional to the change in frequency, $\Delta f$. (Lee et al., 1997)

2.2 Design Considerations

A TSA is formed by slowly increasing the width of a slot from the point of its feed to an open end of width generally greater than $\lambda_0/2$ (Prasad et al., 1979). This is illustrated in figure 2.1. Experimental results done in various journals have confirmed that the impedance, bandwidth and radiation patterns are greatly affected by parameters such as length, width and taper profile of a TSA. The dielectric substrate’s thickness and relative permittivity are also important as they contribute to the efficiency of the antenna. Figure 2.1 and 2.2 show the top view and cross-sectional view of a slotline on a dielectric substrate with its important parameters illustrated. The shaded area in both the figures represents the remaining copper on the dielectric substrate after etching is done.

Fig. 2.1 Top view of Taper Slot Antenna
2.3 Taper Profiles

Many taper profiles exist for a normal TSA. Figure 2.3 shows different planar designs and we can observe that each antenna differs from one another only in the taper profile of the slot. Of all the designs illustrated in figure 2.3 (Lee et al., 1997), only the Vivaldi (Huang et al., 1989) and linearly tapered profile (Prasad et al., 1979) have been thoroughly studied over the past few years.

Planar tapered slot antennas have two common features. The radiating slot acts as the ground plane for the antenna and the antenna is fed by a balanced slotline. However, drawbacks for a planar TSA come in the form of using a low dielectric constant substrate and obtaining an impedance match for the slotline. By fabricating on a low dielectric constant substrate, relatively high impedance is obtained for the slotline. If a microstrip feed is chosen, it makes matching very difficult. Thus, the microstrip to slot transition will limit the operating bandwidth of the TSA.
2.3.1 Effect of Curvature on Taper Profile

Tapered slot antennas with linear, exponential or constant taper profile are commonly reported and their journals can be easily found. However, information on the effects of the curvature on a taper profile is not readily available. From the authors of (Lee et al., 1996), we are able to obtain experimental investigation and results on the effects. The important points will be briefly summarized in this sub-section. For more detailed explanation and illustrations, it is recommended that the particular journal be referred to. Figure 2.4 shows the schematic of linear (1) and exponential (2), (3) and (4) taper profiles.
profiles of a TSA. As seen in the figure, four TSAs of same length and terminating slot width, but with different taper profiles, were fabricated and tested. Fabrication was done on the same type of substrate with the same relative permittivity.

![Figure 2.4 Schematic of TSA Taper Profiles](image)

The cross polarization is generally improved with the decrease in the radius of the curvature except for the E-plane, which will not show any improvement. More importantly, the decrease on the radius of the curvature also reduces the bandwidth of the antenna.

### 2.4 Feeding Techniques

A slot generally always excites a TSA. In order to test and design slotline circuits, it is necessary to have a transition between a slot and another transmission medium (Gupta et al., 1979). These transitions should be very compact and have low loss. Some feeding techniques and their transitions are shown in the figure 2.5 (Lee et al., 1997). The commonly used methods are the coaxial line feed and the microstrip line feed. These will be illustrated and discussed in the next two sub-sections.
2.4.1 Coaxial Line Feed

A coaxial line feed provides a direct path for coupling of fields across the slot (Lee et al., 1997). A commonly used coaxial line to slot transition is shown in figure 2.6. The transition consists of a coaxial line placed perpendicular at the end of an open circuited slot. The outer conductor of the cable is electrically connected to the ground plane on one side of the slot while the inner conductor of the coaxial line forms a semicircular shape over the slot as shown in figure 2.6. This transition has been analyzed in (Knorr, 1974). An equivalent circuit, also from (Knorr, 1974), is shown in figure 2.7.
From the equivalent circuit, we can predict that the slot impedance will be transform to a lesser value, by a factor of $n$, so as to match a 50 Ω coaxial cable. To do this, a slot impedance of around 75 Ω is needed. However, in practice, it is difficult to obtain a slot impedance of around 75 Ω because a slotline impedance of less than 100 Ω will have a very small width and this makes fabrication with etching difficult and inaccurate.

2.4.2 Microstrip Line Feed

A microstrip to slot transition consists of a slot, etched on one side of the substrate, crossing an open circuited microstrip line, located on the opposite side, at a right angle. The slot extends to one quarter of a wavelength beyond the microstrip and the microstrip extends one quarter of a wavelength beyond the slot as shown in figure 2.8. The latter’s wavelength has to minus a length extension of $\Delta L$. The length extension is due to fringing at the end of the open circuited line, which makes the line appear electrically longer (Lee et al., 1997). The length extension can be approximated using the following expression (Hammerstad, 1975):

$$\Delta L = \frac{0.412 \times h \times (\varepsilon_{r,\text{eff}} + 0.3) \left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{r,\text{eff}} - 0.258\right)\left(\frac{W}{h} + 0.8\right)}$$

(2.1)
An equivalent circuit of the microstrip to slot transition is shown in figure 2.9 (Lee et al., 1997). An impedance match between the microstrip and slotline can be obtained at a given frequency by applying equation (2.2). The equation can also be applied to the coaxial to slot transition.

\[
Z_s = n^2 Z_m
\]  \hspace{1cm} (2.2)

where

\[
n = \cos\left(\frac{2\pi n t}{\lambda_o}\right) - \cot(q)\sin\left(\frac{2\pi n t}{\lambda_o}\right)
\]  \hspace{1cm} (2.2.1)

\[
q = \frac{2\pi n t}{\lambda_o} + \tan^{-1}\left(\frac{u}{v}\right)
\]  \hspace{1cm} (2.2.2)

\[
u = \sqrt{\frac{\lambda_o}{\lambda_s}}, \quad v = \sqrt{\left(\frac{\lambda_o}{\lambda_s}\right)^2 - 1}
\]  \hspace{1cm} (2.2.3)

Where, \(Z_s\) = characteristic impedance of the slot,

\(Z_m\) = characteristic impedance of the microstrip,

\(\lambda_o\) = free space wavelength and

\(\lambda_s\) = slotline wavelength

To achieve proper impedance match, multi-step quarter wave transformers are sometimes used. By terminating the microstrip with a radial stub and the slot with an elliptical shaped cavity, the bandwidth can be broadened. Also, when terminating the slot with the elliptical cavity, the operating bandwidth of the transition tends to shift down in frequency (Lee et al., 1997).
2.5 Summary

From this chapter, a better understanding on the characteristics and design considerations inevitably helps in the designing and constructing of a tapered slot antenna. Various taper profiles and feeding techniques were described and illustrated to give the reader different options while designing a TSA. The effects the angle of the taper profile has on the antenna were also highlighted. Finally, the transitions of the two more common feeding techniques, coaxial line and microstrip line, were explained. The overall design of the wide band LTSA was closely modeled after some of the figures presented in this chapter. Figures 2.1 and 2.2 were taken into consideration when designing the linearly taper profile of the slot. Figure 2.8 illustrates the most important considerations that the microstrip to slot transition was designed after. Also later on coaxial fed tapered slot antenna was designed, which has better radiation characteristics as compared to microstrip fed tapered slot antenna. However, a good transition at one particular frequency does not work well over all the frequencies as the wavelength changes with the frequency.
CHAPTER 3

MATHEMATICAL MODELING OF TAPERED SLOT ANTENNA

Experimental investigations have revealed that the electrical and structural properties contribute to the overall performance of the radiating structure. Antenna parameters such as dielectric substrate, its thickness, associated tangential loss; the permittivity variation with frequency and the temperature significantly affect the overall performance of the planar LTSA, especially under high-frequency operations. Other parameters affecting performance include: size of the ground plane, its conductivity (material used), thickness; the dimensions of the slot, the microstrip feed line, taper / flare angle, opening width of the tapered structure at the space interface, lateral edge and feed location.

3.1 Design Guidelines

For years, the design of TSA has been primarily based on empirical approach, which as an initial step, could start with the following simple guidelines: (Lee, “Notch Antennas”)

The aperture width of slot: \( W \geq \lambda_0 \)

\[ 1.05 \leq \frac{c}{v} \leq 1.2 \]

The effective thickness: \( 0.005 \lambda_0 \leq t_{\text{eff}} \leq 0.03 \lambda_0 \)

The taper angle, \( 2 \alpha \), is typically 5 to 12º

The length of the TSA, \( L \), is typically 2 to 12 \( \lambda_0 \)

Where \( c \) is the velocity of light, \( v \) is the velocity of the field along the slot, and \( \lambda_0 \) is the free space wavelength.
The choice of dielectric substrate plays an important role in the design and simulation of the microstrip transmission line as well as any other antennas. Some important dimensions of the dielectric substrate are:

- The dielectric constant.
- The dielectric loss tangent that sets the dielectric loss.
- The thermal expansion and conductivity.
- The cost.
- The manufacturability.
- The thickness of the copper surface.

There are numerous types of substrates that can be used for the design of antennas. They often have different characteristics and their dielectric constants normally range from $2.2 \leq \varepsilon_r \leq 12$. Thick substrates with low relative dielectric constants are often used as they provide better efficiency and a wider bandwidth. However, using thin substrates with high dielectric constant would result in smaller antenna size. But this also results negatively on the efficiency and bandwidth. Therefore, there must be a design trade-off between antenna size and good antenna performance (Bahl et al., 1980).

Tapered slot antennas are well-behaved travelling-wave antennas as long as a condition about the parameters of the substrate is satisfied. In order to state this condition, first the effective thickness of the dielectric substrate ($t_{\text{eff}}$) need to be defined as follows (Kim et al., 1990).

$$\frac{t_{\text{eff}}}{\lambda_0} = \left(\sqrt{\varepsilon_r} - 1\right) \frac{t}{\lambda_0}$$

(3.1)

Where $\lambda_0$ is the free space wavelength at the center frequency, $t$ is the thickness and $\varepsilon_r$ is the dielectric constant of the substrate. The necessary condition for a TSA to possess travelling wave antenna characteristics is (Richard, 1993):
0.005 \lambda_0 \leq t_{\text{eff}} \leq 0.03 \lambda_0  \quad (3.2)

As stated in (Muldavin et al., 1999), for a $t_{\text{eff}} / \lambda_0$ value below 0.005, the antenna will have decreased directivity whereas for values larger than 0.03, unwanted substrate modes will develop that will deviate the antenna from travelling wave antenna characteristics and introduce grating lobes to the radiation pattern.

In general, the design of TSA involves two major tasks:

(1) The design of a broadband transition and feed structure with very wide frequency range and low return loss, and

(2) Determining the dimensions and shape of the antenna in accordance with the required beam width, side lobe, and back lobe etc. over the operating frequency range.

### 3.2 Microstrip Design Formulas

As the one of the objective of this thesis I initially design Linear Tapered slot antenna for which geometry is given in figure 3.1. Design equations for this geometry is stated in (Dwivedi et al., 2008) and also given below. To design a basic microstrip transmission line, one must be able to obtain dimensions such as effective dielectric constant, wavelength and characteristic impedance. This can be calculated through some simple equations that will be shown in the next few sub-sections.

Aperture length and width of the antenna is given as

\[ W \gg \lambda_0 / 2, \quad L = 5 \lambda_0 \quad (3.3) \]

Dielectric thickness $H \gg 0.003 \lambda_0 \quad (3.4)$
The conductor thickness \( t \) is approximately \( 1/\lambda_0 \) satisfying the condition
\[
t \leq 1/(0.5 \lambda_0) \quad (3.5)
\]
Length and width of the slot line is given by
\[
L_s = 0.4 \lambda_0 \text{ to } 0.5 \lambda_0, \quad W_s = 0.2 \lambda_s \quad (3.6)
\]
Length and width of the Microstrip line is given by
\[
L_m = \frac{c}{2 f_r \sqrt{\varepsilon_{\text{eff}}}}
\]
\[
W_m = \frac{7.48 H}{e x p \left( 0.33 \left( \sqrt{\varepsilon_r} + 1.41 \right) \right)} - 1.25 t
\]
\[
(3.7) \quad (3.8)
\]

**Fig. 3.1** Tapered Slot Antenna geometry

### 3.2.1 Effective Dielectric Constant

One might think that the effective dielectric constant \( \varepsilon_{\text{eff}} \) is the same as the dielectric constant, \( \varepsilon_r \), of the substrate. This appears to be true only for a homogeneous structure and not for a non-homogeneous structure. For
microstrip structures, we are able to calculate the effective dielectric constant that comes in two different cases. These two cases are illustrated in figure 3.2 whereby the top diagram shows a microstrip with width, w, greater than the thickness, h, of the substrate (w ≥ h). The opposite can be said about the bottom diagram.

By looking at the diagram with w ≥ h, we can conclude that the circuit performs similar to having two parallel planes as most of the fields as kept under the wide microstrip width. Thus, \( \varepsilon_{r,\text{eff}} \) is approximately equivalent to \( \varepsilon_r \). When \( w \leq h \), half of the fields will be in air with \( \varepsilon_r = 1 \), while the other half of the fields will be confined to the substrate with \( \varepsilon_{r,\text{eff}} = \frac{1}{2}(\varepsilon_r + 1) \).

![Fig. 3.2 Wide and Narrow Microstrip Line](image)

Therefore, the range of a dielectric constant can be said to be:

\[
\frac{1}{2} (\varepsilon_r + 1) \leq \varepsilon_{r,\text{eff}} \leq \varepsilon_r
\]

(3.9)

The following equations can be used to obtain a precise value of \( \varepsilon_{r,\text{eff}} \). Following equations take into consideration negligible thickness of the microstrip.
3.2.2 Wavelength

For a propagating wave in free space, the wavelength of that medium is equal to the speed of light divided by its operating frequency. To obtain the wavelength of a given wave-guide or antenna, the free space wavelength is simply divided by the square root of the effective dielectric constant of the wave-guide. These are shown in equations below.

\[ \lambda_0 = \frac{c}{f_0} \]  
(3.12)

\[ \lambda_m = \lambda_g = \lambda_0 \sqrt{\varepsilon_{r,\text{eff}}} \]  
(3.13)

\[ \lambda_s = \lambda_0 \sqrt{\frac{2}{\varepsilon_r+1}} \]  
(3.14)

Where \( c \) = speed of light, \( f_0 \) = operating frequency, \( \lambda_0 \) = free space wavelength and \( \lambda_g \) = the guide wavelength.

3.2.3 Characteristic Impedance

The characteristic impedance, \( Z_0 \), of any line is the function of its geometry and dielectric constant. For a microstrip transmission line, the characteristic impedance is defined as the ratio of voltage and current of a travelling wave. For a microstrip line with width, \( w \), we are able to calculate the characteristic impedance through the following two equations:

\[ \varepsilon_{r,\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \left( 1 + \frac{12}{w/h} \right)^{\frac{1}{2}} + 0.04 \left( 1 - \frac{w}{h} \right)^2 \right] \text{ for } \frac{w}{h} \leq 1 \]  
(3.10)

\[ \varepsilon_{r,\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + \frac{12}{w/h} \right]^{\frac{1}{2}} \text{ for } \frac{w}{h} \geq 1 \]  
(3.11)
\[ Z_o = \frac{60}{\sqrt{\varepsilon_{r,\text{eff}}}} \ln \left( \frac{8}{w/h} + 0.25 \frac{w}{h} \right) \text{ for } \frac{w}{h} \leq 1 \]  
(3.15)

\[ Z_o = \frac{120\pi}{\sqrt{\varepsilon_{r,\text{eff}}}} \left( \frac{w}{h} + 1.393 + 0.667 \ln \left( \frac{w}{h} + 1.444 \right) \right) \text{ for } \frac{w}{h} \geq 1 \]  
(3.16)
A linearly tapered slot antenna incorporates a slot antenna with a linear tapered profile and is fed by a microstrip line. Both taper profiles and feeding techniques have already been described in chapter 2. Further to improve the radiation characteristics of tapered slot antenna, coaxial fed linearly tapered slot antenna also been designed and simulated.

4.1 Introduction of HFSS

The name HFSS stands for High Frequency Structure Simulator. Ansoft pioneered the use of the Finite Element Method (FEM) for EM simulation by developing/implementing technologies such as tangential vector finite elements, adaptive meshing, etc. HFSS is a high performance full wave electromagnetic field simulator for arbitrary 3D volumetric passive device modeling that takes advantage of the familiar Microsoft Windows graphical user interface. It integrates simulation, visualization and automation in an easy to learn environment. The HFSS Window has several optional panels, listed below.

- A Project Manager which contains a design tree which lists the structure of the Project.
- A Message Manager that allows you to view any error or warning that occurs before you begin a simulation.
- A Property Window that displays and allows you to change model parameters or attributes.
- 3D Modeler Window which contains the model and model tree for the active design.
The Ansoft HFSS Desktop provides an intuitive, easy-to-use interface for developing passive RF device models. Creating designs, involves the following:

- **Parametric Model Generation** – creating the geometry, boundaries and excitations
- **Analysis Setup** – defining solution setup and frequency sweeps
- **Results** – creating 2D reports and field plots
- **Solve Loop** - the solution process is fully automated

To understand how these processes co-exist, examine the illustration shown in figure 4.1.

![Diagram of Process Flow in HFSS](image)

**Fig. 4.1 Process Flow in HFSS**
4.2 Designing of Tapered slot antenna

According to calculated values of length and width of tapered slot as well as substrate, I have designed the model in HFSS. After model has been created, I need to assign boundary conditions. In HFSS, radiation boundaries are used to simulate open problems that allow waves to radiate infinitely far into space. HFSS absorbs the wave at the radiation boundary, essentially ballooning the boundary infinitely far away from the structure. Having the entire model set, I have to give the excitation. The excitation is a waveguide port at the beginning of coax cable. The Process of creating 3D Model is given below.

1. Draw a geometric model.
2. Modify a model’s design parameters.
3. Assign variables to a model’s design parameters.
4. Specify solution settings for a design.
5. Validate a design’s setup.
6. Run an HFSS simulation.
7. Create a 2D x-y plot of S-parameter results.
8. Create a field overlay plot of results.

4.3 Linearly Tapered Slot Antenna Fed with Microstrip Line

4.3.1 Antenna Model

From the microstrip line formulas stated in chapter 3, specification of proposed linearly tapered slot antenna fed with microstrip line is given in table 4.1

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>X Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of Operation</td>
<td>11 GHz</td>
</tr>
<tr>
<td>VSWR</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>Dielectric Material Used</td>
<td>Rogers RT duroid 5880</td>
</tr>
<tr>
<td>Dielectric Constant of Substrate</td>
<td>2.2</td>
</tr>
</tbody>
</table>
### Table 4.1 Proposed Microstrip line fed Linearly Tapered Slot Antenna Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of Substrate</td>
<td>3mm</td>
</tr>
<tr>
<td>Microstrip Line Length</td>
<td>20mm</td>
</tr>
<tr>
<td>Microstrip Line Width</td>
<td>7mm</td>
</tr>
<tr>
<td>Slot Length</td>
<td>14mm</td>
</tr>
<tr>
<td>Slot Width</td>
<td>4mm</td>
</tr>
<tr>
<td>Tapered Length</td>
<td>150mm</td>
</tr>
<tr>
<td>Tapered Width/Aperture Width</td>
<td>16mm</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear</td>
</tr>
</tbody>
</table>

### Fig. 4.2 Model of Microstrip line fed Tapered Slot Antenna

#### 4.3.2 Results

The microstrip line fed LTSA is simulated using HFSS. For this particular antenna, the results taken into considerations were Return Loss, VSWR, Radiation Pattern and Gain of the antenna, which are discussed in following subsections.
4.3.2.1 Return Loss

The bandwidth can be calculated from the return loss (RL) plot. The bandwidth of the antenna is said to be those range of frequencies over which the return loss is greater than 10 dB. From the figure, resonance frequency of this antenna $f_0=11.058\text{GHz}$.

By referring to figure 4.3 and using the equation below, the usable bandwidth of the antenna is calculated to be approximately 50%. Thus, the antenna can be considered to be wide band.

$$BW = \frac{(f_2 - f_1)}{f_0} \times 100\%$$

Where $f_0$ is the frequency at which $S_{11}$ is minimum, $f_1$ and $f_2$ are the frequencies at which $S_{11}$ is at $-10\text{dB}$. 
4.3.2.2 VSWR Plot

Voltage Standing Wave Ratio of LTSA is given in figure 4.4. From the result it can be observed that its value is 1.41 at frequency 11.08GHz, which is as per the specifications.

4.3.2.3 Gain Plot

Total gain of the LTSA is given in figure 4.5. From the result it is 0.6 to 0.7, which is worthless and not desirable as per the specified criteria.
4.3.2.4 Radiation Pattern

The radiation pattern for Φ=0 and Φ=90 degrees would be important. Figure 4.6 and 4.7 below show the 2D and 3D radiation pattern of the antenna at the designed frequency for Φ=0 and Φ=90 degrees.

![Fig. 4.6 Radiation Pattern](image)

![Fig. 4.7 3DRadiation Pattern](image)
4.3.3 Summary

In summary, it can be seen from the simulation results that, the antenna does not perform well at the operating frequency. There is also some deviation from the theoretically expected operating frequency, the main reason for this is the discretization applied during simulation. From return loss and VSWR point of view the result is good, but as can be seen from the gain plot and radiation pattern snap taken from the simulation, one can see that the gain is very low and radiation pattern is having energy directed along only one side form the center of the antenna, therefore some work is needed to be done to tackle this.

4.4 Linearly Tapered Slot Antenna Fed with Coaxial Line

4.4.1 Antenna Model

Specification of proposed linearly tapered slot antenna fed with coaxial line is given in table 4.2.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>C Band</td>
</tr>
<tr>
<td>Frequency of Operation</td>
<td>5 GHz</td>
</tr>
<tr>
<td>VSWR</td>
<td>&lt; 1.2</td>
</tr>
<tr>
<td>Dielectric Material Used</td>
<td>Rogers RT duroid 5880</td>
</tr>
<tr>
<td>Dielectric Constant of Substrate</td>
<td>2.2</td>
</tr>
<tr>
<td>Height of Substrate</td>
<td>5.3 mm</td>
</tr>
<tr>
<td>Ground/Substrate Length</td>
<td>100 mm</td>
</tr>
<tr>
<td>Ground/Substrate Width</td>
<td>100 mm</td>
</tr>
<tr>
<td>Slot Length</td>
<td>6 mm</td>
</tr>
<tr>
<td>Slot Width</td>
<td>4 mm</td>
</tr>
<tr>
<td>Tapered Length</td>
<td>15 mm</td>
</tr>
<tr>
<td>Tapered Width/ Aperture Width</td>
<td>39.7 mm</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear</td>
</tr>
</tbody>
</table>

Table 4.2 Proposed Coaxial line fed Linearly Tapered Slot Antenna Specifications

34
4.4.2 Results

The coaxial line fed LTSA is simulated using HFSS. For this particular antenna, the results taken into considerations were Return Loss, VSWR, Gain Plot, Co & Cross pol components, Radiation Pattern and E-field distribution of the antenna, which are discussed in following subsections.

4.4.2.1 Return Loss

Return Loss graph for the coaxial fed tapered slot antenna is given in figure 4.9, results shows that resonance frequency for this antenna is 5.12 GHz. Hence it can be used for the WLAN applications. Also it has wider band width compared to previously designed patch antennas for same applications.
4.4.2.2 VSWR Plot
Voltage Standing Wave Ratio of LTSA is given in figure 4.10. From the result it can be observed that its value is 1.03 at frequency 5.12 GHz, which is as per the specifications and VSWR value is close to ideal value i.e. 1.

![VSWR Plot]

Fig. 4.10 VSWR Plot

4.4.2.3 Gain Plot
Total gain of the LTSA is given in figure 4.11. From the result it is 7.66, which is very good result and as per the specified criteria.

![Gain Plot]

Fig. 4.11 Gain Plot
4.4.2.4 Radiation Pattern

The radiation pattern for $\Phi=0$ and $\Phi=90$ degrees would be important. Figure 4.12 and 4.13 below show the 2D and 3D radiation pattern of the antenna at the designed frequency for $\Phi=0$ and $\Phi=90$ degrees.

![Fig. 4.12 Radiation Pattern](image)

![Fig. 4.13 3DRadiation Pattern](image)
4.4.2.5 E-field Distribution

E-field Distribution along the radiating slot of LTSA is shown in figure 4.14. From the result one can see that it is radiating from the edges, also its field distribution along the sides needs to be improved.

Fig. 4.14 E-Field Distribution

4.4.2.6 Co- and Cross Polarization Components

Co-polarization means polarization in the desired direction, while Cross polarization (sometimes written X-pol, in antenna slang) is the polarization orthogonal to the polarization being discussed. For instance, if the fields from an antenna are meant to be horizontally polarized, the cross-polarization in this case is vertical polarization. If the polarization is Right Hand Circularly Polarized (RHCP), the cross-polarization is Left Hand Circularly Polarized (LHCP).

This term arises because an antenna is never 100% polarized in a single mode (linear, circular, etc). Hence, two radiation patterns of an antenna are sometimes presented, the co-pol (or desired polarization component) radiation pattern and
the cross-polarization radiation pattern. The cross polarization may be specified for an antenna as a power level in negative dB, indicating how many decibels below the desired polarization's power level the x-pol power level is.

Here results shows the co and cross polarization components are approximately 52 dB apart.

**Fig. 4.15 Co- and Cross Polarization Components**

### 4.4.3 Summary

In summary, it can be seen from the simulation results that, the antenna has better overall performance than antenna designed in section 4.2. It has wider bandwidth and good radiation characteristics as well as gain. Further we can see from the E-field distribution that antenna radiates along the tapered edges, hence it is truly an end-fire antenna. Also for this antenna co and cross polarization components are far apart, which is practically desirable. But still we can improve the radiation pattern and E-field distribution by adding corrugation in tapered slot antenna, which is given in next chapter.
5.1 Suggestions for improvement in previous model

The results obtained from the previous designed microstrip line fed tapered slot antenna using HFSS are not matching to the desired specifications, so coaxial line fed tapered slot antenna has been designed. It is suggested in modification that instead of keeping side of antenna as well as tapered line straight, if slots are inserted in that portion, I can get the better radiation pattern and improved gain. Antenna that one get after the addition of slots are called as corrugated linearly tapered slot antenna. In this particular chapter I have introduce two different method for inserting slots and at the end of chapter both are compared with previously designed model, and finally antenna with best results is fabricated.

One more suggestion is to find out the proper location of feed point. The feed point should be located, where the input impedance is 50 ohms for the resonant frequency. The main advantage of coax feeding scheme is that the feed can be placed at any desired location inside the patch in order to match with its input impedance. This feed method is easy to fabricate and has low spurious radiation. Trial and error method is used to locate the feed point. For different locations of the feed point, the return loss is compared and that feed point is selected where the return loss is most negative on desired Frequency.
5.2 Designing of CLTSA with corrugation along the sides

5.2.1 Antenna Model

The Process of creating 3D Model for CLTSA is given below.

Launch Ansoft HFSS.

Open New Project:

- In an Ansoft HFSS window, from standard toolbar, select the New HFSS Design.

Set Solution Type:

- Choose Driven Terminal as Solution Type

Create the 3D model:

- Set Model Units cm from menu item Modeler>Units
- Set Default material Rogers RT/duriod 5880(tm) using 3D modeler Material toolbar
- Create substrate of length= 100 mm, width =100 mm and thickness h=5.3 mm
- Create Ground plane of length= 100 mm width =100 mm
- Assign Perfect E boundary to the ground plane
- Create slot above the substrate of length= 39.7 mm, width =30 mm
- Insert corrugation of length=3 mm, width= 0.5mm and spacing=1 mm
- Assign Perfect E boundary to the corrugated slot plane
- Cut the ground plane and substrate at appropriate location to give the Coax Feeding
- Create Coax and inner conducting Pin.
- Create Wave port to give the Excitation.
- Create radiation box of air to capture the Radiation and assign radiation boundary to it.
Analysis Setup:
Chapter 5 • Design of Corrugated LTSA In HFSS

Fig 5.2 Analysis Setup

Fig 5.3 Model Validation
5.2.2 Results

The coaxial line fed CLTSA is simulated using HFSS. For this antenna, the results taken into considerations were Return Loss, VSWR, Gain Plot, Co & Cross pol components, Radiation Pattern and E-field distribution of the antenna, which are discussed in following subsections.

5.2.2.1 Return Loss

Return Loss graph for the coaxial fed tapered slot antenna is given in figure 5.5, results shows that resonance frequency for this antenna is 5.2 GHz. Hence it can be used for the WLAN applications. Also it has wider band width approximately equal to 520 MHz.
5.2.2.2 VSWR Plot

Voltage Standing Wave Ratio of CLTSA is given in figure 5.6. From the result it can be observed that its value is 1.03 at frequency 5.2 GHz, which is as per the specifications and VSWR value is close to ideal value i.e. 1.

**Fig. 5.6 VSWR Plot**
5.2.2.3 Gain Plot

Total gain of the CLTSA is given in figure 5.7. From the result it is 8.36 dB, which is very good result and as per the specified criteria. Hence I got in slight increment in gain by adding corrugation.

Fig. 5.7 Gain Plot

5.2.2.4 Radiation Pattern

The radiation pattern for Φ=0 and Φ=90 degrees would be important. Figure 5.8 and 5.9 below show the 2D and 3D radiation pattern of the antenna at the designed frequency for Φ=0 and Φ=90 degrees
5.2.2.5 E-field Distribution

E-field Distribution along the radiating slot of CLTSA is shown in figure 5.10. Here we investigate the effect of corrugation on antenna. Corrugation structures are adopted on both sides of radiating elements to improve the radiation pattern.
Current distribution is examined to analyze the effect of corrugation structure. As shown in Figure 4.14, current are mainly distributed both along the taper at the end of radiating element. Current distribution exclude tapered section of radiating element is caused radiation of unwanted direction which causes higher side lobe and cross-polarization. Current path is arranged to be parallel and opposite in direction by placement of corrugation, thus helping them to minimize the radiation toward the undesired direction. From the result one can see that E-field distribution is improved than in the case of non-corrugated LTSA.

![Fig. 5.10 E-Field Distribution](image)

**5.2.2.6 Co- and Cross Polarization Components**

Co & Cross pol components for CLTSA are given in figure 5.11. Here one can observe that they are far apart, almost cross pol component is 52 dB down the co pol component. Hence it is a practically feasible to fabricate this antenna.
5.2.3 Summary

In summary, it can be seen from the simulation results that, the antenna has better overall performance than antenna designed in section 4.2 and section 4.3. As a result, periodic corrugation structure contributes higher gain, low side lobe levels, and low cross-polarization level. In addition, the proposed antenna has been examined with different number of corrugation which increases from the end of antenna. Finally I got the best results for 16 corrugations of width 1 mm and spacing of 0.5 mm. Current distribution is examined to analyze the effect of corrugation structure. Current path is arranged to be parallel and opposite in direction by placement of corrugation, thus helping them to minimize the radiation toward the undesired direction. Hence better results are achieved for this case. Now in the next section corrugations are added along the tapered length of an antenna, and results are analyzed.
5.3 Designing of CLTSA with corrugation along tapered length

5.3.1 Antenna Model

The Process of creating 3D Model for CLTSA is given below.

- **Launch Ansoft HFSS.**
- **Open New Project:**
  - In an Ansoft HFSS window, from standard toolbar, select the New HFSS Design.
- **Set Solution Type:**
  - Choose Driven Terminal as Solution Type
- **Create the 3D model:**
  - Set Model Units cm from menu item Modeler>Units
  - Set Default material Rogers RT/duriod 5880(tm) using 3D modeler Material toolbar
  - Create substrate of length= 100 mm, width =100 mm and thickness h=5.3 mm
  - Create Ground plane of length= 100 mm width =100 mm
  - Assign Perfect E boundary to the ground plane
  - Create slot above the substrate of length= 39.7 mm, width =30 mm
  - Insert corrugation of varying length , width= 0.5mm
  - Assign Perfect E boundary to the corrugated slot plane
  - Cut the ground plane and substrate at appropriate location to give the Coax Feeding
  - Create Coax and inner conducting Pin.
  - Create Wave port to give the Excitation.
  - Create radiation box of air to capture the Radiation and assign radiation boundary to it.
Chapter 5 - Design of Corrugated LTSA in HFSS

Fig 5.12 3D Model of Modified LTSA (Model C)

Analysis Setup:
Chapter 5 • Design of Corrugated LTSA In HFSS

Fig 5.13 Analysis Setup

Fig 5.14 Model Validation
5.3.2 Results

The coaxial line fed CLTSA is simulated using HFSS. For this antenna, the results taken into considerations were Return Loss, VSWR, Gain Plot, Co & Cross pol components, Radiation Pattern and E-field distribution of the antenna, which are discussed in following subsections.

5.3.2.1 Return Loss

Return Loss graph for the coaxial fed tapered slot antenna is given in figure 5.16, results shows that resonance frequency for this antenna is 5.02 GHz. Hence it can be used for the WLAN applications. Also it has wider band width approximately equal to 400 MHz
5.3.2.2 VSWR Plot

Voltage Standing Wave Ratio of CLTSA is given in figure 5.17. From the result it can be observed that its value is 1.09 at frequency 5.02 GHz, which is as per the specifications and VSWR value is close to ideal value i.e. 1.
5.3.2.3 Gain Plot
Total gain of the CLTSA is given in figure 5.18. From the result it is 7dB, which is good result, but here I got in slight decrement in gain by adding corrugation, which is not desirable.

5.3.2.4 Radiation Pattern
The radiation pattern for $\Phi=0$ and $\Phi=90$ degrees would be important. Figure 5.19 and 5.20 below show the 2D and 3D radiation pattern of the antenna at the designed frequency for $\Phi=0$ and $\Phi=90$ degrees
Fig. 5.19 Radiation Pattern

Fig. 5.20 3D Radiation Pattern

5.3.2.5 E-field Distribution

E-field Distribution along the radiating slot of CLTSA is shown in figure 5.21. Here we investigate the effect of corrugation on antenna. Corrugation structures are adopted along the tapered length of radiating elements to improve the radiation pattern. Current distribution is examined to analyze the effect of
corrugation structure. As shown in Figure 4.14, current are mainly distributed both along the taper at the end of radiating element. Current distribution exclude tapered section of radiating element is caused radiation of unwanted direction which causes higher side lobe and cross-polarization. From the result one can see that E-field distribution is not improved than in the case of non-corrugated LTSA. Hence model B is best suited for fabrication process.

![E-Field Distribution](image)

**Fig. 5.21 E-Field Distribution**

### 5.3.2.6 Co- and Cross Polarization Components

Co & Cross pol components for CLTSA are given in figure 5.22. Here one can observe that they are far apart, almost cross pol component is 45 dB down the co pol component. But this is not good results compared to model B results.
5.3.3 Summary

In summary, it can be seen from the simulation results that, the antenna has better overall performance than antenna designed in section 4.2 and section 4.3, but it is not better than designed model B in section 5.2. Current distribution is examined to analyze the effect of corrugation structure, and it is observed that it is not radiating as well as model B i.e. the case in which corrugations are added along the sides of antenna. Now in the next section I have compared all the models designed with coaxial fed tapered slot antenna.

5.4 Comparison of designed Tapered slot antenna

In this section all the three models Model A (coaxial fed Linearly Tapered Slot Antenna), Model B (coaxial fed Corrugated LTSA with corrugation along the sides) and Model C (coaxial fed Corrugated LTSA with corrugation along tapered length) are compared. From the table 5.1 one can observe that Model B has larger bandwidth, higher gain, VSWR value close to one as well as higher separation between co & cross pol components compared to other designed
models. Here current path is arranged to be parallel and opposite in direction by placement of corrugation, thus helping them to minimize the radiation toward the undesired direction, which can be observe from the E-field distribution. Hence Model B is best suited for the fabrication process.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Loss</td>
<td>-35.63 dB</td>
<td>-36.38 dB</td>
<td>-27.12 dB</td>
</tr>
<tr>
<td>Impedance BW</td>
<td>440 MHz</td>
<td>520 MHz</td>
<td>400 MHz</td>
</tr>
<tr>
<td>VSWR</td>
<td>1.03</td>
<td>1.03</td>
<td>1.092</td>
</tr>
<tr>
<td>Gain</td>
<td>7.6 dB</td>
<td>8.36 dB</td>
<td>7 dB @ 46°</td>
</tr>
<tr>
<td>Co &amp; Cross pol separation</td>
<td>51 dB</td>
<td>52 dB</td>
<td>46 dB</td>
</tr>
<tr>
<td>E-field Distribution</td>
<td>Good</td>
<td>Best</td>
<td>Not good</td>
</tr>
</tbody>
</table>

*Table 5.1 Comparison of Proposed Coaxial line fed Linearly Tapered Slot Antennas*
6.1 Introduction
The fabrication process to realize the designed Corrugated Linearly Tapered Slot antenna is discussed in the first half of this chapter. The tools used to perform the experimentation are presented in the second half of the chapter.

6.2 Fabrication of the Proposed Antenna
Here I have selected Model B for the fabrication Process. This antenna has three layers a ground copper layer, above that dielectric substrate layer and on the top tapered slotted copper layer. A printed circuit board, or PCB, is used to mechanically support and electrically connect electronic components using conductive pathways etched from copper sheets laminated onto a nonconductive substrate. Conducting layers are typically made of thin copper foil. Insulating layers dielectric is typically laminated together with epoxy resin prepreg. There are quite a few different dielectrics that can be chosen to provide different insulating values depending on the requirements of the circuit. Some of these dielectrics are polytetrafluoroethylene (Teflon), FR-4, FR-1, CEM-1 or CEM-3. Well known prepreg materials used in the PCB industry are FR-2 (Phenolic cotton paper), FR-3 (Cotton paper and epoxy), FR-4 (Woven glass and epoxy), CEM-1 (Cotton paper and epoxy), CEM-2 (Cotton paper and epoxy), CEM-3 (Woven glass and epoxy), CEM-4 (Woven glass and epoxy) and CEM-5 (Woven glass and polyester). FR-4 is by far the most common material used today. The board with copper on it is called "copper-clad laminate". Copper foil thickness can be specified in ounces per square foot or micrometers. One ounce per square foot is 1.344 mils or 35 micrometers. It is designed on glass epoxy FR4 substrate having thickness 3.2 mm.
Chapter 6 • Corrugated LTSA Fabrication & Measurement

The vast majority of printed circuit boards are made by bonding a layer of copper over the entire substrate, sometimes on both sides, (creating a "blank PCB") then removing unwanted copper after applying a temporary mask (e.g. by etching), leaving only the desired copper traces.

The proposed antenna in Model B, having substrate thickness decided earlier is 5.3 mm. In market generally available PCB is having substrate thickness is 1.6 mm. So for the fabrication purpose modified antenna is having dimensions different from the earlier one. Also to connect coax cable I have used SMA connector which has dimensions of inner conductor radius =1.3mm and outer cover radius =4.1mm. So according to get the same results as I have got with Model B, I have varied feed locations and corrugation spacing. The fabricated patch antenna and the results of simulated model according to fabricated dimensions are shown below. Also Proposed coax line fed Corrugated Linearly Tapered Slot Antenna Specifications are given in table 6.1.

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>C Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of Operation</td>
<td>5.02 GHz</td>
</tr>
<tr>
<td>VSWR</td>
<td>&lt; 1.1</td>
</tr>
<tr>
<td>Dielectric Material Used</td>
<td>FR4_Glass epoxy</td>
</tr>
<tr>
<td>Dielectric Constant of Substrate</td>
<td>4.4</td>
</tr>
<tr>
<td>Height of Substrate</td>
<td>3.2 mm</td>
</tr>
<tr>
<td>Ground/ Substrate Length</td>
<td>100mm</td>
</tr>
<tr>
<td>Ground/ Substrate Width</td>
<td>100mm</td>
</tr>
<tr>
<td>Slot Length</td>
<td>6mm</td>
</tr>
<tr>
<td>Slot Width</td>
<td>4mm</td>
</tr>
<tr>
<td>Tapered Length</td>
<td>15mm</td>
</tr>
</tbody>
</table>
Table 6.1 Proposed Coaxial line fed Corrugated Linearly Tapered Slot Antenna Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapered Width/ Aperture Width</td>
<td>39.7mm</td>
</tr>
<tr>
<td>Corrugation Length</td>
<td>3 mm</td>
</tr>
<tr>
<td>Corrugation Width</td>
<td>1 mm</td>
</tr>
<tr>
<td>Spacing Between Corrugation</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear</td>
</tr>
</tbody>
</table>

Fig 6.1 Fabricated Corrugated TSA (Front View)
6.2.1 Results

The coaxial line fed CLTSA is simulated using HFSS. For this antenna, the results taken into considerations were Return Loss, VSWR, Gain Plot, Co & Cross pol components, Radiation Pattern and E-field distribution of the antenna, which are discussed in following subsections.

![Fig 6.2 Fabricated Corrugated TSA (Back View)](image)

![Fig 6.3 Return Loss](image)
Fig. 6.4 VSWR Plot

Fig. 6.5 Gain Plot
Chapter 6 • Corrugated LTSA Fabrication & Measurement

**Fig. 6.6** Radiation Pattern

**Fig. 6.7** 3D Radiation Pattern
Chapter 6 • Corrugated LTSA Fabrication & Measurement

6.3 Antenna Measurements

The testing and evaluation of the antenna parameters is performed in antenna ranges. Typically, there exist indoor and outdoor ranges with associated limitations for both. Outdoor ranges are not protected from environmental...
conditions, while indoor ranges are limited by space restrictions. Indoor ranges make use of anechoic chambers, which are chambers lined with radar absorbing material to eliminate reflections from the walls.

There are two basic forms of chambers: rectangular anechoic chambers and tapered anechoic chambers. Rectangular chambers are typically used for frequencies above 1 GHz, while for frequencies below 1 GHz tapered chambers are used as shown in figure 6.10.

Various methods exist to measure the antenna parameters: radiation pattern directivity, gain and polarization. Some of the methods require the Far-Field criterion and uniform plane illumination and some can be performed in the Near-Field of the Antenna Under Test (AUT).

Also antenna Return loss measurement can be possible with the instrument known as Scalar Network Analyzer as shown in figure 6.11.

Fig. 6.10 Tapered anechoic chamber for antenna measurement
In this work return loss and impedance bandwidth measurement results are compared with the simulated results, as shown in table 6.2. Here HP 8757A Scalar network analyzer and HP 8673B synthesized signal generator of frequency 2 to 26 GHz has been used for return loss measurement. As shown in figure 6.12 I have got the return loss of approx. -23 dB and Impedance bandwidth of 800 MHz
Fig. 6.12 Return Loss measurement of proposed CLTSA
### Table 6.2 Comparison of Simulated and measured results for proposed Coaxial line fed Corrugated Linearly Tapered Slot Antenna

<table>
<thead>
<tr>
<th>CORRUGATED LTSA</th>
<th>Simulated Results</th>
<th>Measurement Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating Frequency</strong></td>
<td>5.02GHz</td>
<td>4.9 GHz</td>
</tr>
<tr>
<td><strong>Return Loss</strong></td>
<td>-30 dB</td>
<td>-23 dB</td>
</tr>
<tr>
<td><strong>Impedance Bandwidth</strong></td>
<td>620 MHz</td>
<td>800 MHz</td>
</tr>
</tbody>
</table>
CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

The coax fed corrugated linearly tapered slot antenna proposed in chapter 5 has been fabricated satisfactorily and again simulated results for the fabricated design has been investigated. It can be a useful geometry in wireless applications as mentioned in the body of the thesis. This represents the new technique for improving the radiation characteristics of linearly tapered slot antenna.

In this thesis two aspects of linearly tapered slot antenna has been studied. First I have designed an Linear tapered slot antenna with microstrip feed line, but here results shows that gain of the antenna is very poor as well current distribution over the tapered slot is not matched with the specifications. In the Second technique coax fed tapered slot antenna has been proposed, which shows the good results, but to further improve the radiation characteristics two approaches of adding corrugation in tapered slot antenna have been studied.

First, proposed antenna has been examined with different number of corrugation which increases from the end of antenna and Current distribution is examined to analyze the effect of corrugation structure. Current path is arranged to be parallel and opposite in direction by placement of corrugation, thus helping them to minimize the radiation toward the undesired direction. In this designed antenna (Model B), I got the best results in terms of gain, return loss, co & cross polarization, so it was fabricated. In the Second approach, proposed antenna has been examined with different number of corrugation which increases along the tapered length (Model C), but here one can see the results are not optimized.
At the end from table 6.2, one can observe that proposed antenna simulated and measured results are comparable, hence it is proved that this antenna can be used for wireless applications and it is a wideband antenna.

### 7.2 Future Scope

Based on gathered observations while completing this thesis; following topics were identified which would benefit for further investigation.

- ♦ At present only return loss is measured as antenna parameter. All the other antenna parameters will be measured in future. The simulated, optimized and experimental results would be compared efficiently if the facility is available.

- ♦ The second future work proposal is to provide thorough tests on the proposed design for its antenna characteristics and refinement of the design, to further confirm its usability in the practical application.

- ♦ A third possibility is to realize a corrugated tapered slot antenna array to optimize the results of antenna followed by fabrication and tests to validate the design.

- ♦ A fourth proposal is to further optimize the corrugation slot dimensions and positions of coax feed for higher gain and directivity and to use it in other band or dual frequency applications.
CHAPTER 8

LIST OF PUBLICATION


Appendix A1

An Antenna is a device that converts a guided electromagnetic wave on a transmission line to a plane wave propagating in free space. Thus, one side of an antenna appears as an electrical circuit, while the other side provides an interface with a propagating plane wave. Antenna follows the reciprocity property. That means they can perform the function of transmission and receiving. There are some parameters which are related with the designing of Antennas. They are discussed in the following sections.

A.1 Reflection coefficient and characteristic impedance

The Reflection is the prominent phenomenon at the high frequency applications, which occurs in microwave transmission lines. A Reflection coefficient (Γ) is defined to give measure of this phenomenon. It is derived by normalizing the amplitude of the reflected voltage \( V_{o-} \) to the amplitude of the incident wave \( V_{o+} \) and it is given as,

\[
Γ = \frac{V_{o-}}{V_{o+}}
\]

Now, every transmission line has a resistance associated with it, and comes about because of its construction. This is called its characteristic impedance \( Z_0 \). When the transmission is terminated with load impedance \( Z_L \), the impedance value of load will decide the amount of reflection. If transmission line is terminated with any arbitrary load impedance which is not equal to characteristic impedance of the line \( (Z_L \neq Z_0) \), the reflection takes place. The reflection coefficient can be define in form of characteristic impedance and load impedance as follows,

\[
Γ = \frac{Z_L - Z_0}{Z_L + Z_0}
\]
A.2 Return loss

The Return Loss is a parameter that indicates the amount of power that is lost to the load and does not return as a reflection. The waves are reflected leading to the formation of standing waves, when the transmitter and antenna impedance do not match. Hence the RL is a parameter similar to the VSWR to indicate how well the matching between the transmitter and antenna has taken place. The RL is given as,

$$RL = -20 \log |\Gamma| \text{dB}$$

For perfect matching between the transmitter and the antenna, return loss will be infinite which means no power would be reflected back. For practical applications, a VSWR of 2.0 is acceptable, since this corresponds to a return loss of -9.54 db.

A.3 Radiation pattern

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 co-ordinates. In most cases, the radiation pattern is determined in the far field region and is represented as a function of the directional coordinates. Radiation properties include power, flux density, radiation intensity, field strength, directivity, phase or polarization."

- Isotropic, Directional, and Omni directional Patterns

An isotropic radiator is defined as "a hypothetical lossless antenna having equal radiations in all directions."

A directional antenna is one "having the property of radiating or receiving electromagnetic waves more effectively in some direction than in others."
An Omni directional antenna is defined as one "having an essentially non directional pattern in a given plane and a directional pattern in any orthogonal plane."

A.4 Principal Patterns
For a linearly polarized antenna, performance is often described in terms of its principal E- and H-plane patterns. The E-plane is defined as "the plane containing the electric-field vector and the direction of the maximum radiation," and the H-plane as "the plane containing the magnetic field vector and the direction of the maximum radiation."

A.5 Radiation pattern lobes
Various parts of a radiation pattern are referred to as lobes, which may be sub classified into major or main, minor, side, and back lobes. A radiation lobe is a "portion of the radiation pattern bounded by regions of relatively weak radiation"
A major lobe is defined as "the radiation lobe containing the direction of maximum radiation." A minor lobe is any lobe except a major lobe. A side lobe is "a radiation lobe in any direction other than the intended lobe." A back lobe is "a radiation lobe whose axis makes an angle of approximately 180 with respect to the beam of the antenna."

**A.6 Radiation intensity**

Radiation intensity in a given direction is defined as "the power radiated from an antenna per unit solid angle." The radiation intensity is a far-field parameter; and it can be obtained by simply multiplying a radiation density by the square of the distance.

![Figure A.2 Different representations of directional pattern: (a) rectangular; (b) polar; (c) Three-dimensional and; (d) constant-value contours](image)

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A.7 Directivity

Directivity of an antenna is defined as "the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total power radiated by the antenna divide by $4\pi$. If the direction is not specified the direction of maximum radiation intensity is implied."

For antenna with orthogonal polarization components, we define the partial directivity of an antenna for a given polarization in the given direction as "that part of the radiation intensity corresponding to a given polarization divided by the total radiation intensity averaged over all directions." Directivity is a measure that describes only the directional properties of the antenna, and it is therefore controlled only by the pattern.
A.8 Gain
The ability of the antenna to concentrate energy in a particular direction is defined using the power gain and directivity property of an antenna. Gain of the antenna 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. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted by the antenna divided by $4\pi$. The gain of an antenna is given as (Balanis, 1982),

$$ G = \frac{4\pi U(\theta, \phi)}{P_{in}} $$

Where $P_{in}$ = power radiated by lossless isotropic source

$U(\theta, \phi)$ = radiation intensity of the antenna under test

In other words, the gain of an antenna is a measure of the ability of an antenna to concentrate power into a narrow region of space. When a transmitting antenna with a certain gain is used as a receiving antenna, it will also have the same gain for receiving.

A.9 Voltage standing wave ratio (VSWR)
When the condition of matching is not satisfied, that means, $Z_L = Z_0$, then the power may be reflected back which leads to the creation of standing waves. The standing waves can be characterized by a parameter called Voltage Standing Wave Ratio (VSWR). VSWR can be defined as,

$$ VSWR = \frac{V_{max}}{V_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{1 + S_{11}}{1 - S_{11}} $$

The VSWR expresses the degree of match between the transmission line and the antenna. When the VSWR is 1:1, the match is perfect and all energy is
transferred to the antenna prior to be radiated. In addition, for an antenna to be reasonably functional, a maximum value of VSWR can be considered as 1.5.

**A.10 Bandwidth**

The bandwidth of an antenna is defined as "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard." The bandwidth can be considered to be the range of frequencies, on either side of a center frequency (usually the resonance frequency for a dipole), where the antenna characteristics (such as input impedance, pattern, beamwidth, polarization, side lobe level, gain, beam direction, radiation efficiency) are within an acceptable value of those at the center frequency (Balanis, 1982).

\[
BW_{broadband} = \frac{f_H}{f_L}
\]

\[
BW_{narrowband}(\text{percentage}) = \frac{f_H - f_L}{f_L} \times 100
\]

For broadband antennas, the bandwidth is usually expressed as the ratio of the upper-to-lower frequencies of acceptable operation. For example, a 10:1 bandwidth indicates that the upper frequency is 10 times greater than the lower. For narrowband antennas, the bandwidth is expressed as a percentage of the frequency difference (upper minus lower) over the center frequency of the bandwidth. For example, a 5 percentage bandwidth indicates that the frequency difference of acceptable operation is 5 percentage of the center frequency of the bandwidth.

**A.11 Antenna efficiency**

The total antenna efficiency is used to take into account losses at the input terminals and within the structure of the antenna. Such losses may be due to
APPENDIX A1

- Reflection because of the mismatch between the transmission line and the antenna
- I^2R losses (conduction and dielectric) the overall efficiency is the combination of the reflection efficiency, conduction efficiency and the dielectric efficiency.

A.12 Half power beamwidth
The half-power beamwidth is defined as: "In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half the maximum value of the beam." The beamwidth of the antenna is a very important figure-of-merit, and it is often used to as a tradeoff between it and the sidelobe level; i.e., as the beamwidth decreases the sidelobe increases and vice versa. In addition, the beamwidth of the antenna is also used to describe their solution capabilities of the antenna to distinguish between two adjacent radiating source or radar targets. The most common resolution criterion states that the resolution capability of an antenna to distinguish between two sources is equal to half the first null beamwidth (FNBW/2), which is usually used to approximate the half power beamwidth (HPBW). That is, two sources separated by angular distance equal or greater than FNBW/2 HPBW of an antenna with a uniform distribution can be resolved. If the separation is smaller, then the antenna will tend to smooth the angular separation distance.

A.13 Polarization
Polarization of an antenna in a given direction is defined as "the polarization of the wave transmitted (radiated) by the antenna. Note: - when the direction is not stated, the polarization is not taken to be the polarization in the direction of
maximum gain. "Polarization of a radiated wave is defined as "that property of an electromagnetic wave describing the time varying direction and relative magnetic electric-field vector: specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation." Polarization is the curved traced by the end point of the arrow representing the instantaneous electric-field. The field must observe along the direction of propagation.

Polarization may be classified as linear, circular, or elliptical. If the vector that described 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 general, however, the figure that the electric field traces is an ellipse, and the field is said to be elliptically polarized. Clockwise rotation of the electric field vector is designated as right-hand polarization and counterclockwise as left-hand polarization.
REFERENCES


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