NON RADIATIVE DIELECTRIC (NRD) GUIDE BASED TRANSITIONS

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRONICS AND COMMUNICATION ENGINEERING

(With Specialisation in RF & Microwave Engineering)

By

LALIT KUMAR SAINI

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, ROORKEE
ROORKEE-247 667 (INDIA)
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CANDIDATE'S DECLARATION

I hereby declare that the work carried out in this Dissertation titled **"NON RADIATIVE DIELECTRIC (NRD) GUIDE BASED TRANSITIONS"** is presented on behalf of partial fulfillment of the requirements for the award of the degree of **Master of Technology** with specialization in **RF & Microwave Engineering,** submitted to the Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, India, is an authentic record of my own work carried out from May 2018 to Jun 2019, under the supervision and guidance of **Dr. Nagendra P Pathak,** Professor, Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, India.

I have not submitted the matter embodied in this dissertation for the award of any other degree or diploma.

Date: 2019
Place: Roorkee

(Lalit Kumar Saini)
Enrol. No.: 17533011

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Date: 2019
Place: Roorkee

(Dr. Nagendra P Pathak)
Professor
Department of E & CE
Indian Institute of Technology Roorkee
Uttarakhand-247667
India

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ABSTRACT

This thesis deals with the design and development of a Non Radiative Dielectric (NRD) Guide based transitions which can be useful to develop an integral part of the components for the millimeter wave integrated circuits. NRD is a typical H-waveguide in which the distance or spacing between the two metallic plates is less than the half of the wavelength in vacuum. This was first introduced by the Yoneyama in the year of 1981. This guide offers advantages like low transmission losses, ease of fabrication, suppression of radiation at bends & discontinuities etc. In this thesis work, a NRD guide alongwith its transitions for various other transmission lines like rectangular waveguide, horns and microstrip lines has been proposed in which dielectric strip of Poly Lactic Acid (PLA) has been sandwiched between two parallel metal plates separated by a distance smaller than half a wavelength in vacuum. This dielectric guide is particularly applicable in millimeter (mm) wave integrated circuits, since it is not only small in size, but also gives various advantages as given above. Initially, a waveguide transition for the proposed NRD guide was simulated and analysed, however, it was found that normal or standard waveguide for the NRD guide will not work. Also, it was found to be very costly to fabricate custom or tailor made rectangular waveguide. Thus, other methods like rectangular waveguide with horns and microstrip lines have been used to realize a good transition with low losses. For all the various transitions of NRD guide, ANSYS HFSS software has been used for undertaking the simulation and analysis of the structures. NRD guide has been realized using Polylactic acid (PLA) material as dielectric for a band of 24 GHz frequency with centre frequency at 24.5 GHz. This NRD guide has been prepared by sandwiching PLA strip between Foam strips to provide support to the NRD guide as it is quite small in dimensions. Various results, simulated & measured, have been obtained and same has been presented in this dissertation.

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Chapter 1

Introduction

1.1 Introduction, Background and Motivation

There is a credible growth in new communication systems in this era especially in past two or three decades. Various technologies have been developed since then and are being used in the ever exploding market. Thus, the conventional RF frequency band is now practically used up and allotment to any new systems is no more feasible in this frequency region. To counter this, the microwave and millimetre frequency bands are being utilised as new frequency regions where latest technologies are being developed.

For the frequency classification, the microwaves are spanned from 300 MHz to about 30 GHz whereas the millimetre (mm) waves cover the frequencies from 30 to 300 GHz. The technology for microwave circuits is well-known by now and it is being abundantly utilised in a lot of commercial and military systems. However, the millimetre frequencies band is gaining a lot of interest due to reasons like costly, sufficiently large frequency windows required in the microwave band. In addition to this, millimetre frequencies have some characteristics which differentiate them from RF and microwave frequencies. Few of these advantages are quasi optical propagation, high resolution, high capacity and possibility to re-use frequencies. Apart those, devices, which are operational in millimetre waves, have smaller size and thus light weight than other microwave components. Due to all these reasons the latest communication systems are from low millimetre frequency region which generally spans from 30 to 100 GHz. The examples of such systems include Personal Communication Networks (PCN), Personal Communication Systems (PCS), high speed wireless LAN, vehicle collision avoidance radar systems, intelligent motor roads and many other radar systems.

Practical recognition of the millimetre frequency systems, thus, requires such technologies which are not only ensures the possibility to build the small size integrated circuits but are also compact and have low transmission losses. In addition, the integrated systems should be a compact system of systems with good results. Apart all this it should be cost effective and have simple method for mass production. There are several technologies which are in use at present that accomplish more or less all the criteria listed above.

The discovery of Non Radiative Dielectric (NRD) guide by Yoneyama has given a new path for creation of various components at millimetre frequencies. NRD guide is a modified version of H-guide which was introduced by Tischer in 1953. Both the H-guide and NRD guide has different plate separation. The distance is smaller than for the NRD guide and the greater for the H-guide than the half free space wavelength. Since its inception many components have been devised with modifications of a basic NRD guide.

The NRD guide has gained great attention because it has few attractive features like :

1. **Good Technical Parameters**. NRD guide has no radiation at bends and discontinuities due to cut-off property of a parallel plate waveguide. The transmission losses offered are very low.

2. **Low Cost of Manufacturing**. NRD guide components are very simple in structure and have relatively large dimensions compared to guide wavelength, thus allow easy manufacturing of a complete circuit on a large scale.

3. **Possibility to Integration**. NRD guide technology is quite suitable to fabricate complete integrated circuits including antenna structures. Besides, the integration with other technologies such as microstrip line or rectangular waveguide is possible. This approach allows combining the best features offered by both technologies.

This served as the motivation behind undertaking work of thesis on NRD guide transitions to integrate the NRD guide with rectangular waveguide, rectangular waveguide with horn guides or microstrip lines. The analysis and results given out in this thesis brings out the utilisation of NRD guide components characterized by good technical parameters.

1.2 Non Radiative Dielectric (NRD) Guide

The NRD guide was initially pioneered by Yoneyama in the year 1981. The guide consists of a rectangular slab of dielectric of height 'a' and width 'b', placed between two parallel metallic plates of width such that it is less than half wavelength in free space. Figure 1.1 depicts the NRD purposed by the Yoneyama. The structure is nearly the same as the H-guide which was proposed by the Tischer in 1953.

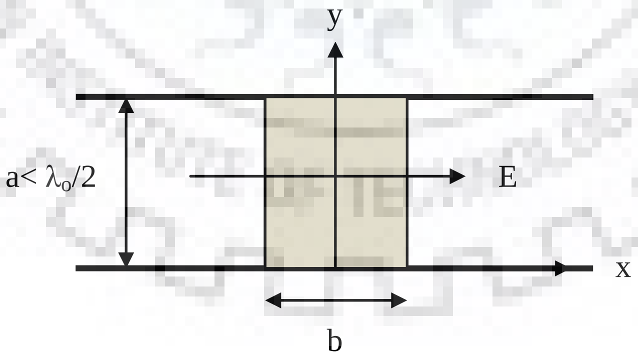


Fig. 1.1 NRD Waveguide Structure

The main difference between the H-guide and the NRD-guide is that the spacing between the metallic plates in the NRD waveguide is less than half the wavelength in a vacuum or free space wavelength, whereas in the H-guide the spacing is more than that. As a matter of fact, the conduction losses in the metallic plates goes down as the spacing is increased and therefore, the spacing is larger in the H-guide which is generally used as a transmission mean for longer distances. On the contrary, the NRD-guide is used at millimeter-wave (mm) frequency range and for integrated circuit applications at such ranges in which very short distances are the characteristic. Due to this, an increase in losses is not considered.

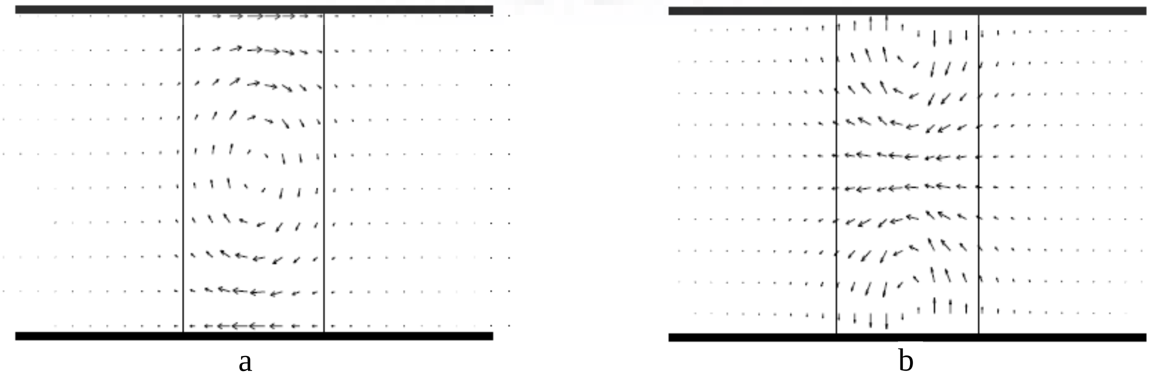
Apart this, electromagnetic (EM) field is restricted in the surrounding area of the region of dielectric due to the presence of dielectric slab, whereas outside that, for considered frequencies, the EM field decays exponentially. Therefore, if the metallic plates are kept adequately far away, the field is quite negligible at the end of the plates. Thus, the case is not greatly differing from an ideal case wherein the plates are infinitely extended.

The important feature of the NRD guide is that the polarisation of the electric (E) field in the mandatory mode is mainly parallel to the two metallic plates or conductive walls. Due to this there is decrease in the conduction losses in the metallic plates or walls as the frequency is increased, whereas, losses are more with the increased frequency if the electric field is perpendicular to the metallic plates or walls. Since the NRD guide has been primarily invented for its realization at millimeter (mm) waves, the chosen polarisation greatly reduces the ohmic losses. The discontinuities like bend or a junction in the case of H-guide results in phenomena like radiation and interference because the desired mode propagates outside being above cut-off.

The dominant mode in the NRD guide is Longitudinal Sectional Magnetic (LSM) mode (also referred as TM_x or E_x modes in which the magnetic field component H_x does not exist). The other mode of propagation in NRD is Longitudinal Sectional Electric (LSE) mode (also referred as TE_x or H_x modes in which the electric field component E_x does not exist). The dominant LSM_{11} mode offers low transmission losses. This way the actual usable bandwidth of NRD guide is restricted by the cut-off frequency ie, fc_{LSM11}, of LSM_{11} mode from the bottom and by the f_{cnr}, the cut-off frequency of the non-radiation condition from the top, thus,

$$fc_{LSM11} < f_g < f_{cnr} = c/2a$$

These advantages of NRD-guide i.e. low radiation on discontinuities & bends and less transmission losses make it fit for construction of compact and high quality millimeter wave integrated circuits. The field distribution in the NRD-guide for LSE and LSM mode is as shown in the figure 1.2 below.



a b

Fig. 1.2 (a) LSE_{11} Mode, Magnetic Field & (b) LSM_{11} Mode, Electric Field

1.3 Principle of Operation of NRD Guide

In the region of millimetre-wave of the frequency spectrum, many dielectric waveguides have been anticipated as possible alternatives for microstrips and striplines, however, at curved or bend sections, the radiation losses are found above reasonable levels. Also the guides like trapped image-guide which uses a metal trough to reflect back the radiated waves has been found successful in decreasing losses at 90° bends. But, the bulky size of the trough is not practical in integrated-circuits applications. Considering these factors, a non radiative dielectric guide was proposed by Yoneyama in 1981. This guide structure looks like Tischer’s H-guide, but have the principle of operation which is very different from H-guide. The structure is as given in Figure 1.1.

The principle of operation of NRD guide is as stated below. When two parallel metallic plates are separated by a distance which is smaller than half a wavelength in vacuum or free space then the EM waves with the electric (E) field parallel to the plates cannot propagate between them because of their cut-off property. However, if any dielectric strips, of some dielectric constant, is placed between these two metallic plates, as depicted in Figure 1.1, then the cut-off is removed and waves propagate freely along the strips. In such cases the radiated waves decay outside the dielectric strip,if any, and bends & junctions can be easily included into integrated circuits. This is the principle of operation of the NRD waveguide.

Mathematically, this principle of operation can be expressed if we consider a straight strip as shown in Figure 1.1. The strip width is considered as **a**, the thickness is taken as **b**. and let’s consider the dielectric constant as $\boldsymbol{\varepsilon_r}$. For analysis, let’s consider that the hybrid modes in the NRD-guide can be represented as the result of TM surface waves which are propagating in an infinite slab of the same material and of the same thickness as the dielectric strip. These waves are bouncing back and forth between the sidewalls. In particular, the cut-off of the dielectric strip can be given as,

$$\lambda_{gn} = 2a, \quad n=0,1,\ldots\ldots$$

where λ_{gn} is the guide wavelength of the TM_n slab mode.

Now, the equation for λ_{gn} is

$$\lambda_{gn} = \frac{\lambda_0}{\sqrt{\epsilon_r - (\lambda_0 q_n / 2\pi)^2}}$$

Where, λ_o is the free space wavelength and q_n is the n^{th} solution of the characteristic equations derived as:

$$\frac{q_n}{\varepsilon_r}\tan\left(\frac{q_n b}{2}\right) - \sqrt{(\varepsilon_r - 1)\left(\frac{2\pi}{\lambda_0}\right)^2 - {q_n}^2} = 0, \qquad n\ even$$

$$\frac{q_n}{\varepsilon_r}\cot\left(\frac{q_n b}{2}\right) - \sqrt{(\varepsilon_r - 1)\left(\frac{2\pi}{\lambda_0}\right)^2 - {q_n}^2} = 0, \qquad n\ odd$$

Thus referring to the $\boldsymbol{\lambda_{gn}}$, the condition for the single mode operation is given as

$$\lambda_{0},\ \lambda_{g1} > 2a > \lambda_{go}$$

where, $\boldsymbol{\lambda_{g0}}$ and $\boldsymbol{\lambda_{g1}}$ are the guide wavelengths of the fundamental and second TM modes of the slab, respectively. $\boldsymbol{\lambda_0}$, vacuum or free space wavelength has been incorporated to suppress the radiated waves. The cross-sectional plane of the field lines are as shown in Figure 1.2(a).

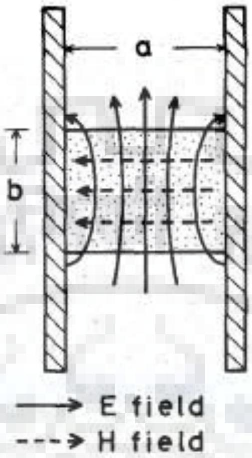


Fig. 1.2(a) Field lines in a Cross-Sectional Plane NRD Waveguide.

Few of the most significant features of NRD-guide, which have been discussed earlier also, are as following:

1. Transmission losses are low.
2. Bends are non-radiating.
3. Discontinuities losses are low.
4. Cost of fabrication is low.
5. Ease of fabrication.
6. Compatible with other already existed technologies.

Some important characteristics which define the NRD guide are as under:

1. **Dispersion Characteristics**. Dispersion curve of a NRD guide is nearly the same to that of a metal rectangular waveguide which is filled with the dielectric material same as that of the dielectric strip. Thus, the NRD guide to be regarded as a dielectric-filled metal waveguide which does not require top and bottom metal plates, so the major sources of conduction loss are removed in these. Although the dispersion characteristics are significantly similar, the bandwidths of the single-mode operation are very different for these two waveguides.

2. **Bandwidth of Single-Mode Operation**. The achievable bandwidth will be wider if the dielectric constant is large, however, losses will be more.

3. **Transmission Loss**. Transmission loss, $\boldsymbol{\alpha_t}$, of NRD guide are mainly of two types ie conduction loss, $\boldsymbol{\alpha_c}$ due to the sidewalls and dielectric loss of the strip, $\boldsymbol{\alpha_d}$.

4. **Coupling Coefficient**. Couplers play important role in millimetre wave application integrated circuits. The coupling coefficient between the dielectric strips is given by,

$$C = (\beta_{e\,-}\,\beta_0\,)/2$$

In which, β_e and β_0 are the even & odd modes phase constants in the double-strip dielectric guide.

5. **Impedances**. The impedances don't directly explain the field performance in the NRD guide, yet, it is an important parameter which is used in the designing of microwave and millimetre-wave circuits or components. There are two main types of impedance which are defined in the waveguides, ie :

(a) **Wave Impedance**. This can be described for an arbitrary point inside the guide, as the ratio of two perpendicular magnetic and electric fields components of the guide.

$$Z = E_x/H_y \qquad \text{,or}$$
$$Z = -E_y/H_x$$

(i) For LSE mode, it is given as,

$$Z = \omega\beta\mu_0\mu_r / (k^2_y + \beta_2)$$

where k_y is a wave number in the y direction and β is a longitudinal phase constant.

(ii) For LSM Mode, it is given as,

$$Z = (k^2_y + \beta_2) / \omega\beta\varepsilon_0\varepsilon_r$$

where k_y is a wave number in the y direction and β is a longitudinal phase constant.

(b) **Characteristic Impedance**. This can be expressed in terms of circuit quantities such as current, voltage and power. The definition of these quantities is specific for each waveguide and depends on waveguide shape and field distribution in a particular waveguide and selected mode. In general, three definitions of characteristic impedances are used. These are,

(i) **Voltage-Current Impedance**. $Z_0 = V/ I$

(ii) **Voltage-Power Impedance.** $Z_0 = I\ V\ I^2 / 2P^*$

(iii) **Power-Current Impedance**. $Z_0 = 2P / I\ I\ I^2$

In which, I and V, are the current and voltage defined in a way that is the most suitable for a particular waveguide. The complex power P is expressed as,

$$P = V\, I^*/ 2$$

These three definitions generally results in giving different values which depends on how the current, voltage and power have been determined. At times it is possible to have the same value for each type of impedance. Usually, the voltage-power definition is used in the NRD guide case. As the field configuration for both LSM & LSE modes are different, thus the separate definition of the voltage-power impedance have been introduced which are given as below,

$$P = -\left(\mathrm{Re}\int_0^a \int_0^b E_y H_x^* \, dx \, dy\right) / 2 \quad \text{........ For LSE Mode}$$

$$P = -\left(\mathrm{Re}\int_0^a \int_0^b E_x H_y^* \, dx \, dy\right) / 2 \quad \text{........ For LSM Mode}$$

1.4 Polylactic Acid (PLA)

The **Poly Lactic Acid** or **Polylactide** (**PLA**) is a bio-degradable and bio-active thermoplastic aliphatic polyester which is derived from the renewable resources, such as corn starch, cassava roots, chips or starch, or sugarcane. In 2010, the PLA had the second highest consumption volume of any bio-plastic in the industry. It is one of the most promising bio-degradable polymers (bio-polymers) and has been the subject of profuse literature over the last decade. It can be processed using large number of techniques and is commercially available at a large scale production. It is widely available in a various range of grades.

It is relatively cheaper and has some noteworthy properties, which make it suitable for different applications. Few of such properties are as under:

1. Soluble in chlorinated solvents, hot benzene and dioxane.
2. Range from amorphous glassy polymer to semi-crystalline and highly crystalline polymer.
3. It has a glass transition temperature 60–65 °C, a melting temperature of 173–178 °C and has a tensile modulus of 2.7–16 GPa.
4. It is heat resistant and can withstand temperatures of 110 °C.
5. Basic mechanical properties exist between those of polystyrene and PET.
6. It can be processed like most thermoplastics into fibre and film.
7. It has easy printability which makes it widely used in 3-D printing.

Due to cheaper in nature, abundantly available and other properties which are listed above, the PLA has many promising applications. Few of these are as listed below:

1. Can be used in 3D printers.
2. It is used as medical implants like anchors, screws, plates, pins, rods, etc.
3. It can also be used as a decomposable packaging material.
4. In the form of a film, it shrinks upon heating, allowing it to be used in shrink tunnels.
5. It is useful for producing loose-fill packaging, compost bags, food packaging, and disposable tableware.
6. In the form of fibers and nonwoven fabrics, it also has many potential uses, for example as upholstery, disposable garment, awnings, feminine hygiene products, and diapers.

Due to the above mentioned properties of this material, it was decided to use it as dielectric in our project and undertake construction of NRD guide for frequency of 24.5 GHz. PLA of various electric permittivity are available in market, however in our project we have chosen PLA with permittivity as 2.7 and loss tangent as 0.008.

Chapter 2

Review of Literature and Problem Statement

2.1 Literature Review

In the year 1981 the Yoneyama published the paper on the subject of Non Radiative Dielectric (NRD) Guide for the first time. A dielectric strip was basically kept in between two parallel metallic plates and these plates are separated by a distance that is smaller than half a wavelength in vacuum or free space. Although its structure generally has resemblance to that of the H-guide, but it is based on a very different principle of operation which has been discussed in chapter 1. The dielectric guides are particularly applicable in millimetre wave regions for its integrated circuits. It gives various important advantages at millimetre wave region which can be summarised as small in size, easy in fabrication and bends and junctions can be incorporated into the integrated circuits with very little radiation and interference. Various basic circuit components, like 90° and 180° bends / T-junctions which are made up of polystyrene strips had been developed to verify the usefulness of such guides in millimetre-wave integrated circuits and components.

The structure of NRD guide is similar to Tischer's H-guide, but has a different principle of operation which has already been discussed earlier in the chapter 1. The NRD guide can suppress the radiation and interference. Thus it can be used greatly for the advantage in millimetre-wave integrated circuits and components.

During the course of time few important strip structures were developed to establish the theory of NRD which are made of polystyrene. Structures have been created like T-junction, 90^0 and 180^0 bends and directional couplers.

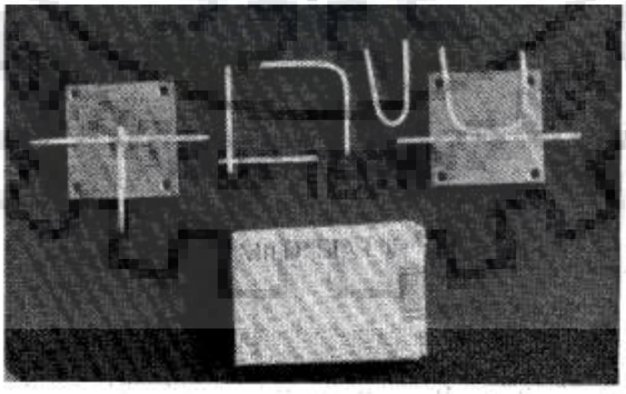


Fig. 2.1 Photograph of various strip structures of polystyrene developed by Yoneyama.

The utilisation of the NRD guide in bending structures is one of the major applications for the millimetre-waves integrated circuits. Although dielectric waveguides have relatively less transmission losses for the straight section, however, at the bends the radiation losses are often found alarming. In the NRD guide, the reflection at the transitions between the straight and curved waveguides has been found the major cause of the bending losses rather than the radiation. The experimental studies have shown that the radiation at the bends in the NRD guide can be almost suppressed provided that the reflection is used to determine a minimum radius of bending rather than the radiation.

Various methods have been experimented to eliminate the reflection, however, one of the most effective is found to be to narrow the strip at the curved section. It was found that the narrower the strip, the lesser the shift of the field maximum and hence the lesser the reflections. However, it was also found that it is to apply to a point because beyond a limit, as the strip narrows, the operational bandwidth of the bend decreases. After considering various other factors, a practical minimum radius of bending is somewhat about one guide wavelength. Thus, it can be seen that sharp bends can be easily built in the NRD guide to realise complex dielectric waveguide components for millimetre-wave integrated circuits and components.

It can be seen that only developing a NRD guide will not be suffice to utilise it effectively for various applications. There is a requirement of efficient interconnections between various different waveguides which is very important for using hybrid structures. Apart that integration with the multipurpose instruments and measurements at microwave and millimetre wave frequencies demand an effective transitions between various available technologies. Also in order to measure NRD systems, these are to be connected to transmission means which are compatible with measurement tools. Such means can be rectangular waveguides, microstrip lines, etc. The main objective in such transition is to limit the mismatch losses which can be done by optimisation processes. For the rectangular waveguide various transitions have been developed like standard waveguide to NRD guide or Horn to NRD guide etc. A transition of microstrip line to NRD guide has also been developed which makes a small and compact design for directly integration with planar microstrip based devices and components. For this an aperture coupling theory has also been developed to support this design.

As discussed earlier various important components based on NRD guide have been developed. One of the important among them is bandpass filter. The only wave parameter required to design such filter is the reflection coefficient. One among these fit in the class of coupled resonator filters which have been studied at great depth by Cohn.

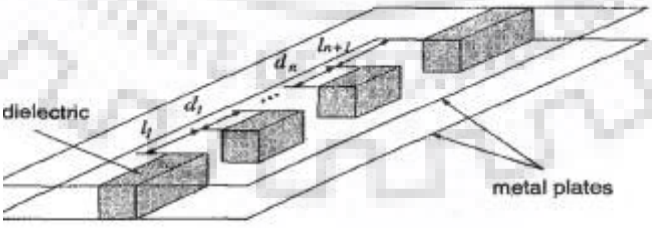


Fig. 2.2 A general view of an NRD-guide Bandpass Filter

Each gap can be seen as a discontinuity with certain scattering properties. Using various formulas, the values of reflection coefficients can be determined which are required at each discontinuity.

There has been many papers, journals etc which have been published since 1981 when Yoneyama first presented his theory. Since then there has been a continuous growth the study of this new field of integrated circuits. At present it is quite a latest technology to look upon and still not much has been progressed in this area.

2.2 Problem Statement

The main objective of the thesis is:

"Integration of NRD guide with rectangular waveguide, rectangular waveguide with horn guides and planar microstrip lines for the further development of Hybrid integrated millimeter-wave circuits".

2.3 Organisation of Thesis

Chapter 1 discusses the background and motivation behind taking up NRD guide as research topic including NRD guide introduction and it's principle of operation.

Chapter 2 discusses the review of various literatures and states the problem taken up in this dissertation.

Chapter 3 discusses transition between a rectangular waveguide and a NRD guide.

Chapter 4 discusses transition between a rectangular waveguide with horn and a NRD guide.

Chapter 5 discusses transition between a microstrip line and a NRD guide.

Chapter 6 discusses the conclusion and the future scope.

Chapter 3

Transition Between A Rectangular Waveguide and A NRD Guide

3.1 Rectangular Waveguide

The rectangular waveguides are most commonly used transmission lines in the majority of power sources and measurement instruments. Now the operating mode of a NRD guide is the LSM_{11} mode, as discussed earlier. Thus, the problem which has to be solved is how to excite this mode in practically realized NRD guide circuits. It has been found that the LSM_{11} mode in NRD guide can be excited by TE_{10} mode of a rectangular waveguide as the electric field patterns of these modes are quite similar. Therefore, a rectangular waveguide can be usually employed to excite NRD guide circuits for various testing and development purposes. However, it must be noted that in practically the realized NRD guides are of very small dimensions whereas the rectangular waveguides are generally available for standard size and dimensions. The problem solution lies in matching of sizes and to solve the integration method.

The thesis work to be undertaken was to develop a NRD guide and its transition system for first for the rectangular waveguide & subsequently for microstrip line at given frequency of 24 GHz. This NRD guide will be supported by the foam material from both the sides which has dielectric constant of 1.2 and loss tangent as 0.001. First task to achieve this complete system was to simulate a NRD guide using PLA as dielectric medium which has the dielectric constant as 2.7 and loss tangent as 0.008 for a frequency band of 24 GHz with a centre frequency at 24.5 GHz. The work was commenced with the review of literatures; few of them have been explained in the previous parts of this report. The simulation was carried on the ANSYS HFSS (High Frequency Structure Simulation) software. The basic work was divided into following sub parts :-

1. To simulate and construct a NRD guide for given frequency.
2. To simulate and analyse transition for rectangular waveguide.

In this chapter the transition between a rectangular waveguide and a NRD guide as been simulated and analysed. The structure was varied numerically and an optimised design has been used to show the transitions. The experimental verification has been carried out in the frequency range of 18 to 28 GHz. After carefully adopting the line of action, it was decided that the transition between a rectangular waveguide and an NRD-guide should have following features:

1. Geometry should be such that the transition guarantees the conversion from TE_{10} rectangular waveguide mode to required dominant LSM_{11} mode in the NRD guide in a required frequency range.
2. The transition should have relatively wide operational bandwidth.
3. It should also have small insertion loss in the operational bandwidth (about -20 dB and less).
4. It should match the geometrical dimension of the NRD guide.

5. Ease of fabrication and low cost of manufacturing.

3.2 Initial Work

Initially, the concentration was paid towards the realization of a NRD guide. Thus, after carrying out basic calculations on the given data ie centre frequency, f_0 = 24.5 GHz and with given dielectric constants of the other materials, the half wavelengths (λ_g) for PLA (dielectric constant as 2.7 and loss tangent as 0.008) and Foam material (dielectric constant as 1.2 and loss tangent as 0.001) have been derived as 3.726 mm and 5.589 respectively. As for NRD the basic rule says that the separation between the walls should be less than the half wavelength, however due to the limitation of use of foam alongside the PLA, the height was fixed as 5.384mm for optimizing and realizing the NRD guide.

The work started with the optimization of the width for the NRD guide (as height freezed at 5.384 mm). The half symmetry method was utilized for the same. The best results which are obtained for the NRD guide with the following dimensions; a = 4.96 mm, b = 2.692mm and c as 10.47mm (complete width of the guide). Figure 3.1 depicts the image of initial NRD guide work.

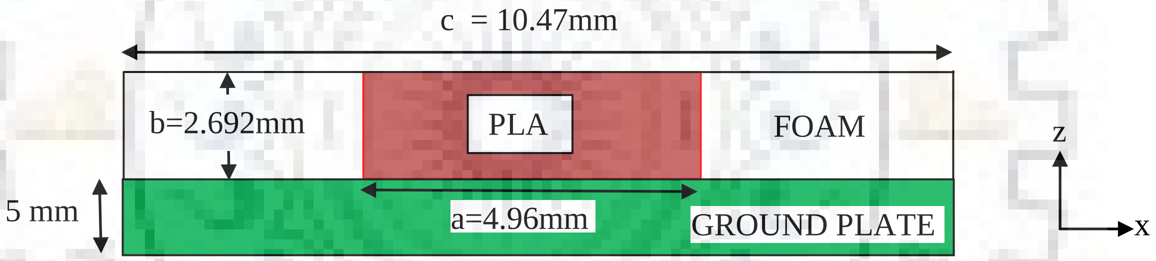


Fig. 3.1 NRD Guide Structure with Dimensions

Post optimization of the NRD guide the following results were obtained which are given in figure 3.3 & 3.4. It was found from the dispersion graph that the two modes of operations are possible for this optimized NRD guide. The S parameter values ie basically S_{12} and S_{21} (being 2 port guide which can be excited from either port) were also obtained and were found satisfactory. The values of S_{12} and S_{21} (in dB) obtained for first two modes for the either ports and have been obtained as - 0.7261 dB at 24.5 GHz and -0.8389 dB at 24.5 GHz, respectively. The size of the PLA strip used in the horizontal plane

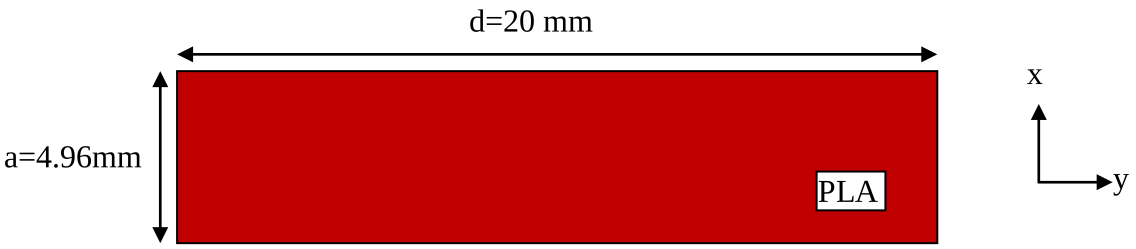


Fig. 3.2 NRD Guide Structure Top View

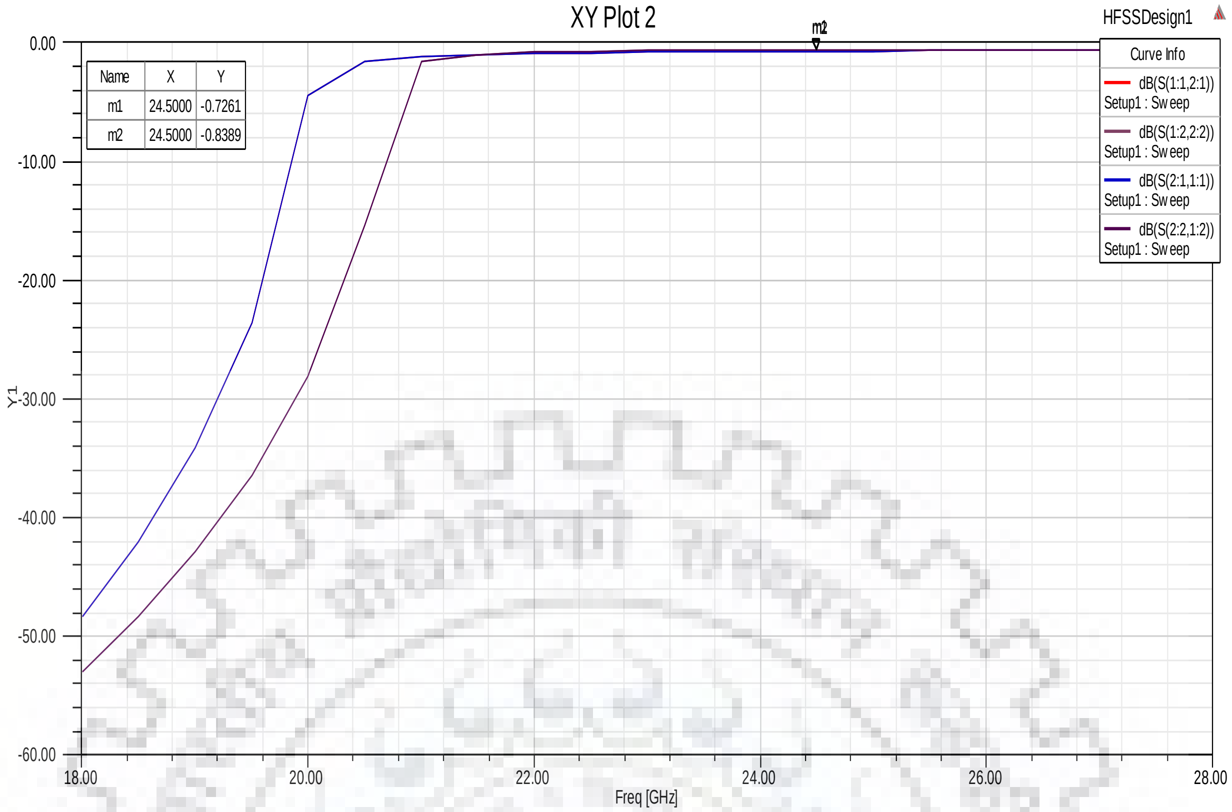


Fig. 3.3 S_{21} Graph Representation at 24.5 GHz

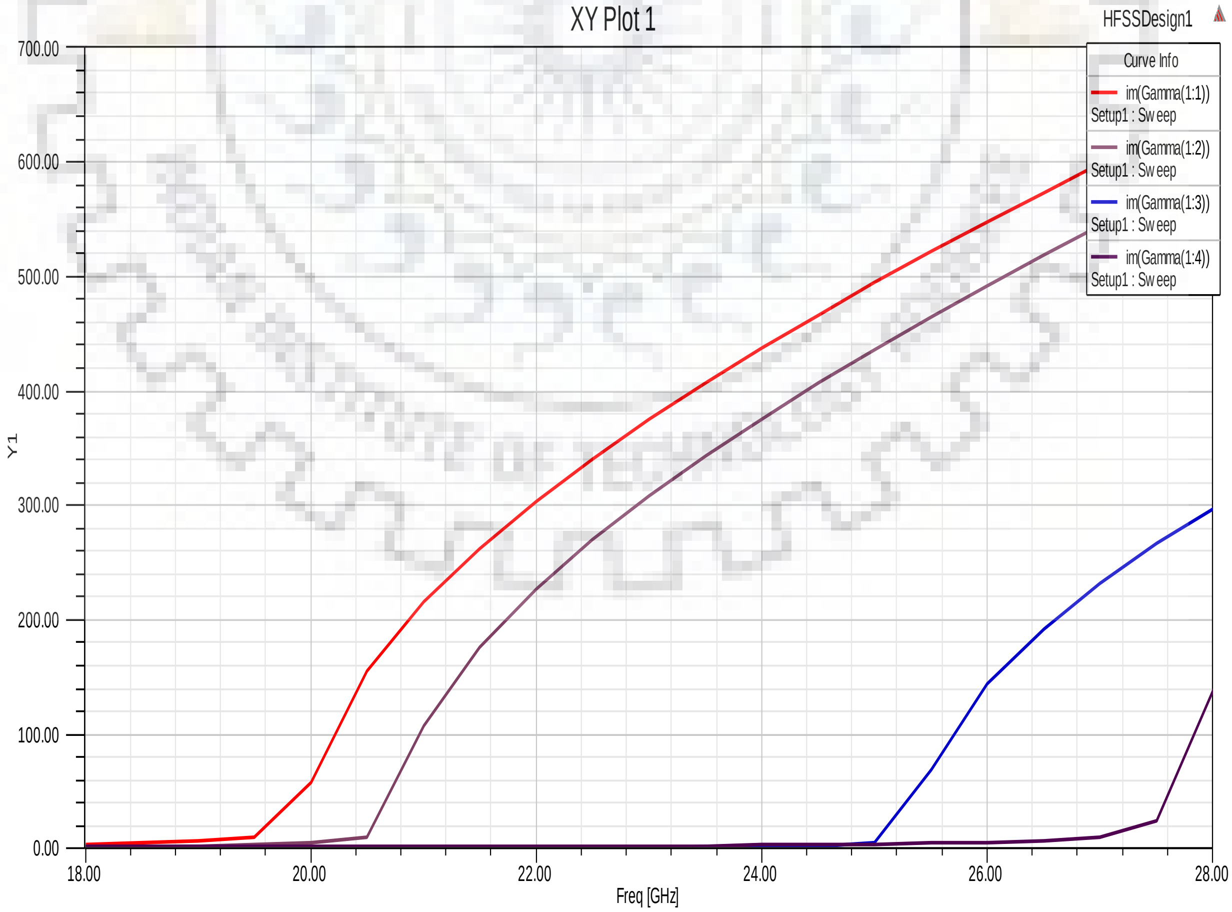


Fig. 3.4 Dispersion Graph

The best optimized results were obtained for this NRD guide using half symmetry method. In this NRD guide, the dielectric strip was of PLA and has been sandwiched between foam supports from the either sides. The results obtained have been displayed above. Thus, with this the first step of our project can be considered completed and this became the base for the further development.

3.3 Simulation and Analysis of Rectangular Waveguide Transitions

With the first step in the requirement being considered completed, the complete concentration then was shifted in achieving the next step ie simulation of this NRD guide with the rectangular waveguide.

To realise a transition from NRD guide to rectangular waveguide, a NRD guide has to go sufficiently into a rectangular waveguide in a manner that it allows smooth wave propagation from one guide to the other and to reduce the physical discontinuity. The various parameters that can influence the discontinuities in such transition are:

1. **Height of the NRD Guide**. Rectangular waveguides which are generally used for such transitions are standard waveguides having specific dimensions which is fixed for the range of frequencies or a particular frequency band. If the height of the NRD waveguide is lower than the one of the rectangular waveguide, a discontinuity will appear. In our case, the height of the guide is 5.384mm which is more than that of WR34 waveguide whose dimension is 4.318mm x 8.636mm. Thus, it will result in discontinuity.
2. **Width of the NRD Guide**. Usually it has same effect as that of the height. The width in our case can be managed and can be kept around 8.636 mm.
3. **Addition of a Taper Section of the NRD Guide**. A taper has to be added to both the extremities of the NRD guide to reduce the influence of rectangular waveguide section.

The influence of these parameters on the transition has been studied using HFSS software and an optimal transition design was developed. During the analysis, it has been established that the performances of the transition are better when the dimensions of the NRD waveguide come closer to that of the rectangular waveguide. The final design is the one presented in Figure 3.5.

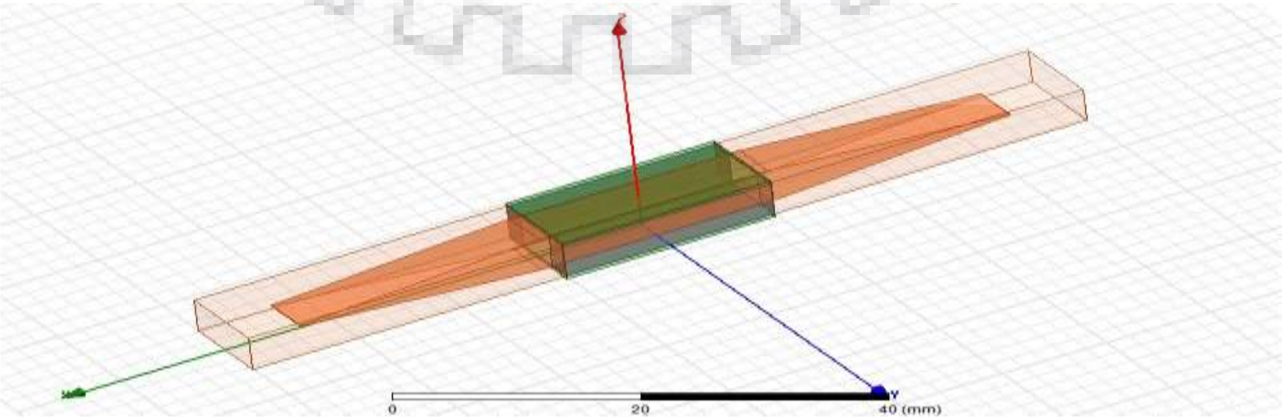


Fig. 3.5 Design of the Final Structure: NRD Guide to Rectangular Waveguide Transitions.

The structure which has been simulated and analysed has been made for dual transitions in order to measure it in transmission. The dimension of the final structure is as under :

	X (in mm)	Y (in mm)	Z (in mm)
DIELECTRIC SLAB	20	4.5	5.384
FOAM	20	8.836	5.384
WAVEGUIDE	30	8.636	5.584
METAL PLATES	20	8.836	0.5

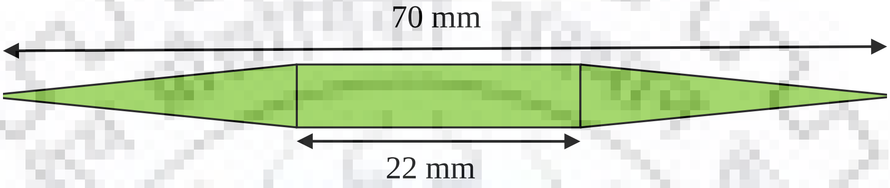


Fig. 3.6 Design of the Dielectric Strip of PLA Strip: Side View

Figure 3.6 represents the dimensions of the PLA dielectric strip used which is tapered from both the ends to reduce the discontinuities. The PLA strip is of 20 mm in size and the tapering ends are 25 mm in dimensions when seen from the side. The strip has been extended 1 mm in both the sides inside the waveguide. The size of the rectangular waveguide is 5.584 mm x 8.636 mm, which are not the standard size of the rectangular waveguide available for this frequency range. Thus, a custom made waveguide has been realised to complete the analysis and this transition. The lower cut-off frequency for this waveguide is 17.35 GHz and the upper cut-off frequency is 32.8 GHz.

Figure 3.7 shows the results of simulation for both S_{21} and S_{11}. The complete analysis was swept from 20 GHz to 28 GHz. The insertion losses are found to be very low around -20 dB and the transmission is found to be around -2.5 dB.

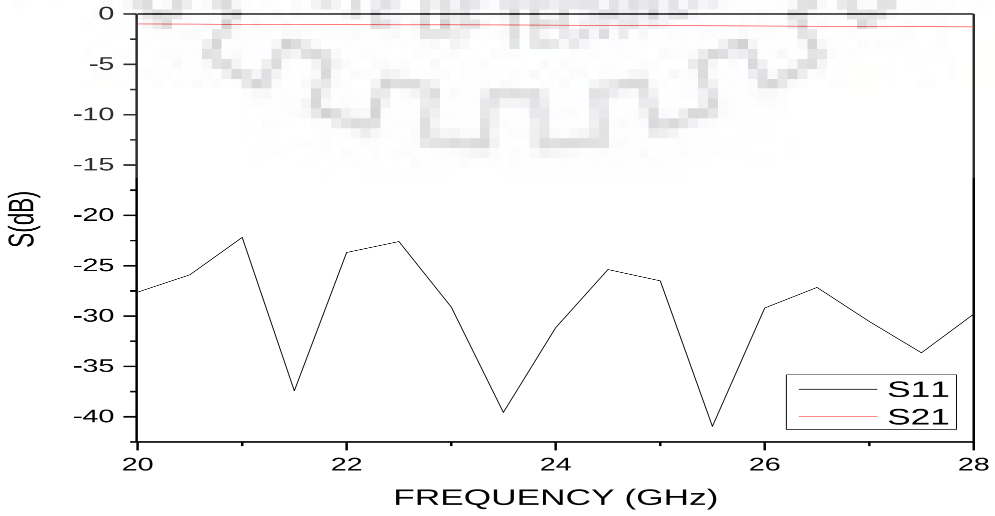


Fig. 3.7 S_{21} and S_{11} Simulation Results

3.4 Rectangular Waveguide Transition : Conclusion

The rectangular waveguide transition results in good transmission of signal which can be seen in the results, however this has few limitations, like:

1. Difficulty in using regular / standard available rectangular waveguides (WR-42 or WR-34) as they may either not fit dimension wise for the transition or may results in bad transmission of particular required frequency of operation.
2. Custom made or tailor made rectangular waveguides would be required to realize practically which are costlier to manufacture.
3. Only one mode has been found propagating in this transition in which electric (E) field is found perpendicular to metallic walls (LSE), thus it will result in more conduction & ohmic losses. The same is shown in the given Figure 3.8.

Fig. 3.8 Mode Propagation in Rectangular Waveguide

4. The dielectric strip used in this simulation and analysis is of PLA which has very high dielectric loss tangent value 0.008. A simulation was run to check the effect of lower loss tangent values. It was found that the S_{21} values have been improved and thus, it is concluded a dielectric with lower loss tangent value would yield best results and thus reduces losses in the transmission. The simulation was carried out for three different values ie 0.008, 0.004, & 0.001. The result so obtained is furnished as under in Figure 3.9.

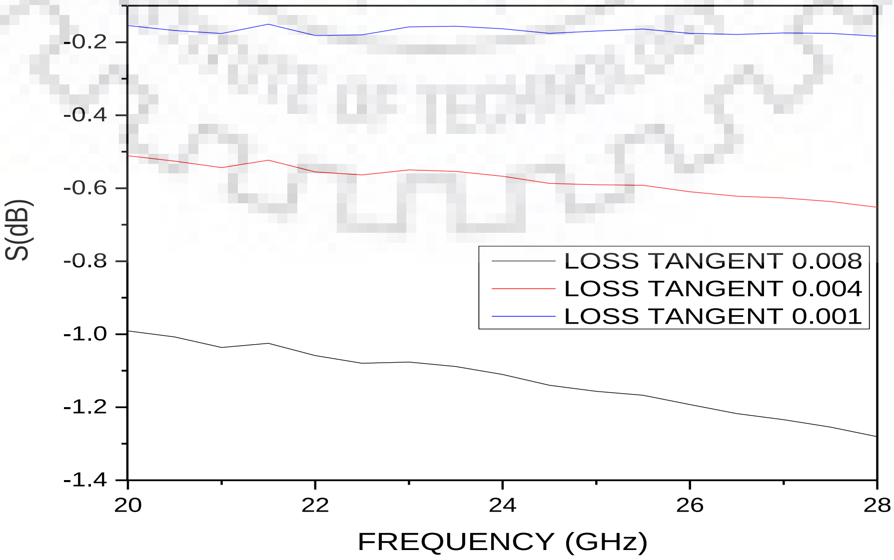


Fig.3.9 S_{21} with Different values of Dielectric Loss Tangent

5. Apart this, the width of the PLA was varied and simulated to check the effect on S_{21} values as while fabricating the PLA due to various unknown reasons the 3D printer does not give a PLA with uniform width and practically it varies 8% to 10% of the finalized value. For the simulation, the width was varied from 4.4 mm to 4.8 mm. It was found that it has negligible effect on the overall result and the result varies from approx -1.06 dB to -1.08 dB only. The simulated result is as shown in the Figure 3.10.

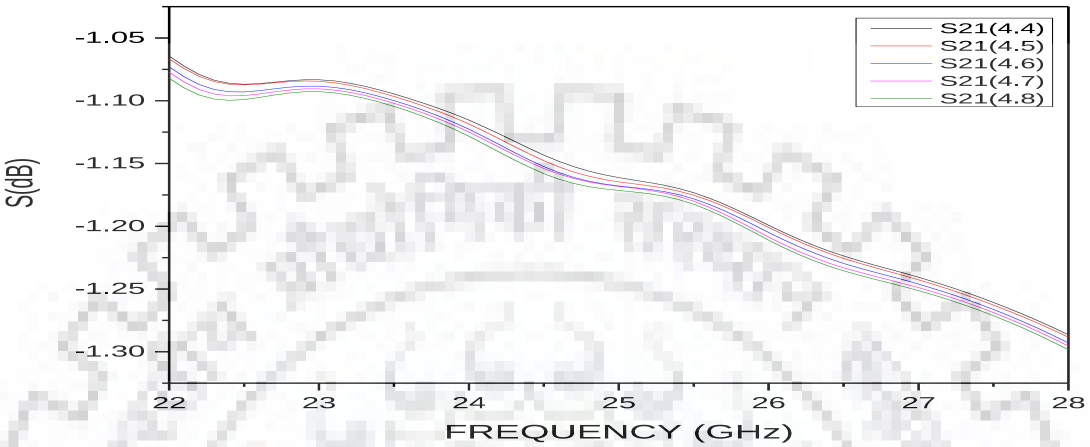


Fig. 3.10 S_{21} with Varied Values of PLA Width

Chapter 4

Transition Between A Rectangular Waveguide with Horn and A NRD Guide

4.1 Rectangular Waveguide with Horn

It was found that the rectangular waveguide though has resulted in good transmission of signal, however, it has many limitations which have been discussed in the conclusion part of the previous chapter. To overcome challenges faced in waveguide transition, a custom made horn is devised to make required mode ie LSM mode propagate in the guide. For such arrangements, a standard rectangular waveguide WR-34 (8.636mm x 4.318mm) having lower and upper cut-off frequencies as 17.357 GHz and 34.715 GHz respectively, has been used with the front having a custom horn for transition from rectangular waveguide to NRD guide.

Transition in this case is done from normal waveguide to custom horn to NRD guide. The optimisation of the structure for this transition is also carried out to limit the mismatch losses and discontinuities. A taper has been added to the both ends of the PLA strip for smooth transition. A NRD guide to rectangular waveguide with horn transition has been simulated and analysed in this chapter. The final design is the one presented in Figure 4.1.

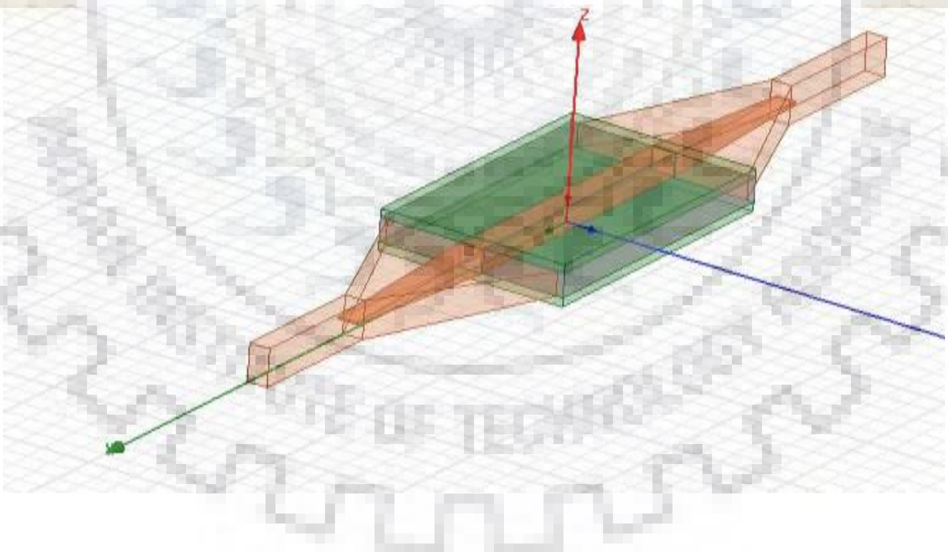


Fig. 4.1 Design of the final structure: NRD Guide to Rectangular Waveguide with Horn transitions.

The dimension of the final structure is as under :

	X (in mm)	Y (in mm)	Z (in mm)
DIELECTRIC SLAB	42	5	5.384
FOAM	60	40	5.384
WAVEGUIDE	30	4.318	8.636
METAL PLATES	60	40	2

This horn is typical horn with the E side flaring outside and the H side tapering inside to easily sit the PLA strip. The PLA slab is extended into the rectangular waveguide and has been made tapered to reduce the mismatch and physical discontinuity. The different views of the horn are given as under in Figures 4.2 to 4.5.

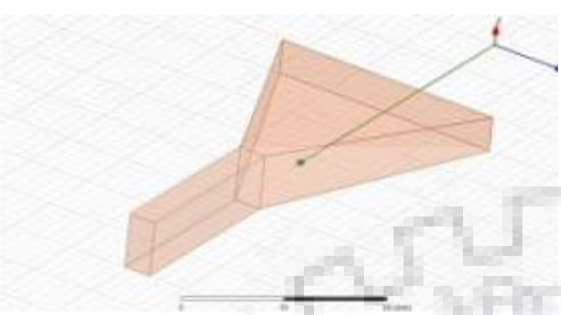


Fig. 4.2 Object View

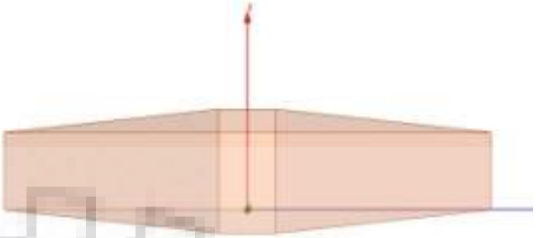


Fig. 4.3 Front View of Horn

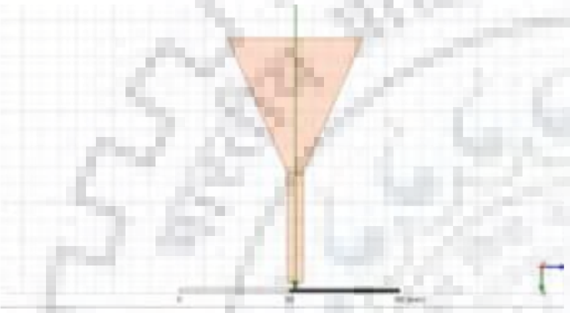


Fig. 4.4 Top View of Horn

Fig. 4.5 Side View of Horn

Figure 4.6 & 4.7 represents the dimensions of the PLA dielectric strip (side & top views) used which is tapered from both the ends to reduce the discontinuities. The PLA strip is of 40 mm in size and the tapering ends are 39 mm in dimensions when seen from the side from the NRD guide end. The strip has been extended 1 mm in both the sides inside the horn waveguide and also into the rectangular waveguide. The size of the rectangular waveguide is 4.318 mm x 8.636 mm, which is WR-34 rectangular waveguide.

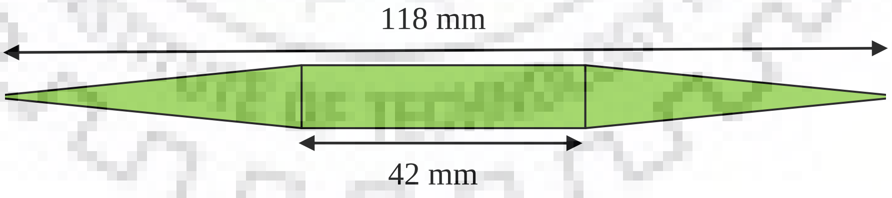


Fig. 4.6 Side View of PLA Strip

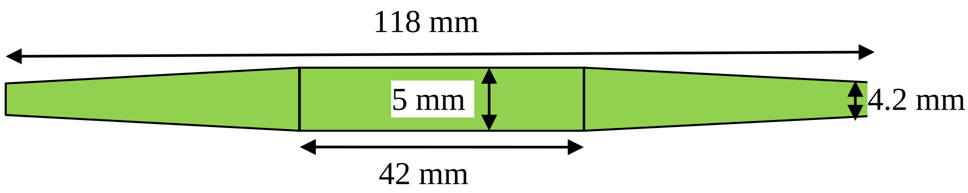


Fig. 4.7 Top View of PLA Strip

A custom made horn has been realised to complete the analysis and this transition. The exact dimensions are as given below in the Figure 4.8.

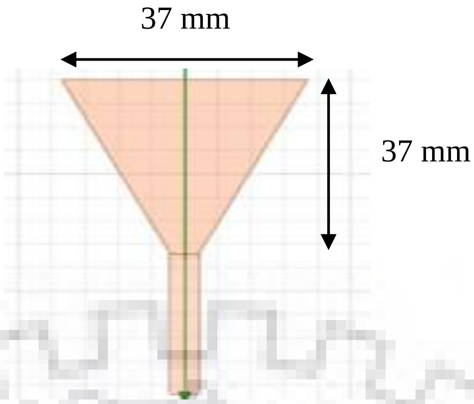


Fig. 4.8 Top View of Horn with Dimensions

Figure 4.9 shows the results of simulation carried out after optimising the structure. The simulation was carried out for the sweep of frequency from 22 GHz to 28 GHz with a spacing of 100 MHz. The transmission losses found are very low, around -5 dB throughout the graph. Even the insertion loss found is below -20 dB at the required frequency band.

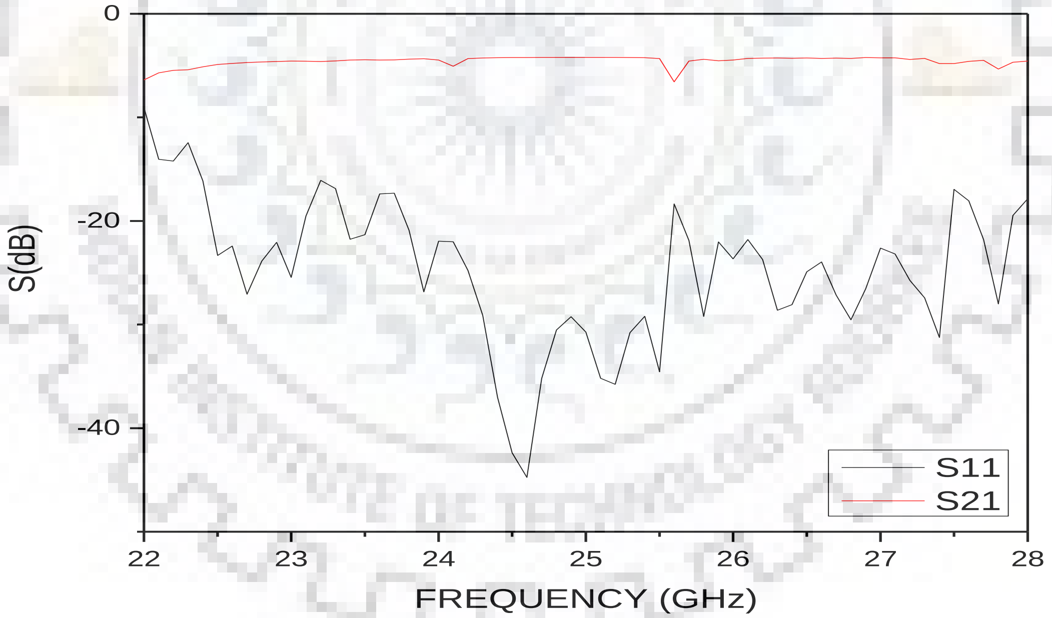


Fig. 4.9 S_{21} and S_{11} Simulation Results

4.2 Rectangular Waveguide with Horn : Conclusion

The rectangular waveguide with horn transition to NRD guide allows LSM mode of propagation which is the preferred mode of transmission in NRD guide and the same has been shown in the figure 4.10 on the next page. The electric fields are found to be travelling parallel to the metallic plates. This results in low losses and yields excellent results in good transmission of signal; same is depicted in the Figure 4.9 above.

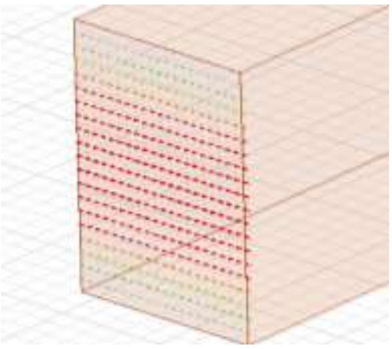


Fig. 4.10 LSM Mode Propagation in Rectangular Waveguide with Horn

However, there are again few limitations to realize this structure practically which are given as below:

1. A custom or tailor made horns are required to realize the structure which are costlier to manufacture.
2. Better results can be yield if dielectric strip of low loss tangent are available.

The losses in the guide were also studied considering low loss tangent materials and the same is compared with the PLA having loss tangent as 0.008. An upward shift in the S21 noticed with which it can be said a dielectric with better loss tangent would result in better transmission. Figure 4.11 depicts the result simulated using loss tangent as 0.001, .004 & 0.008 for PLA.

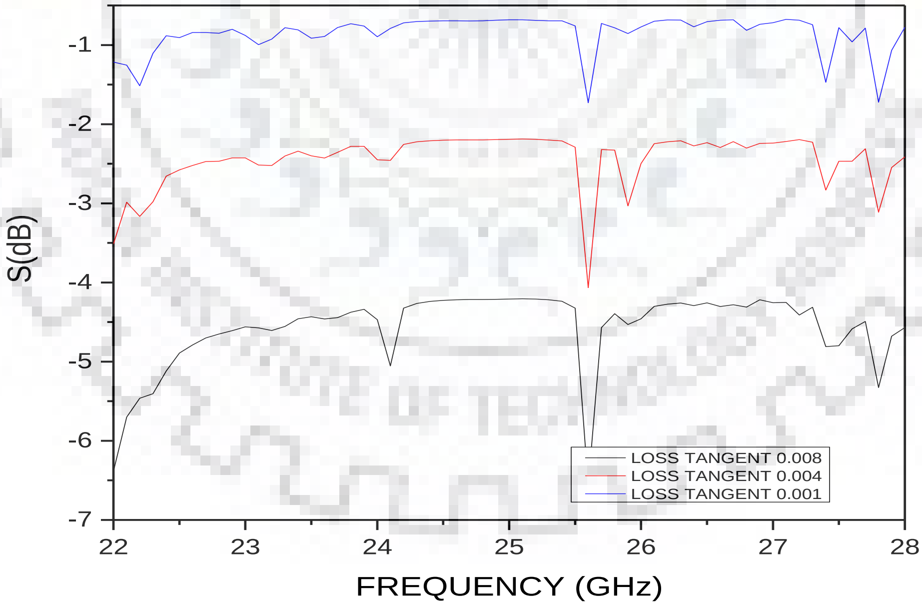


Fig. 4.11 S_{21} for Varied Loss Tangent

Chapter 5

Transition Between A Microstrip Line and A NRD Guide

5.1 Microstrip Line

A couple of transitions have been simulated and analysed from various transmission lines to the NRD guide ie transition from rectangular waveguide & rectangular waveguide with horn to NRD guide and vice versa. However, none of them is found suitable for a integration with the NRD guide. Also, these are costlier methods for the integration with the NRD guide. To cover the voids, a microstrip transition is studied wherein the concept of the aperture coupling is used.

As it is known that a NRD guide is made of a low loss dielectric material sandwiched between two parallel metallic plates with spacing smaller than half wavelength of vacuum. In the transition using microstrip line, an aperture is made in the ground plane of the microstrip line which couples the electromagnetic field with the NRD guide. This leads to the transition achieved by a signal path running from the NRD guide to the microstrip line & vice versa. This transition integrates the planar circuits with the NRD based components in a single block for the best use of the advantages of two different techniques. This technology can also help in developing various components one over the other. Thus, finally, a cost effective and readily available transition using microstrip line has been simulated and analysed for the given problem in this chapter.

The structure was optimized to give best results. PLA strip was sandwiched between the foam sheets and both are rested on the base plate which is made up of Aluminum metal. The base metal is of the dimension of 64 mm x 73 mm. The ears which can be seen on the y-axis to the either side of the axis are also made up of Aluminum metal. The microstrip line with Rogers RT/duroid 5880 (tm) substrate is placed above the PLA. The final design of the structure is shown in the Figure 5.1.

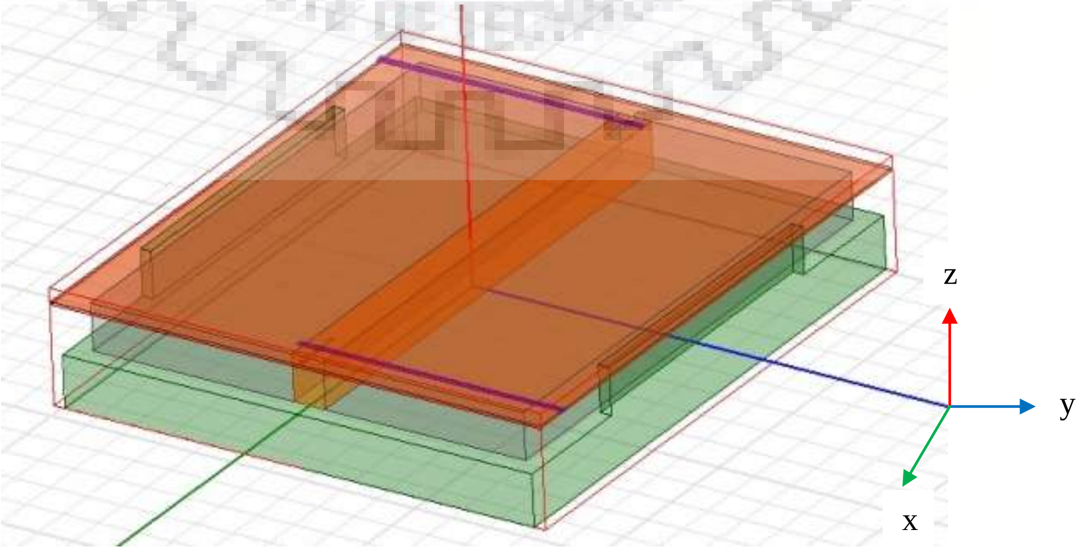


Fig. 5.1 Design of the Final Structure: NRD Guide to Microstrip Line Transitions

The method of developing this transition involves initial simulation of simple microstrip line designed for the required frequency. The microstrip line for required frequency band with the Rogers Substrate was initially simulated and analysed. The designed microstrip line is as shown in the Figure 5.2. The result obtained from the simulation gives good result for both transmission and reflection. Same has been shown in the figure 28 below.

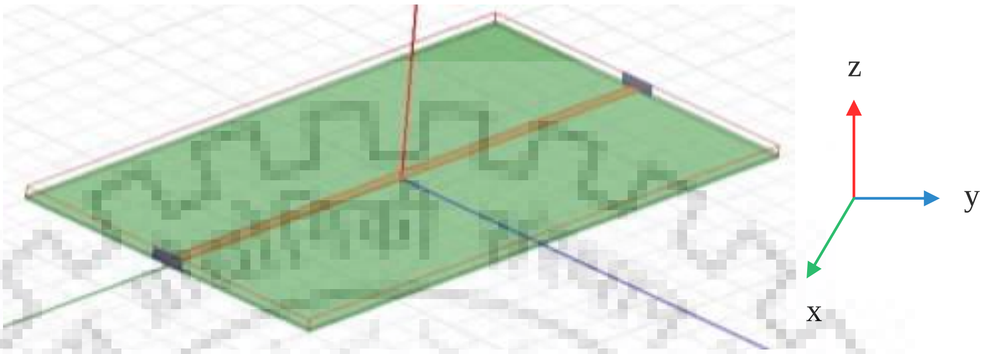


Fig. 5.2 Design of Microstrip Line

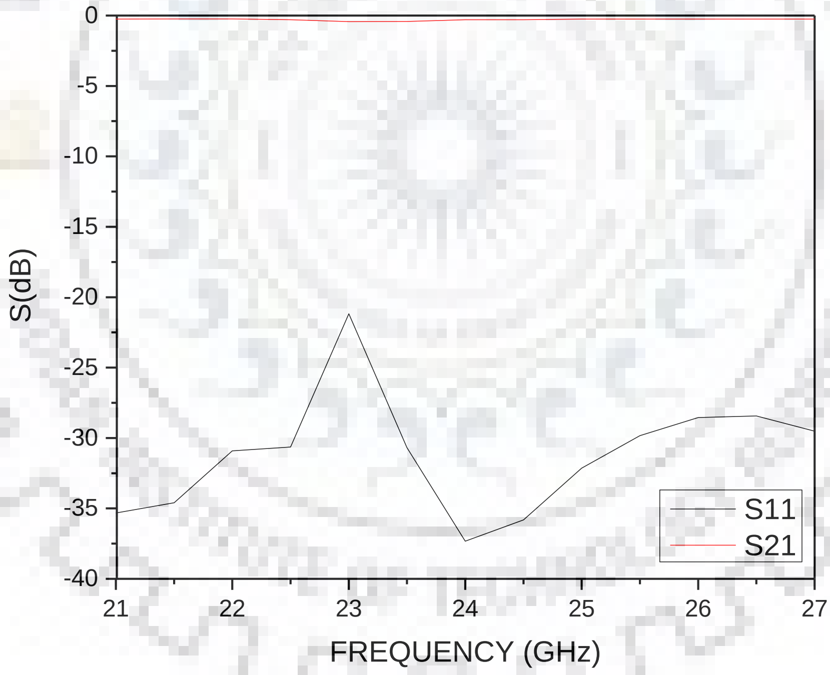


Fig. 5.3 S_{21} and S_{11} Simulation Results

Post simulation of simple microstrip line for the given frequency, a complete transition is simulated which as shown in Figure 5.3. All the parameters and factors were optimised and the result obtained on simulation is as given in Figure 5.4. The transition was simulated in HFSS & analysed. S_{21} noticed is close to -5 dB throughout the required band and a frequency band of approx 250 MHz is obtained. S_{11} at the required frequency band is found to be gone down well below -30 dB. Also only single mode propagates in the structures which agrees the required mode of propagation in NRD guide ie LSM Mode.

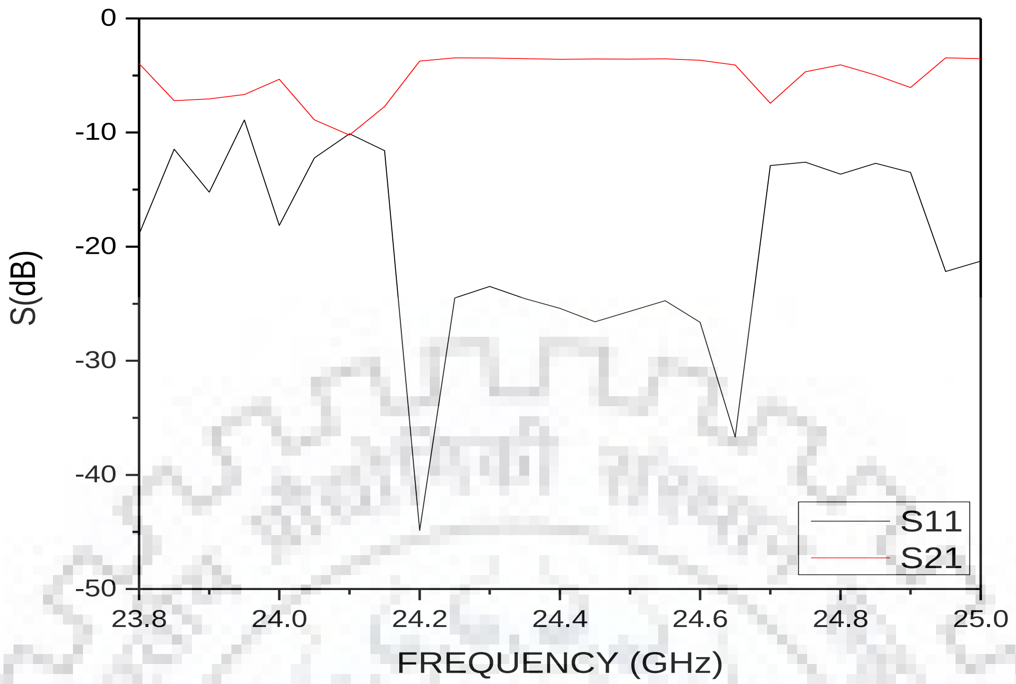


Fig. 5.4 S_{21} and S_{11} Simulation Results for Microstrip Line Transition

The designed structure was finally fabricated and when it is measured the results were found different from the simulated results. Thus the simulated results and the measured results were found to be in huge variance. To overcome this problem, connectors were also simulated with the help of the data sheet available online and the same was again analysed. Figure of the final design with connector is as shown in the Figure 5.5. Result, thus, obtained is as shown in figure 5.6.

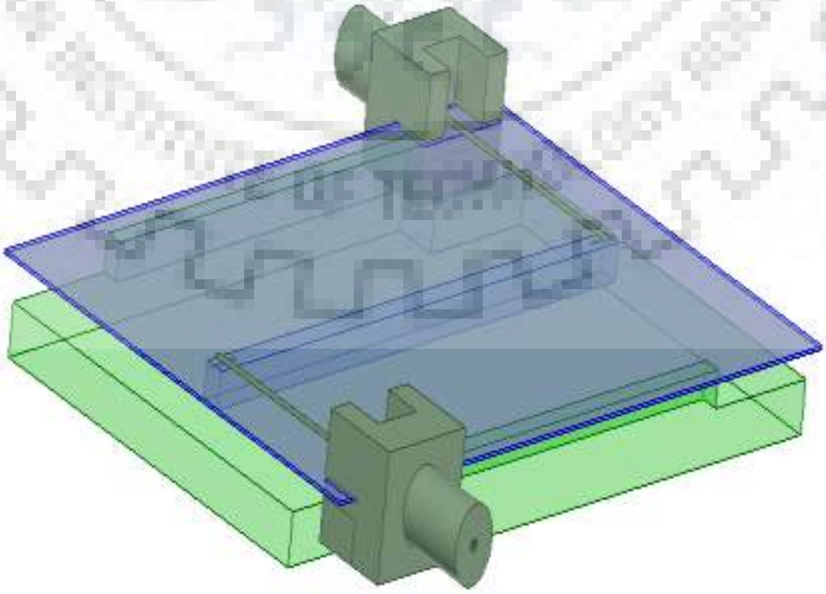


Fig.5.5 Design of Microstrip Line Transition with Connectors

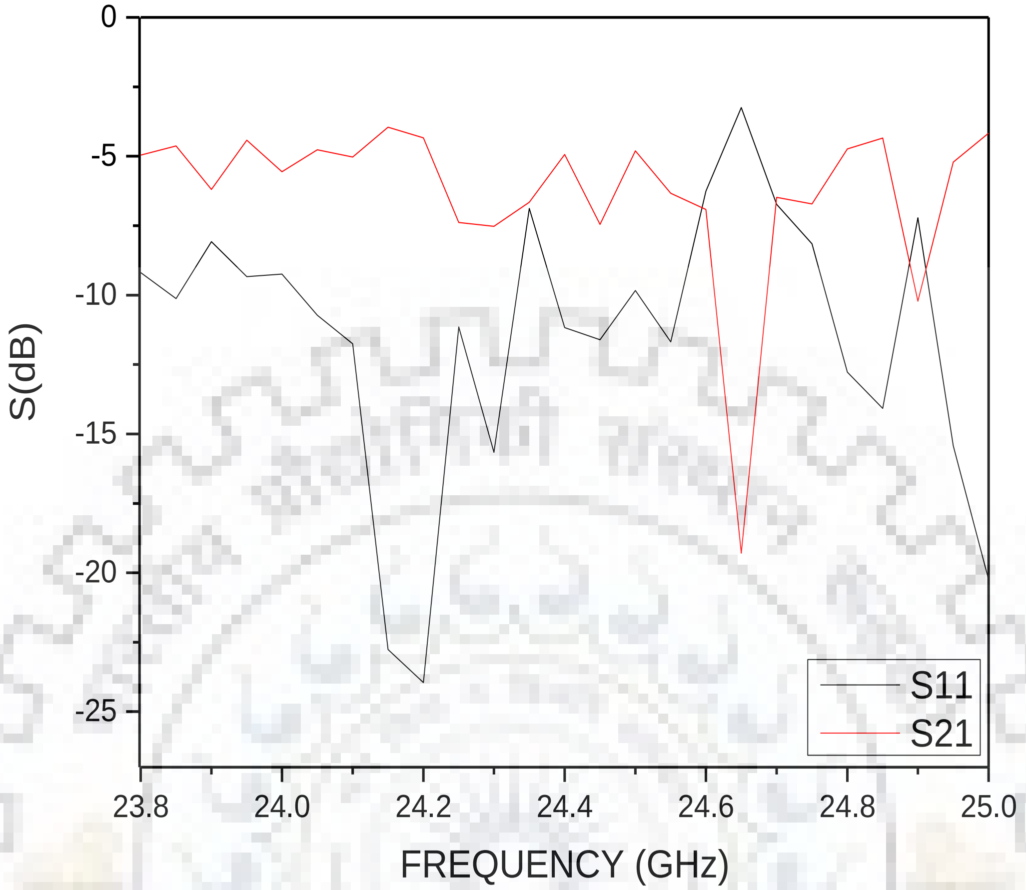


Fig. 5.6 S_{21} and S_{11} Simulation Results

The simulation was carried out for the frequency sweep of 23.8 GHz to 25 GHz with a 100 MHz gap. Variationa in both the S_{11} & S_{21} are noticed. Apart that frequency band has also been found decreased drastically. The S_{11} parameter at the required frequency band has been found gone upto -10 dB. However, single mode of propagation still exist in the system. These changes are mainly due to to mismatching, physical discontinuities, material properties etc.

5.2 Fabrication of Final Design

After simulation and analysis of the structure, the fabrication of the NRD guide along with transition of microstrip line has been carried out. The PLA strip has been fabricated at tinkering lab using Ultimaker 3D printer. Base plate (Aluminum metal) has been fabricated in the required shape & design by mechanical vendor in the local market. The microstrip line has been fabricated in-house using Rogers RT/duroid 5880 (tm) substrate of 0.254 mm thickness. The ground plane of microstrip line, made up of Copper, served as another metallic plate from the top for the NRD guide and foam has been used to sandwich the PLA dielectric strip from either sides. Connectors used in the measurement are of Southwest company which works from DC to 67 GHz. Fabricated components of the structure are as shown in the Figures 5.7 to 5.11 on the next page.

Fig. 5.7 Top View of Microstrip with Connectors

Fig. 5.8 View of Assembled PLA & Foam

Fig. 5.9 PLA Strip

Fig. 5.10 Side View of Assembled Transition

Fig. 5.11 Metallic Base Plate

5.3 Test Set-Up

The assembled structure was to be tested and thus a test set up was done. Keysight PNA-X Network analyser is used for the measurement of assembled NRD guide in the test set-up. The VNA was first calibrated using available calibration kit. It is then connected using cables to the fabricated structure through connectors. The VNA is used to measure both reflections & transmission coefficients. The test set-up image is as shown in the Figure 5.12.

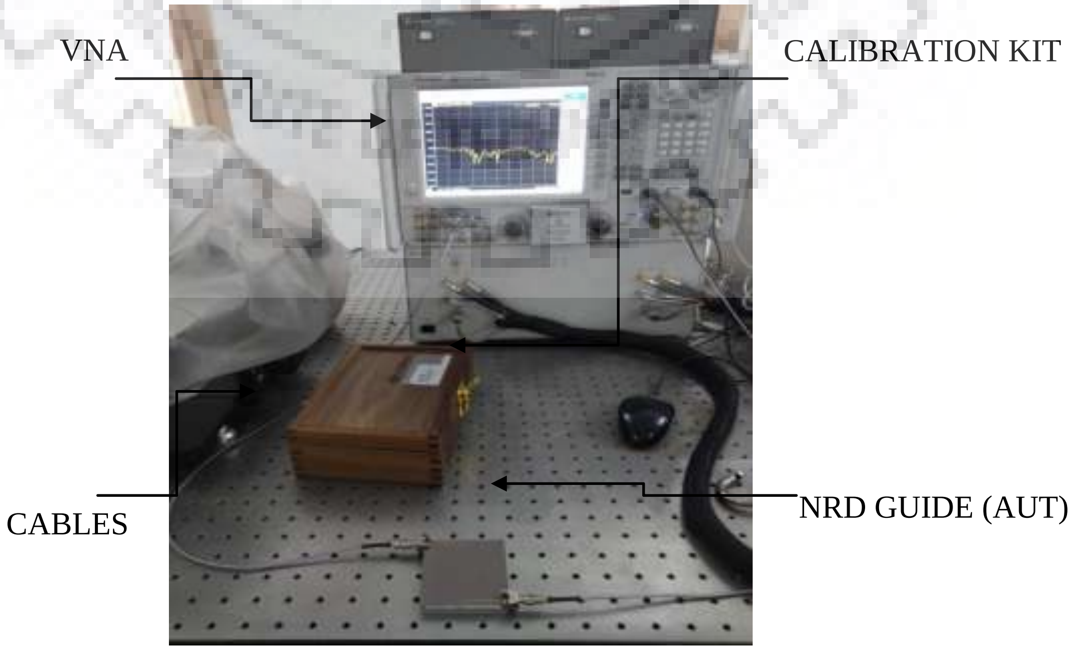


Fig. 5.12 Test Set Up for Testing Fabricated NRD Guide

The measured results obtained from the VNA are given in the Figures 5.13 & 5.14. The figure 5.13 depicts the S_{21} in dB obtained while the figure 5.14 depicts the S_{11} in dB obtained. The measured results found in variance to the simulated results. The S_{21} found is -8.21 dB at 22.45 GHz, thus there is a drop in the measured results and also the frequency has been found shifted. This may be due to the reason that PLA strip was not uniform in the width and during the optimization process, it was noticed that even a small shift of 0.1 mm in the width of the PLA was shifting the band towards some other frequency. S_{11} was found to be -13.49 dB at 22.45 GHz.

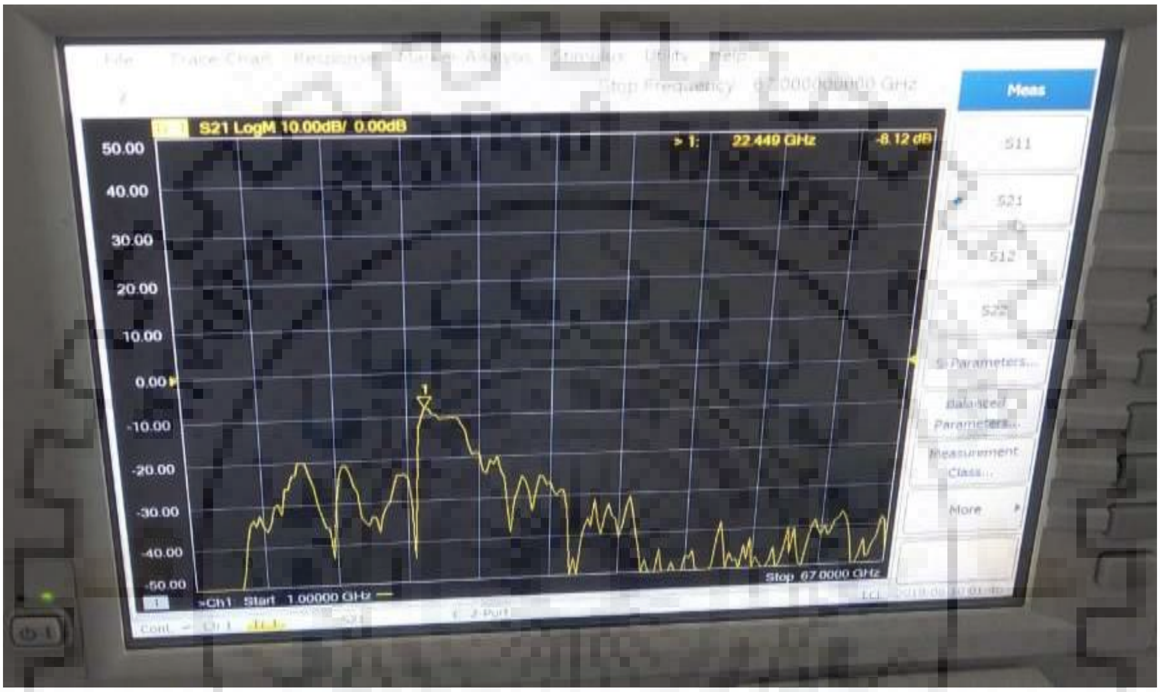


Fig. 5.13 S_{21} (dB) : -8.21 dB at 22.45 GHz

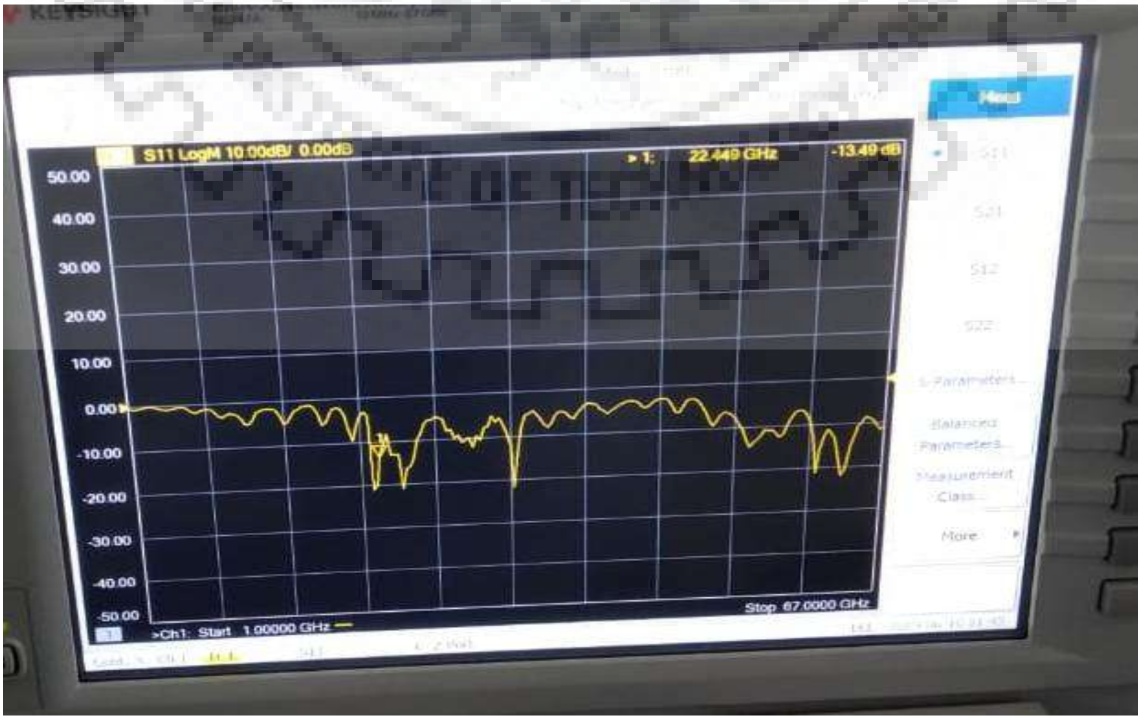


Fig. 5.14 S_{11} (dB) : -13.49 dB at 22.45 GHz

5.4 Microstrip Line Transition : Conclusion

Microstrip line transition to NRD guide has been found to be cheaper to fabricate than other methods. It is also easy to fabricate this structure. The anlysed solution yield good results with a band of approx 250 MHz at centre frequency of 24.5 GHz. The transmission losses are also low. However, when the final structure was fabricated and the same was measured using VNA, the measured and simulated results have been found in variance.

This may be due to reasons as listed below:

1. **Fabrication Issues of PLA Dielectric Strip**. Dielectric strip was found non-uniformly filled and has hollowness inside even when the infill density of the 3D printer was kept at maximum ie at 100%. The same can be seen in the Figure 5.15 below.

Fig. 5.15 Inside structure of the PLA Strip

2. **Non Uniformity in Dimension of PLA Dielectric Strip**. The dielectric strip when measured from one end to the other founds to be non-uniform and the width varies from 4.7 mm to 5.4 mm ie a difference of 0.7 mm. At this frequency even a small variation in the width would result shifting of the frequency band in the NRD guide.
3. **Roughness and Non-Uniform Surface of the Base Plate**. The base plate is made up of the aluminium metal and is very brittle in nature. As the metal plate has to be fabricated and in the absence of in-house facility, a vendor was found ex local market who carried out the required job work on the metal. Even with the best machining, there were many marks on the base plates which worked as discontinuity and the metal was not cut in the dimensions which were required.
4. High precision workmanship required to assemble the complete structure. Even with the best of efforts the assembly had not been fit as per the required dimensions. This results in the variance in the final measured results.
5. Foam strips had glue pasted on their top surfaces causing problems in matching and discontinuity.
6. Gap in foam-PLA joints (physical discontinuity).

Fig. 5.16 Gap in Foam-PLA & Foam-Base Plate

7. Connectors are too heavy vis-à-vis microstrip line, thus bending of microstrip occurs. This can be seen in the Figure 5.16 on the previous page. This causes discontinuity in the structure and thus losses take place.

8. Connectors end not fitting completely on microstrip line and remain outside the microstrip line.

Chapter 6

The Conclusion and Future Scope

The need and rise of necessity of NRD guides in the millimeter-wave domain was established ever since the NRD guide was first introduced by the Yoneyama in 1981. It was seen how the NRD guide is different from the H-waveguide ie in principal operation and in other basic characteristics. It was also seen that there are various important properties which are different from the other waveguides. It was also seen how the PLA will have future in the various domains and especially in the microwave domain. Although PLA is the latest material used in the industry but there are researches going in owing to its properties. This material will surely provide great research area.

After development of the NRD guide and its transition which was done using ANSYS HFSS 15.1. Three transitions simulated and analysed viz-a-viz Rectangular Waveguide, Rectangular Waveguide with Horn and Microstrip Line. Due to the various challenges faced during the fabrication, the Rectangular Waveguide and Rectangular Waveguide with Horn transitions were only simulated and analysed on the HFSS. However, the Microstrip Line to NRD guide transition was fabricated as all required material was readily available.

The rectangular waveguide transition has offered good transmission however required mode of propagation found to be LSE which will only bring more losses and also not the preferred mode of propagation. The best result for the transitions with good matching found in rectangular waveguide with horn transition with required LSM mode propagation. Structure wise also, it was found more robust to realise due to miniaturisation of components at higher frequencies. However, due to the affect of cost of fabrication of these waveguides, work was restricted to the simulation and analysis in this thesis.

Microstrip Line transition has been chosen to be fabricated as almost all required items were readily available in the campus as well as in the local market. However, it offered various challenges to realise the NRD guide physically. Few of these have been discussed in the earlier chapters. The measured result has been found to be below satisfaction due to the various reasons as listed in the conclusion of the chapter 5. However, the limitations at present could not allow further improvements in the design.

In the end, it can be concluded that NRD guide with microstrip line is very effective way for developing small / micro systems at millimetre waves as the complete structure can be developed on the single block.