A Bow Tie type Substrate Integrated Waveguide (BTSIW) with Comparative Study of Feeding Techniques

A

Dissertation

Submitted

in partial fulfillment

for the award of the Degree of

Master of Technology

in Department of Electronics and Communication Engineering

(with specialization in Wireless & Optical Communication)

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July, 2017

Candidate's Declaration

I hereby declare that the work, which is being presented in this Dissertation, entitled **"A Bow Tie type substrate integrated waveguide (BTSIW) with Comparative Study of Feeding Techniques"** in partial fulfillment for the award of Degree of **"Master of Technology"** in Department of Electronics and Communication Engineering with Specialization in Wireless and Optical Communication, and submitted to the **Department of Electronics and Communication Engineering, Malaviya National Institute of Technology, Jaipur** is a record of my own investigations carried out under the Supervision of **Pro**f. **Sanjeev Agrawal**, Associate Professor, Department of Electronics and Communication Engineering, MNIT, Jaipur (Rajasthan).

I have not submitted the matter presented in this Dissertation anywhere for the award of any other Degree.

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CERTIFICATE

This is to certify that Dissertation entitled **"A Bow Tie type substrate integrated waveguide (BTSIW) with Comparative Study of Feeding Techniques"** has successfully been carried out by **Anshu Choudhary** (Enrolment ID: 2015PWC5346) under my supervision and guidance in partial fulfillment of the requirements for the award of Master of Technology Degree in Wireless and Optical Communication from Malaviya National Institute of Technology, Jaipur for the session 2015-2017.

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ABSTRACT

In recent years, with the increasing demand of applications of wireless technologies, the work of exploration of new frequency bands is being done. The V-band is newly explored band which is mainly utilized for inter-satellite communication. There is need of low profile, small size and lighter components in satellite payload. This is featured by using microstrip patch design technology. But there is need to integrate planar as well as non-planar components and microwave as well as millimeter wave devices. This is done using a novel technology called Substrate Integrated Waveguide.

The bow-tie type design with SIW is proposed and also this design is compared with bow-tie type design on single substrate. It can be concluded that the bow-tie pattern showed better results with SIW, which in turn also reduces feeding complexity. The bow-tie pattern with SIW is more directive than the bow-tie pattern on a single substrate. The percentage bandwidth of bow tie with SIW is more than the bow tie on single substrate, i.e. 56% in the range of 18-32 GHz, 28% in 43-57 GHz and 18.9% in 67-81 GHz. It depicts the multiband functionality of proposed design. Further, the optimization of radius of via-holes of substrate integrated waveguide shows the minimum return loss at 0.06mm.

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Introduction

1.1 Introduction

There is leading growth in microstrip patch families with the leading demand and more research in wireless communication. As the more electromagnetic spectrum is explored the research is being enhanced for higher bands of frequencies which lead to reduction in device sizes. As we move towards higher GHz bands the need of low profile microstrip patch devices is felt. As per the recent technologies a lot of work has been accomplished to design millimeter and microwave waveguide components. These components include Substrate Integrated Waveguides also. In the beginning these devices were mostly fabricated using printed circuit board technology. These devices provide several advantages of having compact configuration and light weight, but relative bandwidth do not support this as it is only 5% which could not satisfy Inter Satellite Link requirements. Another critical problem is the high loss at millimeter frequency. Parallel plate slot antennas have the same defects [2]. The substrate integrated waveguide (SIW) can counteract for these problems. It has similar structure as that of a waveguide. In Inter-Satellite Links the reduction in payload of satellite is the major issue as well as need of ultra wideband devices is there. With the advent of semi-conductor technology, the microwave system will play a more significant role in ISLs applications.

Possibly there are two methods to reduce the payload problem on satellites:-

- One by using the higher frequency band for better directivity with low profile antennas
- Other by using wideband antenna for responding to frequency diversity.

As an example, V-band has multi-gigahertz bandwidth. It is very beneficiary for inter satellite communication as the propagation path loss is lower due to absence of oxygen molecules as well as in this frequency band wideband antenna benefits the system with huge information capacity[2]. Hence, this work presents a high-gain plate antenna working at V-band to replace the bulky parabolic antenna to avail both wide bandwidth and high efficiency.

1.2 Waveguides

A waveguide is a hollow structure capable of transferring electromagnetic wave, optical wave or sound waves as shown in Fig. 1.1. Actually, as the wave propagates in free space its power depletes following the inverse square law, so to restrict the wave from spreading to undesired directions the concept of waveguide was introduced. Hence, a waveguide is nothing but a device which let the waves propagated in desired direction and delivers it to the desired location with minimum power losses.

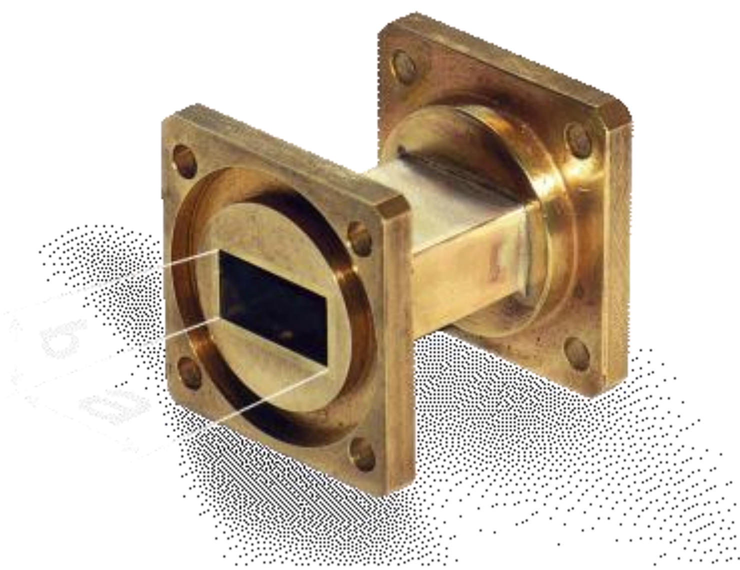


Figure 1.1 Pictorial structure of waveguide

1.2.1 Principle of Operation:

According to electromagnetic wave theory, waves travel in all direction as spherical waves. As per the inverse square law, the power of the wave depletes as the distance of wave increases from the point of its source. So these waves need to be confined in some region which was facilitated by using waveguides. Inside a waveguide waves propagate by undergoing total internal reflection and in ideal condition the waves received at desired end would of equal power as was transferred from source end as shown in Fig. 1.2.

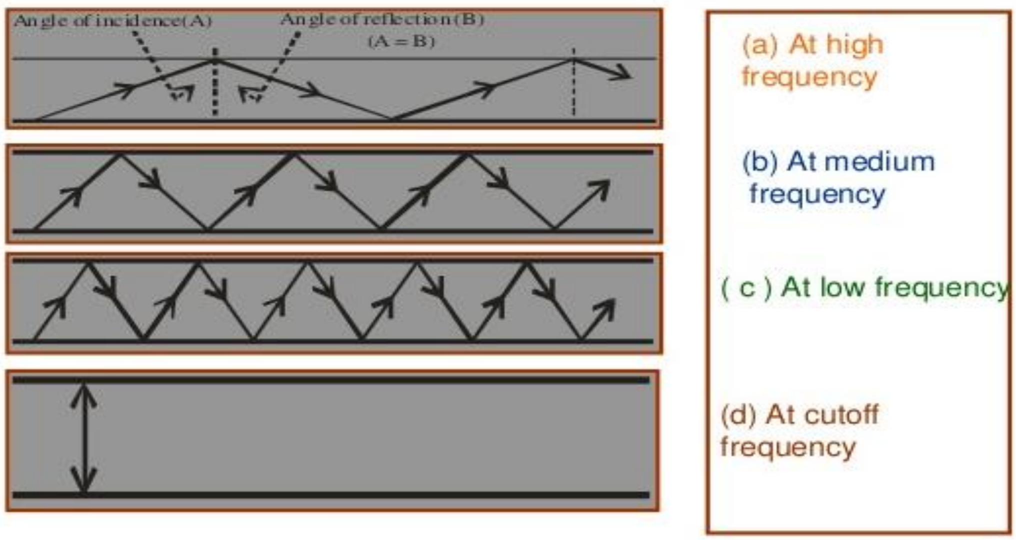


Figure 1.2 Wave paths in waveguide at different frequencies

According to the Maxwell's equations, the electric and magnetic components propagate through a waveguide by making particular forms or shapes called modes. So, based on this there are different types of waves supported inside a waveguide depending on the mode of the waves. A waveguide supports three basic modes i.e. Transverse Electric mode (TE), Transverse Magnetic mode (TM) and Transverse Electromagnetic mode (TEM). Based on these modes waves are broadly classified as given below:

- **TE (Transverse Electric) Waves:**

  In these waves the electric vector is perpendicular to the direction of propagation. These are also called H-waves.

- **TM (Transverse Magnetic) Waves:**

  In these waves the magnetic vector is perpendicular to the direction of propagation. These are also called E-waves.

- **TEM (Transverse Electromagnetic) Waves:**

  In these waves both the electric as well as magnetic vectors are perpendicular to the direction of propagation. These waves are not used in Metallic waveguides but rather used in coaxial and open wire feeders.

The TE or TM waves are suffixed with m and n as shown in Fig. 1.3 which decides the mode of the waves propagating through a waveguide. The value of m and n may vary from 0 or 1 to infinity. But practically these values are finite like TE_{10} or TE_{01} mode. And for each mode there is a cut-off frequency which decides the lower frequency limit below which no signal is transmitted. Or we can say that some portion of the total energy is passed above that frequency and some portion is blocked below that particular frequency. Hence, it is apt to say that a waveguide acts as a High pass filter. As the frequency is increased the number of modes is also increased. But there is a significant mode for the lowest frequency which is called as dominant mode.

The lowest supported mode for rectangular waveguide is TE_{10} mode which occurs when the width of the waveguide is ½ of the wavelength of supported cut-off frequency. And TE_{01} occurs when the height of the waveguide is ½ of the wavelength of supported cut-off frequency.

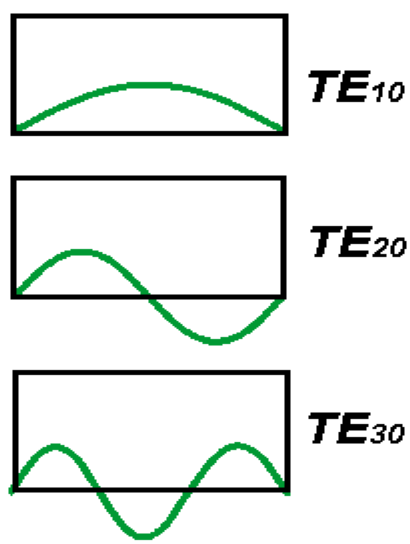


Figure 1.3 Modes of TE wave

1.2.2 Types of Waveguides:

Waveguides are broadly classified as metallic waveguide and dielectric waveguide as shown in Fig.1.4.

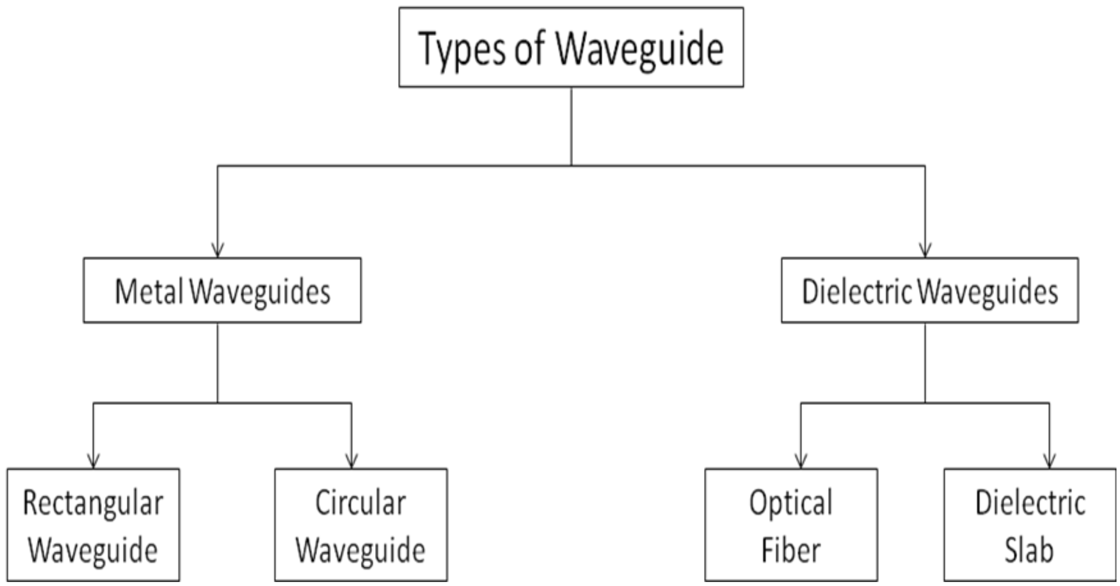


Figure 1.4 Types of Waveguide

- **Metal Waveguides: -** As the name suggests these waveguides are made of hollow metallic conducting pipes. Basically, these waveguides are of two types i.e., rectangular and circular waveguide. In these waveguide the reflection of waves is from the walls of the waveguide.
- **Dielectric waveguides: -** As the name suggests, these waveguides are made of dielectric material and waves propagate along the waveguide by continuous reflections from the interfaces of dielectrics. These are generally of two types i.e., Optical Fiber and Dielectric slab.

1.3 Antenna

In a communication system, an antenna plays a very crucial role as it acts as an interface between transmitter/receiver guiding device and the free space. Basically an antenna is nothing but a transducer which converts alternating current into radio frequency at transmitter end and converts radio frequency into alternating current at the receiver end. Antennas facilitates well for radio equipments and well applicated for mobile system, wireless local area network and satellite communication.

1.3.1 Radiation Mechanism

To create radiations the basic requirement is that there must be a time-varying current and an acceleration of charges in the conducting terminal. This can be proved as follows, consider a conducting volume with total charge Q within volume V moving in the z-direction with a uniform velocity v_z(m/sec.) having q_v(coulomb/m^3) volume charge density, then over the cross section the current density J_z(amperes/m^2) is given as:

$$J_z = q_v \, v_z \tag{1.1}$$

If there is an ideal conductor with q_s (coulomb/m^2) surface charge density, the current density J_s (amperes/m) on the surface is given as:

$$J_s = q_s \, v_z \tag{1.2}$$

If the conductor is of zero radius with q_l (coulomb/m) charge per unit length, then current through the wire is given as:

$$I_z = q_l \, v_z \tag{1.3}$$

If the current is varying with time then the derivative of above equation is given as,

$$l\frac{dI_z}{dt} = lq_l\frac{dv_z}{dt} = lq_l a_z \tag{1.4}$$

The above equation simply depicts that

- If a charge is not in motion then no current would be generated and hence no radiations will be there.
- If charge is in uniform motion:

  1. There will be no generation of radiation if conducting wire is straight.

2. There will be generation of radiation if the conducting wire has some form of discontinuity like a curve, bent or termination.

- If charge is oscillating in time-motion, it radiates even if the conducting wire is straight.

1.3.2 Types of antenna:

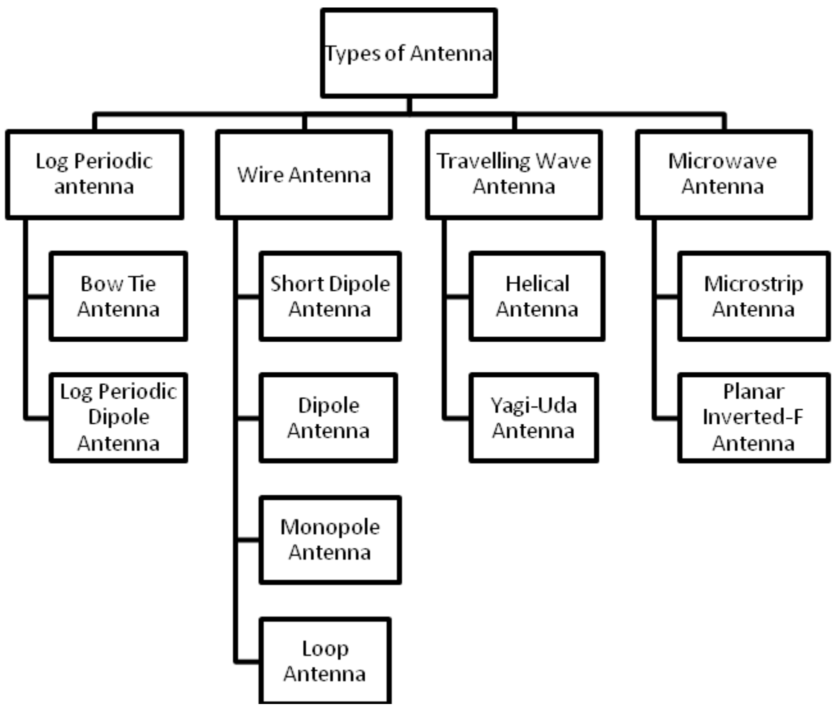


Figure1.5 Flow Chart of types of Antenna

1. **Log-Periodic Antenna:**

This antenna is made of combination of dipoles placed at space intervals in function of logarithmic variation of frequency as shown in Fig. 1.6.

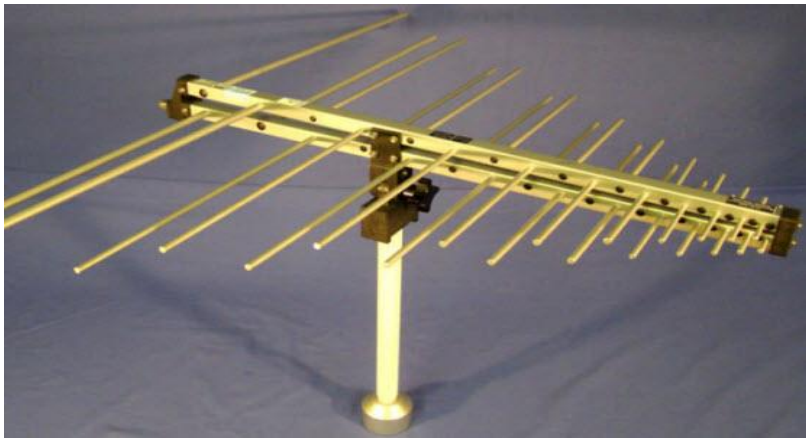


Figure 1.6 Pictorial view of Log Periodic Antenna

This multi-element antenna gives directional beam that works for wide range of frequencies. There are two types of log periodic antenna as follows:-

- **Bow-Tie Antenna: -** The shape of bow-tie antenna looks like a butterfly so it is also called a Butterfly antenna or a Biconical Antenna. A bow-tie antenna is featured with Omni-directional and wideband property.
- **Log Periodic Dipole Array: -** This antenna comprises of the dipole elements starting from front end and ending at rear end. The spacing between these elements decreases from rear end to the front end.

2. Wired Antennas

Wire antenna is simple in structure and cheap by cost. This is also called as linear or curved antenna.

- **Dipole Antenna:** This antenna consists of a conducting section and a radiating section. The conducting section carries current and frequency via two metallic rods. The radiating section converts the electric signal into electromagnetic form. This antenna is easy to construct.
- **Short-dipole Antenna:** A short dipole antenna is nothing but an antenna with radiating length is $1/10^{th}$ of the wavelength of operating frequency. It is the

simplest of all the types of antennas. This antenna gives more emphasis on the size of the radiating element relative to the wavelength of operating frequency.

- **Monopole Antenna:** A monopole antenna has a single rod grounded from one end and radiating at the other end. Total power is radiated in the upper hemisphere area and is half of the total power radiated by dipole antenna but the directivity of monopole antenna is more than that of dipole antenna.
- **Loop Antenna:** A loop antenna is independent of the shape and figure of the antenna. It can be any closed structure ,for instance, circular, rectangular, elliptical etc. Loop antenna comprises the features of both the monopole antenna as well as dipole antenna. These are classified as:
    - **Electrically small loop antenna:** It works at higher frequencies and has small radiation resistance.
    - **Electrically large loop antenna:** It works at lower frequencies and has more radiation resistance.

3. **Travelling Wave Antennas:**

- **Helical Antenna:** In Helical antenna, as the name suggests a helix structure is present which is made by wounding two or three wires. This helix structure is backed by a reflector at one end which is further connected to the feeding terminal.

A helical antenna presents two modes i.e.

- **Normal mode:** In this mode the size of helix antenna is comparatively small so, it can be assumed as a short dipole antenna or a monopole antenna.
- **Axial mode:** In this mode the size of helix antenna is same as its wavelength of the operating frequency. Helix antenna in this mode shows good directional features.

- **Yagi-Uda Antenna:** A yagi-uda antenna consist of a reflector, a driven folded dipole element and directors for forwarding the waves while keeping those in horizontal polarization. This antenna was commonly used for TV signal reception.

4. **Microstrip Antenna**

- **Rectangular Microstrip Patch Antenna: -** A microstrip patch uses the technique of printed circuit board for its designing i.e. made of three layers viz. a metallic ground plane at the bottom, a dielectric substrate and a metallic patch at the top. The metallic patch is used for the actual radiations which can be modified using the appropriate shape. The gain of microstrip patch antenna is too low around 6% but it facilitates with low profile, size and low fabrication cost.

- **Planar Inverted F- Antenna:-** As the name suggests a planar inverted F-Antenna is used to radiate by a metallic planar plate rather than a wire. These plates are designed such that it can be confined for hidden purpose also. These have another advantage of enhanced efficiency due to reduced backward radiation towards the top by absorbing power.

1.4 Microstrip Patch Antenna

In applications like spacecraft, aircraft and satellite communication where the issue of size, weight, cost, ease of installation and performance is much tensed, an antenna with low profile structure, simple, inexpensive and compatible to both planar as well as non-planar surfaces is needed. This feature is facilitated by microstrip patch antenna. A microstrip patch antenna uses the technique of printed circuit board for its designing i.e. made of three layers viz. a metallic ground plane at the bottom, a dielectric substrate and a metallic patch at the top. The metallic patch is used for the actual radiations which can be modified using the appropriate shape like rectangular, circular, square, triangular, ring etc. The patch is usually made of a conductor such as copper or gold. The patch on the dielectric substrate can take any form. The microstrip patch antenna results in low efficiency, very narrow frequency bandwidth and low power but it facilitates with low profile, smaller size and low fabrication cost.

1.4.1 Basic Characteristics

As shown in Fig. 1.7, a radiating patch of thickness (t) is mounted on the dielectric slab of height (h) and dielectric constant (ε_r). The length (L) and width (W) of the radiating patch is chosen according to the operating frequency band.

The general specifications for these parameters are as under:

- Thickness ($t << \lambda_0$) where λ_0 is free-space wavelength.
- Height of substrate ($h << \lambda_0$, usually $0.003\ \lambda_0 \leq h \leq 0.05\ \lambda_0$).
- Length of the patch ($\lambda_0/3 < L < \lambda_0/2$).
- Dielectric constant ($2.2 < \varepsilon_r < 12$).

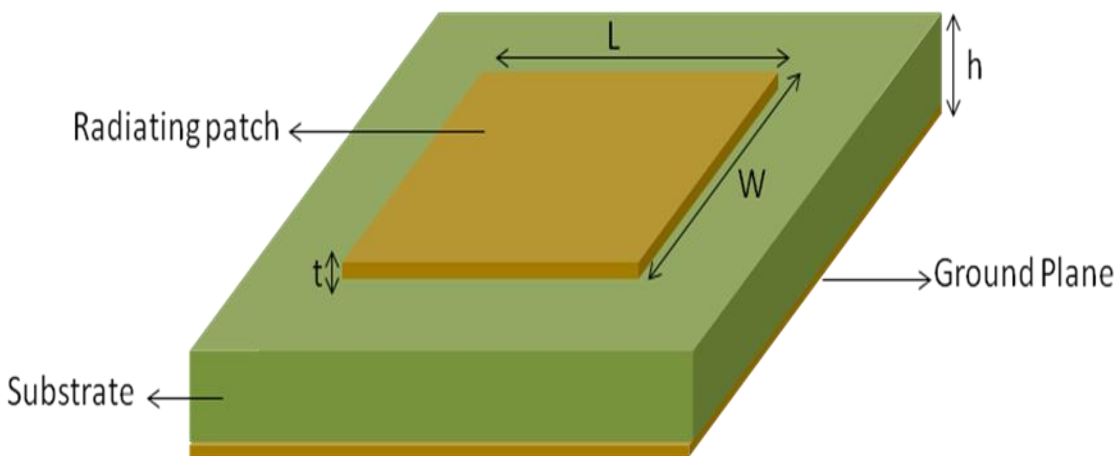


Figure 1.7 Structure of microstrip patch antenna

There are many dielectric materials available for the substrate. The substrate that are mostly preferred for good performance of the antenna are thicker with dielectric constant in the lower range as these can loosely bound fields for radiation, provide larger bandwidth and better efficiency. The substrate with thinner dimensions and dielectric constant in higher range are used in microwave circuitry.

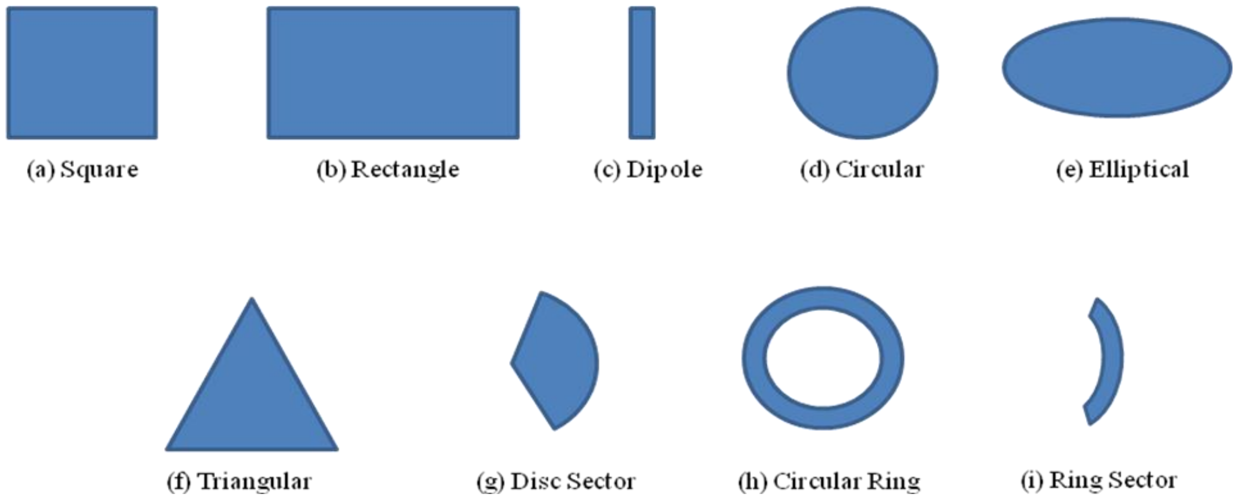


Figure 1.8 Distinct shapes of patch antenna

1.4.2 Feeding Methods

The popular feeding techniques for microstrip patch antenna are as under:

(i) Microstrip line feed

- Inset feed
- Edge feed

(ii) Coaxial probe feed

(iii)Aperture Coupled feed

(iv)Proximity Coupled feed

A microstrip line feed is nothing but a conducting patch strip connected to the basic radiating patch but the width of the line feed is much less than the width of the patch. The microstrip line feed is easy to inset, easy to position and simple to model but as the substrate thickness increases the spurious radiations from patch also increases which in turn limits the percentage bandwidth to typically (2-5%).

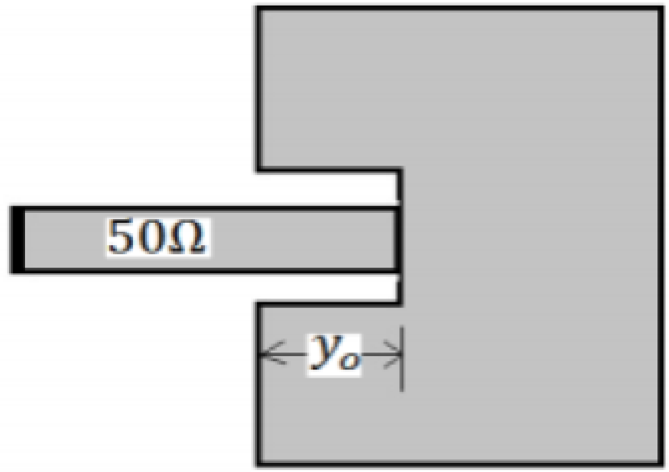


Figure 1.9 Patch antenna with strip line feed

In coaxial line feed the outer conductor of coax is connected to the ground plane while the inner conductor is connected to the patch. This feeding method is widely used as it is easy to model, fabricate and match.

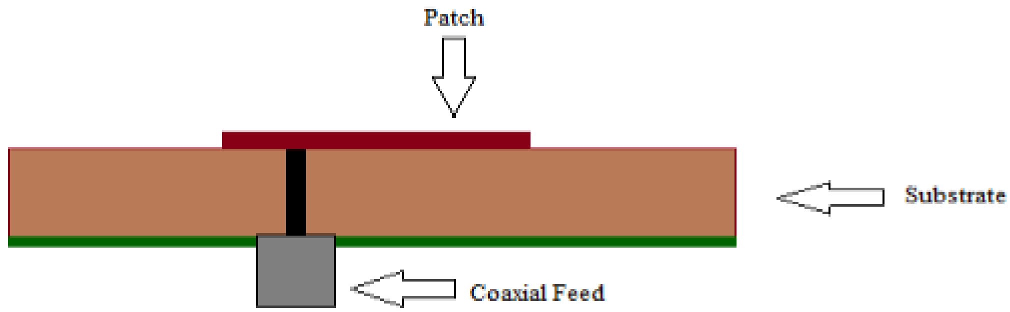


Figure 1.10 Patch antennas with coaxial feed

1.4.3 Advantages

- Low profile structure.
- Light weight.
- Low fabrication cost.
- Conformal to both planar as well as non-planar surfaces.
- Supports linear as well as circular polarization.
- Mechanically robust for rigid surfaces.

1.4.4 Disadvantages

- Low gain.
- Low efficiency.
- Narrow frequency bandwidth.
- Low power handling.
- Spurious radiations at junctions and feed.

1.5 Log-Periodic Antenna

A log-periodic antenna is similar to Yagi-Uda antenna in terms of construction and operation as shown in Fig.1.11. The main advantage of log-periodic antenna is the constant parameter values for long range of frequencies. It consists of logarithmically spaced dipole elements with radiation forwarding from rear end to the front end. The length of rear end dipole element is half wavelength of the operating frequency i.e. the longest element behaves like a half-wave dipole antenna. The radiation resistance is same for all the elements for different frequencies as well. The active region shifts as the frequency of operation changes i.e. all elements will not be active for just a single operating frequency.

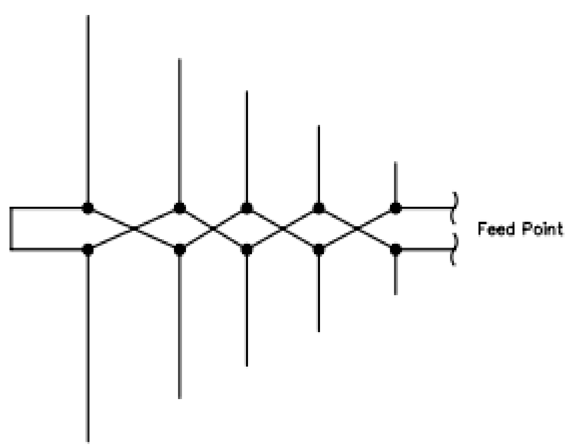


Figure 1.11 Structure of LPDA

There are various types of log-periodic antenna like trapezoidal, slot, zig-zag, V-type and dipole type antenna. Mostly used antenna is log periodic dipole array antenna i.e. LPDA.

1.6 Objectives of Dissertation

The following are the main objectives of this dissertation work:

- Literature survey of SIW and Microstrip patch antenna has been carried out and design using various parameters and dimensions.
- Designing of microstrip patch antenna using Ansoft HFSS has been carried out.
- Designing of SIW based bow-tie microstrip patch antenna using Ansoft HFSS has been carried out.
- A comparative study of microstrip patch antenna without and with SIW has been carried out.

1.7Organization of Dissertation

Including this introductory Chapter, this Dissertation consists of six chapters:

Chapter 2 covers literature survey including historical development of SIW and Microstrip patch antenna.

Chapter 3 covers the introduction and basic principal of operation of SIW.

Chapter 4 consists of bow tie patch antenna basics and mathematical modeling.

Chapter 5 includes introduction of HFSS and simulation of proposed design.

Chapter 6 covers a comparative study of bow tie pattern with and without SIW.

Chapter 7 concludes the work and also includes future scope of work.

Chapter 2

Literature Survey

2.1 Introduction

In this Chapter, review of literature has been carried out. Research papers, books and articles have been used in preparing this dissertation work. For better understanding of the work, historical development is studied firstly. Various researches have been carried out in the field of microwave. The work is carried out in the following steps which involve mathematical modeling and designing of Substrate Integrated Waveguide using HFSS. According to review, the conventional low-cost printed circuit technology gives us a way to integrate the waveguide with microwave and millimeter-wave components. So far, the number of proposed SIW components is huge such as phase shifters, transitions, filters, couplers, diplexers and power dividers. In conventional metallic waveguides, the sidewalls are made of solid fences while in SIW, the waveguide sidewalls are constructed from lined via-holes. SIW structures are fabricated on printed circuit boards. This technology is simpler, cheaper and even lighter than its predecessors. The simulation is made using Ansoft HFSS.

2.2 Historical Development

2.2.1 Historical Development of Waveguide

The first structure of guiding waves was proposed by J.J. Thomas and Oliver Lodge experimentally tested this structure in 1894. In 1897, Lord Rayleigh mathematically analyzed the electromagnetic waves in a metallic cylinder. These electromagnetic waves propagate through the waveguide by undergoing multiple reflections at the walls of a waveguide. Initially at lower frequencies radio communication was developed because these propagated over long distance very easily. These frequencies are not suitable for use in hollow metal waveguides because of long wavelengths large diameter tubes required. Thereafter, the study and research of metal waveguides were started. In 1930, George C. Southworth resumed the practical investigations at Bell Labs. Initially he implied the theory of waves in dielectric rods because he was unknown to the work of Lord Rayleigh. Some of his experiments were unsuccessful because he was not familiar with the concept of cutoff frequency of waveguides that were discussed in Lord Rayleigh's work. John R. Carson and Sallie P. Mead continued this work as theoretical and practical. He discovered that for the TE_{01} mode in circular waveguide as frequency increases, losses decrease and at one time this was a serious contender for the format for long distance telecommunications. However, waveguide is still used in the higher microwave bands from around Ku band upwards.

2.3 Substrate Integrated Waveguide

1. In 1984, Harlan Howe [11] gave the literature review on Microwave Integrated Circuits. MIC is the combination of millimeter components that are merged with user accessible interface without permission. This concept was very important for waveguides bends.

2. In 1995, Adolfo C. Reyes, Samir M. El-Ghazaly, proposed the designing of Coplanar Waveguides and Microwave Inductors on Silicon Substrates. As a substrate material in microwave, Silicon has many advantages including low cost and a mature technology. Finally they demonstrate that high resistivity Si can be used as a microwave substrate.

3. In 2005, L. Yan, W. Hong, K. Wu, T.J. Cui proposed the propagation characteristics of Substrate Integrated Waveguide based on the transmission line. The two empirical equations are proposed for the propagation constants of SIWs, which gives a simple but efficient tool in designing substrate integrated waveguide component.

4. In 2008, Yu Jian Cheng, Wei Hong, Zhen Qi Kuai, Chen Yu, proposed the designing of Substrate Integrated Waveguide (SIW) using Rotman Lens and its application in Multibeam array antenna. The experiments were carried out at frequency 28.5 GHz with seven input ports.

5. In 2010, A. Corona-Chavez and T. Itoh proposed a new method to achieve wide pass-band characteristics on Substrate Integrated Waveguide (SIW) tunnel section. It showed that due to the frequency dispersive nature of the effective permittivity in a waveguide, three in-band longitudinal resonant-modes can be excited from the waveguide-feed interaction.
6. In 2011, B.T.P.Madhav, J.Chandrasekhar Rao, analysed the performance of square patch antenna on strip line feed and co-axial feed. This analysis stated that the strip line feeding is preferable because of impedance mismatching with the case of coaxial feeding. Coaxial feeding requires number of trial and error methods for getting impedance bandwidth perfectly. Whereas for the strip line feeding impedance related problems can be almost avoided.
7. In 2014, Xia-Ping Chen and Ke Wu, Montreal Polytechnic, proposed the technique of substrate integrated waveguide cavity resonator filter. Provided several techniques for improving the stopband specification of direct-coupled substrate integrated waveguide filter. Featured the SIW resonator as compared to microwave resonator in viewpoint of tradeoff between cost and loss.
8. In 2015, Stefano Moscato, Nicolò Delmonte and Lorenzo Silvestri proposed the technique for designing Compact substrate integrated waveguide (SIW) components on paper substrate. These components are particularly suitable for the implementation of eco-friendly wireless systems for the future generation of wireless sensor networks (WSN) and of the Internet of Things (IoT).
9. In 2015, Jie Wu, Student Member, IEEE, Yu Jian Cheng, Senior Member, IEEE, and Yong, Member, IEEE, proposed the technique for inter-satellite links using integrated plate array antenna structure. It realized the microstrip patch along with substrate integrated waveguide and waveguide power divider. A complete array was designed for power division and the feeding of these array is based on novel feeding technique of slot feed.

Chapter 3

Substrate Integrated Waveguide

3.1 Introduction

The history of waveguide is about 100 years old. Faraday and Maxwell's theory of electromagnetic and Lord Rayleigh's idea of sound, waves in fluids and liquid waves flow through a hollow conductor helped in giving the idea of waveguide. Earlier, the lower frequencies of electromagnetic spectrum were used for the transmission of electrical signal with two-wire system or single wire system with Earth as the return but this was based on TEM mode only i.e. the electric and magnetic components are perpendicular to the direction of propagation. The similar model was accepted for transmission of optical signal over free space. Hence the concept of propagating electromagnetic signal whether in free space or along a conducting material on transverse plane wave paradigm (TE, TM or TEM) emerged.

A conventional waveguide is a 3-D rectangular structure having dimensions of width and height represented as 'a' and 'b' respectively. Width is usually greater than the height of the waveguide. As shown in Fig. 3.1 the cross-section is in x-y plane. The length of the waveguide is along the z-axis. A waveguide is surrounded by metallic walls with hollow space inside. The hollow space in the waveguide can be filled with the air or dielectric material. The waves inside the waveguide propagate by following the zig-zag path with multiple reflections from the wall. The direction of propagation is along the length of the waveguide i.e. along the z-direction.

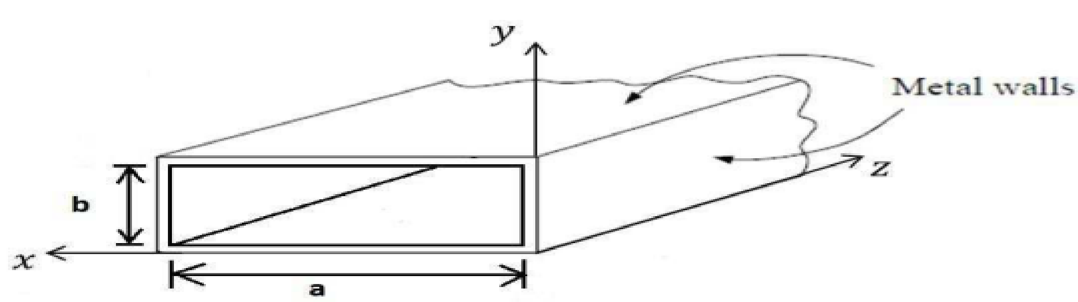


Figure 3.1 Cross section of waveguide in x-y plane

The propagation of waves through the waveguide is mostly made in TE mode i.e. electric component perpendicular to the direction of propagation. As shown in Fig. 3.2 the vertical lines show the electric component of the waves and circular dashed loops show the magnetic component of the waves. The dots represent the upward waves of electric component and the crosses represent the downward waves of electric component.

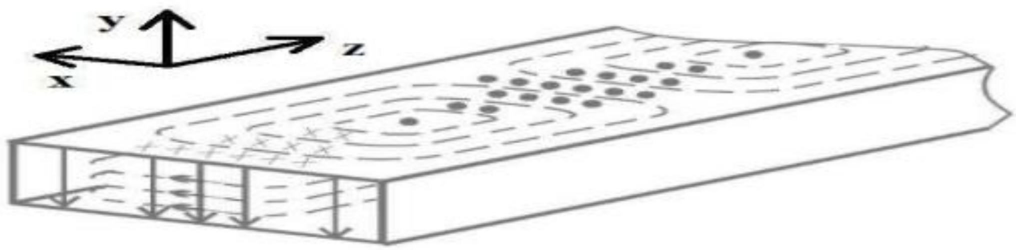


Fig. 3.2 Electric and magnetic components of wave

As per recent trending technologies, a lot of work has been accomplished to design millimeter and microwave waveguide components. These components include Substrate Integrated Waveguide (SIW) as well. These devices are mostly fabricated using printed circuit board technology. SIW facilitates to experience the waveguide scenario comprising of planar as well as non-planar structures [16]. SIW also facilitates us to integrate millimeter as well as microwave components. So far, the number of proposed SIW components is huge such as phase shifters, transitions, filters, couplers, diplexers and power. The top and bottom layers in the SIW are conductive in nature and these layers sandwich a dielectric layer between them.

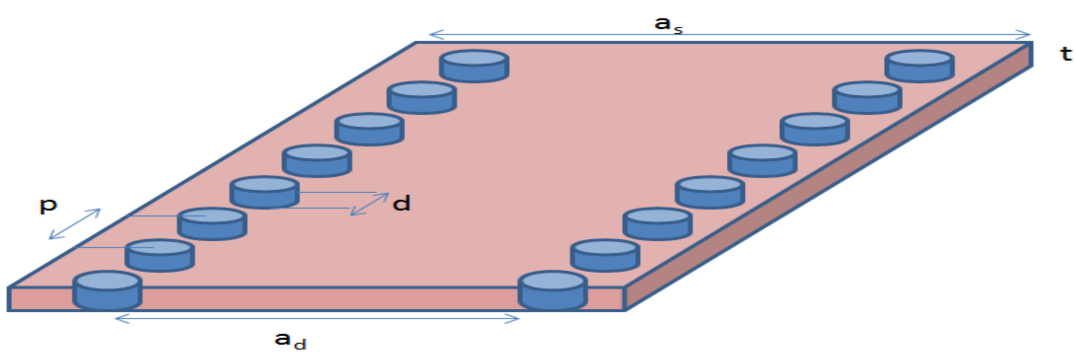


Figure 3.3 3-D view of Substrate Integrated Waveguide on dielectric substrates

In conventional metallic waveguides, the sidewalls are made of solid fences while in SIW, the waveguide sidewalls are constructed from lined via-holes, as shown in Fig.3.3. SIW structures are fabricated on printed circuit boards. This technology is simpler, cheaper and even lighter than its predecessors. The proposed design is simulated using Ansoft HFSS [15].

3.2 Mathematical modeling

In conventional metallic waveguides, the sidewalls are made of solid metallic fences while in Substrate Integrated Waveguide, the sidewalls are constructed from metallic via-holes lined in two rows at the edges. Let say the width of the substrate to be a_s and width of the substrate upto inserted metallic via-holes is a_d, then the relationship between a_s and a_d is by Eq.3.3,

$$a = \frac{c}{2f_c} \tag{3.1}$$

$$a_d = \frac{a}{\sqrt{\varepsilon_r}} \tag{3.2}$$

$$a_s = a_d + \frac{d^2}{0.95p} \tag{3.3}$$

Where c is the speed of light i.e. 3×10^8m/sec, f_c is the centre or operating frequency, ε_r=2.2 for polypropylene substrate used for SIW.

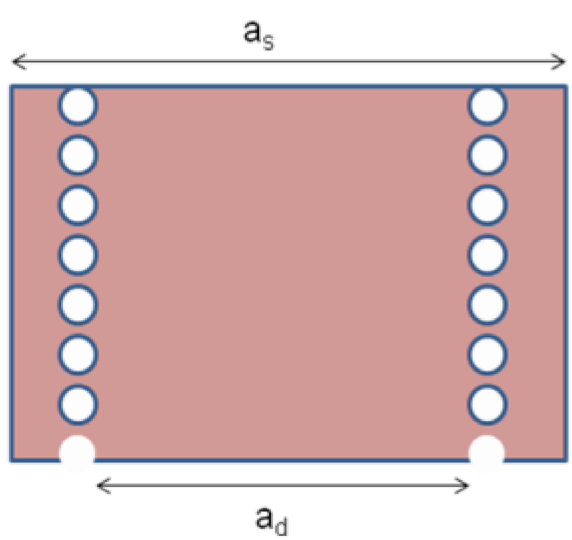


Figure 3.4 Top view of SIW

Here, the design parameters introduced in Eq. 3.4 are pitch ‘p’ (distance between the centres of two via holes) and diameter‘d’ (diameter of a metallic via hole). These design parameters for substrate integrated waveguide are obtained using a wide band of 30-96GHz. The mathematical formulations for these parameters is given as [16],

$$\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_r(2\pi f)^2}{c^2} - (\frac{\pi}{a})^2}} \quad (3.4)$$

$$d < \frac{\lambda_g}{5} \quad (3.5)$$

$$p < 2d \quad (3.6)$$

$$s = p - d \quad (3.7)$$

Where λ_g is wavelength of SIW and ‘s’ is spacing between two via-holes.

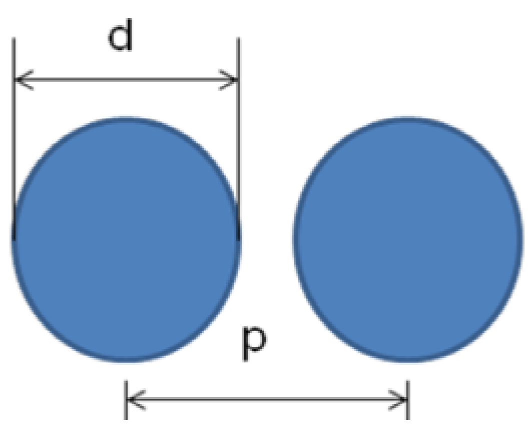


Figure 3.5 Via-holes of SIW

3.3 Designing of SIW

Steps 1:- For applications like Inter-Satellite communication V-band (40-75 GHz) is selected for which the centre frequency (f_c) is 57.5GHz

Step 2:- Before the calculation of width of SIW i.e. the gap between the two rows of metallic via holes, the width ‘a’ is calculated using Eq.3.1

$$a = \frac{c}{2f_c}$$

Put value of $c=3\times10^8$m/sec., f_c=57.5GHz

$$a = 2.608mm$$

Step 3:- Now the actual width of the waveguide within which the waves will be confined is calculated using Eq.3.2

$$a_d = \frac{a}{\sqrt{\varepsilon_r}}$$

Put value of ε_r=2.2 for polypropylene substrate used for SIW and value of 'a' from step 2.

$$a_d = 1.758mm$$

Step 4:- Calculate guide wavelength using Eq.3.4 for the values 'p' and'd'

$$\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_r(2\pi f)^2}{c^2} - (\frac{\pi}{a})^2}}$$

$$\lambda_g = 2.82mm$$

Step 5:-Assume the value of diameter by putting value of λ_g from step 4 in Eq.3.5

$$d < \frac{\lambda_g}{5}$$

$$d < 0.9527mm$$

$$d = 0.2mm$$

Step 6:- Assume the value of pitch by putting value of'd' from step 5 in Eq.3.6

$$p < 2d$$

$$p < 1.9054mm$$

$$p = 0.22mm$$

Step 7:- Calculate spacing between the via holes by using 'p' and'd'

$$s = p - d$$

$$s = 0.02mm$$

Step 8:- The width of the substrate including the two rows of metallic via holes is calculated using Eq.3.3

$$a_s = a_d + \frac{d^2}{0.95p}$$

Put the value of a_d, d and p from step 3, 5 and 6 respectively.

$$a_s = 2.2843mm$$

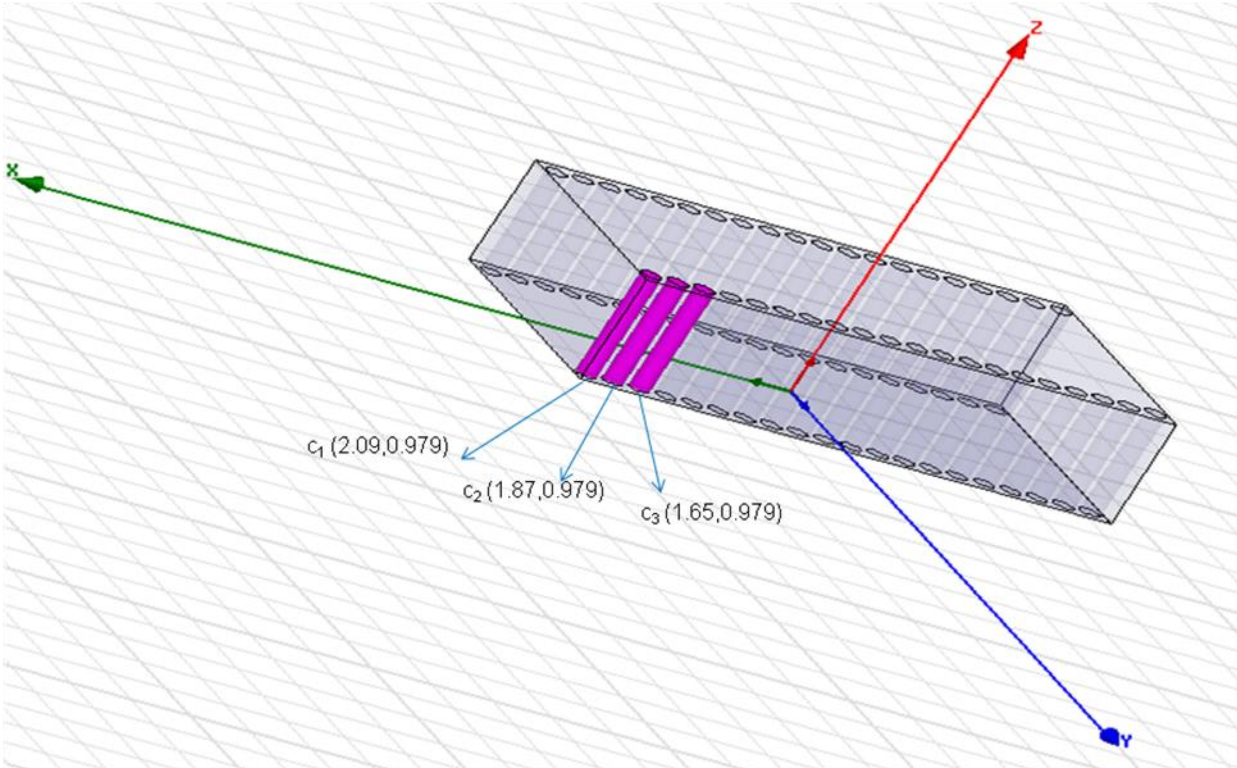


Figure 3.6 Coordinates of metallic via holes of SIW

3.4 Advantages and disadvantages of SIW

3.4.1 Advantages

- Planar Configuration with low profile.
- Easy to integrate with both planar and non-planar circuit structures.
- Light weight and low cost.
- Easy to fabricate.
- High gain and front to back ratio.
- Low cross-polarization.

3.4.2 Disadvantages

- Suffers leakage losses.
- Dielectric losses are effective with directly proportional to frequency.

Chapter 4

Bow-Tie Type Antenna

4.1Introduction

Microstrip patch antenna is very significant invention for applications that need low profile, small size and light weight structures. Microstrip patch antenna uses printed circuit board technology for fabrication which comprises of a dielectric substrate sandwiched between bottom ground plane and top patch layer. The patch layer is the actual radiating surface which decides the application for which the antenna is going to be used. The design, dimensions and pattern of the patch decides the application of the patch antenna. There are many available shapes for microstrip patch antenna. The basic shapes are square, rectangular, triangular, elliptical or circular. One of these shapes is a bow-tie type antenna.

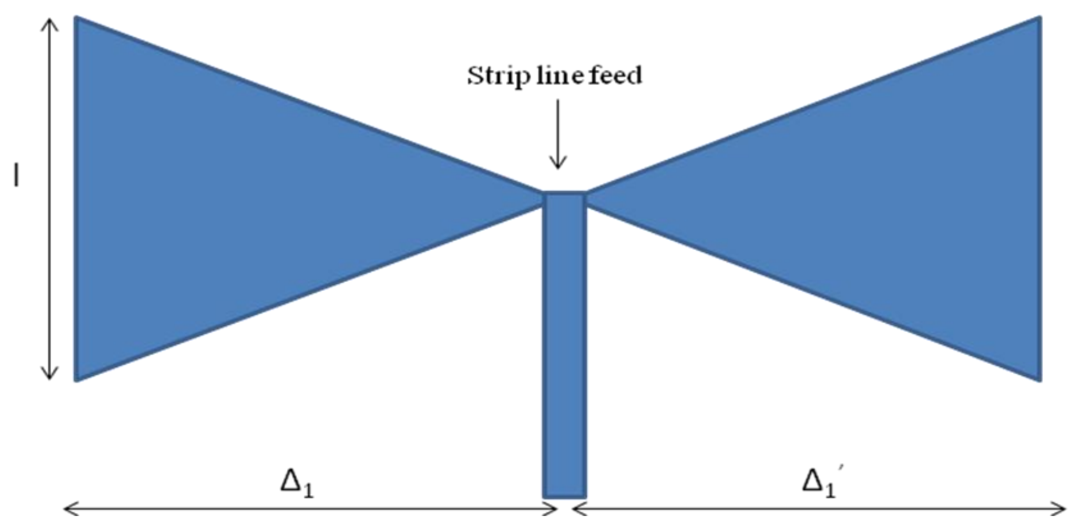


Fig. 4.1 A Bow Tie Antenna with Strip line feed

As shown in fig. bow-tie type antenna is a combination of a triangular patch antenna with its mirror image. The triangular patch can be redesigned to another shape confined to triangular shape only. The mirror image design is such that the feed line lies between the radiating terminals. Feeding the bow-tie antenna can be done by using both strip line method as well as co-axial method [7]. The strip line method is preferred as compared to the co-axial feeding because the problem of impedance mismatching persists in the co-axial feeding. Also, co-axial method requires hit and trial method for proper positioning of the feed so that better impedance bandwidth could be achieved. Slit feeding can also be used for better impedance matching and reduced feeding complexity. The triangular pattern can be made using other shapes also. In this thesis, the bow tie shape comprises of log periodic antenna in which two log periodic antenna are placed with one being the mirror image of the other. A log periodic antenna is the antenna for which impedance and radiation pattern remain constant as a function of frequency.

4.2Mathematical Modeling

The triangular patch of bow tie antenna comprises of log periodic design. The log periodic design is such that it is independent of the frequency. To achieve the feature of frequency independence, the antenna elements should contract or expand according to the frequency or if the antenna cannot be adjusted mechanically then the size of radiating elements must be proportional to the wavelength. The principle of log periodic can be easily understood by using Log Periodic Dipole Antenna (LPDA), according to which,

- The dimensions of the antenna elements increase proportionally with the distance from the feed point as shown in Fig.4.2. For this the ratio between length of consecutive elements i.e. l_n and l_{n+1} should be constant but increasing with the distance from origin point [17].
- The spacing between consecutive elements i.e. d_n and d_{n+1} is increasing in such a manner that their ratio is also constant [1].

  That means,

$$\tau = \frac{l_{n+1}}{l_n} = \frac{d_{n+1}}{d_n}$$

Where, τ is design parameter, or periodicity factor or scale factor;   Also τ <1.

l_n and l_{n+1} are the lengths of consecutive elements of antenna.

d_n and d_{n+1} are the spacing between consecutive elements of antenna.

The relationship between l_n and d_n is given by Eqn. 4.2

$$\sigma = \frac{d_n}{2l_n}$$

Where σ is the spacing factor.

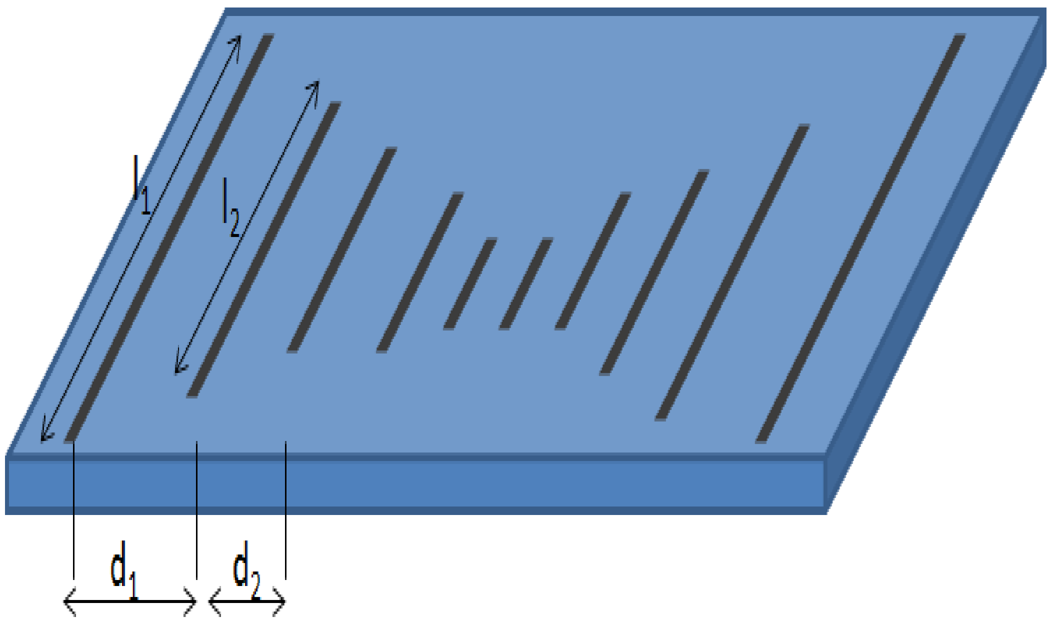


Figure 4.2 Log Periodic structure as a patch design

In bow tie pattern an angle is formed at converging or diverging end and this angle is called as the apex angle (α). Another expression for spacing factor in terms of scale factor (τ) and apex angle (α) is given by Eqn.4.3,

$$\sigma = \frac{1}{4}(1 - \tau)\cot(\alpha) \quad (4.3)$$

$$\sigma_{opt} = 0.243\tau - 0.051 \quad (4.4)$$

At an appropriate value of apex angle (α) the optimum value of spacing factor (i.e. σ_{opt}) is obtained. On using these values of σ_{opt} and τ for calculation of l_n and d_n, we get the different dimensions as under,

$$l_2 = \tau l_1$$

$$l_3 = \tau l_2$$

$$l_4 = \tau l_3$$

.

.

.

$$l_{n+1} = \tau l_n$$

Similarly, the values of d_n are obtained as under,

$$d_2 = \tau d_1$$

$$d_3 = \tau d_2$$

$$d_4 = \tau d_3$$

.

.

.

$$d_{n+1} = \tau d_n$$

4.3Designing of Bow tie antenna

The bow tie antenna patch is formed over the top layer of substrate integrated waveguide. The parameters required for designing are calculated using given steps as well as the parameters calculated for substrate integrated waveguide.

Step 1:- Calculate the values of l_1, l_2, l_3…. l_n using the value of τ in Eqn.4.1

$$\tau = \frac{l_{n+1}}{l_n}$$

$$l_1 = 2.158mm$$

$$l_2 = \tau l_1$$

$$l_2 = 1.72mm$$

$l_3 = \tau l_2$ and so on.

Step 2:- Calculate the value of σ_{opt} using the value of τ in the Eqn.4.4

$$\sigma_{opt} = 0.243\tau - 0.051$$

$$\sigma_{opt} = 0.1434$$

Step 3:- Calculate the values of d_1, d_2, d_3…. d_n using the value of τ in Eqn.4.1

$$\tau = \frac{d_{n+1}}{d_n}$$

$$d_1 = 0.618mm$$

$$d = \tau d_1$$

$$d_2 = 0.495mm$$

$d_3 = \tau d_2$ and so on.

The log periodic dipole antenna pattern designed is consisting of 20 elements (including the 10 elements of mirror image). The values of calculated length and spacing of all the corresponding elements is given in Table 4.1.

Table 4.1 Dimensions of LPDA elements

LPDA element	Length of element (mm)	Distance between consecutive elements (mm)
1	2.158	0.618

2	1.720	0.495
3	1.381	0.396
4	1.104	0.316
5	0.883	0.253
6	0.707	0.202
7	0.565	0.162
8	0.452	0.129
9	0.362	0.103
10	0.289	0.083

The values of l_n and d_n are used to design the bow tie pattern as the patch antenna on the top layer of substrate integrated waveguide. The designed bow tie patch antenna with its coordinate values is shown in Fig. 4.3.

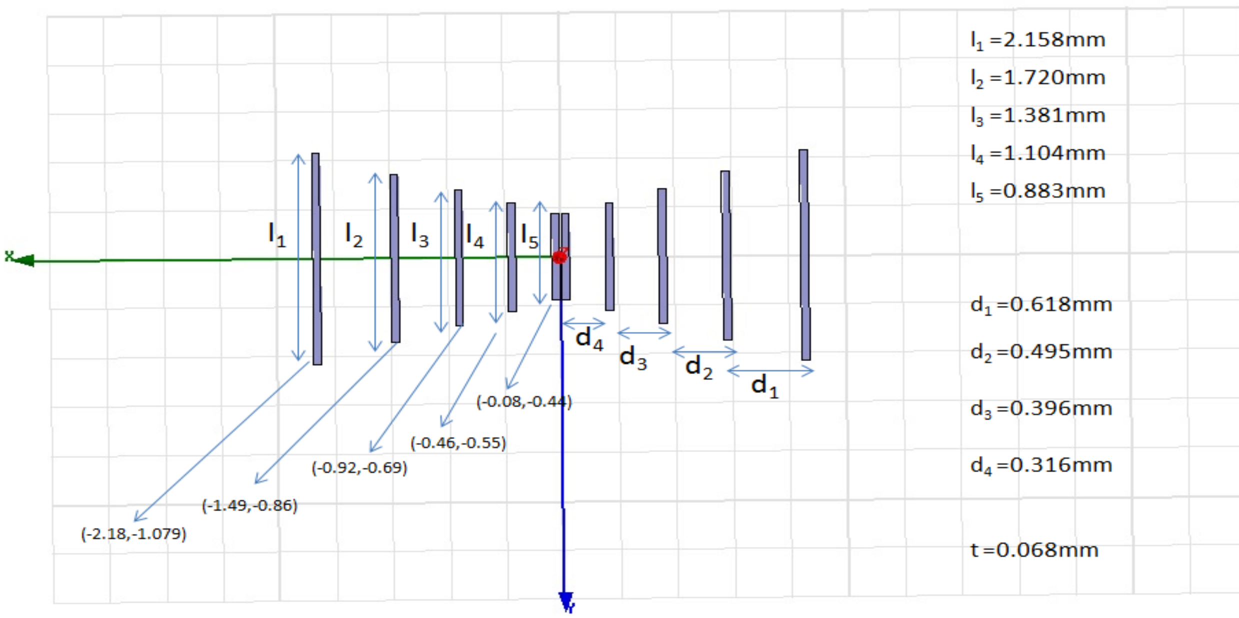


Fig. 4.3 Bow Tie Patch design using LPDA

4.4 Designing Bow tie with SIW

The bow tie pattern is mounted as the top copper radiating layer on the substrate integrated waveguide after bonding film.

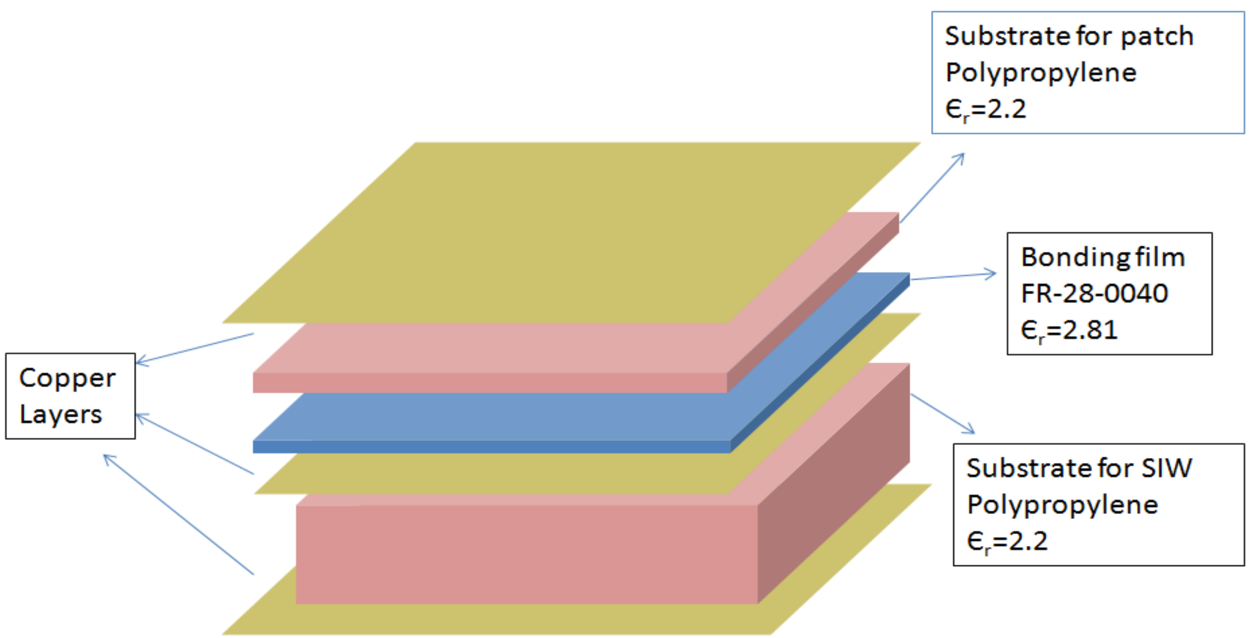


Figure 4.4 Layers of proposed design

In this configuration two substrates are connected with a bonding film with each other as shown in Fig. 4.4, which can be easily fabricated through a standard multi-layer PCB process. It has six layers from top to bottom, i.e., the top copper layer, the substrate for patches, the bonding film, the middle copper layer, the substrate for SIW and the bottom copper layer [2]. Radiating patches and microstrip lines are etched on the top copper layer.

Chapter 5

HFSS

5.1 Introduction

HFSS is a High Frequency Structure Simulator which is used for 3D devices modeling. It is used for simulation of high-performance full wave electromagnetic field. It provides an interactive platform for determining the electromagnetic behavior of 3D devices. This software package uses tetrahedron as the basic mesh component. HFSS provides easy to grasp environment for solid modeling, visualization, simulation and automation.

HFSS provides computation of:

- Characteristic impedance of ports.
- Attenuation and propagation constants.
- Basic EM field parameters.
- Near and far field radiations.
- S-parameter for respective port impedances.
- Eigen and EM modes of structures.

Panels of Ansoft HFSS window:

- **Project Manager:** It consists of complete design tree which gives the list of all the structures of project.
- **Message Manager:** It displays warnings, errors or completion message before or after the simulation.
- **Property Window:** It enables us to change the attributes or parameters of the designed models.
- **Progress Window:** It shows the progress of solution with respect to frequency sweep.

- **3D Modeler Window:** It displays the actual model or 3D device that we are designing.

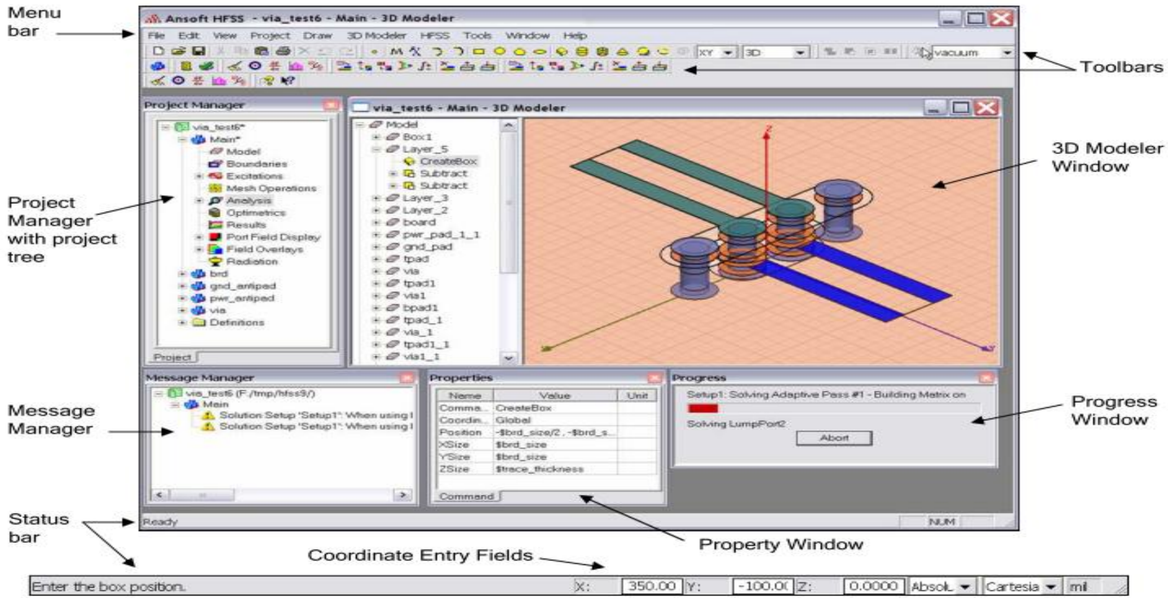


Figure 5.1 Panels of Ansoft HFSS

5.2 Simulation of proposed design

5.2.1 Designing of Bow Tie on single substrate

Step 1:- Draw the copper ground plane of 4.4mm×2.2843mm and put the required co-ordinate dimensions. This is the bottom most and the first layer of a microstrip patch antenna.

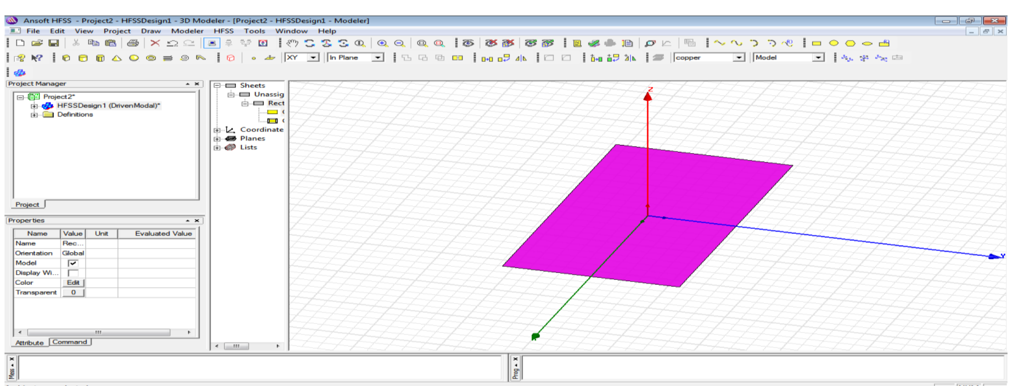


Figure 5.2 Ground plane of Patch antenna

Step 2:- Draw the substrate of 4.4mm×2.2843mm×0.508mm. This layer confines the actual radiations and act as a mediating layer between ground plane and the radiating patch.

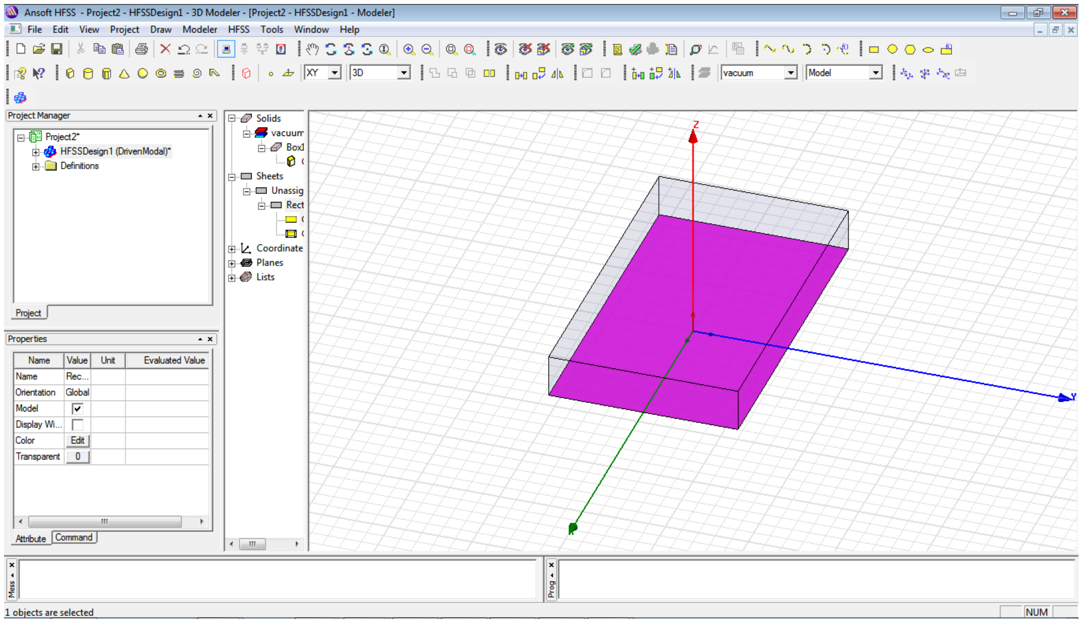


Figure 5.3 Substrate of Patch antenna

Assign the material of substrate as polypropylene with ε_r=2.2

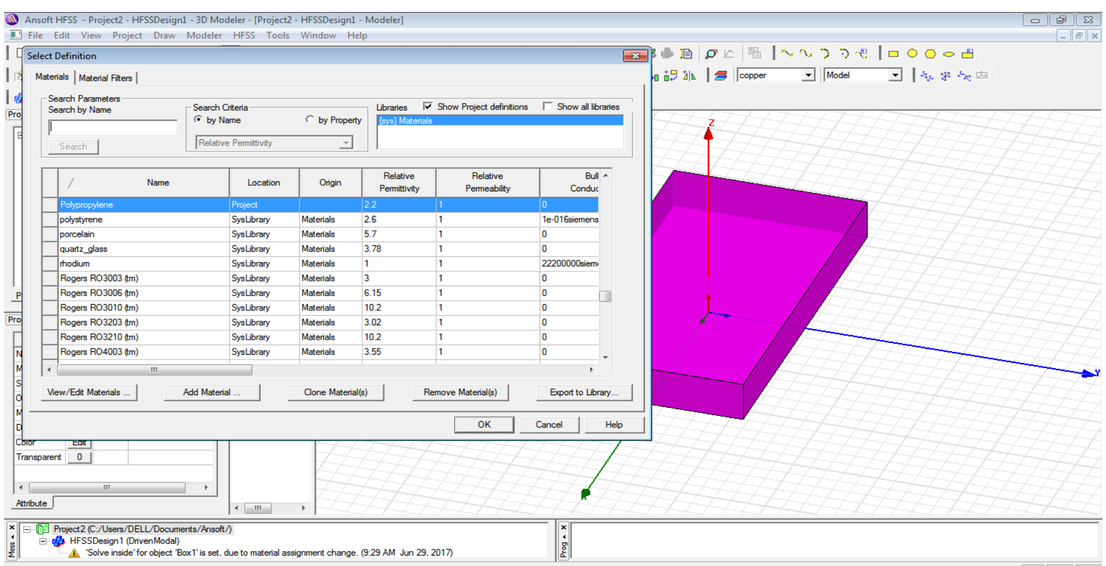


Figure 5.4 Substrate material of patch antenna

Step 3:- Design the bow tie pattern as the patch design on the substrate and then unite all the 10 elements of antenna after drawing to make a single patch design.

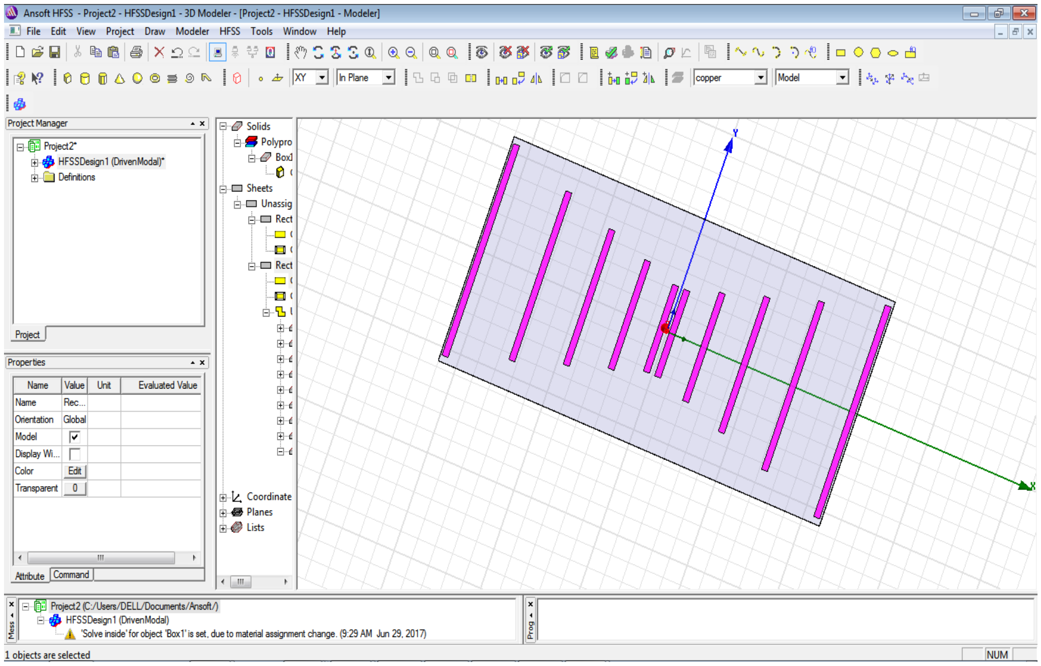


Figure 5.5 Bow tie patch design

Step 4:- In the design of bow-tie pattern without substrate integrated waveguide feeding is given using strip line feed.

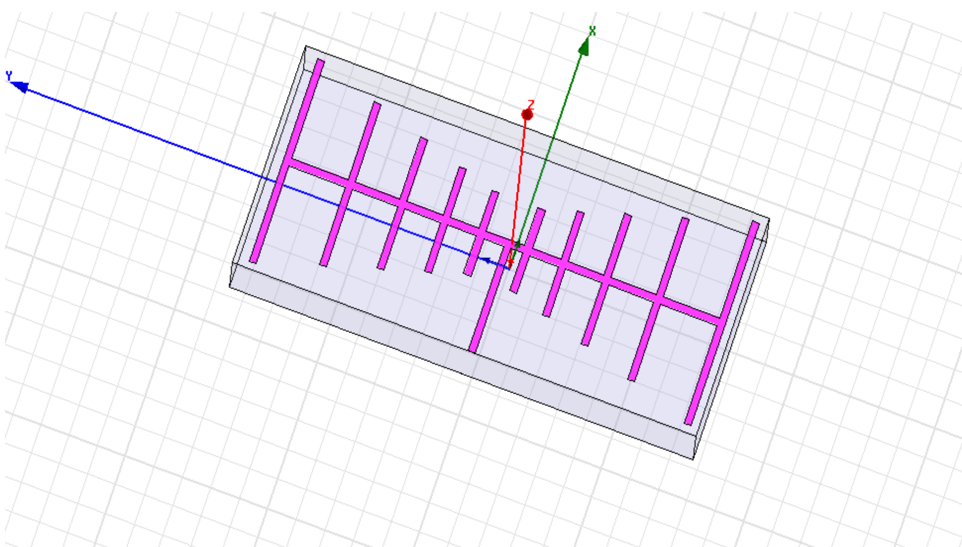


Figure 5.6 Strip line feed to bow tie patch

Step 5:-An echoic chamber is used for practical realization of radiations from an antenna. Similarly for simulation purpose a vacuum radiation box is used. The dimensions of echoic box needs to be larger than the complete patch design.

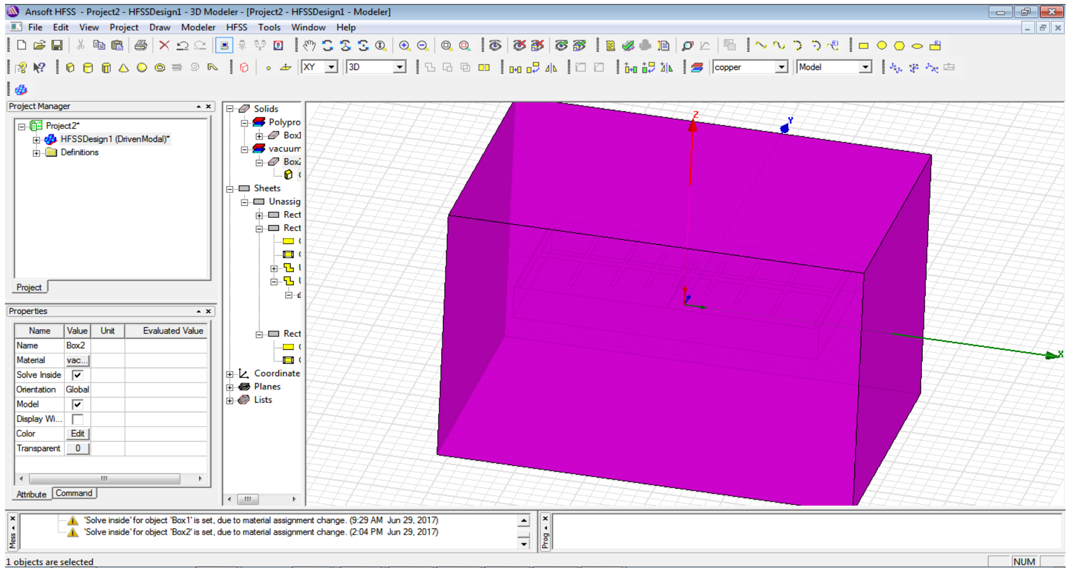


Figure 5.7 Radiation box

Step 6:- Assign the boundary of E-field to all the conducting regions i.e. ground plane and the radiating patch. And also assign the radiation boundary to the radiation box

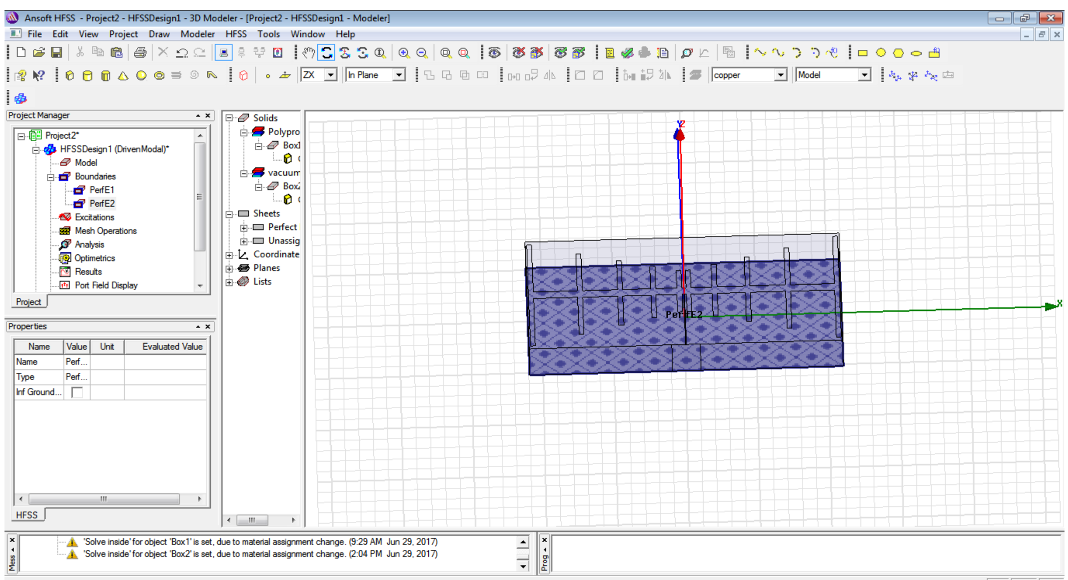


Figure 5.8 E-field boundary on ground plane

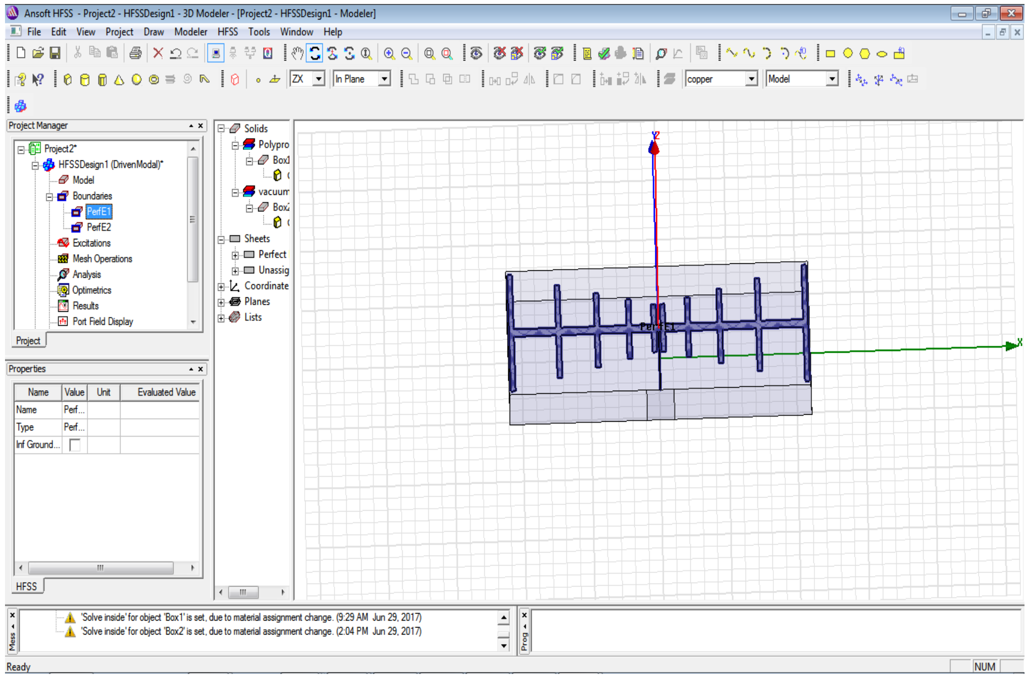


Figure 5.9 E-field boundaries on patch

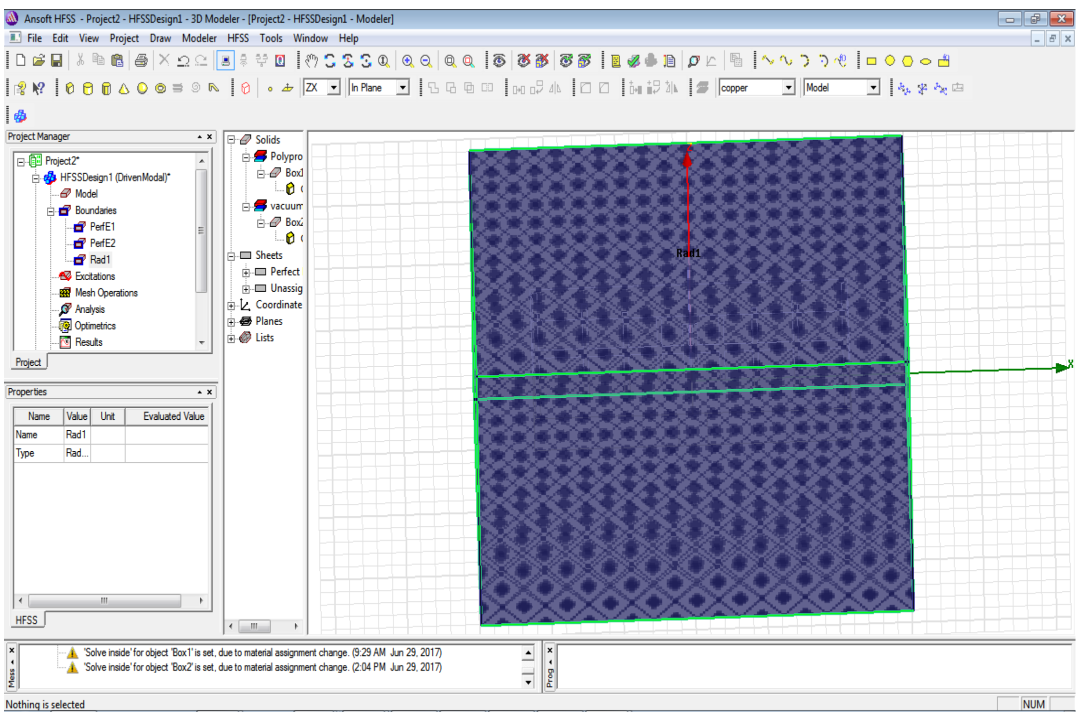


Figure 5.10 Radiation boundaries on radiation box

Step 7: For strip line feed to the bow tie pattern give lumped excitation to the strip line.

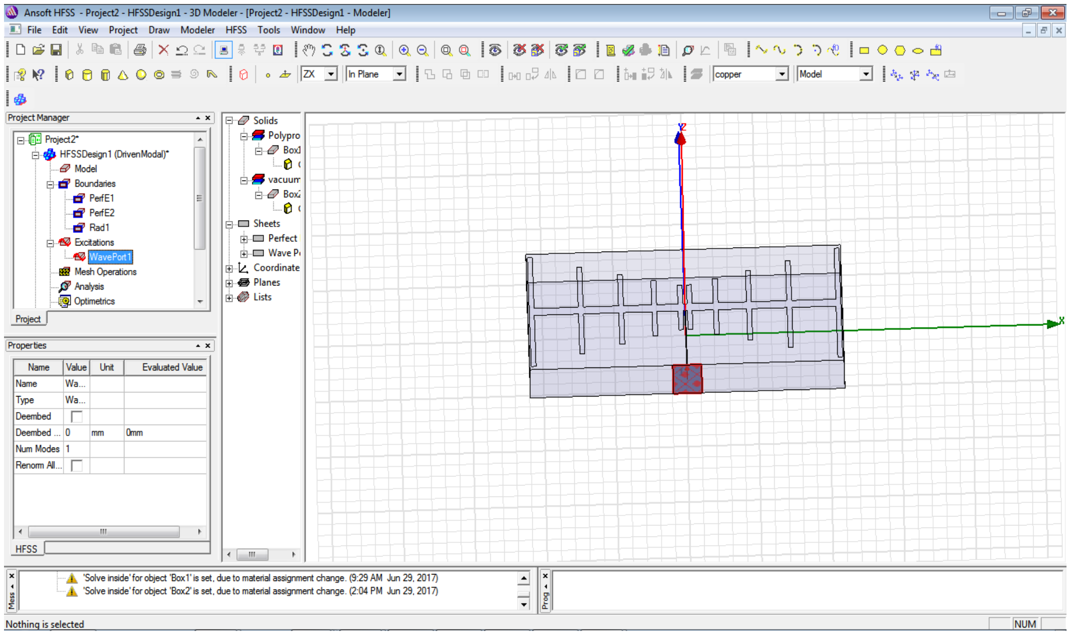


Figure 5.11 Excitation to the patch

Step 8: Set up the frequency sweep for v-band from 30GHz to 75GHz with center frequency being 57.5GHz.

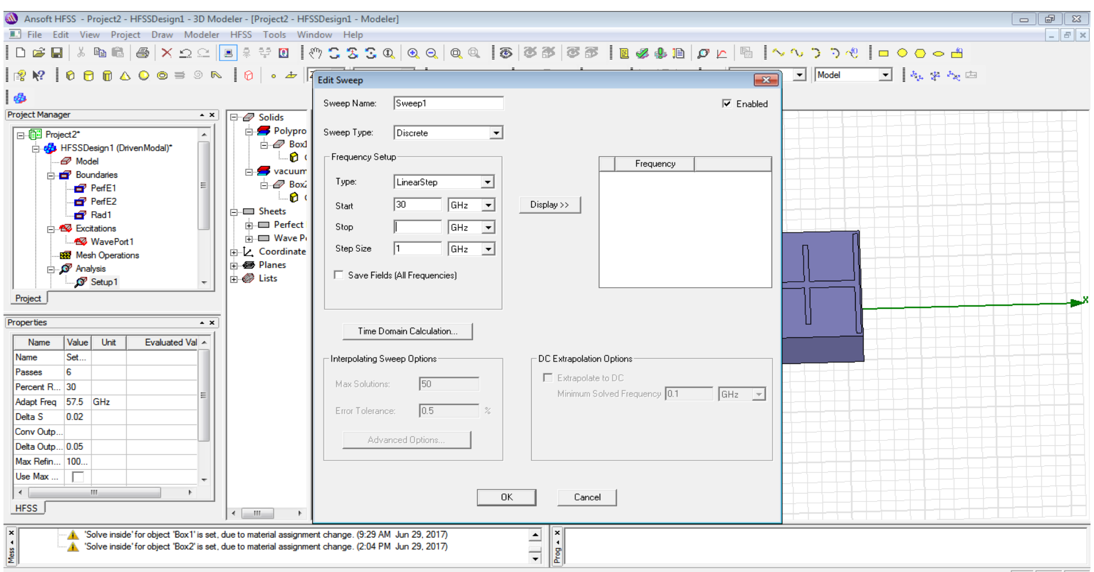


Figure 5.12 Setting of sweep frequency

Step 9: Check validation i.e. check for any error relevant to the design prior to simulation.

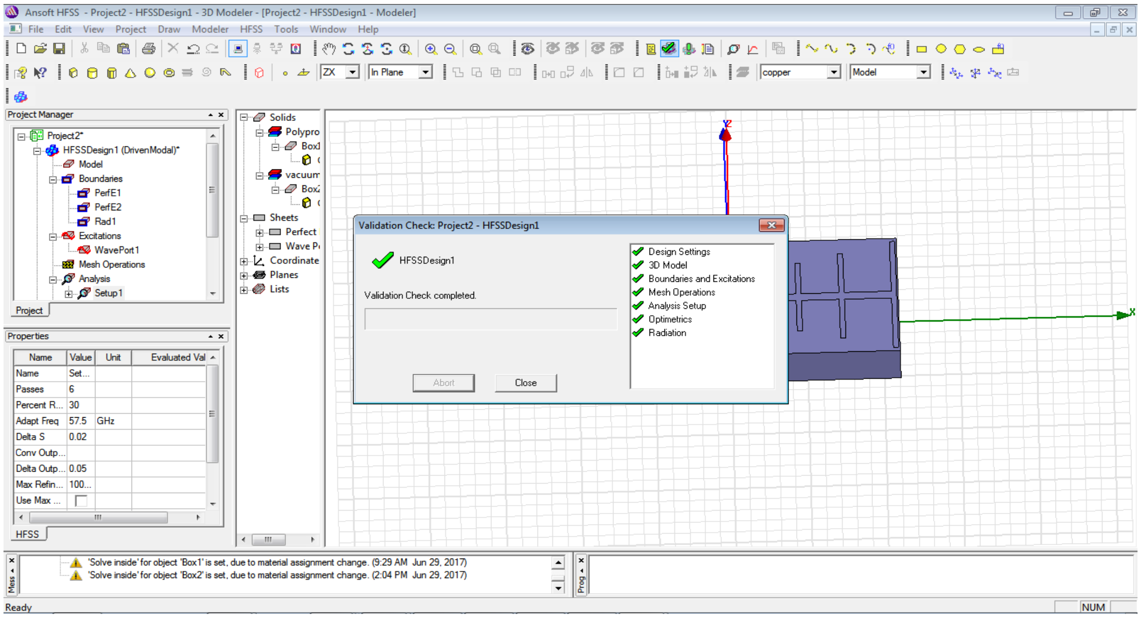


Figure 5.13 Validating the design

Step 10:- Analyze. i.e. simulate the design for results. The simulation is done for every iteration step of frequency.

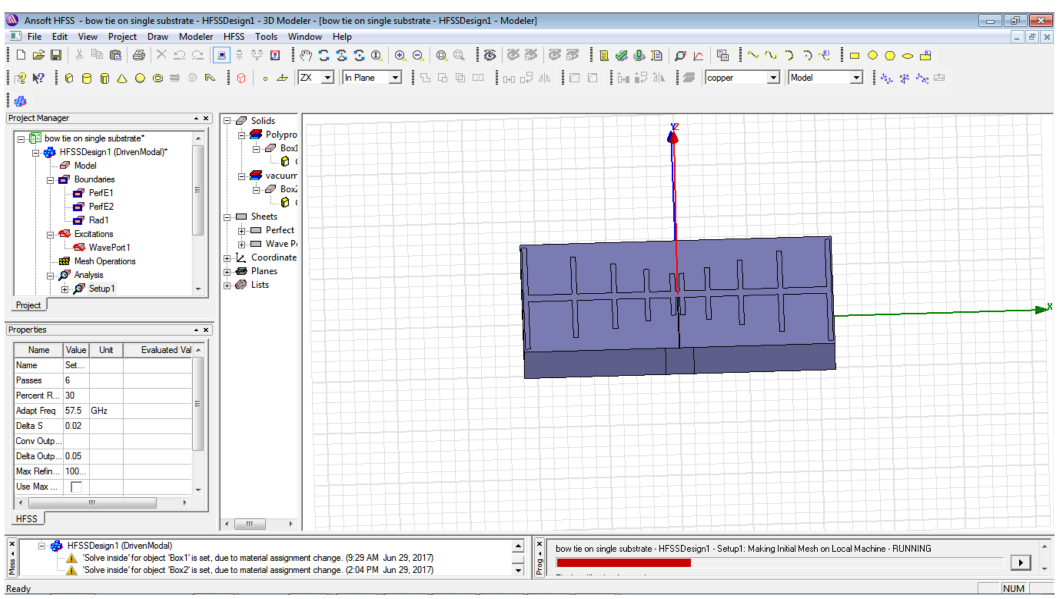


Figure 5.14 Simulation progress

5.2.2 Design of Bow tie with SIW

Step 1:- Draw the bottom layer of Substrate Integrated Waveguide of copper of 4.4mm×2.2843mm and put the required co-ordinate dimensions.

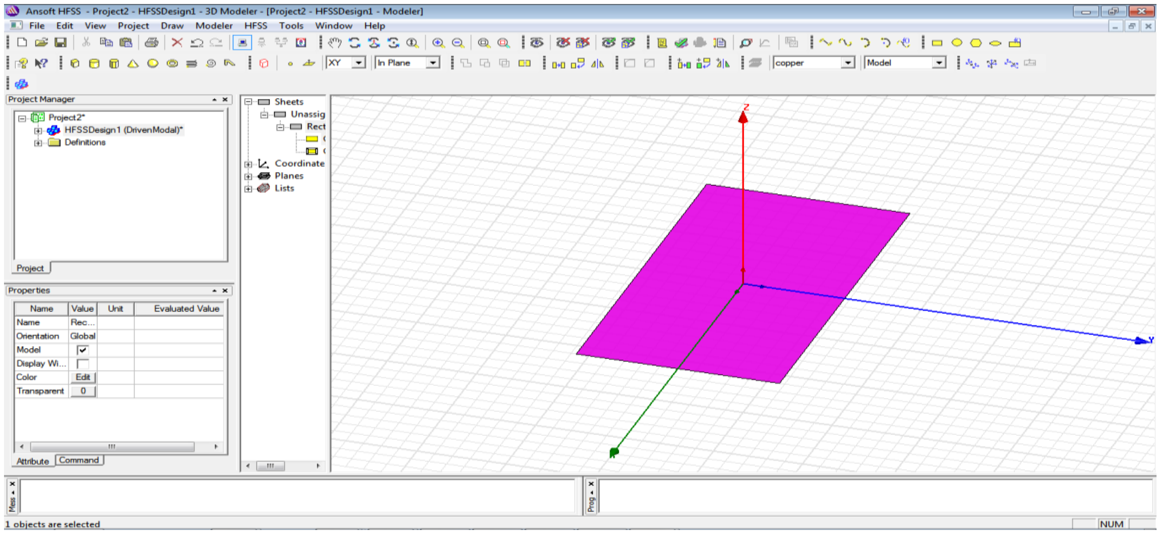


Figure 5.15 Ground plane of SIW

Step 2:- Draw the first layer of substrate of 4.4mm×2.2843mm×0.508mm polypropylene with dielectric constant (ε_r= 2.2).

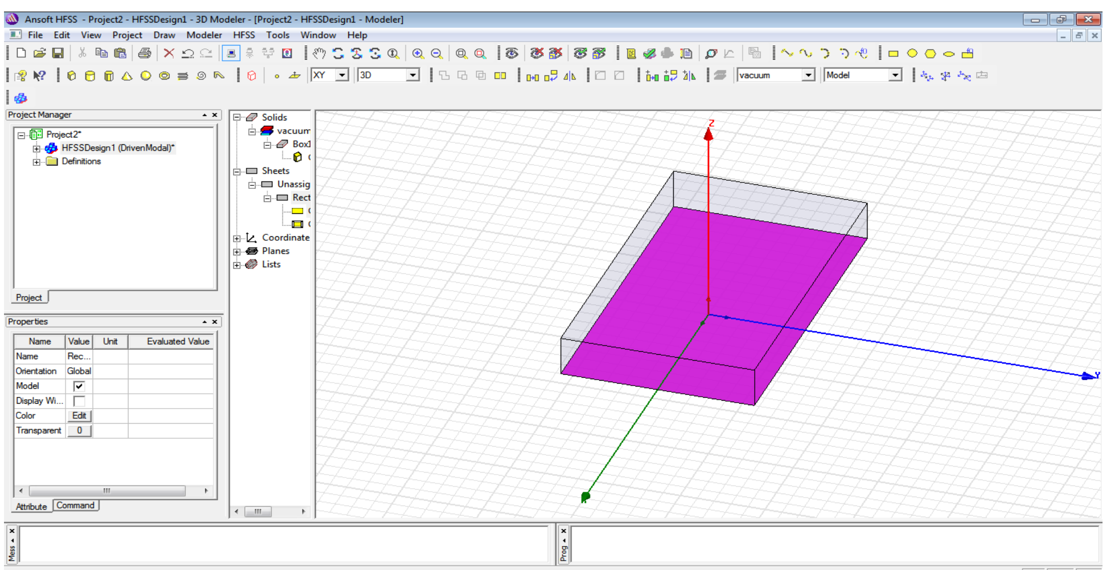


Figure 5.16 First layer of Substrate of SIW

Step 3: Draw upper copper layer of SIW with etched slot feed for excitation transition.

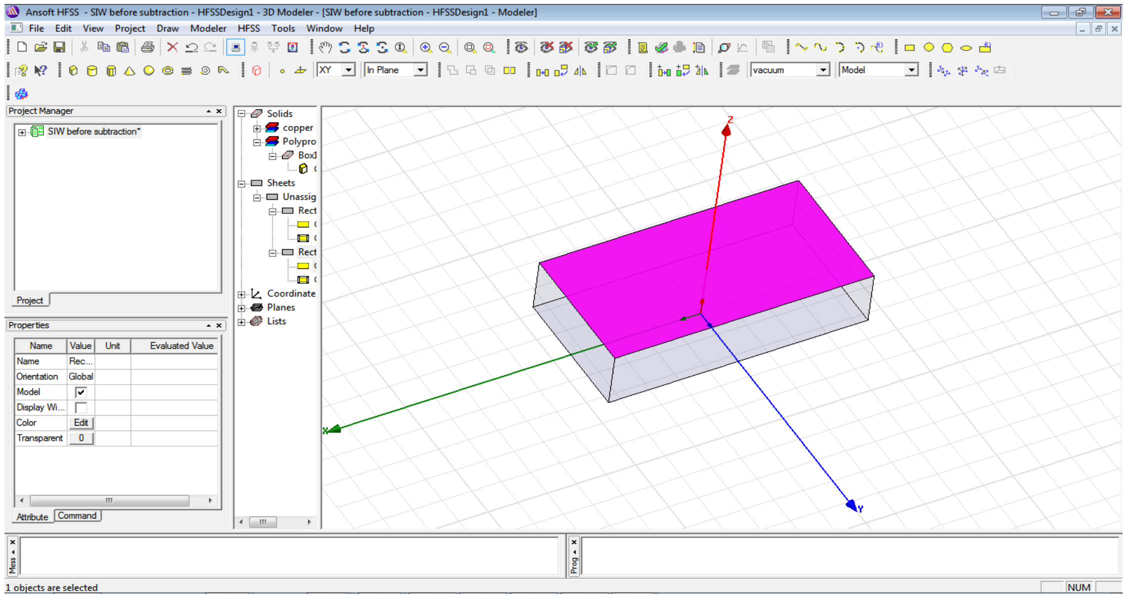


Figure 5.17 Copper layer for feed transition

Step 4:- Make metallic via holes through the substrate. These via holes are made by inserting cylinders through the substrate at the specific coordinate values.

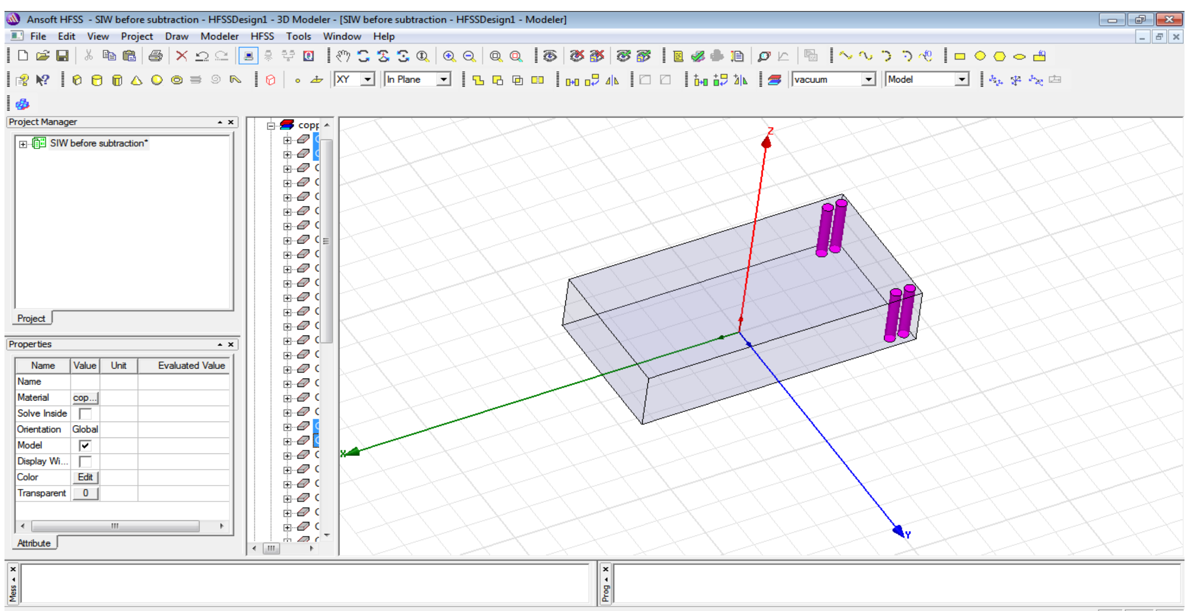


Figure 5.18 Metallic via-holes

Make slot feed transition.

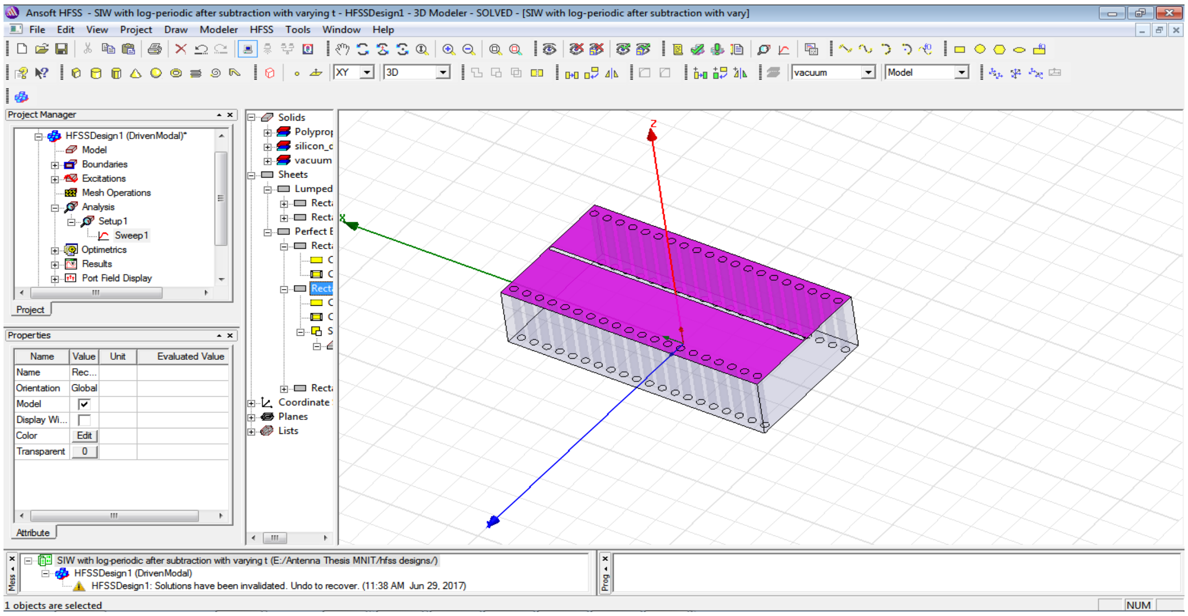


Figure 5.19 Slot feed transition

Step 5: Make bonding film of FR-28-0040 (ε_r=2.8).

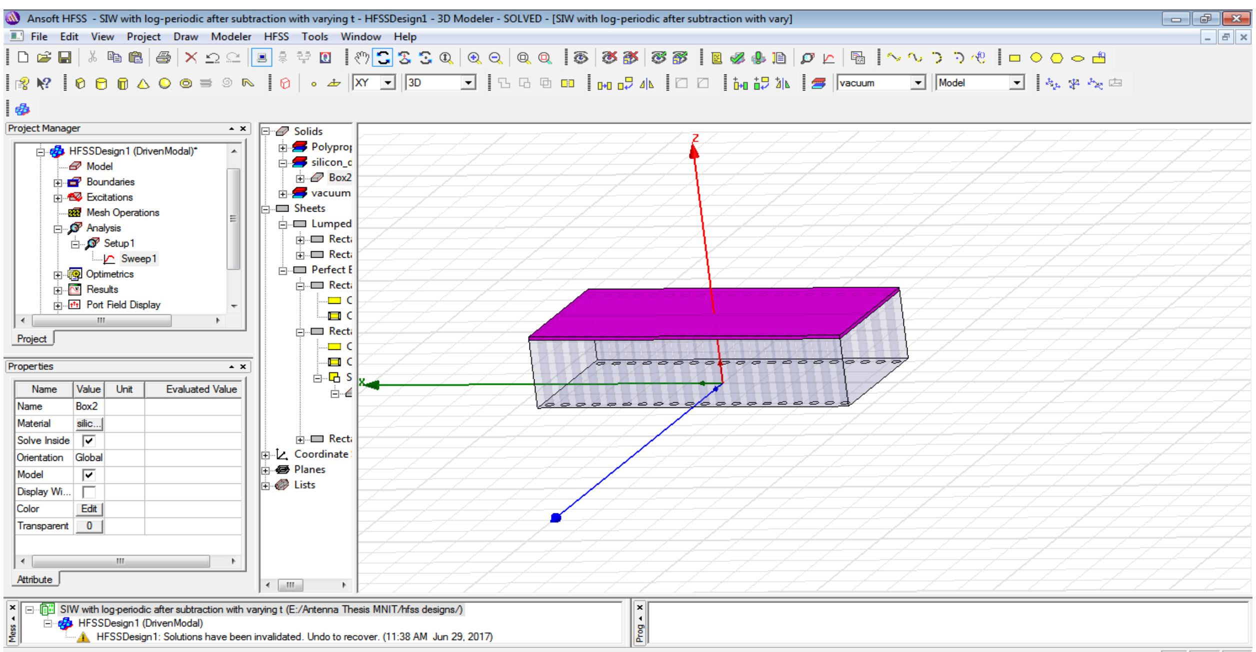


Figure 5.20 Bonding film

Step 6:- Make polypropylene substrate on the bonding film.

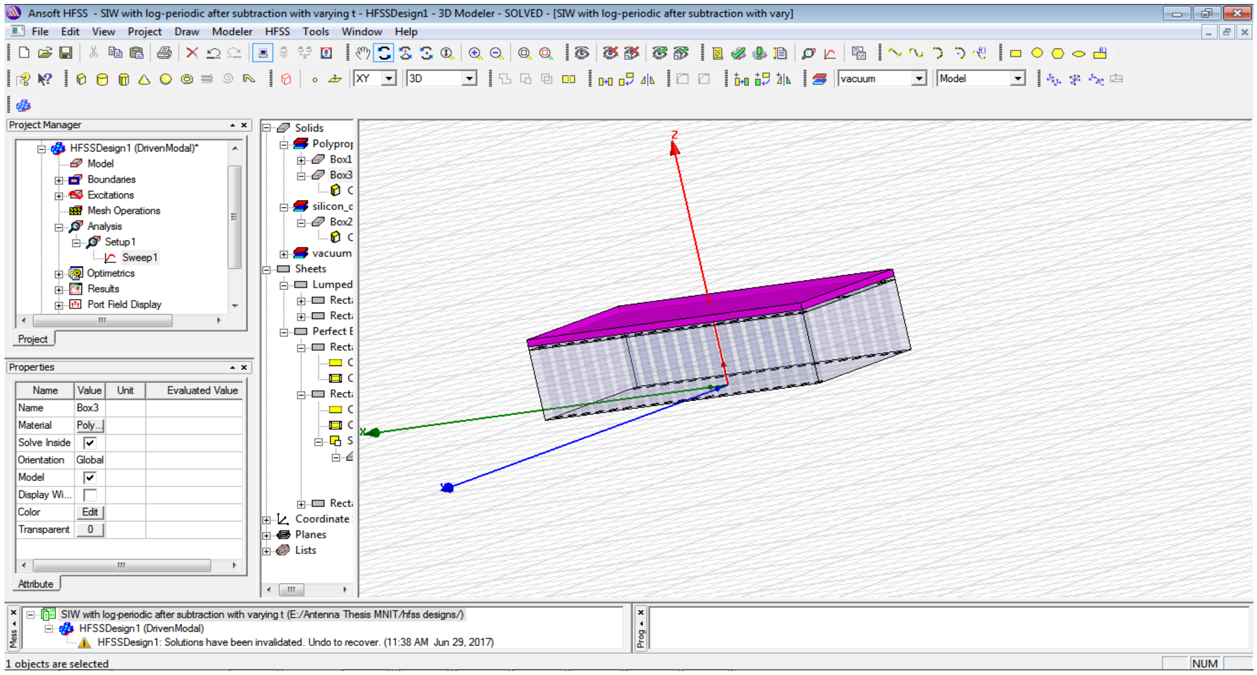


Figure 5.21 Second layer of Substrate of SIW

Step 7:- Make Bow Tie Patch design on the second layer of SIW. This is the actual radiating patch.

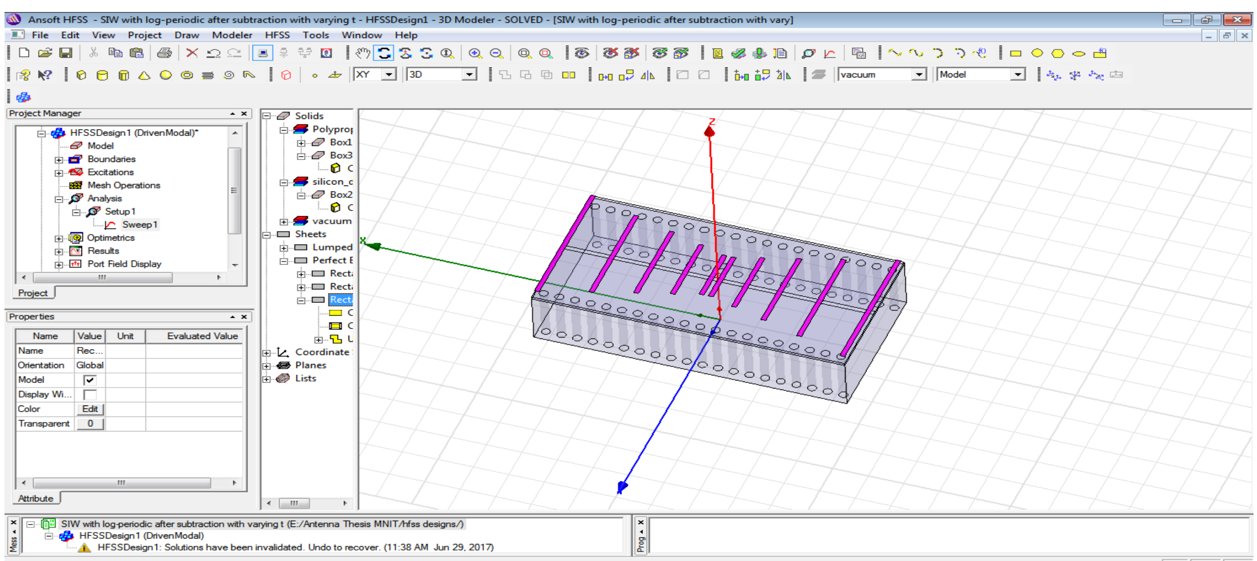


Figure 5.22 Bow tie patch design

Step 8:- Make vacuum radiation box.

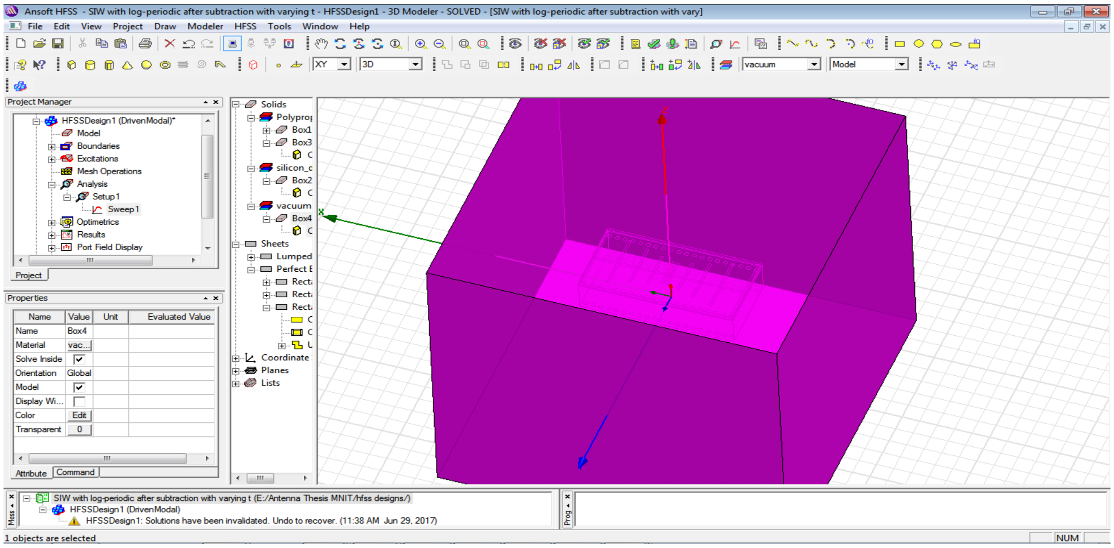
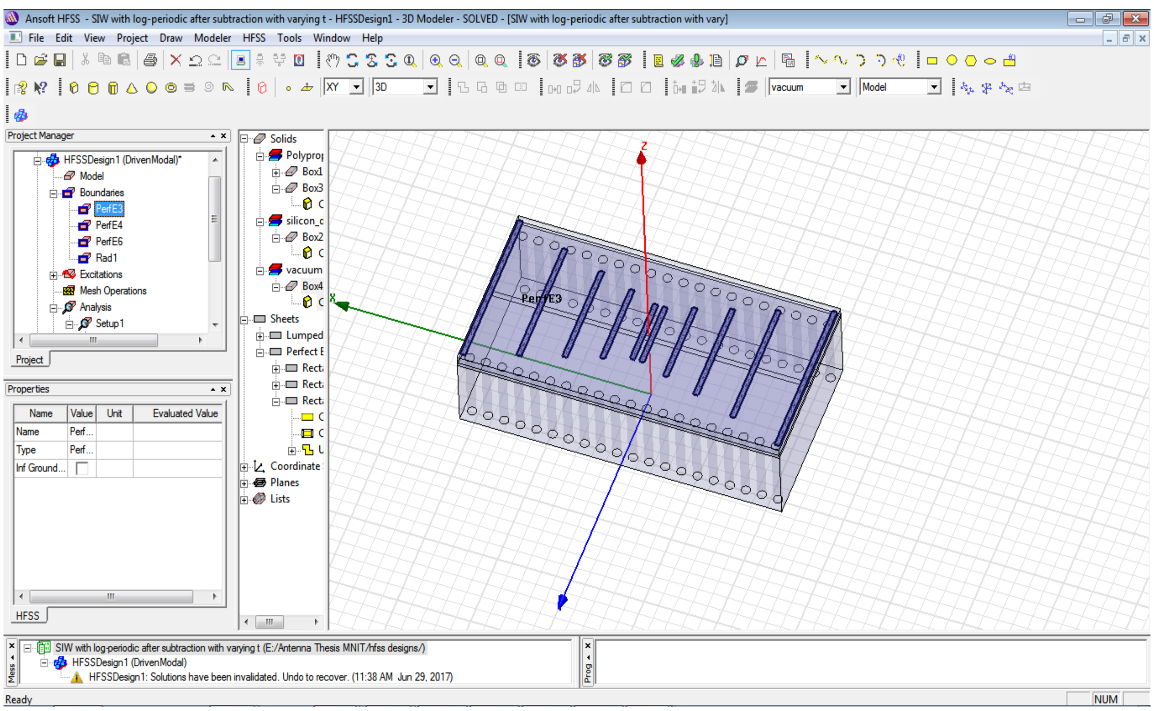


Figure 5.23 Radiation Box

Step 9:- Assign boundaries.



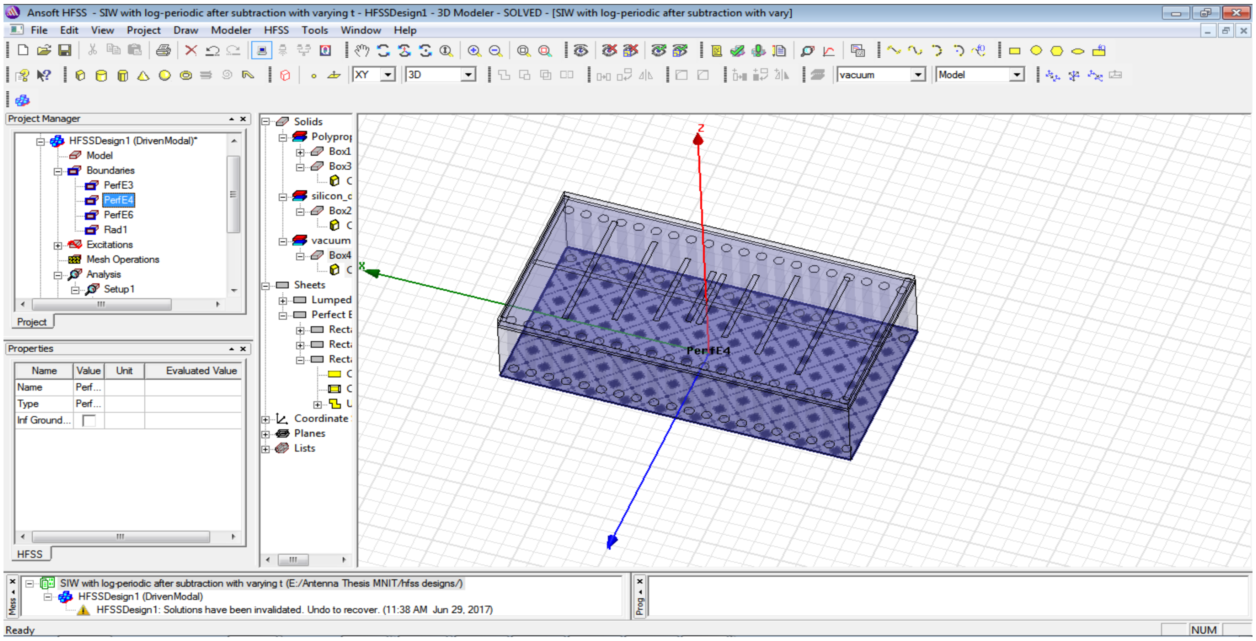
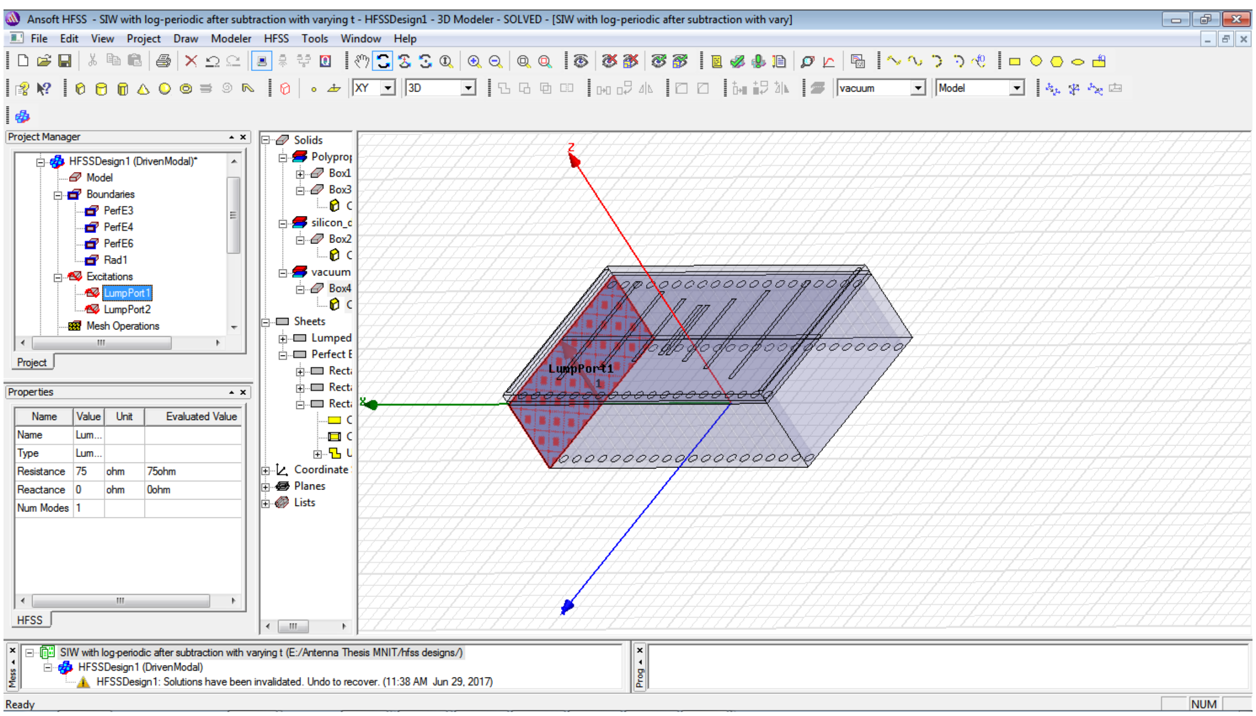


Figure 5.24 E-Field boundary of conducting plane

Step 10:- Assign Excitation.



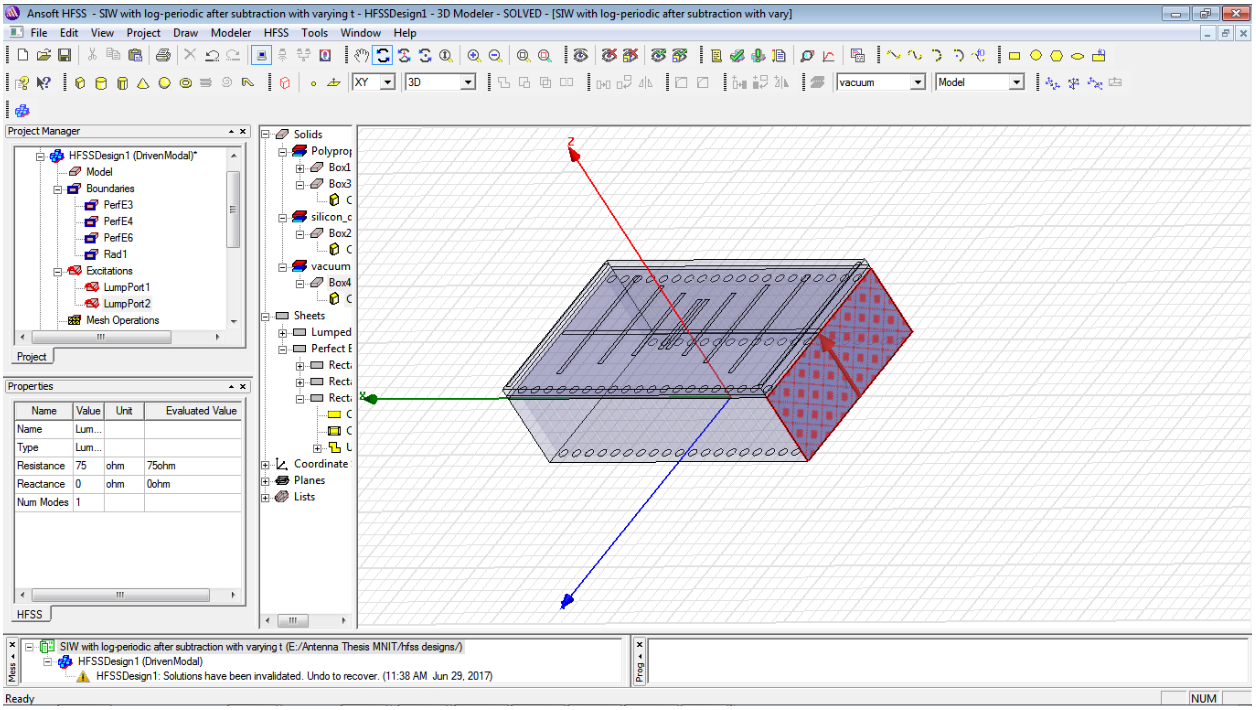


Figure 5.25 Lump port excitation on SIW

Chapter 6

Comparative Study

This Chapter shows a comparative study between design of microstrip patch antenna without SIW and with SIW have been carried out in Ansoft HFSS software.

6.1 Comparison of Simulation Results

The comparative analysis of several parameters viz. return loss, voltage standing wave ratio, radiation pattern etc. is made for bow-tie pattern on substrate integrated waveguide and bow-tie pattern on single substrate. For feeding the bow-tie pattern on SIW, a rectangular slot is made in the middle copper layer while in bow-tie pattern on single substrate the feeding is done through microstrip line [7]. The metalized holes along with the middle copper layer and the bottom copper layer make the substrate integrated waveguide.

- **Comparison on the basis of S-parameter**

S-parameter of bow tie pattern without and with SIW is shown in Fig.6.1 and Fig.6.2 respectively.

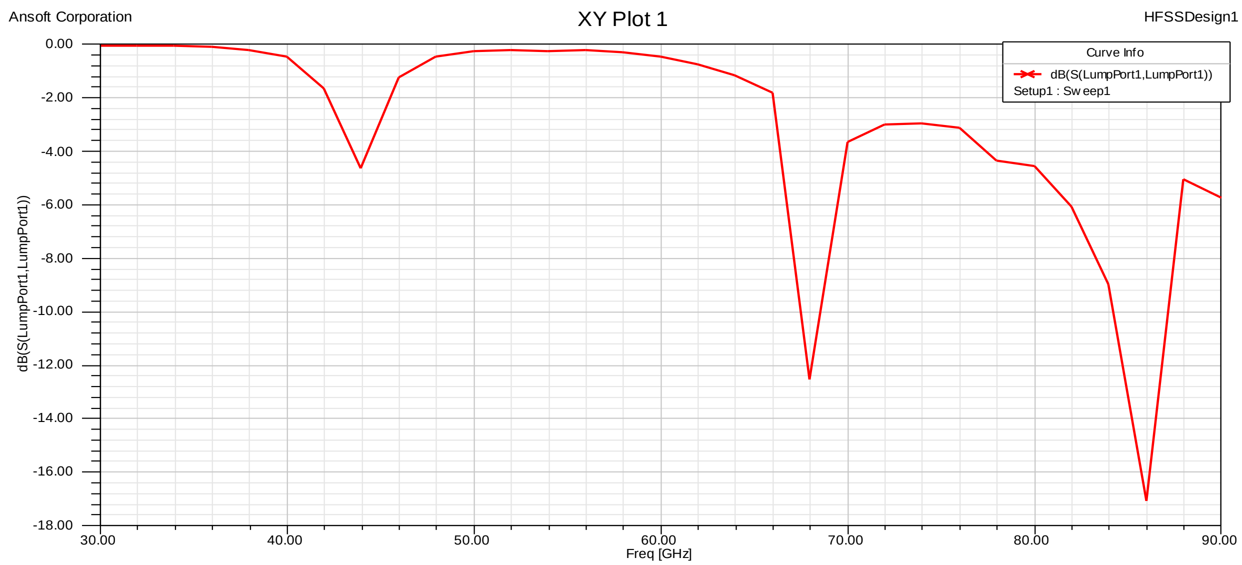


Figure 6.1 Graphical representation of S-parameter of bow tie pattern without SIW

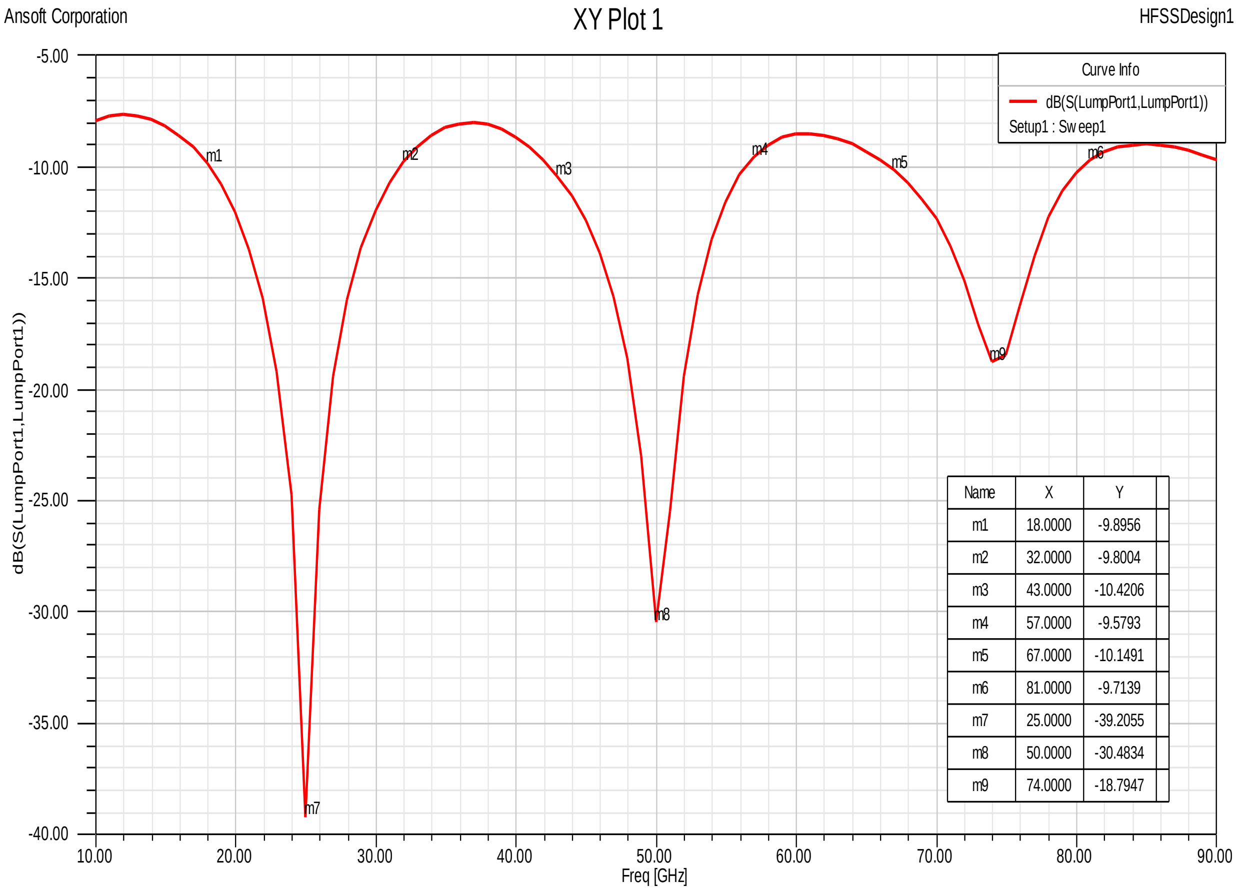


Figure 6.2 Graphical representation of S-parameter of bow tie pattern with SIW

This comparison shows that the percentage bandwidth for bow tie pattern without SIW is 0.58% at 68GHz and 2.95% at 88GHz. And percentage bandwidth for bow tie pattern with SIW is 56% for 18-32GHz, 28% for 43-57GHz and 18.9% for 67-81GHz. It depicts that due to presence of slot feed the relative percentage bandwidth is better in the bow tie pattern with SIW.

- **Comparison on the basis of radiation pattern**

Radiation pattern of bow tie pattern without and with SIW is shown in Fig.6.3 and Fig.6.4 respectively. This comparison shows that bow tie pattern with SIW gives better directivity as compared to bow tie pattern without SIW.

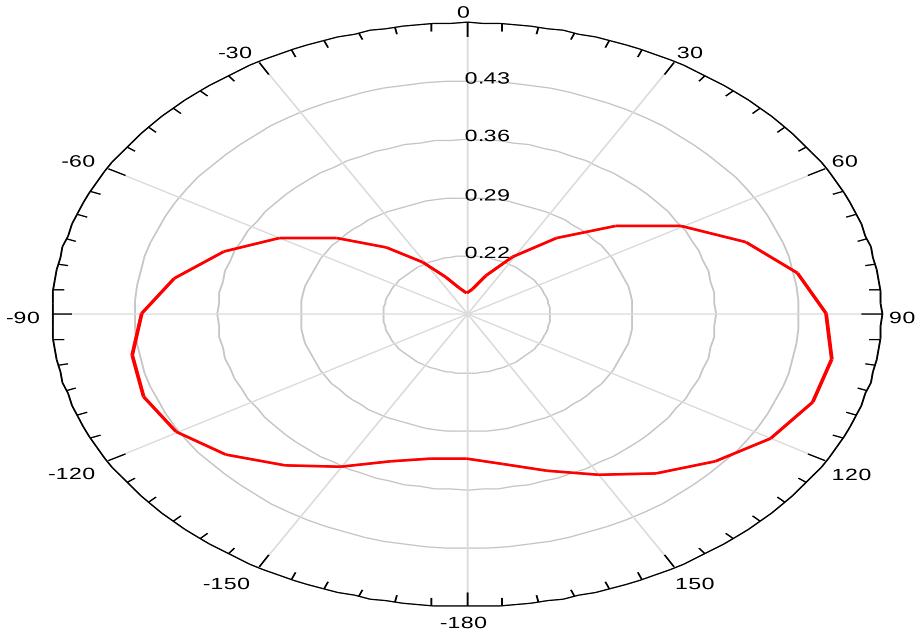


Figure 6.3 Radiation pattern of Bow tie pattern without SIW at 57.5GHz for ϴ=90º

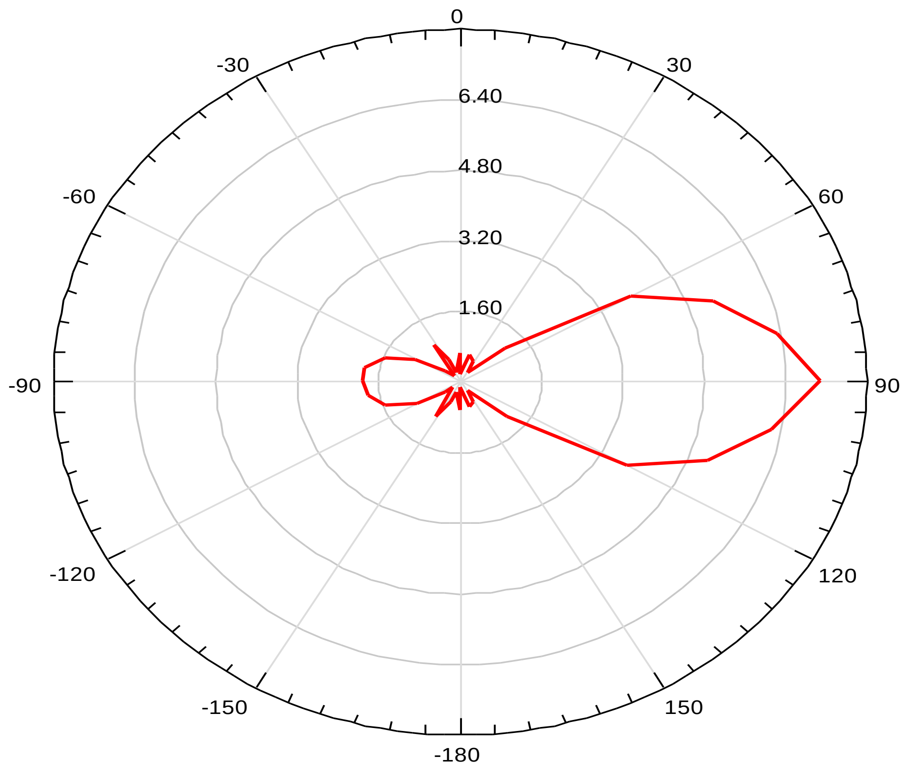


Figure 6.4 Radiation pattern of bow tie pattern with SIW at 57.5GHz for ϴ=90º

- **Comparison on the basis of VSWR:**

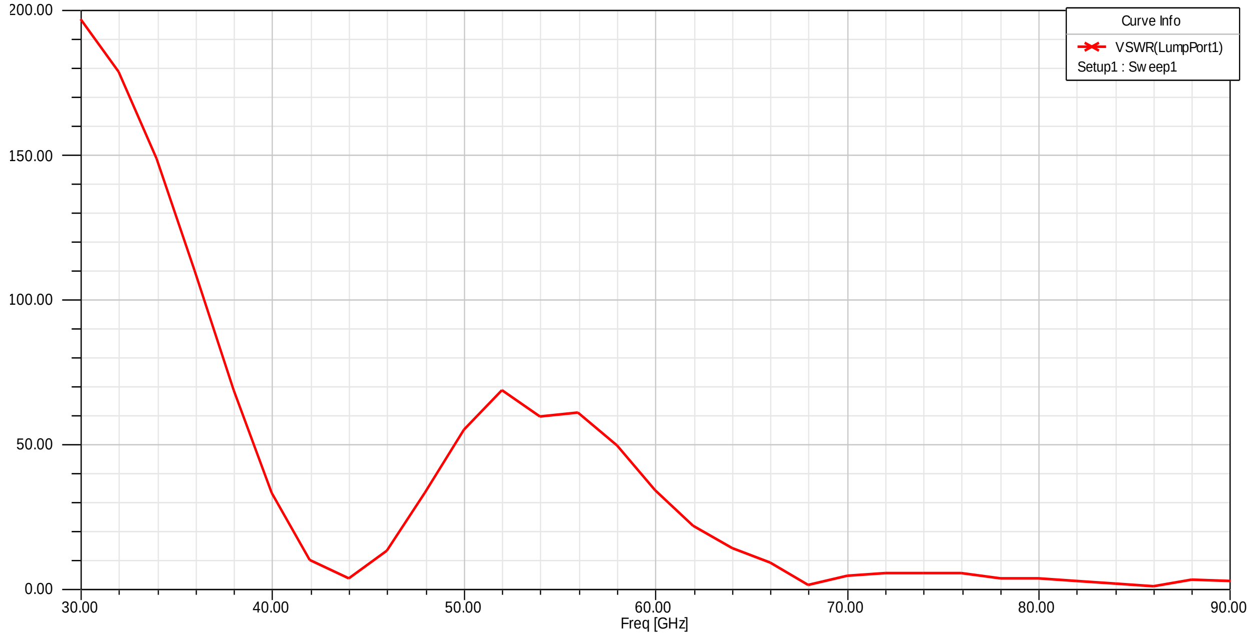


Figure 6.5 VSWR of bow tie pattern without SIW

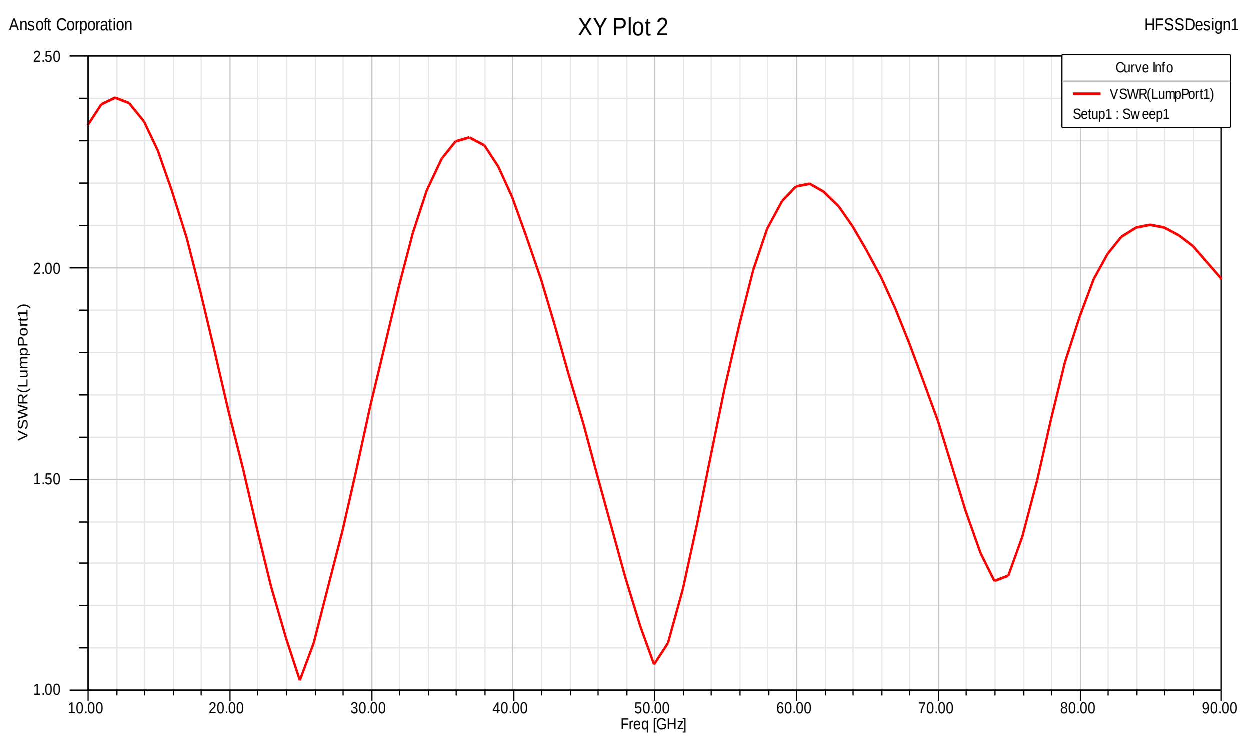


Figure 6.6 VSWR of bow tie pattern with SIW

Optimization for radius of via-holes of SIW:

The radius of via-holes of substrate integrated waveguide plays a significant role in leakage pattern. As the radius of via-holes increases the waveguide will approach the conventional waveguide and some parameters like return loss or voltage standing wave ratio begins to deteriorate. The radius of via-holes can be approximated using $d<\lambda_g/5$ but still it needs optimization for exact value of radius. For obtaining optimum value of radius of via-holes the plot is obtained between radius of via-holes and return loss after simulation as shown in the plot.

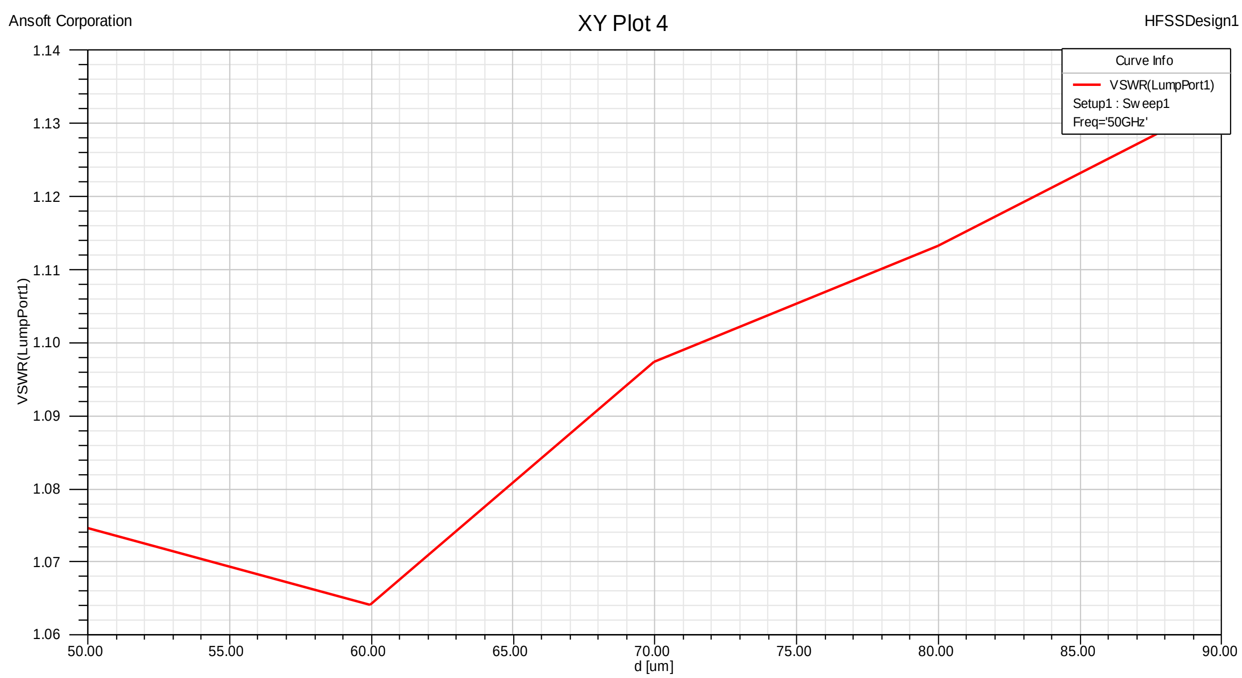


Figure 6.7 Optimum value of VSWR is obtained for radius=0.06mm

Chapter 7

Conclusion and Future Works

The designing of bow tie pattern with SIW is the focus of current research work because of its robustness. This design has been simulated in Ansoft HFSS software.

In this dissertation, the designing of microstrip patch bow tie pattern with and without SIW have been carried out. Also, the parameters such as S-parameter, gain and VSWR have also been compared. The simulation results have been shown at each step of designing and thereafter a comparative study has been given between Bow Tie pattern with and without SIW. From this design it can be concluded that the bow-tie pattern showed better results with SIW, which in turn also reduces feeding complexity. The bow-tie pattern with SIW is more directive than the bow-tie pattern on a single substrate.

It can be inferred from the results that as the radius of via-holes increases the return loss and VSWR increases. So the optimized value of 0.06mm radius is chosen for via-holes.

The present work opens a lot of new avenues and directions for research in the field of microwave. Some of the possible directions for the future work can be:

- Designing Substrate integrated waveguide with different pattern on it to achieve several applications of power divider, coupler, splitter etc.
- Designing complete array of the elements on substrate integrated waveguide to achieve better broadband feature with conformal gain.
- The idea of reconfigurable antenna can also be implemented for substrate integrated waveguide

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