# High Gain Dielectric Loaded Exponentially Tapered Slot Antenna Based on Substrate Integrated Waveguide for V-Band Wireless Communications

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***Abstract*** **─** The conception of Substrate Integrated Waveguide (SIW) technology and Exponentially Tapered Slot (ETS) antenna are together used to design a high gain, and efficient planar dielectric loaded antenna for V-band wireless communications. To increase the gain of the antenna, a dielectric loaded portion is used in front of the antenna which works as a dielectric guiding structure and SIW is used to feed the proposed antenna. The dielectric loaded ETS antenna and compact SIW feed are fabricated on a single substrate, resulting in low cost and easy fabrication. The antenna with elliptical shaped dielectric loaded is fabricated using printed circuit board process. The measured gain of the single element antenna is 10.2 dB, while the radiation efficiency of 96.84% is obtained at 60 GHz. The Y-junction SIW power divider is used to form a 1×2 array structure. Measured gain of the 1×2 array antenna is 11.2 dB, while the measured radiation pattern and gain are almost constant within the wide bandwidth of the antenna.

***Index Terms*** **─** 60 GHz, antenna, ETS dielectric loading, millimeter waves, SIW.

## I. INTRODUCTION

Millimeter (Mm) wave technology, system, and applications have been one of the newest topical discussions in academic laboratories, technical sessions, and commercial boardrooms since the early time [1,2]. Strong and growing interest in this specific electromagnetic spectrum is being fueled by a popular recognition that this frequency range allows effectively bridging the gap of well apparent technology between electronics and wireless communication. We will focus specifically on 60 GHz antenna, which has emerged as one of the most encouraging contenders for multi gigabit wireless communication systems. The 60 GHz technology offers various recompenses over present wireless communication systems. One of the deciding aspects that mark 60 GHz technology gaining significant interest recently is due to the huge unrestricted bandwidth (up to 7 GHz) available worldwide [3]. This huge bandwidth represents great potentials in terms of capacity and flexibility that makes 60 GHz technology mainly attractive for gigabit wireless applications.

Antennas with excellent design can improve the performance of communication. Many types of antenna structures are considered not suitable for 60 GHz WLAN/WPAN applications due to the requirements for low cost, small size, and light weight [4]. In addition, 60 GHz antennas also require to be operated with constant gain and high efficiency over the broad frequency range. Recently, the technology of planar integrated antenna [5] has been developed for Mm wave applications due to the trend of the integration in radio frequency front-end circuits and systems. As the operating frequency of wireless systems move into Mm wave range in order to provide gigabits per second service, there is an increasing demand of high gain antennas used for consumer devices. The desired antenna has to be compatible with integrated circuits, and possess high gain and small side lobe. When integrated into consumer devices, should also have the benefits of small size

*Submitted On: September 9, 2013*
*Accepted On: October 4, 2014*

and low production cost [6].

The concept of SIW technology makes it possible to realize the waveguide in a substrate and provides a sophisticated way to integrate the waveguide with microwave and millimeter wave planar circuits using the conventional low-cost printed circuit technology. In particular, a number of SIW based slot antennas have been reported in recent years. These antennas consist of single layer of dielectric substrate and are fed from one end through a coplanar feed network which significantly increases the size of the antenna. Furthermore, radiation from microstrip feed lines and junctions severely negotiate the low side-lobe level of the slot antenna and increases cross-polarization [7-10].

Therefore, this work targets on addressing challenges in designing dielectric loaded ETS antenna using SIW technology for the realization of V-band wireless communications, particularly at 60 GHz utilizing 3D electromagnetic software CST Microwave Studio, and comparison with Ansys HFSS validates the design procedure. The work in this paper is organized as follows; Section II deals with step by step design procedure for the ETS antenna, simulation, measurement results and discussions. Section III deals with ETS array antenna simulation and measurement results obtained in our present work and discussions. Finally, Section IV gives conclusions.

## II. DIELECTRIC LOADED EXPONENTIALLY TAPERED SLOT ANTENNA DESIGN

The ETS antenna is also known as flared notch or Vivaldi antenna, is among one of the most promising antenna satisfying all requirements described in the technical challenges [11]. It is fundamentally a planar traveling wave antenna with end fire radiation. The flared notch antenna comprising a plurality of flared disposed immediately adjacent each other, each having a direction of maximum gain which is directed in a different direction. The ETS antenna containing a two flares in the same plane providing the gain in specific direction with wider main lobe. This antenna is the preferred candidate for Mm Wave applications due to its wide bandwidth, low cross-polarization and highly directive patterns. A major advantage of this antenna type is that the wide bandwidth and maximum gain can be achieved using exponentially tapered profiles with dielectric loading [12]. The proposed dielectric scheme provides an interesting alternative. This antenna is integrated by using a single substrate. It is easy to fabricate and the structure is compact [13]. To eliminate the higher order modes in the waveguide, the thickness of the substrate is restricted. The loaded dielectric slab in front of the antenna can be considered as a dielectric guiding structure excited by the exponential flare resulting in a wider beamwidth and maximum gain. The compact Mm wave antenna with dielectric loading can achieve a broadband performance and offer several advantages over other counterparts such as relatively low insertion loss, better VSWR, good design tolerance and circuit size compactness [14,15].

### A. Replacing waveguides with equivalent SIW

The conventional waveguide technology still plays an important role in Mm wave circuits and systems, which takes the advantages of low loss, high Q-factor and high power handling capability. But its bulky structure makes it difficult to fabricate it at low cost and integrate it into planar structure. So the SIW technology makes it possible to realize the waveguide in a substrate and provides a sophisticated way to integrate the waveguide with Mm wave planar circuits using the conventional low cost printed circuit technology [16-19]. Here, the dielectric filled waveguide is transformed to SIW by the support of vias for the side walls of the waveguide. In the SIW design, the following conditions are required. The metalized via hole diameter is:

$$d < \lambda_g / 2 \, . \qquad (1)$$

The spacing between the via holes is:

$$P < 2d \, . \qquad (2)$$

The physical width of SIW is:

$$a = a_d + (d^2 / (0.95p)) \, . \qquad (3)$$

The calculated values of the physical width of SIW is 2.0 mm, metalized via hole diameter is 0.30 mm, and space between via holes is 1.0 mm.

### B. Microstrip to SIW transition

The microstrip line is used to transfer the power to antenna. This transmission line is connected to the feed waveguide in the bottom layer. The transition between microstrip line and SIW is critical for achieving good impedance matching and small return loss. A tapered transition was suggested, which is useful in most applications [20].

In order to make a good transition from the microstrip to the SIW, first of all, it is necessary to calculate the guide impedance of the SIW which is given by:

$$Z_g = Z_{TE}(\pi^2 b / 8a). \quad (4)$$

For the calculation of the guide impedance, it is also necessary to calculate the wave impedance of TE mode which is given by:

$$Z_{TE} = j\omega\mu / \gamma = \sqrt{\mu / \xi} \times (\lambda_g / \lambda). \quad (5)$$

In our transition, the width of 50 Ω microstrip line is like to the width of SIW physical width to achieve impedance matching with low insertion loss and nullify the higher order modes. The width of the 50 Ω microstrip line is 2 mm, is calculated from above equations.

### C. Design of the antenna

The ETS antenna radiating tapered profile is described by an exponential function. The antenna is excited via the microstrip line to SIW transition. The transition construction exploits wideband features of a microstrip radial stub used as a virtual wideband short. The microstrip is virtually shunted to the second half of the strip line metallization, while the first half serves as a ground metallization for the microstrip line. It is necessary to transform the impedance of the input feeding microstrip line to the input impedance of the transition. Therefore, the linear microstrip taper is used as the input impedance transformer [21]. Instead of using the wideband balun, a SIW has been employed to feed an ETS antenna.

Antenna tapers is defined as exponential curves in the x-y plane. To comply with the antenna board dimensions and slot line parameters, the following exponential taper curve definition equation is used [22,23]:

$$y = C_1 e^{ax} + C_2, \quad (6)$$

where ‘a’ is the rate of opening the exponential taper, and $C_1$ and $C_2$ can be calculated by the starting and ending points of the taper P1($x_1$, $y_1$) and P2($x_2$, $y_2$):

$$C_1 = (y_2 - y_1)/(e^{ax_2} - e^{ax_1}), \quad (7)$$

$$C_2 = (y_1 e^{ax_2} - y_2 e^{ax_1})/(e^{ax_2} - e^{ax_1}). \quad (8)$$

The antenna length $L_A$, aperture width $W_A$, and substrate thickness t, all directly affect the radiation performance of the ETSA. The flare angle is distinctive to linear tapered designs and determines the antenna’s input impedance. The directivity increases as the length $L_A$ of an antenna is increased. For lengths between three and eight wavelengths, the increase is linear according to below equation:

$$D = 10 L_A / \lambda_o. \quad (9)$$

The performance of antenna depends upon the thickness *t* and the dielectric permittivity $\xi_r$ [24] as given in (10):

$$f_{substrate} = \frac{t(\sqrt{\xi_r} - 1)}{\lambda}. \quad (10)$$

For enhanced performance it should lie within a range given by:

$$0.005 \le f_{substrate} \le 0.03. \quad (11)$$

The EM surface wave in the antenna substrate is attached to the metal tapers in the antenna. Primarily, when for most taper profiles the separation is moderately small, the EM wave is closely bound to the tapers. As the taper separation increases, the EM wave becomes progressively less attached to the metal tapers. This continues until after a taper separation of a half wavelength has been reached and the EM wave begins to radiate into free space. This means that the aperture width $W_A$ must be greater than a half wavelength in any ETS antenna design in order to efficiently radiate.

The antenna designed to radiate at 60 GHz. Figures 1, 2 and 3 illustrate layout of a modeled SIW based ETS antenna without dielectric loading, rectangular dielectric loading and elliptical dielectric loading respectively by using CST Microwave Studio.

Table 1 shows the parameters of the antenna obtained using equations (1)-(11). The shape of the curvature influences the traveling wave in two main areas. First is the beginning of the taper and the second is the wide end of the taper. On both places, a reflection of the traveling wave is likely to occur. Therefore, smoother taper in the neck minimizes the reflection there [25,26]. This can be achieved with higher value of ‘a’. The beamwidth in the H-plane can be controlled through the flare in the H-plane. The beamwidth in the E-plane is determined by the flare in the E-plane that is limited. In some Mm wave applications, a wider beamwidth in the E-plane is also desired. For this purpose, a dielectric slab is placed in front of the flare of the ETS antenna. This slab serves as the dielectric guiding structure in the E-plane. In the H-plane, for an ETS antenna with maximum gain, the flare phase distribution along the H-plane is nearly uniform without the dielectric loading.

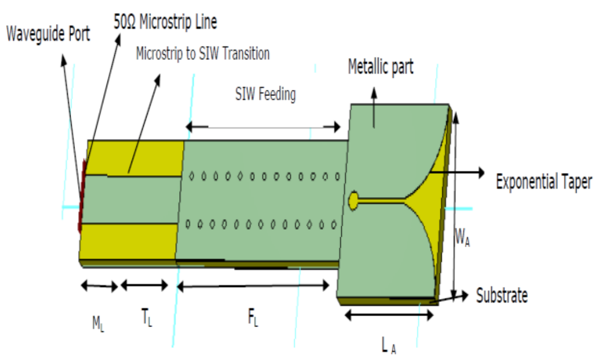



Fig. 1. ETS antenna without dielectric loading.

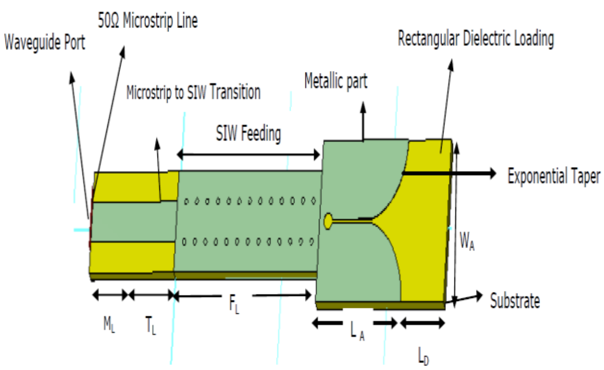



Fig. 2. ETS antenna with rectangular dielectric loading.

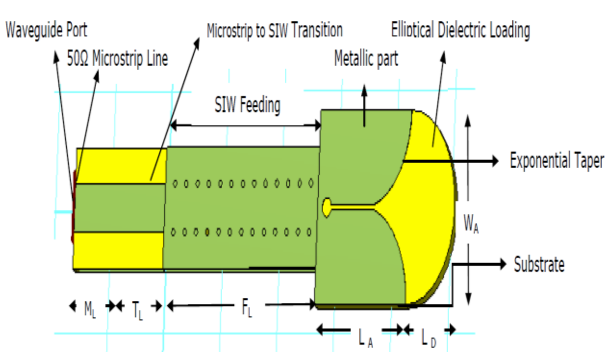



Fig. 3. ETS antenna with elliptical dielectric loading.

Table 1: Dimension of the antenna (unit: mm)

| Symbol | Value (mm) |
|---|---|
| $L_A$ | 8 |
| $W_A$ | 8 |
| $L_D$ | 4 |
| $F_L$ | 13.5 |
| $T_L$ | 5 |
| $M_L$ | 3 |

**D. Optimization of ETS antenna**

The SIW based ETS antenna with elliptical dielectric loading modeled utilizing CST Microwave Studio. Once the model has been formulated, an optimization algorithm can be used to find its best solution. The newly implemented trust region framework algorithm can work the sensitivity information to cut down optimization time dramatically. The yield analysis for complex three dimensional models is now available at virtually no additional computational rate. Trust-region methods define a region around the current iterate within which they trust the model to be an adequate representation of the objective function, and then choose the step to be the approximate minimizer of the model in this region. In effect, they choose the direction and length of the step simultaneously. If a step is not acceptable, reduce the size of the region and find a new minimizer. In general, the direction of the step changes whenever the size of the trust region is altered. According to the target of this antenna at 60 GHz, the radius of vias was modified to provide a better return loss. The parameter '*d*' was swept from 0.135 to 0.165 mm using trust region framework algorithm in CST to find the best performance of the antenna. A new trust region framework algorithm is very efficient for a direct 3D EM optimization, especially in conjunction with the sensitivity analysis [27].

**E. Simulation and measurement**

The antenna structure is simulated without dielectric loading using 3D electromagnetic software CST Microwave Studio as shown in Fig. 1, the gain is 7.2 dB, main lobe direction is 81$^{o}$, return loss is -12.07 dB, VSWR is 1.66 and side lobe level is -4.0 dB. A rectangle and elliptical dielectric loading is placed in front of the antenna flare works as dielectric guiding structure to increase the gain, reduce the side lobe level of the antenna and respective structures are shown in Figs. 2 and 3. Figure 4 shows that the elliptical dielectric loading gives higher gain compared to the rectangle dielectric loading with the same length.

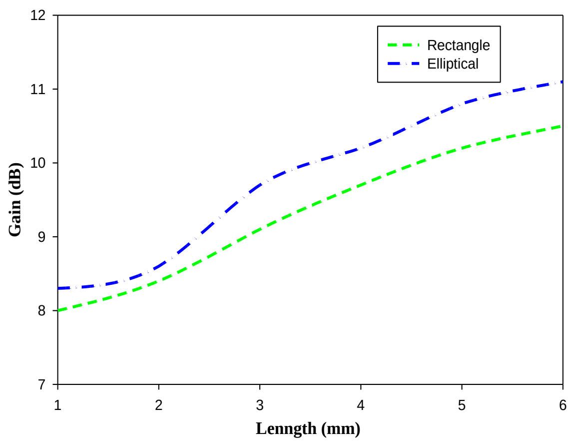



Fig. 4. Gain versus length of the dielectric loading.

When the length of dielectric loading is 4 mm, gain of rectangle and elliptical is 8.3 dB and 10.2 dB respectively. Further, the rectangle and elliptical dielectric loading are explored. Table 2 shows the performance comparison of the dielectric loading at 60 GHz. The dielectric loaded antenna was suggested in [28], which are useful in high gain applications. However, in the dielectric loaded antenna using SIW technology provides slightly higher gain with wider main lobe directions at 60 GHz.

Table 2: Performance comparison of the dielectric loading at 60 GHz

| Dielectric Loading | Gain (dB) | Main Lobe (degree) | $S_{11}$ (dB) | VSWR | Side Lobe (dB) |
|---|---|---|---|---|---|
| Without | 7.2 | 80 | -12.07 | 1.66 | -4.0 |
| Rectangle | 8.3 | 82 | -11.43 | 1.73 | -3.8 |
| Elliptical | 10.2 | 84 | -12.23 | 1.64 | -6.2 |

The simulated results of 3D radiation pattern, $S_{11}$ parameter, and VSWR for the antenna with elliptical dielectric loading is shown in Figs. 5, 6 and 7. Compared with elliptical dielectric loaded antenna, the gain of the antenna without dielectric loading is increased by 3.0 dB, $S_{11}$ parameter has decreased by -0.16 dB and main lobe direction is increased by $4^{o}$ with less side lobe level.

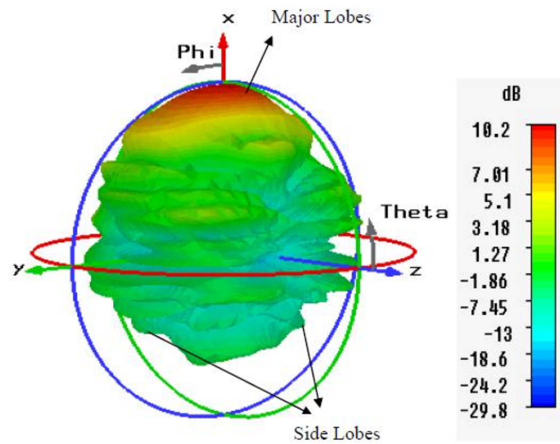



Fig. 5. Simulated 3D radiation pattern of antenna with elliptical dielectric loading.

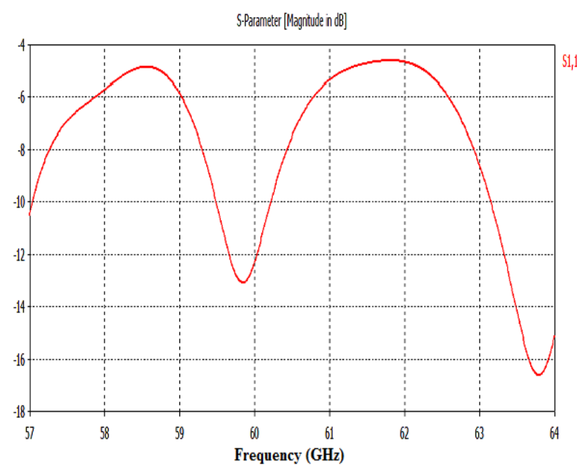



Fig. 6. Simulated $S_{11}$ parameter of antenna with elliptical dielectric loading.

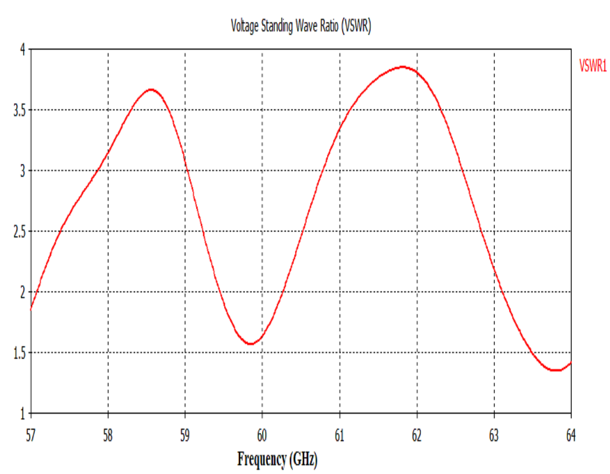



Fig. 7. Simulated VSWR of antenna with elliptical dielectric loading.

From these results it is seen that elliptical dielectric loading with the antenna gives higher gain with marginally broader main lobe direction at 60 GHz. The ETS antenna provides high gain and main lobe direction depending on the length dielectric loading.

Figures 8, 9 and 10 prove the validation of the designed elliptically dielectric loaded antenna. A slight difference in the two simulated values is because of the two different numerical methods employed in CST and HFSS. The CST employs FDTD (Finite Difference Time Domain) and HFSS employs FEM (Finite Element Method).

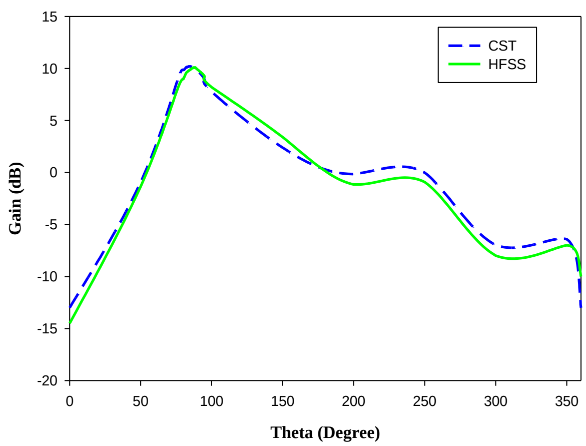



Fig. 8. Simulated gain comparison between CST and HFSS for antenna with elliptical dielectric loading.

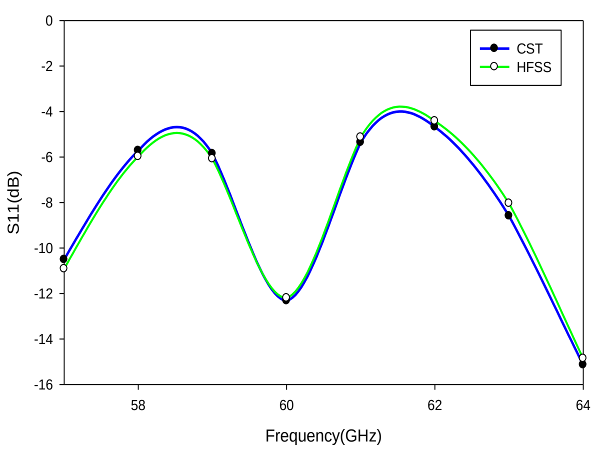



Fig. 9. Simulated $S_{11}$ parameter comparison between CST and HFSS for antenna with elliptical dielectric loading.

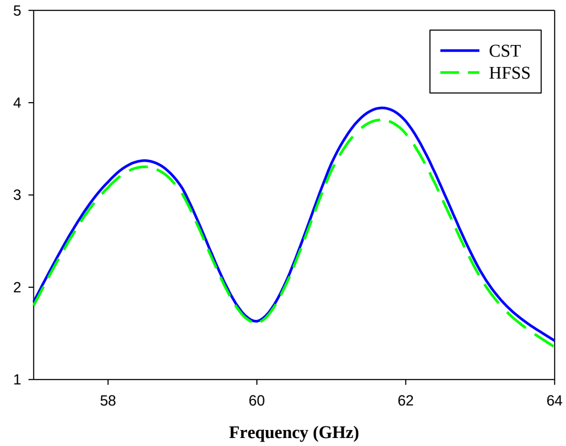



Fig. 10. Simulated VSWR comparison between CST and HFSS for antenna with elliptical dielectric loading.

The performance comparison of antenna with elliptical dielectric loading using 3D electromagnetic software CST and comparisons with HFSS validate the design procedure based on antenna gain, $S_{11}$ and VSWR. It is perceived that there is good agreement in the simulated results between the gain, $S_{11}$ and VSWR.

A slight difference in the two simulated values is basically because of the two different numerical methods employed in CST and HFSS. Further, the SIW based ETS antenna efficiency with elliptical dielectric loading is also analyzed and found that the radiation efficiency is 96.84% and total efficiency is 91.05%.

The antenna without dielectric loading and elliptical dielectric loading with optimized dimensions are fabricated on Rogers RT Duroid 5880 high frequency substrate with a thickness of 0.787 mm, relative permittivity of 2.2, relative permeability of 1 and loss tangent of 0.0009. The top side of the antenna having radiating flare and other side is ground plane. The photograph of fabricated antenna without dielectric loading and elliptical dielectric loaded ETS antenna is shown in Figs. 11 and 12.

The measurements were carried out in Sub Millimeter Wave Laboratory (SMWL) at RCI, Hyderabad. To measure the return loss of the antenna, Vector Network Analyzer (AB Millimeter Wave's-MVNA-8-350) is calibrated in single port and the return loss is tested at 60 GHz. To record the gain and radiation pattern, the VNA is calibrated in two port mode. The separation between the antennas is maintained to be greater than the far field requirement. The elliptical dielectric loaded antenna simulated and measured results of $S_{11}$ parameter, gain and radiation pattern are shown in Figs. 13, 14 and 15. A slight difference is observed between the measured value and simulated value. The difference between the measured and simulated $S_{11}$ of the antenna is caused by the microstrip to SIW transition. But the results from simulation and measurement are in good agreement.

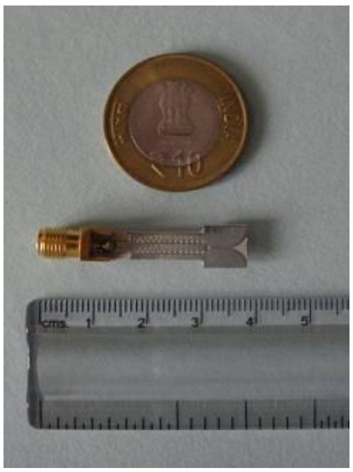


Fig. 11. SIW based ETS antenna without dielectric loading.

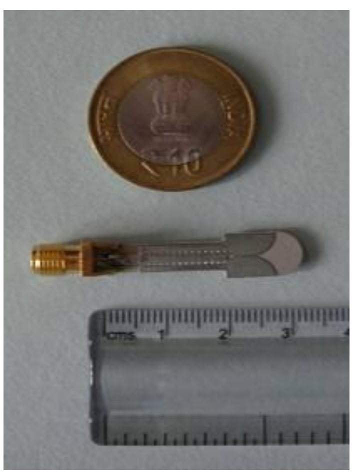


Fig. 12. SIW based ETS antenna with elliptical dielectric loading.

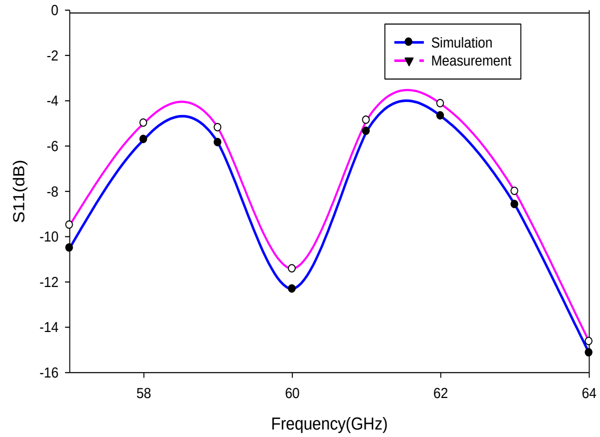



Fig. 13. Measured and simulated $S_{11}$ parameter for antenna with elliptical dielectric loading.

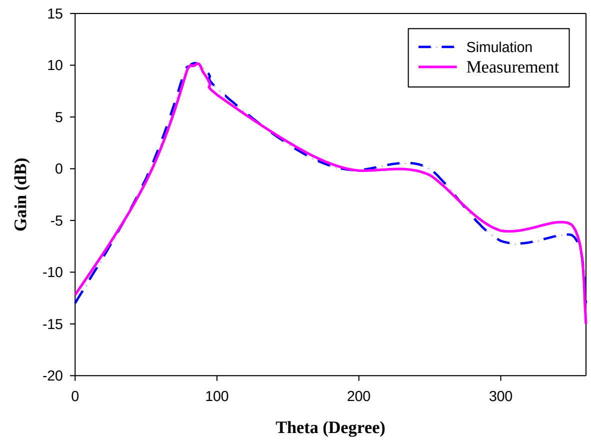



Fig. 14. Measured and simulated gain for antenna with elliptical dielectric loading.

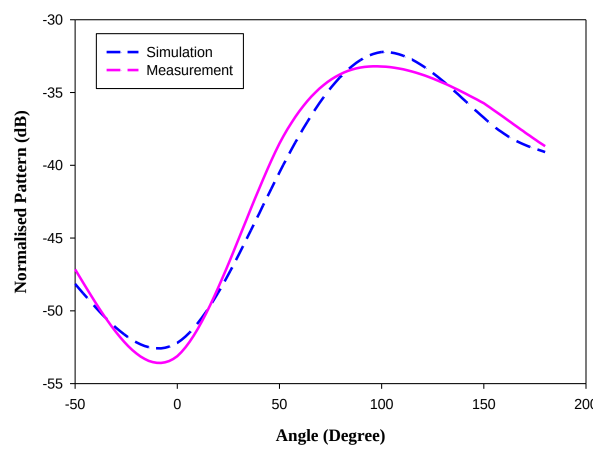
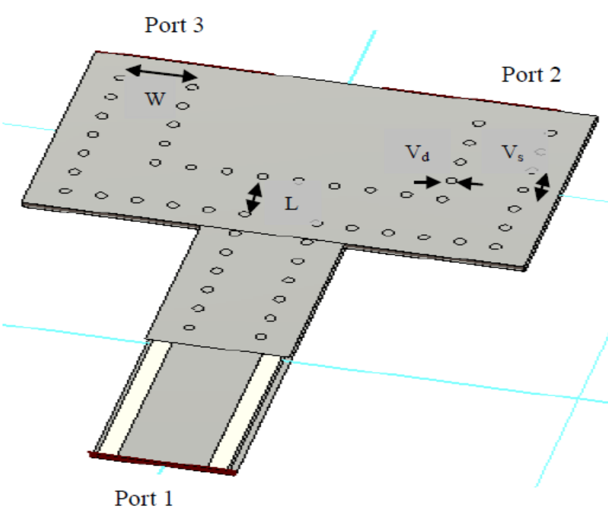



Fig. 15. Measured and simulated radiation pattern for antenna with elliptical dielectric loading.

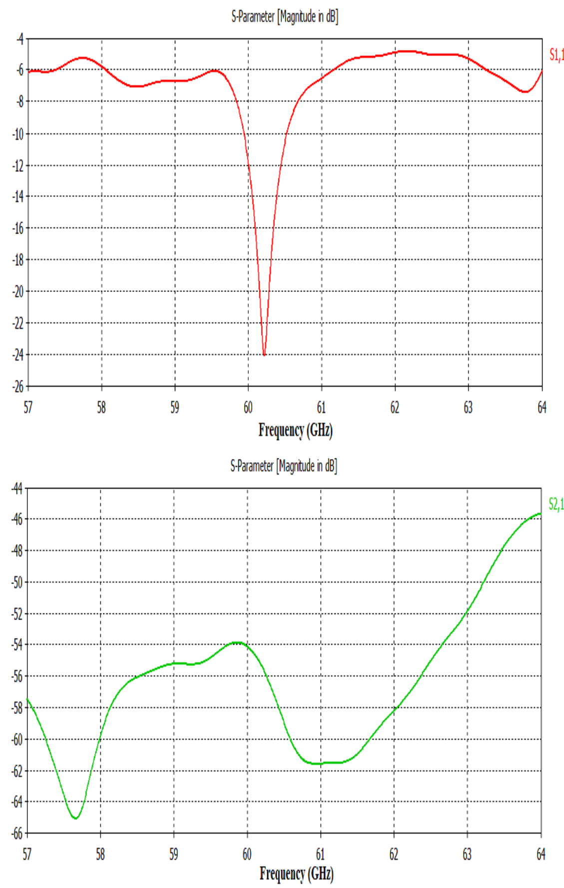
## III. 1×2 PLANAR DIELECTRIC LOADED ETS ANTENNA ARRAY

A new Y-junction two way power divider is proposed to feed ETS array antenna. In the SIW Y-junction two way power divider, a metallic via as an inductive post, which is short circuited between two wide walls of the waveguide, is set to increase reflectance. Based on conventional waveguide transmission theory, the inductive post is equivalent to a parallel susceptance. Optimization of the inductive matching post diameter and position was performed in order to achieve a low return loss at 60 GHz. The Simulated $S_{11}$ and $S_{21}$ plots of the Y-junction two way power divider are shown in Fig. 16.

The ETS antenna array structure is fabricated in a single layer structure using Rogers RT Duroid 5880 with a thickness of 0.787 mm. Figure 17 shows the photograph of the fabricated elliptically dielectric loaded ETS antenna array. The simulated and measured $S_{11}$ and gain of the antenna array are shown in Figs. 18 and 19. When compare simulated and measured $S_{11}$ parameter of the antenna array, the simulation results show that much of the loss is caused by the dielectric loss effect at the feed network. The bandwidth of the antenna array covers the entire V-band, while the gain of the antenna is retained nearly constant within a wide bandwidth of the antenna array. The apparent difference between the simulated and measured gain might be due to the calibration related tolerance range of the antenna reference in the anechoic chamber.




(a)




(b)

Fig. 16. (a) Geometry of power divider, and (b) simulated $S_{11}$ and $S_{21}$ of the Y-junction power divider; W=2 mm, L=2 mm, $V_d$=0.3 mm, and $V_s$=0.7 mm.

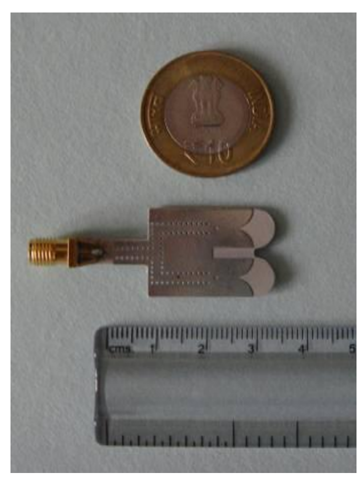


Fig. 17. Photograph of the fabricated ETS antenna array with elliptical dielectric loading.

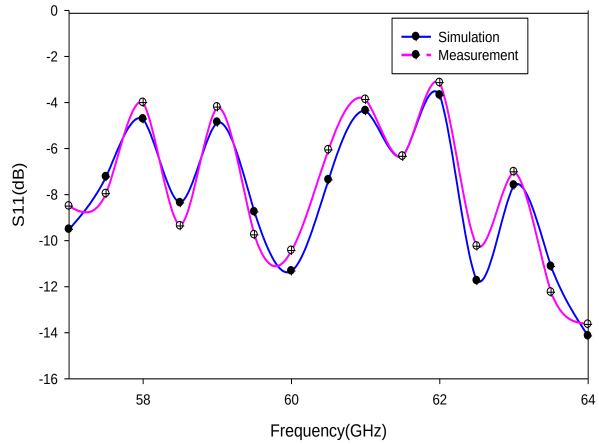



Fig. 18. Measured and simulated $S_{11}$ Parameter comparison of elliptical dielectric loaded ETS antenna array.

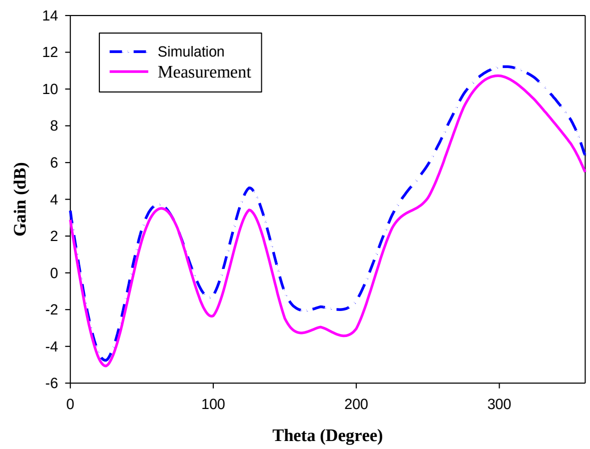



Fig. 19. Measured and simulated gain comparison of elliptical dielectric loaded ETS antenna array.

## IV. CONCLUSION

The use of Mm wave techniques offers many advantages for short-range wireless communication systems compared to radio techniques at lower frequencies. Besides, a new adaptation between microstrip line and SIW is proposed, which is predominantly useful in V-band wireless communication applications. The SIW technology with emulated waveguides can be utilized to eliminate the unwanted radiations from feed, particularly when compared to similar structures built using microstrip lines. A novel configuration of SIW based ETS antenna with dielectric loading is designed, fabricated and measured. The proposed antenna measured gain of the single element antenna is 10.2 dB, return loss is -12.23 dB, VSWR is 1.64 and main lobe direction is 84 degree at 60 GHz. While the gain of the 1×2 antenna array is 11.2 dB, return loss is -7.36 dB, VSWR is 1.89 and main lobe direction is 120 degree at 60 GHz. It is also observed that with proper selection of dielectric structures and its parameters, marginally more gain with broader main lobe direction for the given antenna can be achieved. The reasonable agreement between the simulated and measured results shows that the designed antenna with elliptical dielectric loading is useful for the variety of wireless applications at Mm wave frequencies.

## ACKNOWLEDGEMENT

Authors are very much grateful to the DRDO, Government of India for providing financial patronage in executing this research work.

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