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DIELECTRIC LOADED EXPONENTIALLY TAPERED SLOT ANTENNA UTILIZING SUBSTRATE INTEGRATED WAVEGUIDE TECHNOLOGY FOR MILLIMETER WAVE APPLICATIONS

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Abstract—A novel compact dielectric loaded Exponentially Tapered Slot (ETS) antenna using Substrate Integrated Waveguide (SIW) technology is presented in this paper for Millimeter (Mm) wave wireless communication applications. The dielectric loaded ETS antenna and compact SIW feed are fabricated on a single substrate. The compact SIW feeding structure results in a considerable reduction in size and eliminates the unwanted radiations from feed. The proposed antenna is designed, fabricated, and investigated at 60 GHz. Furthermore, the proposed antenna design is simulated using electromagnetic software CST Microwave Studio and the comparison is made with Ansys HFSS to validate the design procedure. The measurement results are compared with simulated results.

1. 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 factors that mark 60 GHz

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technology gaining significant interest recently is due to the huge unrestricted bandwidth (up to 7 GHz) available worldwide [3, 4]. 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 applications due to the requirements for low cost, small size, and light weight. 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. The antenna, when integrated into consumer devices, should also have the benefits of small size and low production cost [6].

The conventional waveguide technology is still the mainstream for designing high performance Mm wave systems. But their relatively high cost and difficult integration prevent them from being used in low cost, high volume applications. In addition, the traditional waveguide technique cannot be used to reduce the weight and volume [7]. 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 negotiation the low side-lobe level of the slot antenna and increases cross polarization [8–10].

Therefore, this work targets on addressing challenges in designing dielectric loaded ETS antenna using SIW technology for the realization of Mm wave based 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 2 deals with step by step design procedure for the ETS antenna. Section 3 deals with simulation and measurement results obtained in our present work and discussions. Finally, Section 4 gives conclusions.

2. ANTENNA DESIGN

The ETS antenna is also known as flared notch or Vivaldi antenna and among one of the most promising antennas satisfying all requirements described in the technical challenges [11]. It is fundamentally a planar traveling wave antenna with end fire radiation. 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].

2.1. Replacing Waveguides with Equivalent SIW

At Mm wave frequencies waveguide devices are preferred; though their manufacturing process is challenging. 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 condition are required.

The metalized via hole diameter is

$$d < \lambda_g/2 \tag{1}$$

where λ_g is guided wave length.

The spacing between the via holes is

$$P < 2d \tag{2}$$

The Physical width of SIW is

$$a = a_d + \left(d^2/(0.95p)\right) \tag{3}$$

where a_d is dimension of the waveguide.

The SIW structure is shown in Figure 1 where 'a' and 'd' are represent the physical width of the SIW and metalized via hole's diameter, respectively, and '**p**' is the space between the via holes. The calculated values of the physical width of SIW is 2.0 mm, metalized via hole's diameter is 0.30 mm, and space between the via holes is 1.0 mm.

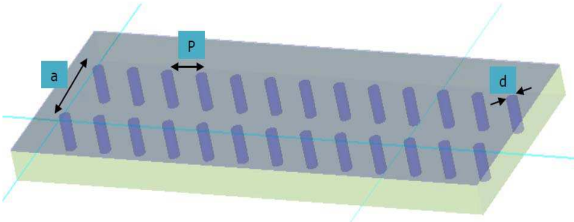

Figure 1. SIW structure.

2.2. 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 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. The microstrip to SIW transition is shown in Figure 2.

The simulation results for its reflection and transmission coefficients are shown in Figure 3(a) and Figure 3(b). The reflection and transmission coefficient values at 60 GHz are −4.47 dB and

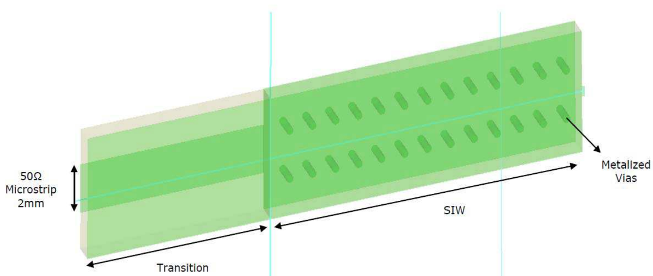

Figure 2. Microstrip to SIW transition.

−16.66 dB, respectively. From this result, the maximum power is transferred from microstrip to SIW and achieved good impedance match between them with the suppression of higher order modes.

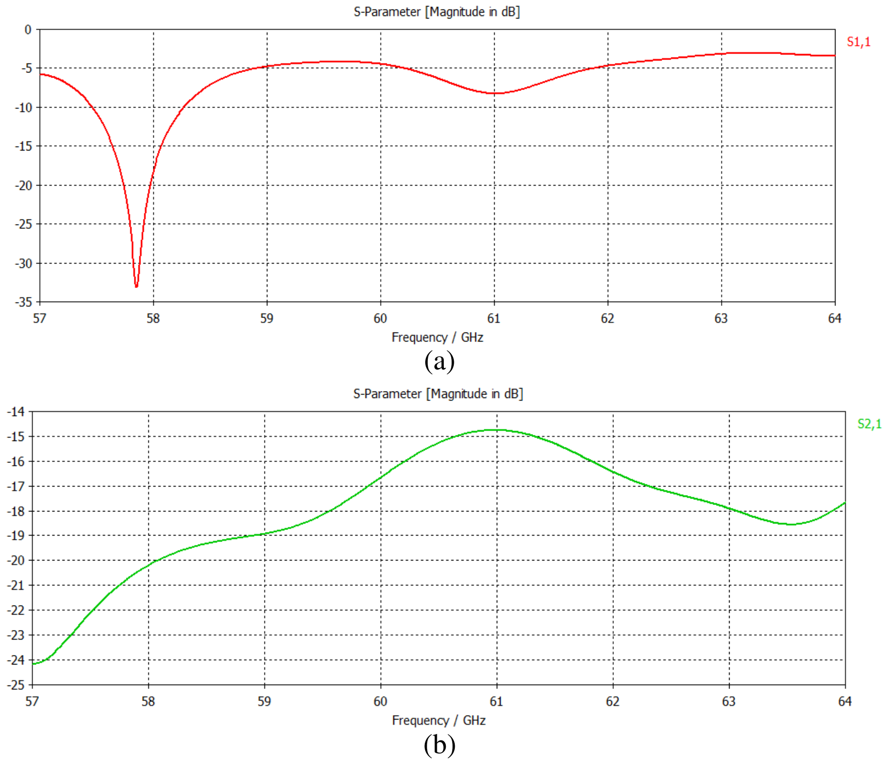

Figure 3. (a) Magnitude of reflection coefficient of the microstrip to SIW transition. (b) Magnitude of transmission coefficient of the microstrip to SIW transition.

2.3. Modeling ETS 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, following exponential taper curve definition equation is used [22, 23],

$$y = C_1 e^{ax} + C_2 \tag{4}$$

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 $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$,

$$C_1 = (y_2 - y_1) / \left(e^{ax_2} - e^{ax_1}\right) \tag{5}$$

$$C_2 = \left(y_1 e^{ax_2} - y_2 e^{ax_1}\right) / \left(e^{ax_2} - e^{ax_1}\right) \tag{6}$$

The antenna designed to radiate at 60 GHz. Figure 4, Figure 5 and Figure 6 illustrate the 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 above equations. The shape of the curvature influences the traveling wave in

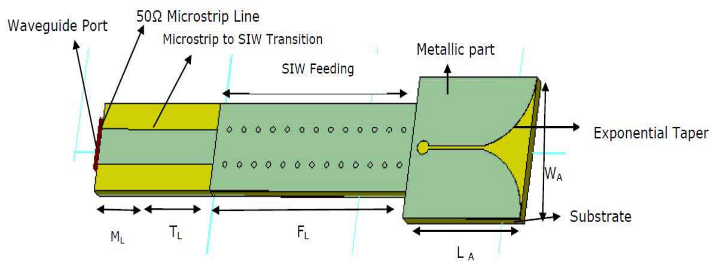

Figure 4. SIW based ETS antenna without dielectric loading.

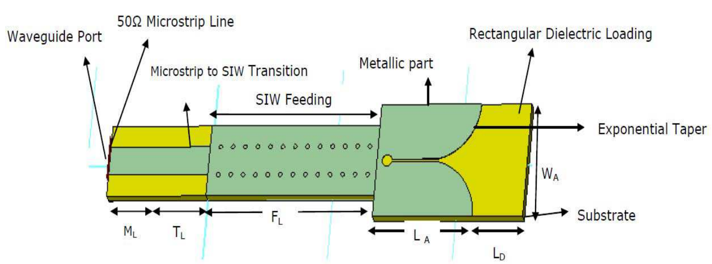

Figure 5. SIW based ETS antenna with rectangular dielectric loading.

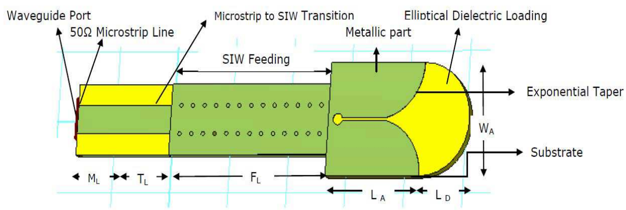

Figure 6. SIW based ETS antenna with elliptical dielectric loading.

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 [24, 25]. 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.

Table 1. Parameters of antenna.

Parameters	L_A	W_A	L_D	F_L	T_L	M_L
Value (mm)	8	8	4	13.5	5	3

2.4. Design 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. 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 [26].

3. SIMULATION AND MEASUREMENT RESULTS DISCUSSIONS

The antenna structure is simulated without dielectric loading using 3D electromagnetic software CST Microwave Studio as shown in Figure 4, the gain is 7.2 dB, main lobe direction is 81°, 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 and respective structures are shown in Figure 5 and Figure 6. The length of the dielectric loading versus gains of the antenna is shown in Figure 7.

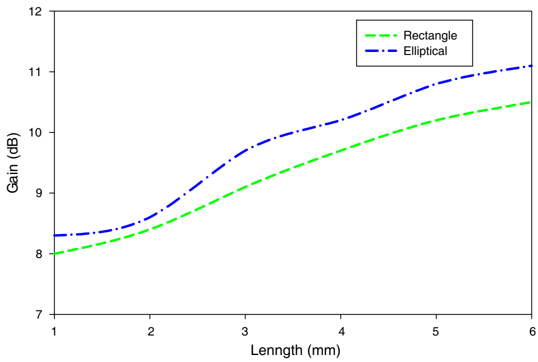

Figure 7. Gain versus the length of the loaded dielectric.

From this figure it is seen that the gain increases with the increase of dielectric loading length. When the length of dielectric loading is 4 mm, the gain of rectangle and elliptical is 8.3 dB and 10.2 dB respectively. Further, the rectangle and elliptical dielectric loading are investigated. The Table 2 shows the performance comparison of the dielectric loading at 60 GHz. The dielectric loaded antenna was suggested in [27, 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.

The simulated results of 3D radiation pattern, S_{11} parameter, and VSWR for the antenna with elliptical dielectric loading is shown in Figure 8, Figure 9, and Figure 10.

Compared with elliptical dielectric loaded antenna, the gain of the antenna without dielectric loading is increased by 3.0 dB, S_{11} parameter decreased by −0.16 dB, and main lobe direction increased by 4 degree with less side lobe level. 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

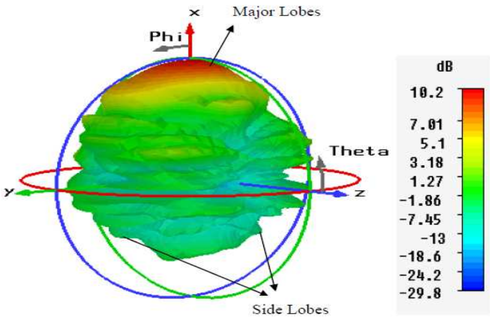

Figure 8. Simulated 3D radiation pattern of antenna with elliptical dielectric loading.

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

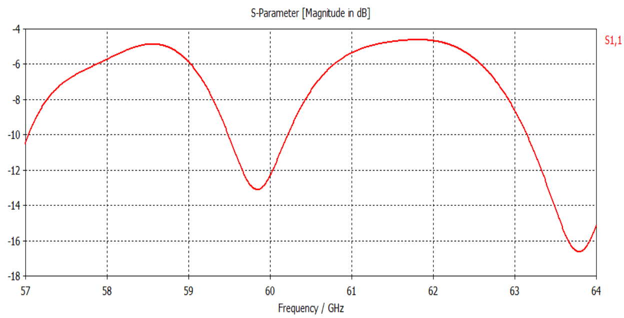

Figure 9. Simulated S_{11} parameter of antenna with elliptical dielectric loading.

length dielectric loading. Figure 11, Figure 12 and Figure 13 prove the validation of the designed elliptically dielectric loaded antenna.

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

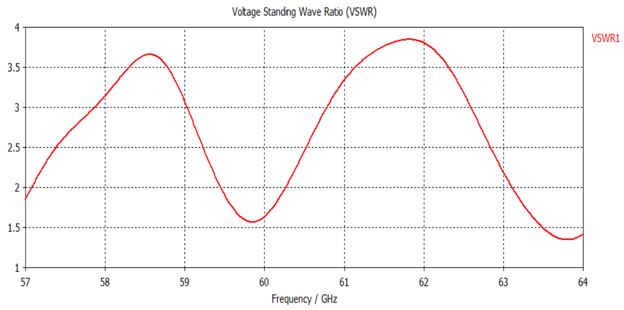

Figure 10. Simulated VSWR of antenna with elliptical dielectric loading.

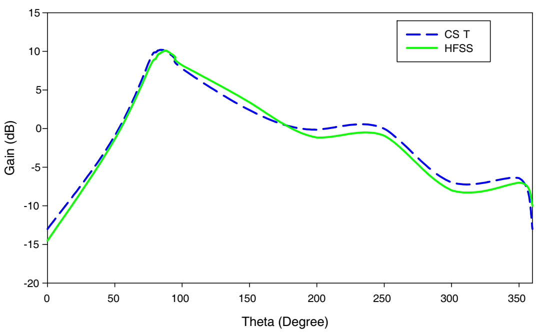

Figure 11. Simulated gain comparison between CST and HFSS for antenna with elliptical dielectric loading.

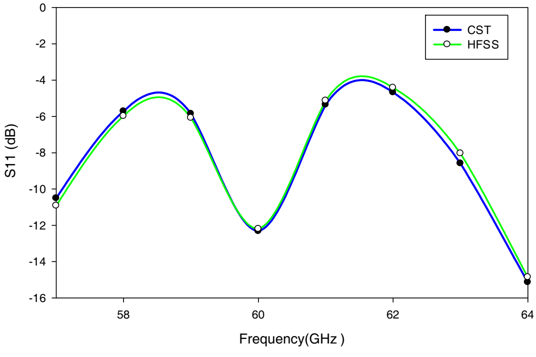

Figure 12. Simulated S_{11} parameter comparison between CST and HFSS for antenna with elliptical dielectric loading.

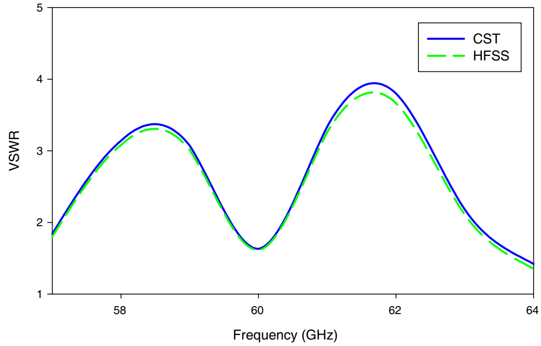

Figure 13. Simulated VSWR comparison between CST and HFSS for antenna with elliptical dielectric loading.

VSWR. It is observed that there is good agreement of the gain, S_{11} and VSWR between the simulated results. 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 91.05%.

The antennas 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

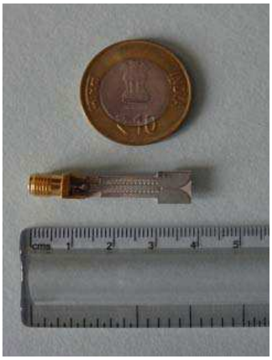

Figure 14. SIW based ETS antenna without dielectric loading.

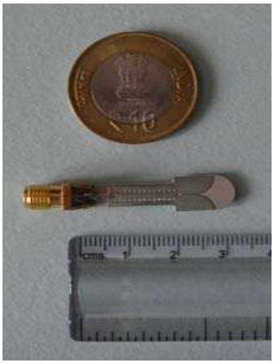

Figure 15. SIW based ETS antenna with elliptical dielectric loading.

0.0009. The top side of the antenna has radiating flare, and the other side is ground plane. Photographs of fabricated antenna without dielectric loading and elliptical dielectric loaded ETS antenna are shown in Figure 14 and Figure 15.

The simulated and measured results of S_{11} parameter, gain and radiation pattern of elliptical dielectric loaded antenna are shown in Figure 16, Figure 17 and Figure 18. A slight difference is observed between the measured and simulated values. The difference between the measured and simulated S_{11} of the antenna is caused by the microstrip to SIW transition. But basically the results from simulation and measurement are in good agreement.

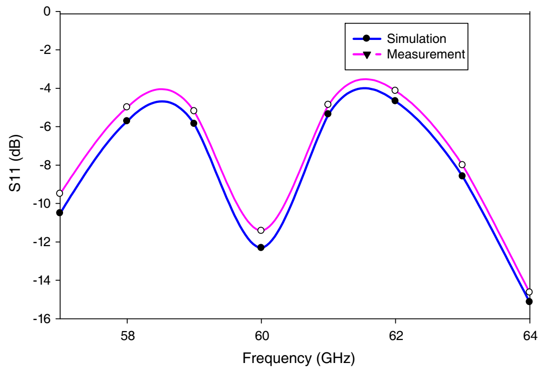

Figure 16. Measured and simulated S_{11} parameter for antenna with elliptical dielectric loading.

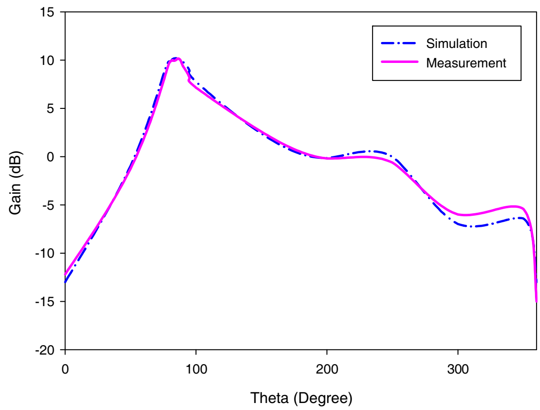

Figure 17. Measured and simulated gain for antenna with elliptical dielectric loading.

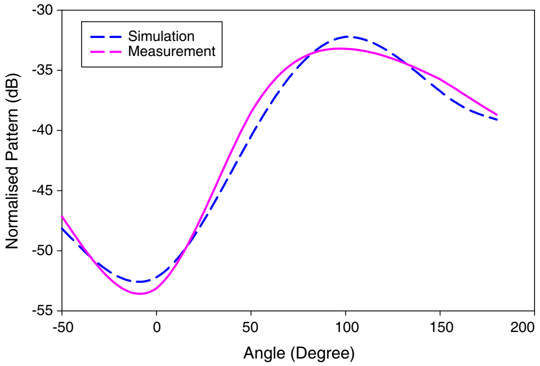

Figure 18. Measured and simulated radiation pattern for antenna with elliptical dielectric loading.

4. CONCLUSIONS

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 Mm wave wireless communication applications where the waveguide width is small. 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 proposed, designed, fabricated and measured. The proposed antenna results show that the gain is 10.2 dB, return loss −12.23 dB, VSWR 1.64, and main lobe direction 84 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 Mm wave wireless applications at 60 GHz.

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