Investigations on Corrugation Issues in SIW based Antipodal Linear Tapered Slot Antenna for Wireless Networks at 60 GHz

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Abstract ─ In recent days, substrate integrated waveguide (SIW) technology is attracting a lot of interest in the development of millimeter-wave (MmW) based circuits due to its inherent advantages. Tapered slot antenna (TSA) with antipodal geometry is used to surmount the impedance matching constraint and to enhance electrical performance including gain, side lobes levels, and main beam pattern. This paper focuses on the design of antipodal linear tapered slot antenna (ALTSA) using SIW technique at 60 GHz for wireless local area network (WLAN) and wireless personal area network (WPAN) applications. The size of the proposed antenna is very compact (43.29 mm × 9.93 mm × 0.381 mm) and the substrate used is RT/ Duroid 5880. Corrugations have been investigated on both the edges to improve antenna gain, front-to-back ratio, and radiation patterns. Numerical simulations are performed using 3D-EM tools, high frequency structure simulator (HFSS) and CST microwave studio (CST MWS). The obtained results reveal that when corrugation is introduced in the antenna there is a significant improvement of 3 dB in gain, respectively. This study has been reported earlier in other frequency bands but rarely any literature has been reported of such development at 60 GHz.

Index Terms - ALTSA, corrugation, CST MWS, front to back ratio, HFSS, MmW, and SIW.

I. INTRODUCTION

The evolution of new generation wireless communication systems is highly dependent on the deployment of millimeter-wave (MmW) based radio technologies. With the available bandwidth of 7 GHz, the unlicensed 60 GHz band (57 GHz – 64 GHz) is of great interest for the new generation wireless local area network (WLAN) and wireless personal area network (WPAN), which will allow multimedia downloads at ultra-high speed with data rate of 1 Gbps [1]. The propagation characteristics of the 60 GHz band are characterized by high levels of oxygen absorption and rain attenuation. This limits the range of communication systems using this band. However, it will allow a high level of frequency re-use and therefore makes it attractive for a variety of short-range wireless communication applications [2].

Recently, there has been a great deal of interest in antennas for millimeter wave applications. Tapered slot antenna (TSA) has been widely used to take advantage of high gain, low side-lobe level characteristics, ease of implementation, and broadband characteristics [3]. TSA is a popular choice for applications such as ground penetration surveillance, medical imaging security, road surface scanning [4], and numerous wireless communication applications [5]. Many of the new radar systems reaching the fleet over the next few years will use frequency or phase-sensitive antennas and antennas that can electronically scan the azimuth as well as elevation. TSA can be a good candidate for such antenna systems.

Many designs for taper have been proposed and developed by researchers all over the world [6-9]. One such type of antenna is antipodal linear tapered slot antenna (ALTSA). Researchers around the globe have given high attention to ALTSA

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for its salient performances, which includes narrow beamwidth, high element gain, and wide bandwidth [10]. It has been reported that a reduced antenna width is associated with degradation in radiation pattern, which is a significant problem for the design of compact TSAs [11]. ALTSA has been investigated widely in academic and industry focusing the ultra-wideband (UWB) and very high frequency (VHF) range [8-12], hardly any work is present in the extremely high frequency (EHF) range. Substrate integrated waveguide (SIW) technology has been proposed for MmW circuits and investigated by researchers from various parts of the world in the past 15 years [13]. In [14], a simple technique for propagation characteristics for SIW has been studied and proposed. Waveguides are basically a device for transporting electromagnetic energy from one region to another. In this study, it is composed of two rows of metalized via-holes, which are connected with two metal plates on the top and bottom sides. The mechanism on which SIW operates is very much similar to a rectangular waveguide. SIW inherits most of the advantages of the conventional metallic waveguides like complete shielding, low loss, high quality factor and high power-handling capability [15].

TSA with corrugation structure have been used to reduce tapered slot antenna width without any significant degradation in the radiation pattern [11-13]. In applications such as MmW radar and communication systems using directional antenna, it is preferred that the antenna should have a high front to back ratio (F/B) and directivity. Corrugation has been proven successful in TSA structures for F/B ratio, gain, and beamwidth improvement [16].

Selection of simulation tool can be made based upon the simulation data uncertainties, simulation time, model design limitation, and hardware requirement. Due to complex MmW antenna design, computational electromagnetic (CEM) field model is inevitable. CEM models the interaction of magnetic and electric field with physical objects and their environment to find the numerical approximation of Maxwell's equation. High frequency structure simulator (HFSS) based on finite element method (FEM) and CST microwave studio (CST MWS) based on finite difference time domain method (FDTD) are specialized software that solve the subset of Maxwell's equations [17].

Thus, this paper focuses on the effect of corrugation in SIW fed ALTSA, designed for WLAN and WPAN applications at 60 GHz. Comparison of results using electromagnetic solvers HFSS and CST MWS have been made for accuracy and simulation time. Section II deals with design, simulation and measured results are presented in section III, followed by conclusions in section IV.

II. ALTSA ARCHITECTURE AND DESIGN

The ALTSA is designed on 0.381 mm RT/Duroid 5880 substrate with dielectric constant ε_r = 2.2 and tan δ = 0.0004. Figure 1 depicts a configuration of the proposed ALTSA with the SIW feeding, which consists of two flares. On one side, the input track is flared to produce half of the linear TSA and then on the other side of substrate the ground plane is flared in the opposite direction. One of the advantages of the antipodal geometry is that it does not need to layout any stubs on the printed circuit board (PCB) to achieve impedance matching.

The input impedance of the ALTSA is high and that of the SIW is low, which causes a mismatch problem. To solve this problem, the flares are designed in a way that they overlap each other. The SIW feeding structure has two periodic rows of metalized cylindrical vias connecting the upper and lower flares of ALTSA, which acts as dielectric filled rectangular waveguide. The center frequency of proposed antenna is 60 GHz and length of tapered slot line is 4.5 λ. Table 1 provides various parameters of SIW based ALTSA.

The performance of ALTSA depends upon the thickness t and the dielectric permittivity ε_r [18] as given in equation (1),

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

For better performance it should lie within a range given by equation (2),

$$0.005 \le f_{substrate} \le 0.03 . \quad (2)$$

When the distance between the via-holes are electrically small (< 0.2 λ), SIW can be replaced by rectangular waveguide [13]. SIW can be commonly used as transmission line, which is similar to rectangular waveguide in terms of mode and cut-off frequency properties.

The cut-off frequency is a frequency at which all lower frequencies are attenuated by the waveguide and above the cut-off frequency all higher frequencies propagate within the waveguide. The cut-off frequency depends on the shape and size of the cross section of waveguide. The larger the waveguide, the lower the cut-off frequency of antenna. The effective width of the SIW structure W_s [18] is calculated based on equation (3),

$$W_s = W_{SIW} - 1.08\frac{D}{P} + 0.1\frac{D}{W_{SIW}} \quad (3)$$

where, D is the diameter of the via, P is the space between the vias and W_{SIW} is the SIW width. The cut-off frequency is given by equation (4)

$$f_{c,mn} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}, \quad (4)$$

where, c is the speed of light and ε_r is the relative permittivity.

Table 1: Dimension of ALTSA.

Parameter	**Dielectric Substrate: RT/duriod (ε_r =2.20, h=0.381mm)**	
	Symbo l	**Value mm**
ALTSA Length	L1	44.61
SIW Length	L2	22.36
Taper Length	L3	4.93
Microstrip Line Length	L4	1.2
ALTSA Width	W1	9.93
Overlapping Area Width	W2	1.8
Taper Width	W3	3.12
Microstrip Line Width	W4	0.8
SIW Width	W_{SIW}	6.2
Diameter of Vias	D	0.6
Pitch of Vias	P	0.90

Both D and P should be measured precisely to ensure loss free radiation between the metallic vias because of diffraction. Following equations (5) and (6) allows us to do the same [18],

$$D \leq \frac{\lambda_g}{5}, \quad (5)$$

where, λ_g is the guided wavelength and,

$$P \leq 2D. \quad (6)$$

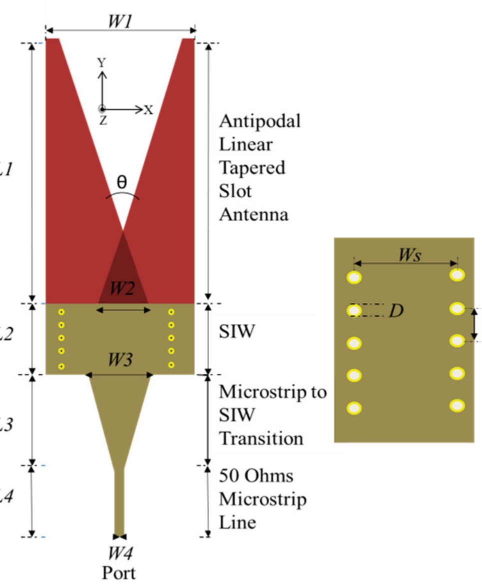


Fig. 1. Proposed ALTSA design.

The size of the excitation port also plays a vital role in performance of antenna. There are several rules for determining the port size. The port peripheries should touch the ground plane of the transmission line and the width of the port should be wide enough to avoid the adjacency of the signal strip and port periphery [15]. For matching the low characteristic impedance of SIW a linearly tapered microstrip is used. The microstrip is designed based upon the equations given in [19].

A. Corrugation structures

Further, outer rectangular corrugation structures are applied to the ALTSA design. On small antennas, undesired surface currents on the outlines lead to near field radiation and thereby lead to reduced gain as well as high side lobe levels [11, 12]. For antenna pattern improvement the concept of corrugation structures have been studied. Corrugations have been proven successful in tapered slot antenna structures for improvement of gain and front to back ratio [16]. Corrugations are well known in the design of horn antennas in order to suppress higher modes. Therefore, they guarantee the polarization pureness of the antenna [18].

B. Outer rectangular corrugation

Figure 2 shows the ALTSA with outer rectangular corrugation structure. The length and the width are selected to be 1.25 mm (RC_l) and 0.5 mm (RC_W), respectively with 0.5 mm spacing (RC_S) between the rectangular corrugations, made on the outer edges of the ALTSA.

III. SIMULATIONS AND RESULTS

The HFSS and CST MWS are the simulation softwares (SS) used to simulate the ALTSA at 60 GHz. In the current implementation, the antenna is first designed and simulated using HFSS. For the validation of simulated results obtained, the antenna with same dimension is designed and simulated using CST MWS. HFSS simulation offers a reliable mesh adaptation algorithm and several simulation coverage criteria. For CST simulation, mesh definition has a significant influence on representation of areas that includes ports.

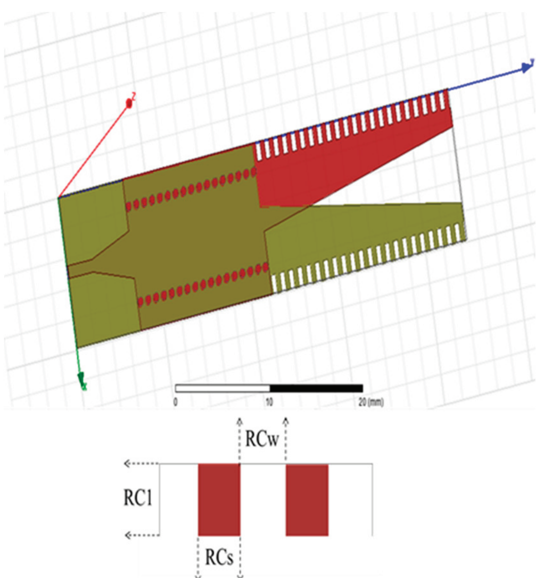
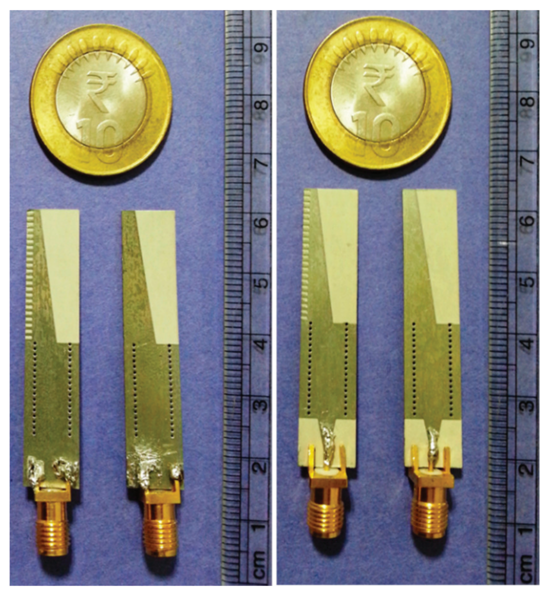


Fig. 2. ALTSA with outer corrugation.

In these areas, mesh step is decreased until the relevant mesh vertices are accurately positioned as start and end points for integration across ports. Due to ALTSA geometry and higher frequency, it is observed that a high number of meshes are needed to accurately model the structure and simulate the electromagnetic response. The total computing time is about 30 minutes for both the 3D-EM tools and the computing platform is Intel Core i7 with 24 GB random access memory (RAM). The simulation result indicates the return loss, distribution of current, and gain of ALTSA.

Figure 3 shows the plain and corrugated ALTSA fabricated on an RT/Duroid 5880 dielectric substrate with thickness of 0.381 mm. The simulated return loss shown in Figs. 4 and 5 illustrate that the return loss for corrugated ALTSA is good at 60 GHz band and the bandwidth is approximately 3 GHz, which is around 38.5 % of the total spectrum under observation in both the SS. E-plane is the plane containing the electric field vector and the direction of maximum radiation. The electric field or "E" plane determines the polarization or orientation of the radio wave.



(a) (b)

Fig. 3. Photographs of plain ALTSA and ALTSA with corrugation, (a) upper side and (b) lower side.

For a vertically-polarized antenna, the E-plane usually coincides with the vertical/elevation plane. For a horizontally-polarized antenna, the E-Plane usually coincides with the horizontal/azimuth plane. E- and H-planes should be 90 degree apart. The magnetizing field or "H" plane lies at a right angle to the "E" plane. For a vertically polarized antenna, the H-plane usually coincides with the horizontal/azimuth plane. For a horizontally-polarized antenna, the H-plane usually coincides with the vertical/elevation plane. This is important, since MmW applications need a good stability of radiation pattern and directivity.

In an antenna pattern, the half power beam width is the angle between the half-power (-3 dB) points of the main lobe, when referenced to the peak effective radiated power of the main lobe. The 3dB beamwidth for plain ALTSA and ALTSA with outer rectangular corrugation is within the range of 32° ≈ 38°, while the SLL is between -4 dB and -9 dB in both the SS.

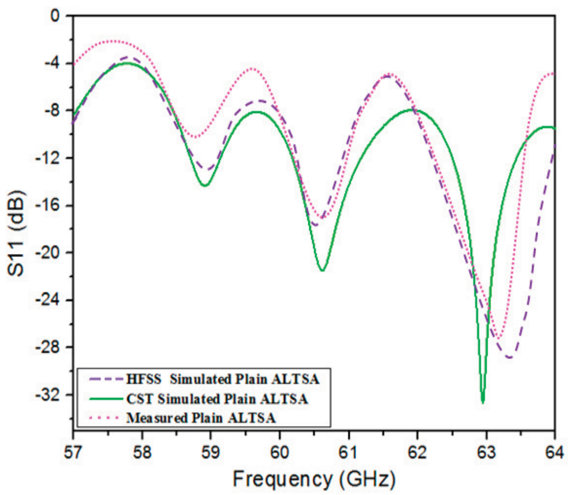


Fig. 4. Simulated and measured S_{11} parameters of plain ALTSA.

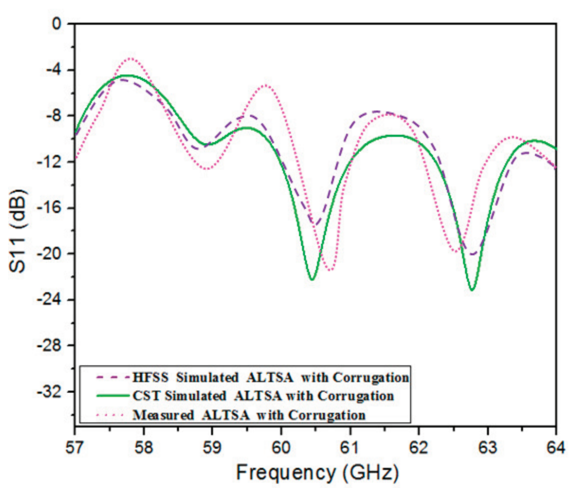


Fig. 5. Simulated and measured S_{11} parameters of ALTSA with corrugation.

Figure 6 shows current distribution in ALTSA in HFSS and CST MWS. It is observed that corrugation on outer edges of ALTSA contributes higher gain. The gradually flared edges can be considered to accommodate a continuous change of wavelength over a broad frequency range, which results in the broadband impedance matching performance. Figures 7 and 8 show the simulated and measured gain of ALTSA along the boresight, which is observed to be 13.2 dB in HFSS and 13 dB in CST MWS for plain ALTSA while the measured gain is observed to be 12.6 dB. A slight difference in two simulated results can be observed, which is basically due to the different numerical methods employed in CST MWS and HFSS. Similarly, for the corrugated ALTSA the gain is observed to be 16.2 dB in HFSS and 16.1 dB in CST MWS. The measured gain is observed to be 16 dB. Simulated and measured results indicate that corrugation effects have significant impact on return loss, radiation pattern, and antenna gain.

IV. CONCLUSIONS

In this research work, ALTSA with and without outer rectangular corrugations are designed and simulated utilizing Ansys's HFSS and CST MWS for 60 GHz wireless communications. The simulated results were compared with the measured values obtained from the fabricated antenna. The results from simulation and measurement were observed and the performance of the antenna in relation to gain and beamwidth has been analyzed. The corrugations on the outer edges of the antenna change the surface current distribution increasing the gain. The proposed antenna has low side and back lobes, and a high gain. For validation, the results of HFSS and CST MWS simulations were compared with the measured results and are observed to be in good agreement.

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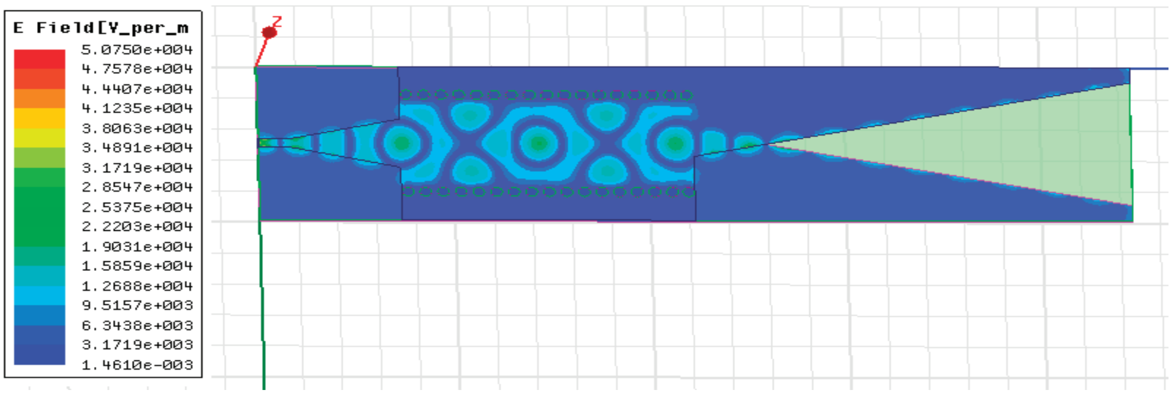
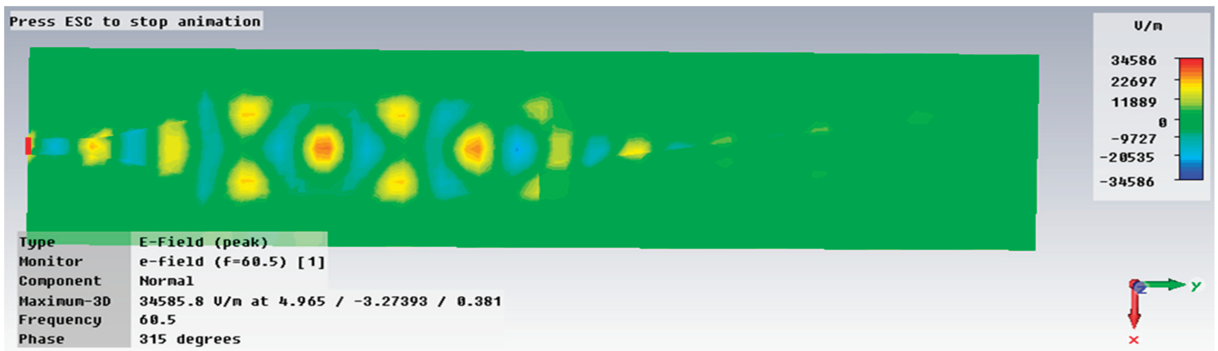


(a)



(b)

Fig. 6. Current distribution on plain ALTSA simulated in (a) HFSS and (b) CST MWS.

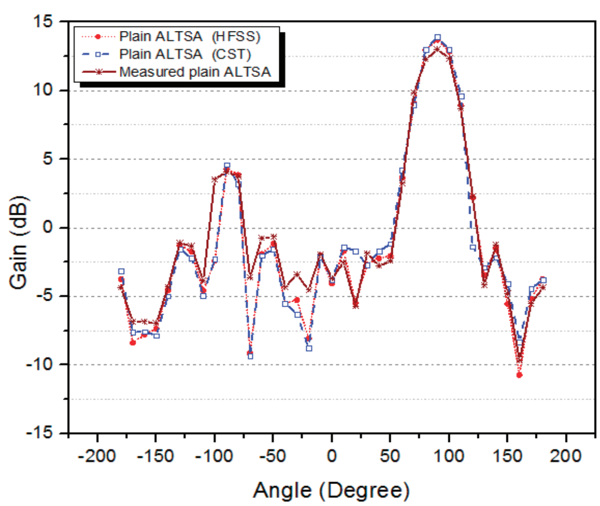


Fig. 7. Simulated and measured gain of plain ALTSA.

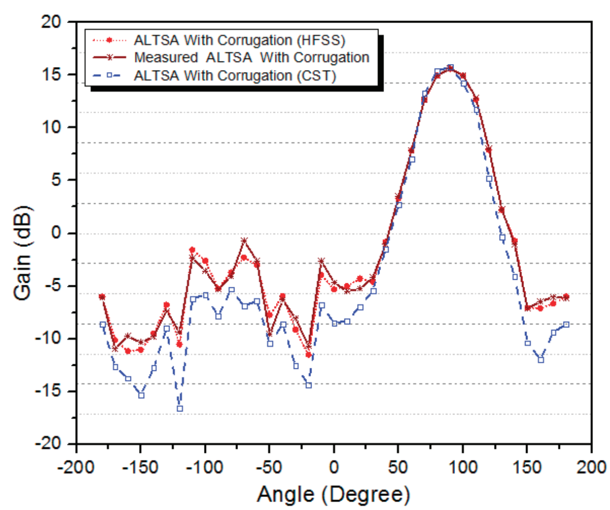


Fig. 8. Simulated and measured gain of corrugated ALTSA.

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