Antipodal Linear Tapered Slot Antenna with Dielectric Loading Using Substrate Integrated Waveguide Technology for 60 GHz Communications

Nishesh Tiwari and T. Rama Rao

Department of Telecommunication Engineering
SRM University, Chennai, Tamilnadu-603203, India
nitizaz@gmail.com, ramaraot@outlook.com

Abstract **─** The 60 GHz band is capable of providing high speed communication. In this paper a substrate integrated waveguide (SIW) fed high gain antipodal linear tapered slot antenna (ALTSA) is presented. In order obtain high gain the dielectric loading is applied to the ALTSA in addition to the corrugation structure. Using SIW technology, a highly efficient, compact and low cost planar design is realized. An electromagnetic field simulation tool is used for design and simulation of the antenna. SIW power divider is used for designing 1x4 ALTSA array. To validate the proposed design, prototype is fabricated and measured. The simulated results agree well with the measured values which validates the proposed design. The measured return loss of 1x4 ALTSA array is better than 12 dB over the entire 60 GHz band (57 GHz - 64 GHz). The measured gain of 1x4 ALTSA array is 23.1 $\pm$ 0.5 dBi over the 60 GHz band.

Index Terms **─** ALTSA, dielectric loading, high gain, millimeter wave, SIW, 60 GHz.

I. INTRODUCTION

In recent years the demand of large bandwidth for high speed communication is growing at a faster pace. The 60 GHz band (57 GHz - 64 GHz) is capable of providing high speed wireless communication permitting transfer of high volumes of uncompressed data at the speed of multi-gigabit per second [1-2]. The losses associated with the microstrip circuit are quite high in the millimeter wave frequency band. Therefore, more efficient technology like the substrate integrated waveguide (SIW) is needed. SIW has the positive traits of the traditional rectangular waveguide such as low loss, high quality factor, complete shielding and capability of handling high power along with the advantage of low cost and planar circuit design [3-4]. Numerous research works involving SIW have been reported for many years [3-6]. The 60 GHz band suffers from attenuation due to atmospheric absorption. This requires the use of high gain antennas to overcome the losses. Tapered slot antennas (TSA) are popular for their wide bandwidth, good return loss and high gain. Antipodal linear tapered slot antenna (ALTSA) is a type of TSA which uses antipodal geometry in its design where the top and bottom metallized parts on a substrate are tapered in opposite direction. Researchers have designed antipodal Vivaldi antenna with wide bandwidth ranging from 4-50 GHz in [7]. The antenna gain varies from 3-12 dBi over the bandwidth. In [8], a high gain antipodal Fermi tapered slot antenna with gain of 18.75 dBi at 60 GHz has been proposed. In [9], Hao et al. introduced a novel technique for feeding ALTSA with SIW where the top and bottom tapered edges are overlapped to overcome the impedance mismatch between the ALTSA and SIW feed. TSA with corrugation structure have been used for reducing the width of the antenna while minimizing any significant degradation in radiation pattern [10-11]. This helps in making the antenna array of compact size. Further, corrugation is also known for increasing antenna gain, reducing side lobe level and reducing cross polarization, thus improving the overall performance of antenna. In [11], Djerafi et al. have developed rectangular corrugated ALTSA array with quasi triangular power divider. The gain of the 1x12 array is 19.25 dBi. In [12], Shrivastava et al. have presented corrugated ALTSA for 60 GHz band. In [13], Dae-Myoung et al. have developed ALTSA with half circular slots as corrugation structure. The gain at 7 GHz is 12.4 dBi. Dielectric loading also helps in enhancement of antenna gain. By placing the dielectric slab in front of the antenna its gain can be increased. The dielectric slab in this case acts as a guiding structure [14] and enhances the gain of the antenna [15]. In [16], dielectric loading is applied to a planar SIW horn antenna to narrow down the E-plane beamwidth and increase the gain. In [14] Ghassemi et al. have developed a high gain ALTSA array with SIW horn structure and rectangular dielectric loading for E and W band. The gain of 1x4 ALTSA array is 19$\pm$1 dBi.

In this paper, ALTSAs having rectangle with semi-circular top shaped dielectric loading structures are used to obtain a high gain antenna array in the 60 GHz band. The antenna array is designed and simulated in Ansys HFSS software. It is fabricated on Rogers RT/Duroid 5880 substrate which has dielectric constant of 2.2 and

Submitted On: December 29, 2016
Accepted On: March 18, 2017

thickness of 0.254 mm.

II. ANTENNA DESIGN

A. Design of SIW

SIW structure is shown in Fig. 1. In SIW there are two rows of metallic vias embedded in the dielectric substrate which act as waveguide by connecting the two parallel metal plates on the top and bottom. The two rows of vias act as the walls of the rectangular waveguide along with the top and bottom metal plates. Nevertheless, though SIW has electrical similarities to rectangular waveguide and provides advantages similar to the rectangular waveguide, it is also prone to leakage problem if the design rules are not followed properly. Some design rules and equations have been formulated by researchers in the past for proper design of SIW. The via diameter and the space between the vias should be selected as per Equations (1) and (2) respectively [17]:

$$D_{via} < \frac{\lambda_g}{5}, \quad (1)$$

$$S \leq 2D_{via}, \quad (2)$$

where λ_g is the guided wavelength, D_{via} is the diameter of the via and S is the space between the vias. The effective width of the waveguide is given by Equation (3) [18]:

$$W_{eff} = W_{siw} - 1.08\frac{{D_{via}}^2}{S} + 0.1\frac{{D_{via}}^2}{W_{siw}}, \quad (3)$$

where W_{eff} is the effective width, W_{siw} is the width of the SIW which is 2.69 mm, D_{via} is the diameter of the via which is 0.4 mm and S is the space between the vias which is 0.7 mm. The cut off frequency for the SIW in TE mode 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 f_c is the cutoff frequency, m and n are the mode numbers, ε_r is the dielectric constant, a is the width of the waveguide and b is the height. For a given waveguide the dominant mode is the mode having lowest cut-off frequency. In rectangular waveguide TE_{10} is the fundamental mode and same is also true for SIW. Figure 2 shows the E-field distribution in the SIW.

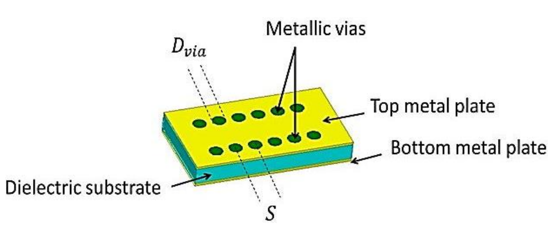

Fig. 1. SIW structure.

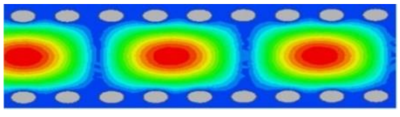

Fig. 2. E-field distribution in SIW.

B. Dielectric loaded ALTSA array

An ALTSA is a type of TSA. Yngvesson et al. have reported that the performance of TSA is sensitive to the thickness t and the dielectric constant ε_r in [19]. Hence, a factor $f_{substrate}$ for efficient performance of TSA has been defined as:

$$f_{substrate} = \frac{t(\sqrt{\varepsilon_r} - 1)}{\lambda_0}. \quad (5)$$

For good performance of tapered slot antenna the substrate thickness should satisfy Equation (6). Here, with substrate thickness of 0.254 mm $f_{substrate}$ is 0.024, which satisfies Equation (6):

$$0.005 \leq f_{substrate} \leq 0.03. \quad (6)$$

The authors have presented a dielectric loaded ALTSA in [20]. Four such ALTSAs are placed adjacent to each other to form 1x4 ALTSA array. Figure 3 shows the 1x4 array configuration. The dimension of the antenna array is listed in Table 1. The inter-element spacing for the ALTSA array is 11.25 mm.

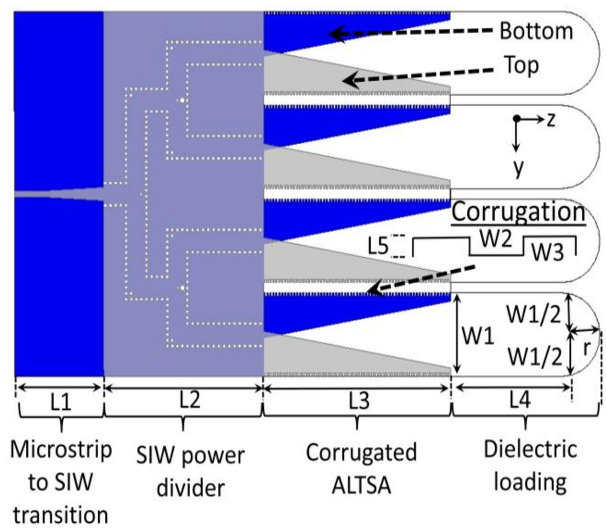

Fig. 3. ALTSA array configuration.

Table 1: Dimension of ALTSA array

Parameter	Value (Unit: mm)
L1	12
L2	21.38
L3	25
L4	15
L5	0.4
W1	10
W2	0.2
W3	0.2
r	5

SIW power divider is used for the design of 1x4 ALTSA array. The SIW power divider feeds each of the four ALTSA with power of same amplitude and phase. Figure 4 shows the design of SIW power divider with E-field distribution. Proper placements of the inductive posts are essential for proper division of the power. In Fig. 4, Da = 0.3, Db = 0.3, Dc = 0.6, Dd = 0.4, La = 0.95, Lb = 0.15, Lc = 0.2, Ld = 0.32, Le = 0.25, Lf = 21.38, Wr = 19.81 and Ws = 8.56. Figure 5 shows the simulated S-parameters of the SIW power divider. From Fig. 5, it is observed that S11 is below -10 dB from 57 GHz to 64 GHz. Also, S21, S31, S41 and S51 have similar magnitudes over the 60 GHz band. The simulated phase at the output of the SIW power divider is shown in Fig. 6. From Fig. 6, it is seen that the phases of S21, S31, S41 and S51 are similar.

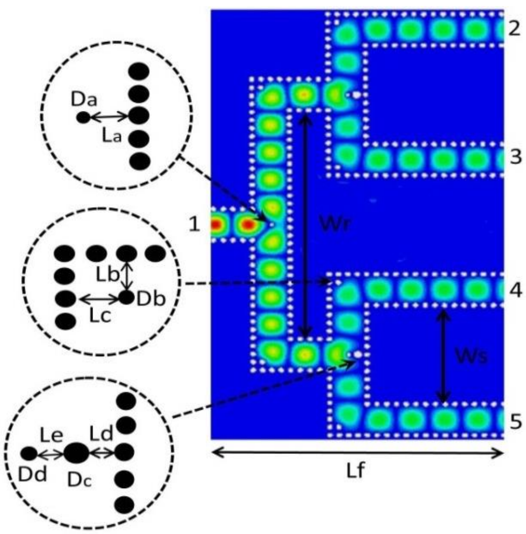

Fig. 4. SIW power divider schematic and E-field distribution

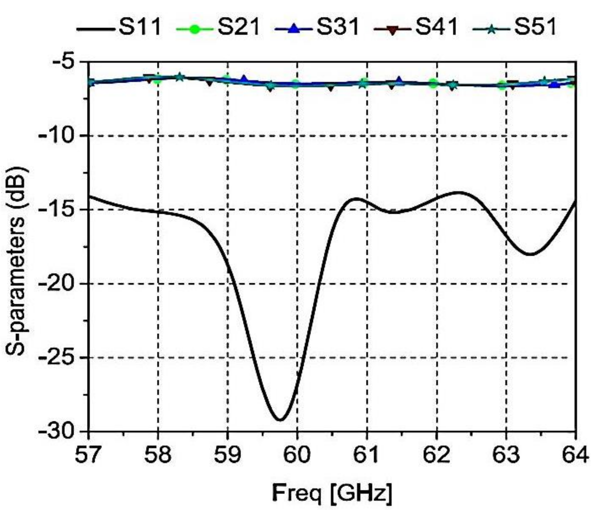

Fig. 5. Simulated S-parameters of SIW power divider.

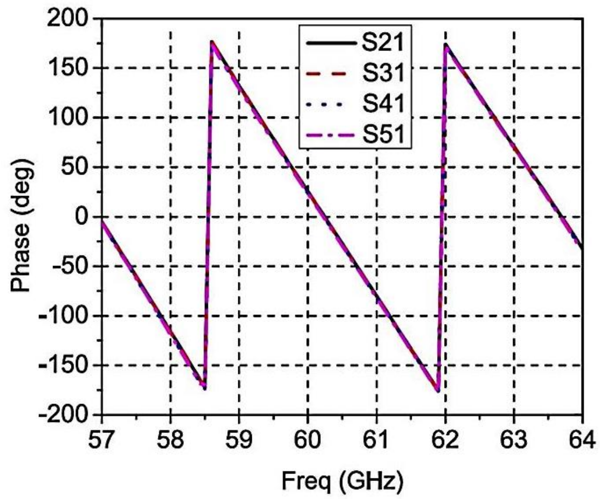

Fig. 6. Simulated phase at output of SIW power divider.

Figure 7 shows the simulated radiation patterns at 58, 60, 62 and 64 GHz. It is seen that the side lobe levels for both E-plane and H-plane are below -12 dB. Further, the cross polarization levels are also below -18 dB. Front to back ratio is a useful parameter used in describing the performance of directive antennas. In highly directive antennas, it is desirable to focus all radiated energy in the front direction and keep the energy radiated in unwanted direction (i.e., back side) to the minimum. In Fig. 8, the simulated front to back ratio of the antenna array shown. The front to back ratio is observed to be between 28-34 dB in the 60 GHz band.

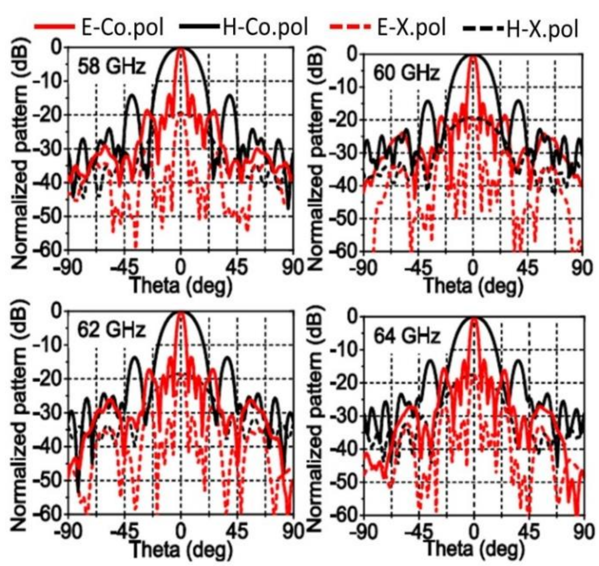

Fig. 7. Simulated radiation patterns.

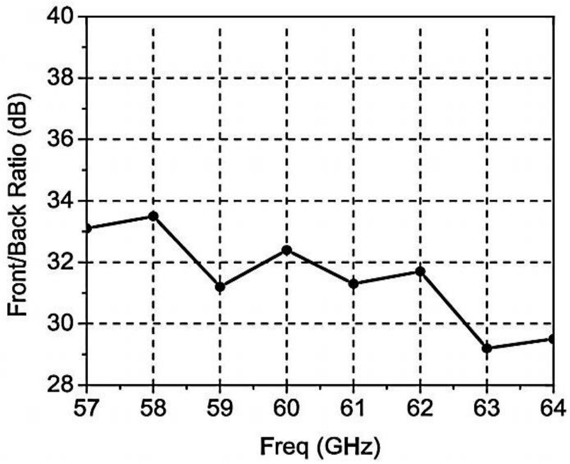

Fig. 8. Simulated front to back ratio.

III. MEASUREMENT

Figure 9 shows the fabricated antenna array. The dimension of the ALTSA array is 78.38 mm x 43.75 mm x 0.254 mm. Figure 10 shows the simulated and measured return loss and gain of the proposed 1x4 ALTSA array. The S11 parameters and gain of the antenna array are measured utilizing MVNA 8-350 with probe station. The measurement of radiation pattern is performed in far field anechoic chamber. From Fig. 10, it is observed that the simulated and measured return losses are better than 12 dB over the 60 GHz band. At 60 GHz the measured return loss is better than 24 dB. It is observed that there is good agreement between the measured and simulated results. Some slight differences between the simulated and measured results can be attributed to fabrication and calibration related tolerances. Further it is seen that the gain is almost flat over the 60 GHz band. Similarly, from Fig. 10 the simulated gain is observed to be 23 $\pm$ 0.4 dBi and the measured gain is seen to be 23.1 $\pm$ 0.5 dBi over the 60 GHz band.

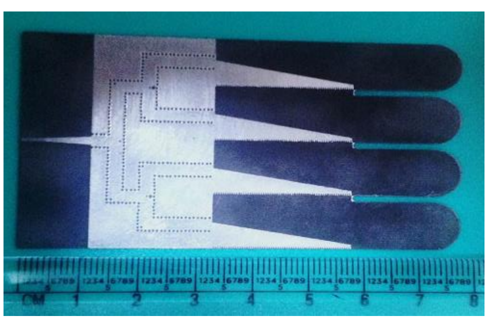

Fig. 9. Fabricated 1x4 ALTSA array.

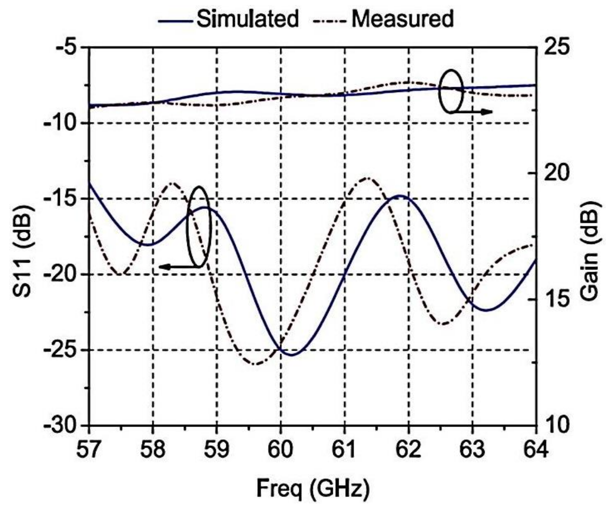

Fig. 10. Measured gain and return loss of ALTSA array.

Further, simulated and measured E-plane radiation pattern is shown in Fig. 11. The simulated E-plane beamwidth is seen to be 7° and the measured E-plane beamwidth is observed to be 8°. The measured and simulated side lobe levels in E-plane are at -15 dB. Similarly, from Fig. 12 the simulated H-plane beamwidth is observed to be 25° and the measured H-plane beamwidth is observed to be 27°. The simulated and measured side lobe levels in H-plane are at -14 dB. However, overall it is observed that there is a good agreement between the simulated and measured results.

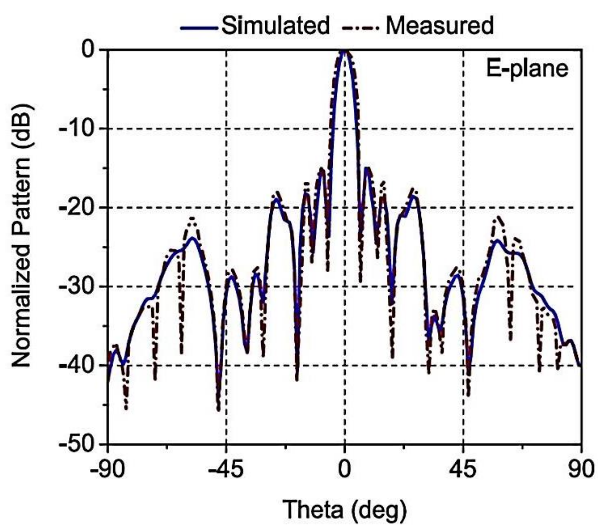

Fig. 11. Measured E-plane radiation pattern of ALTSA array at 60 GHz.

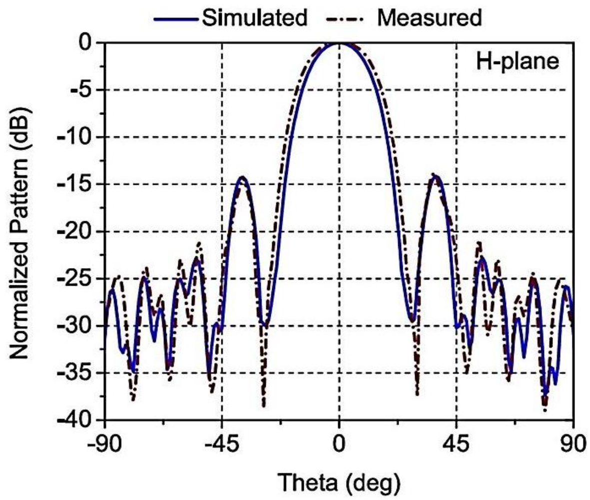

Fig. 12. Measured H-plane radiation pattern of ALTSA array at 60 GHz.

The comparison of other antenna arrays with this work is listed in Table 2. Numerous antenna arrays have been reported over the years for applications related to millimeter wave band. The general trend has been moving towards low cost, light weight and high gain antenna arrays. ALTSA with SIW feed can cater to those requirements. SIW fed ALTSA are known for high gain and wide bandwidth.

Table 2: Comparison with other antennas

Parameters	[21]	[14]	This Work
Antenna type	L-probe patch	ALTSA	ALTSA
Impedance bandwidth	29%	41%	11.6%
Operating frequency	60 GHz	80 GHz	60 GHz
No. of elements	16	4	4
Peak gain (dBi)	17.5	20	23.6

From the above table, it is observed that in [14] the peak gain of 20 dBi has been achieved with 4 ALTSA elements. Similarly, in [21] peak gain of 17.5 dBi has been reported but the number of elements used in the array is 16. In this work, peak gain of 23.6 dBi is achieved with four ALTSA elements. Though the impedance bandwidth of the antenna in this work is smaller than other antennas in the table, it should be noted that 11.6% covers 57-64 GHz and it is enough for multi-Gbps speed communication in 60 GHz band.

IV. CONCLUSION

In this paper, a high gain corrugated ALTSA array with dielectric loading for wireless communication application in the 60 GHz band is presented. The proposed design is validated with measurement of the fabricated prototype. Good agreement is seen between the simulated and measured results. The proposed antenna design has good return loss and high gain over the 60 GHz band. Overall, the proposed 1x4 ALTSA array has large bandwidth, high gain, compact size, light weight and is easy to fabricate using the low cost PCB technology. The single layer SIW design also suits mass fabrication. Hence, it is a suitable candidate for high speed communication in 60 GHz band.

ACKNOWLEDGMENT

Authors are very much obliged to ISRO, Government of India, for the assistance provided for the execution of this research work.

REFERENCES

[1] P. Smulders, “Exploiting the 60 GHz band for local wireless multimedia access: Prospects and future directions,” *IEEE Communications Mag*azine, vol. 40, no. 1, pp. 140-147, 2002.

[2] A. Valdes-Garcia, S. Reynolds, A. Natarajan, D. Kam, D. Liu, J. W. Lai, Y- L. O. Huang, P.-Y. Chen, M. D. Tsai, J. H. C. Zhan, S. Nicolson, and B. Floyd, “Single element and phased array transceiver chipsets for 60 GHz Gb/s communicat-ions,” *IEEE Communications Magazine*, vol. 49, no. 4, pp. 120-131, 2011.

[3] M. Bozzi, L. Perregrini, K. Wu, and P. Arcioni, “Current and future research trends in substrate integrated waveguide technology,” *Radioengineer-ing*, vol. 18, no. 2, pp. 201-209, 2009.

[4] Y. J. Cheng, P. Chen, W. Hong, T. Djerafi, and K. Wu, “Substrate integrated waveguide beamforming networks and multibeam antenna arrays for low-cost satellite and mobile systems,” *IEEE Antennas and Propagation Magazine*, vol. 53, no. 6, pp. 18-30, 2011.

[5] S. E. Hosseininejad, N. Komjani, H. Oraizim, and M. T. Noghani, “Optimum design of SIW longitudinal slot array antennas with specified radiation patterns,” *ACES Journal*, vol. 27, no. 4, pp. 320-325, April 2012.

[6] R. Rezaiesarlak, M. Salehi, and E. Mehrshahi, “Hybrid of moment method and mode matching technique for full-wave analysis of SIW circuits,” *ACES Journal*, vol. 26, no. 8, pp. 688-695, August 2011.

[7] J. Bai, S. Shi, and D. W. Prather, “Modified compact antipodal Vivaldi antenna for 4-50 GHz UWB application,” *IEEE Transactions on Micro-wave Theory and Techniques*, vol. 59, no. 4, pp. 1051-1057, 2011.

[8] Z. Briqech, A. Sebak, and T. A. Denidni, “High gain 60 GHz antipodal Fermi tapered slot antenna

with sine corrugation," *Microwave and Optical Technology Letters*, vol. 57, no. 1, pp. 6-9, 2015.

[9] Z. C. Hao, W. Hong, J. Chen, X. Chen, and K. Wu, "A novel feeding technique for antipodal linearly tapered slot antenna array," *Proceedings of IEEE MTT-S Microwave Symposium Digest*, pp. 12-17, June 2005.

[10] S. Sugawara, Y. Maita, K. Adachi, and K. Mizuno, "Characteristics of a mm-wave tapered slot antenna with corrugated edges," *Proceedings of IEEE MTT-S Microwave Symposium Digest*, pp. 533-536, 1998.

[11] T. Djerafi and K. Wu, "Corrugated substrate integrated waveguide antipodal linearly tapered slot antenna array fed by quasi-triangular power divider," *Progress in Electromagnetic Research C*, vol. 26, pp. 139-151, 2012.

[12] P. Shrivastava and T. R. Rao, "Antipodal linear tapered slot antenna based radio link characterization in narrow hallway environment at 60 GHz," *J. Infrared Milli. Terahz Waves*, DOI 10.1007/s10762-016-0282-9.

[13] D. M. In, S. Pyo, H. S. Lee, M. J. Lee, and Y. S. Kim, "Antipodal linearly tapered slot antenna using unequal half-circular slotted sides for gain improvements," *Proceedings of Asia-Pacific Microwave Conference*, pp. 2036-2039, 2010.

[14] N. Ghassemi and K. Wu, "Planar high-gain dielectric-loaded antipodal linearly tapered slot antenna for E and W band gigabyte point to point wireless services," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 1747-1755, 2013.

[15] T. R. Rao, C. Sarath, N. Tiwari, and R. Jyoti, "Design of SIW fed antipodal linearly tapered slot antennas with curved and hat shaped dielectric loadings at 60 GHz for wireless communications," *IEEE 5th Asia-Pacific Conference on Antennas and Propagation (APCAP)*, pp. 309-310, 2016.

[16] H. Wang, D. G. Fang, B. Zhang, and W. Q. Che, "Dielectric loaded substrate integrated waveguide (SIW) H-plane horn antennas," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 3, pp. 640-647, 2010.

[17] K. Wu, D. Deslandes, and Y. Cassivi, "The substrate integrated circuits - A new concept for high-frequency electronics and optoelectronics," *Proceedings of Telecommunications in Modern Satellite, Cable and Broadcasting Service*, vol. 1, pp. III-X, October 2003.

[18] M. Bozzi, A. Georgiadis, and K. Wu, "Review of substrate-integrated waveguide circuits and antennas," *IET Microwaves Antennas and Propagation*, vol. 5, no. 8, pp. 909-920, 2011.

[19] K. S. Yngvesson, T. L. Korzeniowski, Y. S. Kim, E. L. Kollberg, and J. F. Johansson, "The tapered slot antenna - A new integrated element for millimeter wave applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 37, no. 2, pp. 365-374, 1989.

[20] N. Tiwari and T. R. Rao, "A substrate integrated waveguide based antipodal linear tapered slot antenna for 60 GHz wireless communications," *ACES Express Journal*, vol. 1, no. 8, pp. 220-223, 2016.

[21] L. Wang, Y. X. Guo, and W. X. Sheng, "Wideband high gain 60 GHz LTCC L-probe patch antenna array with a soft surface," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 1802-1809, 2013.

Nishesh Tiwari is currently pursuing Ph.D. from Department of Telecommunication Engineering at SRM University, India. He received his M.Tech Degree in Telecommunication Networks from SRM University in 2012. He is a Student Member of IEEE. His current research interests are Antennas and Propagation, Microwave Photonics and Wireless Sensor Networks.

T. Rama Rao is a Professor of Telecommunication Engineering at SRM University, India, and has a long-standing research experience on radiowave propagation studies for wireless communications. In the past, he has worked at Aalborg University, Denmark as a Research Professor in an EU funded project on cellular networks capacity enhancement, at Universidad Carlos III de Madrid, Spain, and at the University of Sydney, Australia, as a Visiting Professor. He is a Member of IEEE, WWRF, IET, ACM, and IETE.