Performance Investigations with Antipodal Linear Tapered Slot Antenna on 60 GHz Radio Link in a Narrow Hallway Environment

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Abstract—The performance of wireless communication systems is predominantly dependent on propagation environment and respective radiating antennas. Due to the shorter wavelength at Millimeter Wave (MmW) frequencies, the propagation loss through surroundings in indoor environments is typically very high. To improve the channel capacity and to reduce inter-user interference, a high gain directional antenna is desired at MmW frequencies. Traditional antennas used in MmW devices are not suitable for low-cost commercial devices due to their heavy, bulky and expensive configurations. This paper focuses on design and development of a very compact (44.61 mm × 9.93 mm × 0.381 mm) high gain Antipodal Linear Tapered Slot Antenna (ALTSA) utilizing Substrate Integrated Waveguide (SIW) technology at 60 GHz. Received signal strength (RSS), path loss (PL) and capacity are studied for MmW based wireless applications utilizing electromagnetic (EM) computations and Radio Frequency (RF) experiments in narrow hallway environment.

1. INTRODUCTION

With the huge availability of bandwidth, Millimeter Wave (MmW) frequencies, particularly at unlicensed 60 GHz bands, are more of interest for many researchers, as gigabit-fidelity (Gi-Fi) wireless communications are going to play predominant roles in all application areas of wireless world [1, 2] for wide variety of high-definition multimedia applications. The propagation characteristics of the 60 GHz band are characterized by high levels of oxygen absorption and rain attenuation [2, 3]. This limits the range of communication systems; however, it makes 60 GHz attractive for a variety of short-range wireless communication applications [1, 4]. Resulting from short transmission distances, these communications are highly secure and virtually interference-free operation. In addition to large bandwidth, MmW enables integration of the whole transceiver inside a small chip due to the short wavelength (λ) of 5–7 mm.

However, at 60 GHz path loss (PL) is more severe than at 2 or 5 GHz, and implementing a highly integrated transceiver in CMOS will be a challenging task. This higher free space loss can be compensated by the use of antennas with more pattern directivity, high gain and adaptive arrays. For the MmW based wireless applications, the antenna should satisfy a few characteristics of high directivity, enough bandwidth for rich multimedia content, small size for portable use, narrow beam width and low side lobe levels (SLL) [4]. Conventionally, horn, reflector and lens antennas have been used in MmW devices. These antennas have high gain and efficiency, but they are not appropriate for low-cost commercial devices because they are costly, heavyweight, bulky and cannot be integrated with solid-state devices [4]. Recently, there has been a great deal of interest in microstrip and slot antennas for MmW applications to take advantage of their moderately high gain, wide bandwidth and relatively low SLLs. These antennas are of low profile, light weight and easy to integrate with other planar devices [4]. Tapered Slot Antenna (TSA) is a popular choice for applications such as ground penetration

surveillance, medicine, imaging, security and numerous other wireless communication applications [5, 6]. Many designs for TSA has been proposed and developed by various researchers all over the world [7, 8]. One such type of antenna is Antipodal Linear Tapered Slot antenna (ALTSA). ALTSA has been investigated widely in academic and industry focusing on the ultra-wideband (UWB) and very high frequency (VHF) range [8–11], and hardly any work is present in the extremely high frequency (EHF) range. Compared to the traditional TSA, antipodal geometry has been incorporated to provide proper impedance matching without any stubs on the PCB and for better current distribution on the antenna surface [9].

Microstrip feeding system suffers from significant tradeoffs of cost, size and performance at microwave and MmW frequencies. Substrate Integrated Waveguide (SIW) feeding technology for MmW circuits has been investigated by researchers from various parts of the world in the past 20 years for its high Q-factors and integrations [12]. SIW technology inherits most of the advantages of the conventional metallic waveguides such as complete shielding, low loss, ease of fabrication, high quality factor and high power-handling capability [11–13]. In addition, broadband operation is achieved with the help of optimized overlap matching section and by using via-hole arrangement. Electric field leakage is reduced and insertion characteristic improved [10, 12, 13].

It has been reported that a reduced antenna size is associated with degradation in radiation pattern and current distribution, which is a significant problem for the design of compact TSAs [10, 13]. TSAs with corrugation structure have been used to reduce tapered slot antenna width without any significant degradation in the radiation pattern [10]. In applications such as MmW radar and communication systems using directional antenna, it is preferred that the antenna has a high front to back (F/B) ratio and directivity. On small antennas, undesired surface currents on the outlines lead to near-field radiation and thereby lead to reduced gain as well as high SLL [10, 14]. Corrugation has been proven successful in TSA structures for F/B ratio, gain and beamwidth improvement [13–15].

Owing to the 60 GHz propagation characteristics due to the presence of oxygen molecules in the atmosphere, the strong attenuation of 60 GHz signals results in high level of security and low interference with adjacent channel, consequently permitting a larger number of users to be collocated within a certain area [1–3]. However, in the MmW bands the additional attenuation due to the oxygen absorption, other gaseous loss and rain in the transmission medium are the potential hitches in terms of signal coverage in WLANs and WPANs [16–18]. For the next generation WLAN and WPAN communications utilizing MmWs particularly at 60 GHz, radio channel propagation characteristics in typical indoor environments with a realistic channel model will be very helpful for better understanding of propagation mechanisms and effects [18]. Due to shorter wavelength, the multipath is more evident in indoor scenarios, where the specific layouts and interior of building can become the single most dominant factor in the propagation of fields within the environment [16, 17]. Precise estimation of propagation loss offers improved planning and deployment of access points in indoor environments. Commercial ray tracing software tool Wireless InSite from Remcom and Radio Frequency (RF) equipment from Keysight Technologies were used to analyze the antennas and its propagation characteristics. As the PL is high at 60 GHz, high antenna gain is required to compensate channel loss, and the maximum radiation should be directive towards the receiver to maximize the coupling between devices.

Thus this work focuses on design and development of ALTSA with outer rectangular corrugation utilizing SIW feed, which is used to measure the radio link characteristics in a hallway scenario for 60 GHz wireless communications.

2. ANTENNA ARCHITECTURE AND DESIGN

The size of the proposed ALTSA is $43.29 \, \text{mm} \times 9.93 \, \text{mm} \times 0.381 \, \text{mm}$, which is designed on a $0.381 \, \text{mm}$ RT/Duroid 5880 substrate [15] with dielectric permittivity $\varepsilon_r = 2.20$ and $\tan \delta = 0.0004$. Figure 1 depicts the proposed corrugated ALTSA with the SIW feeding. On one side, the input track is flared to produce half of the linear tapered slot antenna, and on the other side of substrate, the ground plane is flared in the opposite direction to form the overall balanced antipodal. The length of tapered slot line is 4.5λ. The input impedance of the ALTSA is high, and that of the SIW is low which causes a mismatch. To solve this problem, the flares are designed in a way that they overlap each other. The performance of ALTSA depends upon the thickness and the dielectric permittivity of the substrate. Equation (1),
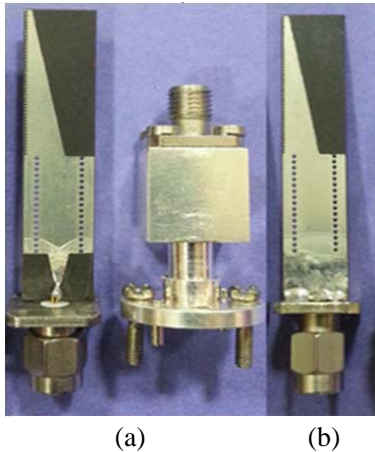
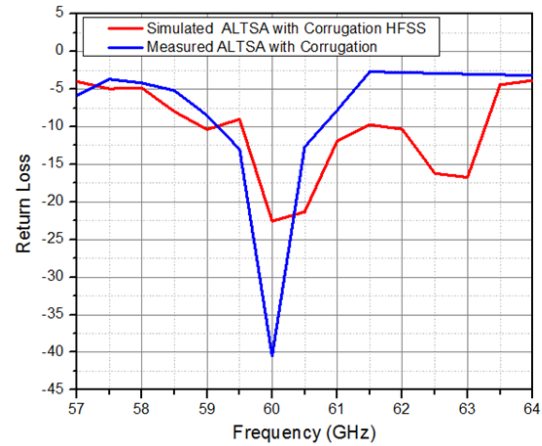**Figure 1.** Photographs of corrugated ALTSA, (a) upper side, (b) lower side.

Figure 2. Simulated and measured return loss of corrugated ALTSA.

defines the effective thickness of the substrate [19],

$$t_{eff} = t \left(\sqrt{\varepsilon_r - 1} \right) \tag{1}$$

For better performance, effective thickness should lie within a range given in Equation (2),

$$0.005 \leq \frac{t_{eff}}{\lambda} \leq 0.03 \tag{2}$$

SIW can be commonly used as a transmission line which is similar to the rectangular waveguide in terms of mode and cut-off frequency properties. 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. When the distance between the via-holes are electrically small ($< 0.2\lambda$), rectangular waveguide can be replaced by SIW [11]. The distance between the vias, P, should be measured precisely to ensure loss-free radiation between the metallic vias because of diffraction. Following Equation (3) and Equation (4) allows us to do the same [11, 15].

$$D \leq \lambda_g/5 \tag{3}$$
$$P \leq 2D \tag{4}$$

where, D is the diameter of the via.

Corrugations are well known in the design of horn antennas in order to suppress higher modes. Therefore, they guarantee the polarization pureness of an antenna [14]. A planar corrugated surface of $\lambda/4$ depth blocks the propagation of an oblique plane wave whose path is perpendicular to the corrugation independent of the direction of the electric field, thus helping them to minimize the radiation toward the undesired direction. Outer rectangular corrugation structures are applied to the ALTSA design. The length and width are selected to be 1.25 mm and 0.5 mm, respectively, with 0.5 mm spacing between the rectangular corrugations, made on the outer edges of the ALTSA.

The measurements were carried out in Sub Millimeter Wave Laboratory (SMWL) at RCI, DRDO, Hyderabad, India. To connect ALTSA to the transceiver, microstrip line is soldered with a Sub-Miniature version A (SMA) connector and connected to the adapter. To measure the return loss of the antenna at 60 GHz, Vector Network Analyzer (VNA) (AB Millimeter Wave's — MVNA-8-350) is calibrated in single port. To obtain the antenna pattern in E-plane and H-plane, VNA is calibrated in two-port mode. Scalar horn antenna is used as a reference antenna and is connected to port one, and the test antenna is connected to port two. The separation between the antennas is maintained to be greater than the farfield requirement. Figure 2 illustrates the return loss for corrugated ALTSA. The observed return loss for corrugated ALTSA is −41.6 at 60 GHz, and the bandwidth of the antenna is 1.5 GHz. The 3 dB beamwidth for ALTSA with corrugation is 36°, and the gain observed is 16.5 dB which is better than other similar works available in literature [10, 20–22]. Figure 3 illustrates the E and
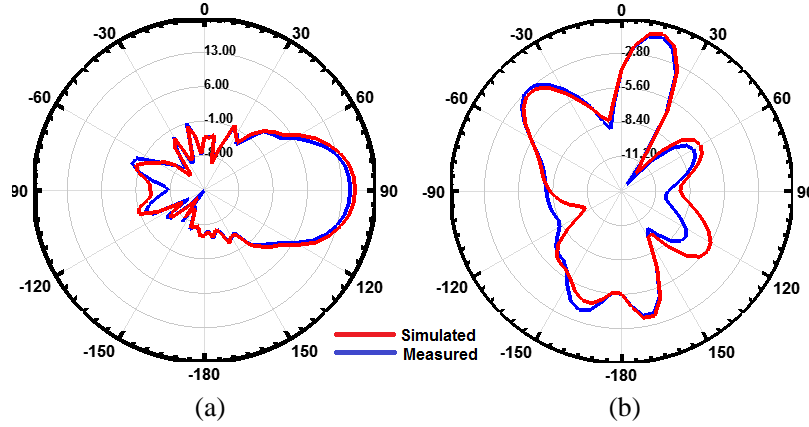
Figure 3. (a) E plane. (b) H plane radiation pattern of corrugated ALTSA.

H planes of corrugated ALTSA. Simulated and measured results indicate that the corrugation effects have a significant impact on the return loss, radiation pattern and antenna gain. It is noticed that the main lobe direction is along the bore sight. This is important, since MmW applications need a good stability of radiation pattern and directivity. Further, the radiation efficiency of corrugated ALTSA is 96.84%, which is also better than a similar research work presented in [22].

3. RADIO LINK STUDY

The following section focuses on aspects concerning the wireless radio link propagation at 60 GHz in narrow hallway environment using corrugated ALTSA.

3.1. Measurement and Simulation Setup

Measurements were carried out in the hallway located on the 13th floor of Tech Park building of SRM University, Chennai, India (GPS Coordinates: 12°49′29.35″N, 80°02′42.88″E). The narrow hallway environment has $14\,\text{m} \times 1.83\,\text{m} \times 3\,\text{m}$ dimensions, in a modern multi-storied building. The left and right walls of the narrow hallway are made of concrete (relative permittivity $\varepsilon_r = 7.0$) with glass windows ($\varepsilon_r = 4.0$). The floor is covered with porcelain tiles ($\varepsilon_r = 6.0$), and the concrete ceiling is covered with gypsum board ($\varepsilon_r = 3.0$). The same environment with the exact dimensions is approximated
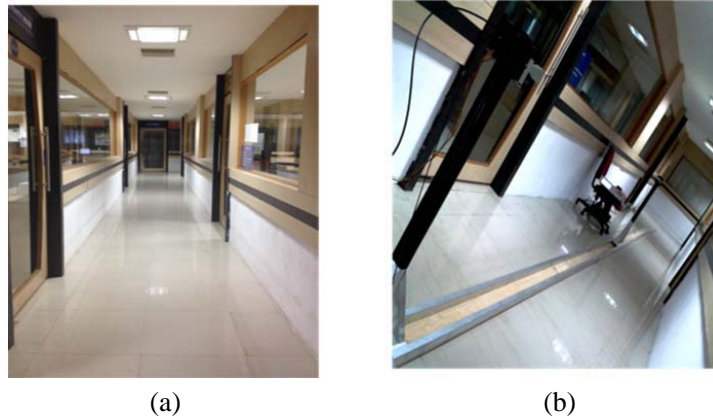

Figure 4. (a) Photo of narrow hallway located on the 13th floor of Tech Park building of SRM University, Chennai. (b) Photo of narrow hallway along with measurement setup.

in the Remcom Wireless InSite [23] to simulate the radio link characteristics. The Transceiver pair (TRA-5960FW) [24] with ALTSA antenna is used to carry out the measurements. To generate 60 GHz frequency, a reference signal of 10 MHz for phase-locked loop and an intermediate frequency of 3 GHz were fed to the transmitter through signal generator (Keysight's N5182A MXG) [25]. The receiver was connected to the spectrum analyzer (Keysight's N9010A EXA) [26]. The transmitter and receiver antenna were mounted on a controllable positioning device at the height of 1.5 meter. During the acquisition by the help of the positioner receiver antenna was moved over a distance of 15 meters. Figures 4(a) and (b) depict photographs of the hallway along with measurement setup. Figures 5(a) and (b) depict photos of measurement setup with reference antenna and with ALTSA. Table 1 lists the parameters used in the analysis.
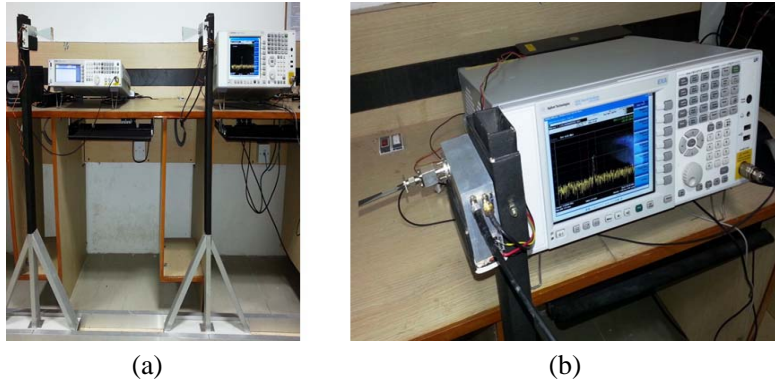

(a)   (b)

Figure 5. (a) Photo of measurement setup with reference antenna, (b) with ALTSA.

Table 1. Parameters used in the analysis.

Parameters	Values
Transmitter Power	10 dBm
Center Frequency	60 GHz
Transmitter Antenna gain (Horn)	25.3 dB
Receiver Antenna gain (ALTSA)	16.5 dB
Bandwidth	1.5 GHz
Noise figure	6 dB
Thermal Noise	-174 dBm/Hz
Center Frequency	60 GHz

3.2. Performance Analysis

Precise estimation of propagation loss offers improved planning and deployment of MmW based short-range wireless access points in indoor environments. For short distance communication, the linearity of the receiver decides the communication performance whereas the noise figure of the receiver and transmitter dictates the coverage range [27]. The value of the received signal strength obtained from measurements is utilized for PL calculations. The large scale fading for 60 GHz includes the PL exponent and statistical variation due to shadowing [2, 3, 27]. Log Normal Shadowing model is given in Equation (5) [28], where PL_{d0} is the PL at reference distance 1 meter in dB, d_0 the reference distance, d (meters) the transmitter-receiver separation distance, and n the PL exponent. The PL exponent n indicates the average rate at which the received signal power decreases with the separation distance. The random variable X_σ accounts for log-normal shadowing and has a gaussian distribution with random

values and standard deviation in dB.

$$PL_{LN}\,(\text{dB}) = PL_{d_0}\,(\text{dB}) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{5}$$

Predicted and measured values show acceptable agreement, with the conclusion that such simulation methods provide a reasonable and time competent alternative to measurements for the investigation, modeling and planning of wireless indoor networks. Figure 6 shows the received signal strength (RSS) distribution at 60 GHz. The grid of receivers is set with the same characteristics in LOS and NLOS locations along the entire floor. The signal strength distributions show that good signal strength is achieved over a short distance LOS scenario nonetheless achieving a higher intensity, which makes 60 GHz suitable candidate for short distance secure communication. For the validation of ALTSA for indoor applications and comparison, PL values were simulated and measured using traditional horn antenna. From the results, it is observed that the PL values for ALTSA and Horn have good agreement. Figure 7 compares the PL models for LOS scenario at 60 GHz, which shows that in LOS scenario, the PL exponent n is 2.12, and shadowing is 6.69 dB. PL models are needed to estimate the signal to noise power (SNR) and interference levels as a function of separation distance between two devices. The ratio
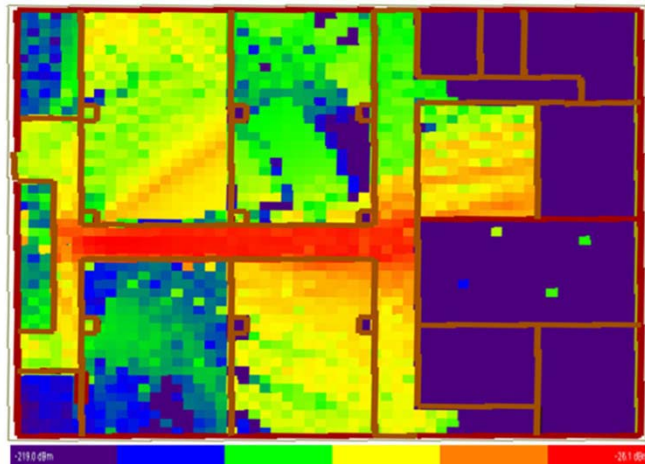

Figure 6. RSS Distribution in three dimensional design of the 13th floor Tech Park building of SRM University, Chennai, India using ALTSA.
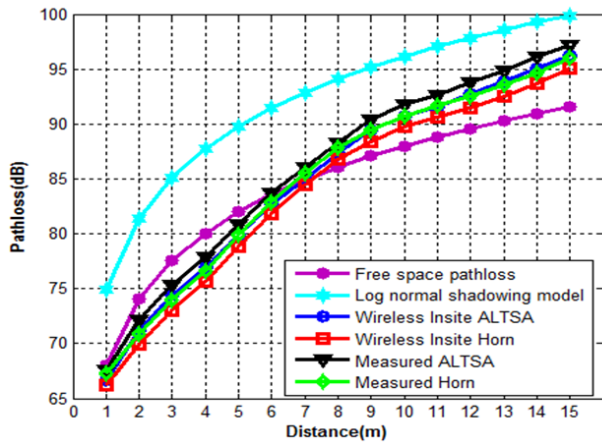

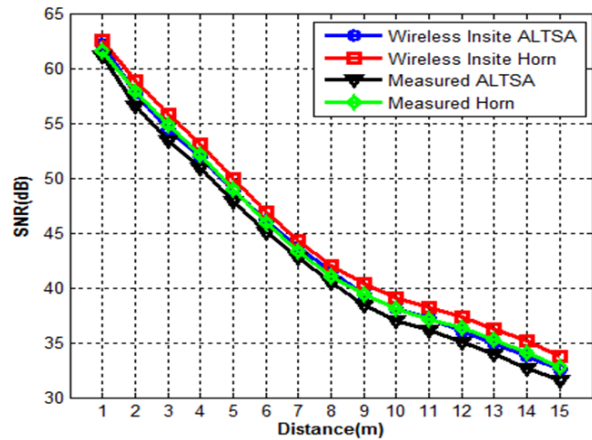**Figure 7.** Path loss value in narrow hallway environment.

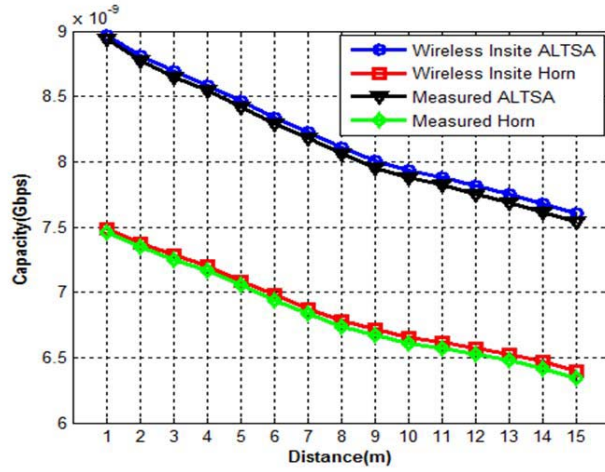**Figure 8.** Maximum achievable SNR in narrow hallway environment.

Figure 9. Maximum achievable capacity in narrow hallway environment.

of SNR can be obtained using the received power R_P given in Equation (6) [29–31], where $10 \log(kT_{syst})$ is the thermal noise for a system temperature of 17°C, NF_{RX} the noise figure of the receiver in dB, and W the bandwidth of the signal in hertz.

$$SNR = R_p - (10 \log(KTsyst) + 10 \log(W) + NF_{RX}) \tag{6}$$

As 60 GHz has the potential to provide the multi-gigabit data rates, it can be used for high definition multimedia transmissions. The channel capacity (C) defines the maximum achievable throughput in the specified channel condition. Capacity is set by the bandwidth and SNR and can be given as Equation (7) [28–31].

$$C = W * \log_2(SNR + 1) \tag{7}$$

Figures 8 and 9 show the SNR and maximum achievable capacity value in a narrow hallway environment. It is observed that the capacity and SNR decreases with the increase in distance. It shows with 1.5 GHz bandwidth of ALTSA maximum data rate increases up-to 9 Gbps.

4. CONCLUSIONS

To validate the antenna design for 60 GHz-based indoor wireless communications, indoor radio link characterization has been made in a narrow hallway environment utilizing RF experiments and EM simulations. With 16.5 dB gain of the ALTSA, the PL varies from 70 dB to 100 dB in a narrow hallway within an operating space of 15 meters which shows a good agreement with traditional horn antenna performance and that the capacity decreases with increasing distance. The horn antenna bandwidth of 1.25 GHz gives the maximum data rate of 7.5 Gbps, whereas 1.5 GHz bandwidth of ALTSA the maximum data rate increases up to 9 Gbps. The propagation properties of ALTSA at 60 GHz and compact size make it viable to be integrated on the same substrate with other MmW receiver or transmitter components for ultra-high-speed multimedia wireless applications. However, due to the complex nature of MmW propagation, there are still a lot of unknowns that need to be quantified before its deployment. With this in mind, the work presented in this paper serves as a valuable contribution to the deployment of MmW based wireless communication systems/devices which will proliferate in coming years.

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REFERENCES

1. Yong, S. K., P. Xia, and A. V. Garcia, *60 GHz Technology for Gbps WLAN and WPAN*, 1st Edition, John Wiley and Sons Ltd., Chichester, UK, 2011.

2. Rappaport, T. S., J. N. Murdock, and F. Gutierrez, "State of the art in 60-GHz integrated circuits and systems for wireless communications," *IEEE Proc.*, Vol. 99, No. 8, 1390–1436, Aug. 2011.

3. Smulders, P., "Exploiting the 60 GHz band for local wireless multimedia access: Prospects and future directions," *IEEE Commuunication Magazine*, Vol. 2, No. 1, 140–147, Jan. 2002.

4. Huang, K. C. and D. J. Edwards, *Millimetre Wave Antennas for Gigabit Wireless Communications*, 1st Edition, John Wiley, Chichester, UK, 2008.

5. Namas, T. and M. Hasanovic, "Ultrawideband antipodal Vivaldi antenna for road surface scanner based on inverse scattering," *Proc. of 28th Annual Review of Progress in Applied Computational Electromagnetics*, 882–887, Ohio, 2012.

6. Coburn, W. K. and A. I. Zaghloul, "Numerical analysis of stacked tapered slot antennas," *Proc. 28th Annual Review of Progress in Applied Computational Electromagnetics*, 112–117, Ohio, 2012.

7. Chang, D. C., B. H. Zeng, and J. C. Liu, "Modified antipodal Fermi antenna with piecewise-linear approximation and shaped-comb corrugation for ranging applications," *IET Microwaves, Antennas and Propagation*, Vol. 4, No. 3, 399–407, Mar. 2010.

8. Rodenbeck, C. T., S. G. Kim, W. H. Tu, M. R. Coutant, S. Hong, M. Li, and K. Chang, "Ultrawideband low cost phased array radars," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 12, 3697–3703, Dec. 2005.

9. Sugawara, S., Y. Maita, K. Adachi, and K. Mizuno, "Characteristics of a mm-wave tapered slot antenna with corrugated edges," *IEEE MTT-S International Microwave Symposium Digest*, 533–536, Baltimore, 1998.

10. Djerafi, T. and K. Wu, "Corrugated substrate integrated waveguide (SIW) antipodal linearly tapered slot antenna array fed by quasi-triangular power divider," *Progress In Electromagnetics Research C*, Vol. 26, 139–151, 2012.

11. Bozzi, M., L. Perregrini, K. Wu, and P. Arcioni, "Current and future research trends in substrate integrated waveguide technology," *Radioengineering*, Vol. 18, No. 2, 201-206, 2009.

12. Hao, Z. C., W. Hong, J. X. Chen, X. P. Chen, and K. Wu, "A novel feeding technique for antipodal linearly tapered slot antenna array," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, 1641–1643, China, 2003.

13. Huang, T. J. and T. H. Heng, "Antipodal dual exponentially tapered slot antenna (DETSA) with stepped edge corrugations for front-to-back ratio improvement," *Proc. of IEEE International Workshop on Electromagnetics, Applications and Student Innovation (iWEM)*, 48–51, Taipei, Aug. 2011.

14. Yoon, D. G., Y. P. Hong, Y. J. An, J. S. Jang, U. Y. Pak, and J. G. Yook, "High-gain planar tapered slot antenna for Ku-band applications," *Proc. of IEEE Asia-Pacific Microwave Conference Proceedings (APMC)*, 1914–1917, Yokohama, 2010.

15. Shrivastava, P., D. Chandra, N. Tiwari, and T. R. Rao, "Investigations on corrugation issues in SIW based antipodal linear tapered slot antenna for wireless networks at 60 GHz," *Applied Computational Electromagnetics Society ACES*, Vol. 28, No. 10, 960–968, Oct. 2013.

16. Vettikalladi, H., O. Lafond, and M. Himdi, "High-Efficient and high-gain superstrate antenna for 60-GHz indoor communication," *IEEE Letters on Antennas and Propagation*, Vol. 8, 1422–1425, Jan. 2010.

17. Ghosh, T. A., M. C. Thomas, R. Cudak, P. Ratasuk, F. Moorut, W. Vook, T. S. Rappaport, G. R. MacCartney, S. Sun, and S. Nie, "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," *IEEE Journal on Selected Areas in Communications*, Vol. 32, No. 6, 1152–1163, Jun. 2014.

18. Maltsev, A. R., A. Maslennikov, A. Evastyanov, A. Khoryaev, and A. Lomayev, "Experimental investigations of 60 GHz WLAN systems in office environment," *IEEE Journal on Selected Areas in Communications*, Vol. 27, No. 8, 1488–1499, Oct. 2009.

19. Ellis, T. J. and G. M. Rebeiz, "Mm-wave tapered slot antennas on micromachined photonic bandgap dielectrics," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 2, 1157–1160, San Francisco, Jun. 1996.

20. Yoon, D. G., Y. P. Hong, Y. J. An, J. S. Jang, U. Y. Park, and J. G. Yook, "Broadband high-gain linearly tapered slot antenna with outside corrugations," *IEICE Electronics Express*, Vol. 8, No. 4, 202–208, 2011.

21. Wang, W., X. Wang, W. Wang, and A. E. Fathy, "Planar high-gain antipodal linearly tapered slot antenna for passive millimeter-wave focal plane array imaging," *IEEE International Symposium on Phased Array Systems & Technology*, 267–271, Waltham, MA, USA, Oct. 2013.

22. Ismail, M. and A. R. Sebak, "High-gain SIW-based antipodal linearly tapered slot antenna for 60-GHz applications," *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, 217–218, Memphis, Tennessee, USA, Jun. 2014.

23. http://www.remcom.com/wireless-insite.

24. Yang, K. S., S. T. Choi, S. Nishi, K. Tokuda, and Y. H. Kim, "60 GHz high integrated transceiver for broad band short distance communication," *Proc. of URSI GA 2005*, C-06, 2005, Access Mode: http://www.ursi.org/Proceedings/ProcGA05/pdf/C06.4%2801679%29.pdf.

25. http://www.keysight.com/en/pd-797248-pn-N5182A/mxg-rf-vectorsignal-generator?&cc=IN&lc=eng.

26. http://cp.literature.agilent.com/litweb/pdf/5989-6529EN.pdf.

27. Suiyan, G., "Performance and capacity analysis of 60 GHz WPAN channel," *Microwave and Optical Technology Letters*, Vol. 51, No. 11, 2671–2675, 2009.

28. Yong, S. K. and C. C. Chong, "An overview of multi gigabit wireless through millimeter wave technology: Potentials and technical challenges," *EURASIP Journal on Wireless Communications and Networking*, Vol. 2007, Article ID 78907, 2007.

29. Liu, C. E., R. Skafidas, and R. J. Evans, "Capacity and data rate for millimeter wavelength systems in a short range package radio transceiver," *IEEE Transactions on Wireless Communications*, Vol. 9, No. 9, 903–906, Mar. 2010.

30. Kumar, A. and T. R. Rao, "Analysis of planning and deployment issues for short-range gigabit wireless communications at 60 GHz," *International Journal of Microwave and Optical Technology*, Vol. 9, No. 2, 156–163, Mar. 2014.

31. Ramesh, S. and T. R. Rao, "Indoor radio link characterization studies for millimeter wave wireless communications utilizing dielectric loaded exponentially tapered slot antenna," *Journal of Electromagnetic Waves and Applications*, Vol. 29, No. 4, 551–564, 2015.