Multi-Beams Waveguide Slot Antennas at X-Band for Wireless Communications Systems

Hatem Oday Hanoosh, M. K. A. Rahim, N. A. Murad, and Yaqdhan Mahmood Hussein

Advanced RF & Microwave Research Group (ARFMRG)
School of Electrical Engineering, Faculty of Engineering
Universiti Teknologi Malaysia (UTM), 81310
UTMJB Johor, Malaysia
Hatem.altaee1990@gmail.com, mdkamal@utm.my, noorasniza@utm.my, Yaqthanm.79@gmail.com

Abstract **─** This paper focuses on the design of a multi-beams antenna using waveguide slots technology at X-band. The multi-beams radiation is proposed to expand the coverage of the single antenna, thus more capacity is enabled. Waveguide slots antenna is a well-known antenna for high power and gain transmission capabilities. Therefore, it is preferred. In this work, four variations of waveguide slots antennas are studied. The slot distribution covers one to four broad and narrow walls of the waveguide. This technique enables multi-beams patterns. The performance of the proposed antennas is simulated using CST microwave software. The simulated responses of the antennas show that a good matched with return loss greater than 10 dB at the desired frequency. The four proposed antennas achieved a good gain between 6.3 and 7.4 dB with directional beamwidth of 15 degree. The proposed antennas are suitable for implementing in radar applications.

Index Term **─** CST, multi-beams, slots antenna, waveguide.

I. INTRODUCTION

The backbone of the proposed cellular technology is changed to form wireless connection by using higher frequency spectrum [1]. Hence, higher spectrum has been assigned for outdoor links due to high path loss at higher frequencies, cost effective components, and other related factors. However, this technology on other hand suffers from severe challenges, including large propagation loss, signal absorbing, low gain of the proposed antenna, and low transmitted power. Waveguide slots antenna technology has been preferred in the past few years as a new inventive solution to allow higher gain, higher data rates, and power efficiency especially in the Cellular [2-5]. Rectangular waveguides have been used for many decades in microwave applications, with standard bands ranging from 1 GHz up to 300 GHz [3]. Slotted antenna arrays on waveguides are popular in navigation, radar and other high-frequency systems. The antenna is of interest due to its' low-loss property especially at high frequencies and thus possessed high efficiency [4].

Recently, a dual-beams waveguide slotted antenna is presented in [6]. The slots are distributed on the broad walls of the waveguides with directivity and gain of 14 dB at 28 GHz. Other types of waveguide slots antenna with implementing in the narrow-wall of the waveguide structure are introduced in [7-9]. The designs suffer from high grating lobes and lower gain than 10 dB. Additionally, dual-band dual-polarization waveguide slots antenna at 30 and 35 GHz is proposed in [10]. The narrow wall is implemented with 9×10 inclined slots array at 35 GHz to form horizontal polarization, and 8×10 longitude slots array is distributed on the broad wall at 30 GHz to form vertical polarization. However, the slots distributed on the narrow wall of the waveguide suffered from side lobes and grating lobes due to the small offset between the slots.

Therefore, this paper focuses on designing the waveguide slotted antenna operating at X-Band, providing a high gain, low side lobes, and multi-beams. Four waveguide slotted antennas are investigated in this paper. The antennas are implemented with 4 slots on narrow and broad walls of the waveguide structure. The performance of the proposed antennas is simulated using Computer Simulation Technology (CST) software. The paper is divided as follows: section 2 presents the design process, Section 3 discusses the results in term of simulation responses, and Section 4 concludes the paper.

II. WAVEGUIDE SLOT ANTENNA DESIGN

Commonly, the slots are represented as shunt elements in transmission line. The circuit for the slot is illustrated in Fig. 1. The G represents the conductance of the slot, and B represents the susceptance of the slot. The slot used in this research is cut in the longitude direction

Submitted On: February 28, 2020
Accepted On: April 26, 2020

of the waveguide structure. Each slot has length of L and width of W, the distance between two centered slots is d, and the offset from the center line is x as seen in Fig. 2. The distance d between the slots is designed to be half the guided wavelength. Thus, it would be 180-degree phase shift between the radiating slots [12-15]. The offset x is calculated using the normalized Conductance Gn equations [15]:

$$G_n = \sum_{n=1}^{N} g_n = 1, \tag{1}$$

$$g_n = \left[2.09 \frac{\lambda g}{\lambda 0} \cdot \frac{a}{b} \cdot cos^2 \frac{\pi \lambda 0}{2 \lambda g}\right] sin^2 \frac{\pi x}{a}, \tag{2}$$

a and b are the inner dimensions of the waveguide (as shown in Fig. 3), which is used WR-90 standard waveguide, and λ_0 is the free space wavelength and λg is the guided wavelength, while N is the slots number. The antenna physical dimensions with the gain and the beamwidth of the slotted waveguide antenna are calculated using equations below [15]:

$$\lambda_g = \frac{\lambda 0}{\sqrt{1-\left(\frac{\lambda 0}{2a}\right)}}, \tag{3}$$

$$Gain = 10 \times log\left(\frac{N.d}{\lambda 0}\right)\ dB, \tag{4}$$

$$Beamwidth = 50.7 \times \frac{\lambda 0}{\frac{N}{2}.d}\ degree, \tag{5}$$

$$d = \lambda_g/2, \tag{6}$$

$$L = 0.98\ \lambda_0/2, \tag{7}$$

$$W = \lambda_g/20, \tag{8}$$

Where L is the slot length, W is the slot width, and d is the spacing between slots. From equation (3) it can be clearly noticed that the slot parameters are obtained from the center operating frequency and its guided wavelength. In addition, the gain and beamwidth are effected with two important parameters; the wavelength and the number of the slots. Beside the distance between slots (d) is also effected to these parameters. For instance, if the number of the slots (N) increases, the gain is increased [15]. However, the guided wavelength (λ_g) is increased which leads to increase the distance between slots and size of the waveguide accordingly [15]. Therefore, for this work a four slots are chosen to be implemented on the waveguide walls to maintain a reasonable size and optimal gain.

Generally, the waveguide structure is propagated at TE_{10} mode with both E-field and H-field are positioned within narrow and broad walls of the waveguide as shown in Fig. 2. To allow the slot radiation, a cutting will be made through the H-field lines at maximum flux [15]. This will generate one beam at one of which wall is used. To enable multiple beams (two or more than), the slots are cut on each wall side of the waveguide. For example, if the slot cutting is on broad and narrow walls of the waveguide, it will be generated a dual beam in the direction of the cutting slots. Figure 3 shows the standard distribution of the slots with dimensions on the waveguide structure.

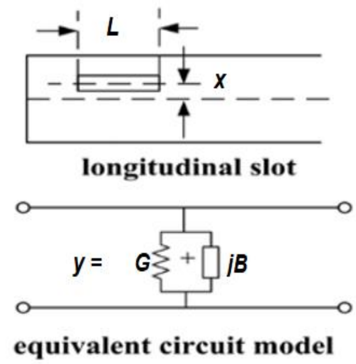


Fig. 1. Slot circuit representations [11].

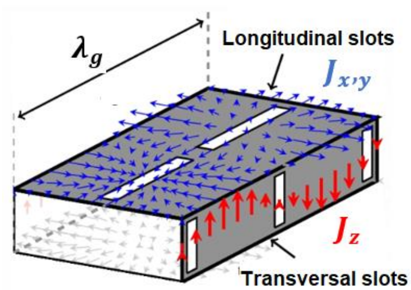


Fig. 2. The E-field and H-field distributed lines in the rectangular hollow waveguide [15].

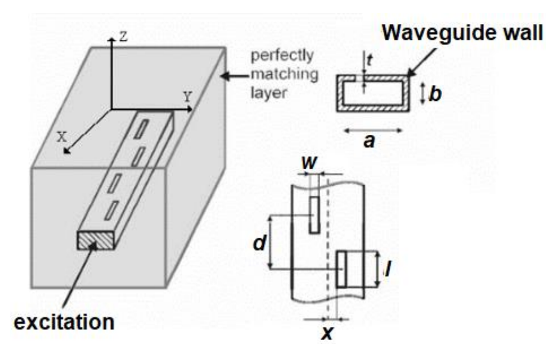


Fig. 3. Waveguide slot antenna. Standard waveguide slots antenna structure [12].

Therefore, a dual, triple, and four beams waveguide slots antennas are designed. Referring to Fig. 4 (a), the first antenna (Antenna 1) is designed by distributing four slots on one broad wall and one narrow wall of the waveguide. This will enable a dual beam generated from two different directions. The slots are distributed in symmetrical offset x from the centerline of the waveguide (for all designs). The second antenna (Antenna 2) is implemented with same number of the slots as in Antenna 1.

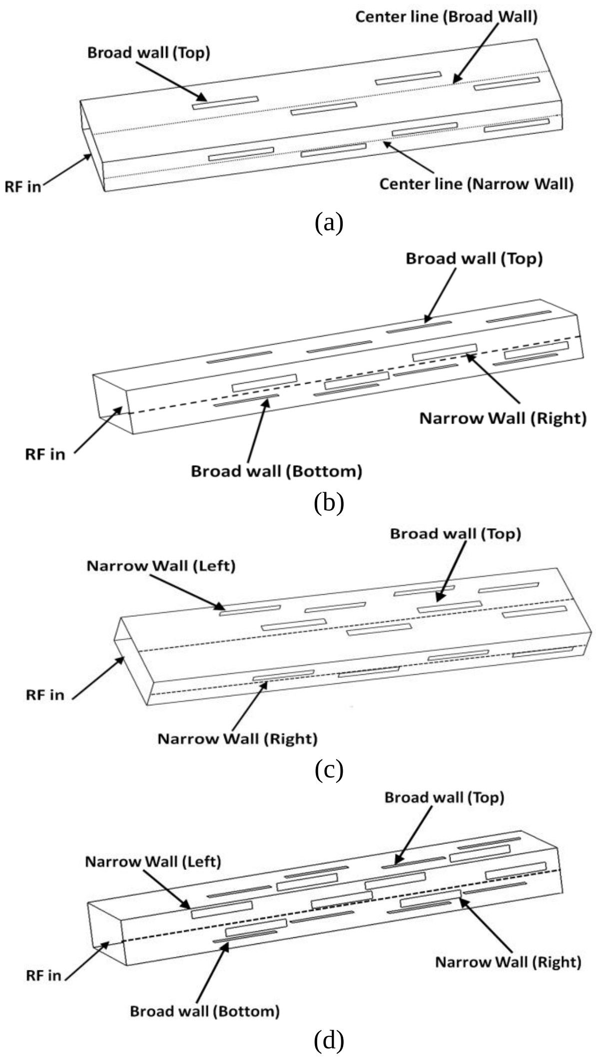


Fig. 4. The proposed antennas: (a) Antenna 1, (b) Antenna 2, (c) Antenna 3, and (d) Antenna 4.

The slots are distributed in two broad walls and one narrow wall of the waveguide. This will enable triple beams. The first two beams from the broad walls is radiated oppositely to each other and the third beam is generated from the narrow wall. The third antenna (Antenna 3) is similar to Antenna 2, whereas the slots distribution are in one broad wall and two narrow walls of the waveguide. The last antenna (Antenna 4) is designed with slots implementation on all the waveguide walls, which allows a four beams generations. Figure 4 and Table 1 shows the proposed antennas with their slots distribution and final dimensions of all the antenna designs respectively.

Table 1: The final dimensions of the proposed antennas at X-band (All dimensions are in mm)

Parameter/ Antennas	Ant.1	Ant.2	Ant.3	Ant.4
Broad Wall				
a	22.86	22.86	22.86	22.86
d	18.69	18.69	18.69	18.69
x	1.5	1.5	1.5	1.5
Slot length (L)	13.4	13.4	13.4	13.4
Slot width (W)	1.72	1.72	1.72	1.72
Narrow Wall				
b	10.16	10.16	10.16	10.16
d	18.69	18.69	18.69	18.69
x	1.5	1.5	1.5	1.5
Slot length (L)	13.4	13.4	13.4	13.4
Slot width (W)	1.72	1.72	1.72	1.72
Wall Distribution				
Sided walls	One broad and one narrow	Two broads and one narrow	One broad and two narrows	All

III. RESULTS AND DISCUSSIONS

The proposed designs are simulated by CST software and the performance in terms of return loss, directivity, gain, efficiency, and radiation patterns are analyzed. Figure 5 shows the simulated return loss of all the proposed designs. From the analysis, Antenna 1 and Antenna 2 have a maximum return loss of 22.7 dB and 22 dB at specific frequency of 9.22 GHz and 9.2 GHz respectively. Antenna 3 has a maximum return loss of 13 dB at 9.012 GHz. The shifting in frequency below the desired frequency happened due to the implementation of the slots on both side of the narrow walls. This is could be caused by the offset *x* from the centerline in the narrow wall of the waveguide, which effects the E-field lines that shifted the frequency. Antenna 4 showed a good return loss of 21 dB at 8.95 GHz. The shifting frequency in Antenna 4 is similar to Antenna 3, since the slots are also distributed within the sides of the narrow walls.

The simulated gain, directivity, and efficiency of the proposed antennas are shown in Fig. 6. Antenna 1 and Antenna 2 has maximum gain of 6.3 dB and 6.58 dB at the desired frequencies correspondingly. These gains are reordered from the radiating slots in the broad walls of the waveguide structure. In the same time, Antenna 3 and Antenna 4 showed a good gain performance of 6.9 dB and 7.4 dB at 9 and 8.95 GHz. Additionally, all antennas are noticed with good efficiency ranging from 75% to 92%.

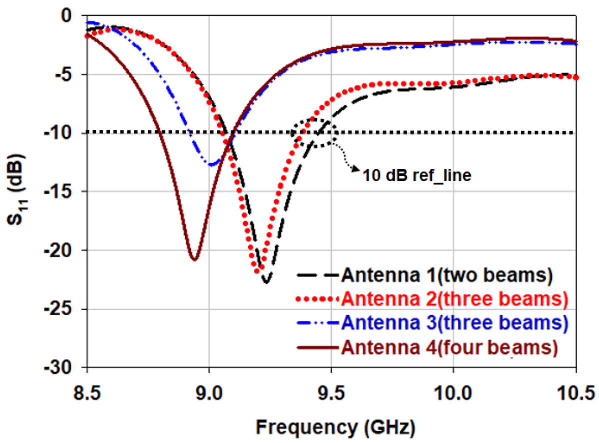
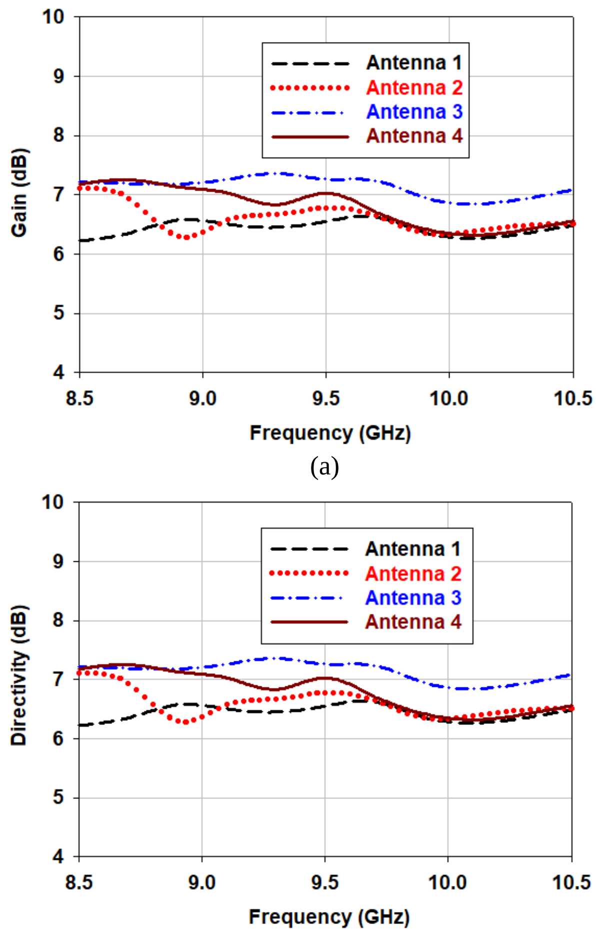
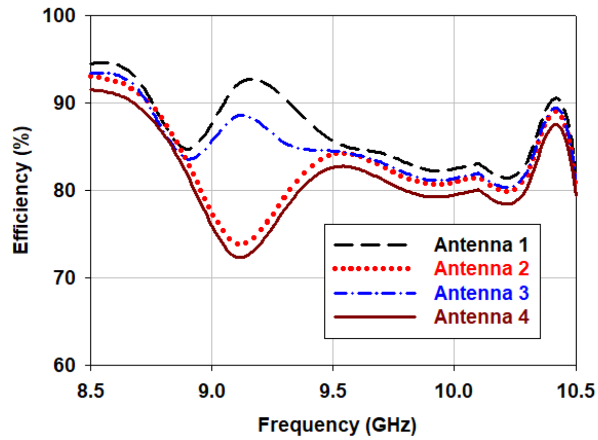


Fig. 5. The return loss of the proposed antennas.



(a)

(b)

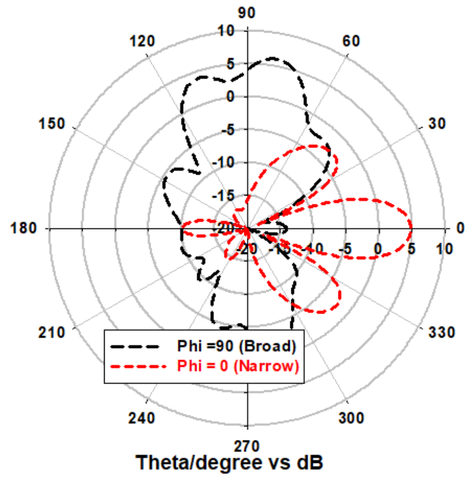


(c)

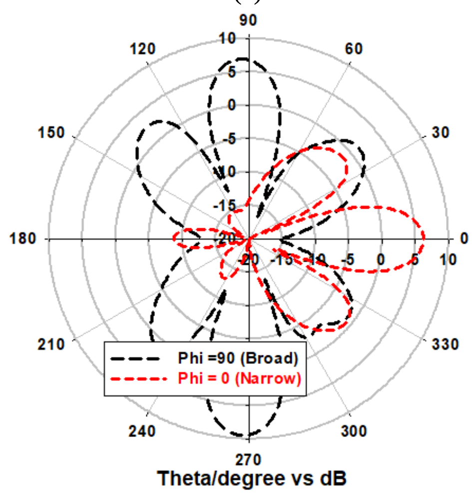
Fig. 6. The performance of the proposed antennas: (a) gain, (b) directivity, and (c) efficiency.

The radiation patterns of the proposed antennas are illustrated in Fig. 7. The radiation pattern analysis has performed on each antenna with broad and narrow wall of the waveguide. Firstly, Antenna 1 in Fig. 7 (a) has dual beams from broad and narrow wall. When Phi = 90 degree (broad wall), the beam is in one direction with slidelobes of -5 dB and grating lob of 0 dB. At narrow wall (Phi =0), one beam is noticed with slidelobes of -10 dB and grating lobes of -5 dB. Hence, dual beams are enabled from Antenna 1. Secondly, Antenna 2 (as in Fig. 7 (b)) has dual beams from the broad walls and one beam from the narrow walls. However, a high grating lobes are seen from the broad wall of 5 dB. Despite these grating lobes, a triple beams are clearly observed. Thirdly, Antenna 3 (as in Fig. 7 (c)) showed a good triple beams with low slidelobes of -10 dB at broad wall and -5 dB at narrow walls. The beams are from two sided narrow walls and one broad wall. Nevertheless, Antenna 4 (Fig. 7 (d) showed a high level of grating and slidelobes of 5 dB and 0 dB respectively. This could be due to the slots radiation from all the walls which makes it difficult to differentiate the four beams from others. Hence, more analysis and investigation should be taken to enhance and reduce these grating and slidelobes.

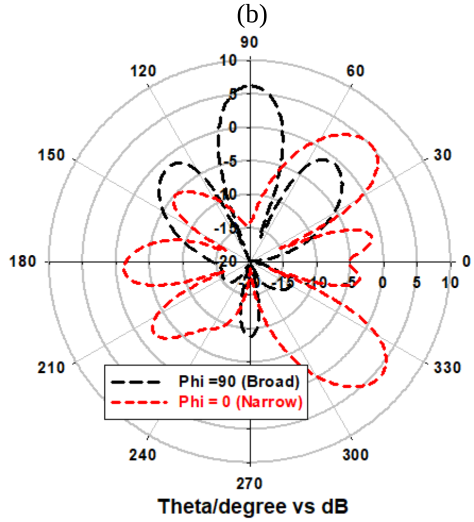
Table 2 shows the comparison between the four antennas performance, and Table 3 compares this work in respect with other researches. As summary, it can be concluded that multi beams property can be achieved by using one single waveguide structure. Taking the advantage of signals are confined within the broad and narrow walls of the waveguide



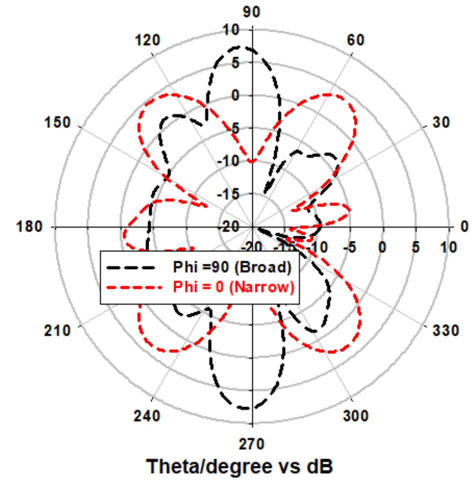
(a)



(b)



(c)



(d)

Fig. 7. The radiation patterns of the proposed antennas. (a) Antenna 1, (b) Antenna 2, (c) Antenna 3, and (d) Antenna 4.

Table 2: The performance of the proposed antennas

Variables	Ant.1	Ant.2	Ant.3	Ant.4
Frequency (GHz)	9.22	9.2	9.012	8.95
Return loss (dB)	22.7	22	13	21
Bandwidth (MHz)	400	400	200	300
Gain (dB)	6.3	6.58	6.9	7.4
Efficiency	92%	75%	87%	84%
Beams	Dual	Triple	Triple	Four

Table 3: Comparison with other works

Waveguide slots Antennas at X-band			
Parameters/Antennas	Ref. [16]	Ref. [17]	This work
Return loss (dB)	16	17	20
Frequency (GHz)	10	9.5	9.2
Gain (dB)	10	18	6.3-7.4
Efficiency (%)	90	84	75-92
Number of beams	One beam	One beam	Dual, triple and four

IV. CONCLUSION

In this work, four types of waveguide slots antennas are presented at X-band. The antennas are implemented on both broad and narrow walls of the waveguide structure to enable dual, triple, and four beams. Four slots are distributed symmetrically on the broad and narrow walls of the waveguide, whereas a total of eight slots implemented at Antenna 1, twelve slots implemented at Antenna 2 and Antenna 3, and sixteen slots implemented at Antenna 4. The performance of the proposed antennas showed a good return loss of greater than 10 dB and a gain range of 6.3 to 7.4 dB. The dual beams with gain of 6.3 dB are obtained in both H-plane and E-plane. Antenna 2 and antenna 3 has a triple beams with gain of 6.58 dB and 6.9 dB in both broad and narrow walls directions. Antenna 4 has four beams with gain of 7.4 dB. These proposed antennas could be useful for radar and wireless applications at X-band.

ACKNOWLEDGMENT

The authors would like to thank the Ministry of Higher Education (MOHE), School of Postgraduate Studies (SPS), Research Management Centre, Advanced RF and Microwave Research Group, School of Electrical Engineering, and Universiti Teknologi Malaysia (UTM), Johor Bahru, for the support of the research under Grant 09G19/06G15/04G65.

REFERENCES

[1] N. Duc Anh and D. T. Do, "The maximal SINR selection mode for 5G millimeter-wave MIMO: Model systems and analysis," *Indonesian Journal of Electrical Engineering and Computer Scienc*., vol. 7, no. 1, pp. 150-157, 2017.

[2] I. Hosako, N. Sekine, and M. Patrashin, "At the dawn of a new era in terahertz technology," *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1611-1623, 2007.

[3] T. S. Rappaport, J. N. Murdock, and F. Gutierrez, "State of the art in 60-GHz integrated circuits and systems for wireless communications," *Proceedings of the IEEE 2011*, vol. 99, no. 8, pp. 1390-436, 2011.

[4] A. M. Mousa, "Prospective of fifth generation mobile communications," *International Journal of Next-Generation Networks (IJNGN*), vol. 4, no. 3, pp. 203-207, 2012.

[5] S. Chen and J. Zhao, "The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication," *IEEE Communications Magazine*, 2014.

[6] M. W. Sabri, N. A. Murad, and M. K. A. Rahim, "Highly directive 3D printed dual beam waveguide slotted antenna for millimeterwave apllications," *Microwave and Optical Letters (MOTL*), vol. 61, pp. 1566-1573, 2019.

[7] E. Hossain, "Evolution toward 5G multi-tier cellular wireless networks: An interference management perspective," *IEEE Wireless Communications*, vol. 21, no. 3, pp. 118-127, 2014.

[8] W. Xidong, Y. Fan, and A. Jinfang, "Circularly polarized waveguide antenna with dual pairs of radiation slots at Ka-band," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2947-2950, 2017.

[9] D. Ali, S. T. Wayne, and G. Kamran, "Split-ring slot in the broad-wall of a rectangular waveguide," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 991-994, 2014.

[10] L. Teng, M. Hongfu, and D. Wenbin, "Design and implementation of dual- frequency dual-polarization slotted waveguide antenna array for Ka-band application," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 1317-132, 2014.

[11] D. S. Ramkiran, B. T. P. Madhav, K. Narasimha Reddy, S. Shabbeer, Pr. Jain, and S. Sowmya, "Coplanar wave guide fed dual band notched MIMO antenna," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 6, no. 4, pp. 1732-1741, 2016.

[12] K. Sakakibara, T. Watanabe, K. Sato, and K. Nishikawa, "Millimeter-wave slotted waveguide array antenna manufactured by metal injection molding for automotive radar systems," *Ieice Transactions on Communications*, E84-B (9), 2001.

[13] G. P. Le Sage, "3d printed waveguide slot array antennas, *IEEE Access*, vol. 4, pp. 1258-1265, 2016.

[14] J. Tak, A. Kantemur, Y. Sharma, and H. Xin, "A 3-D-printedw-band slotted waveguide array antenna optimized using machine learning," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 11, pp. 2008-2012, 2018.

[15] R. S. Elliott, *Antenna Theory and Design*, Revised Edition, John Wiley & Sons, pp. 305-315, 2003.

[16] Y. E. Yamac and A. Kizilay, "A waveguide slot array antenna design for X-band radar," *2016 9th International Kharkiv Symposium on Physics and Engineering of Microwaves, Millimeter and Submillimeter Waves (MSMW)*, Kharkiv, pp. 1-5, 2016.

[17] P. Kumar, A. Kedar, and A. K. Singh, "Design and development of low-cost low sidelobe level slotted waveguide antenna array in X-band," in *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 11, pp. 4723-4731, 2015.