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Review on Millimeter Wave Antennas- Potential Candidate for 5G Enabled Applications

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Abstract

The millimeter wave (mmWave) band is considered as the potential candidate for high speed communication services in 5G networks due to its huge bandwidth. Moreover, mmWave frequencies lead to miniaturization of RF front end including antennas. In this article, we provide an overview of recent research achievements of millimeter-wave antenna design along with the design considerations for compact antennas and antennas in package/on chip, mostly in the 60 GHz band is described along with their inherent benefits and challenges. A comparative analysis of various designs is also presented. The antennas with wide bandwidth, high-gain, compact size and low profile with easiness of integration in-package or on-chip with other components are required for 5G enabled applications.

1. Introduction

The operation of 5G enabled applications will be determined based on the spectrum selection, propagation characteristics, antenna technology, transceiver integration, and digital signal processing of wideband technology. The mmWave spectrum is the potential candidate for such wireless technologies due to its huge bandwidth. Therefore, the substantial knowledge about the mmwave spectrum and their characteristics has been collected and a great deal of work has been done toward evolving 5G wireless systems for commercial applications in the last few years. The attractive features of 60 GHz wireless system make it a choice for such wireless systems. The antenna is the most crucial components of wireless systems as it intensely affects the total receiver sensitivity, thus transceiver designs and choices of digital modulation schemes and the link budget. As a result, the investigation of 60 GHz antenna technology has attracted increasing attention and remarkably, the analysis and design of those antennas is widely reported in numerous research papers [1-8].In [2], a multi-layer antenna is presented with mounted horn integrated on FR4, which can achieve a gain of 11.65 dBi. A low-loss/cost substrate integrated waveguide (SIW) feeding scheme to microstrip printed antenna (MPA) is presented in [9] for the first time with the aim of improving the radiation efficiency which was degraded due to conventional planar feeding arrangement in 60-GHz band. In [3], SIW-fed patch array antenna is proposed that can realize a gain 19.6 dBi. The Yagi antenna using LTCC technology in [4] has a max gain of 6 dBi. The 4 × 4 array of Yagi antenna in [5] can achieve a maximum gain of 18 dBi. Nevertheless, these antennas structures are either multi-layered or complex structures, which perhaps fetch difficulties in fabrication. For simplicity of fabrication, Printed log-periodic dipole array (PLPDA) antennas are designed in the mmwave frequency which provides enormous bandwidth with stable gain over the entire frequency range as well as simple geometrical design [10]. A planar fan-like antenna has also demonstrated in [8], which has a peak gain of 7.6 dBi for 60 GHz antenna. Recently, a simple planar antenna with two blade-like antipodal tapered slot patches is reported. The antenna can achieve gain of 10 dBi across 57–64 GHz [11].

It is found from the open literature that there have been many significant developments in the past few years on mmWave antennas. This paper surveys recent advances in research related to mmWave antennas hoping that it will provide valuable information to the reader whose intention is to do research in the area of mmWave antennas for possible integration in future 5G wireless systems. The paper is structured as follows: section 2 describes the regulations and antenna gain requirement for 60 GHz communication. Section 3 highlights the desirable properties of 60 GHz antennas. Section 4 discusses the recent developments of 60 GHz antenna technology with a performance comparison of various designs. The integration of 60 GHz antenna focuses in section 5. Finally, the author draws a conclusion in section 6.

2. 60 GHz regulations and Link budget analysis

The radio-frequency covering the range 30 to 300 GHz is termed as millimeter-wave frequency or extremely high-frequency. The mmWave frequency has appealed a lot of attention due to multi-gigabit communication services including high definition multimedia interface, uncompressed high definition video streaming, high-speed internet, wireless gigabit Ethernet, and close-range automotive radar sensor. However, there have been apprehensions about exploiting mmWave frequency bands owing to higher penetration, precipitation, and foliage losses and the actual amount of these additional propagation losses is varied based on building material, the strength of rain, or the thickness of foliage [12]. The phenomenon of larger path loss and oxygen absorption of 10 to 15 dB per km near 60 GHz band makes 60-GHz link small which allow frequencies to be reused more often to increase the network capacity. This is an attractive feature in developing system design for future 5G wireless communication but required high gain antenna. Therefore, antenna arrays with high gain and high-efficiency characteristics are desired in the system design to reduce the cost as well as system performance improvement. Link budget analysis is required to obtain entailed antenna gain for 60 GHz communication. The link budget for largely integrated 60-GHz radios is inadequate. The low transmit power (shown in table 1) and huge path loss at 60 GHz band (68 dB @ 1 m) demands the directional antennas for high data rate, mainly for line-of-sight (LOS) applications. A list of allocated spectrum with maximum transmission power for 60 GHz radio is shown in table 1.

In case of non-line-of-sight applications, antenna array with high gain and beamforming capabilities is expected for enhancing the link budget and avoiding multipath propagation loss. This usually requires larger arrays, but again high precision fabrication techniques are required as well as error tolerant designs and low loss interconnection. In all cases adequate broadband channel models are required to enable system level design.

Table 1: Spectrum with maximum transmission power for 60 GHz radio

Countries	Spectrum (GHz)	Maximum Tx power (mW)	Maximum antenna gain (dBi)
Japan	59-66	10 mW-250mW	47
USA	57-64	500	-
Canada	57-64	500	-
Australia	59.4-62.9	10	-
Europe	57-66	20	37
China	59-64	10	34
Korea	57-64	10	-

3. Design considerations for mmWave antennas

The 5G wireless communication systems need to be designed to support high speed and high data rates with maximum coverage for different applications, such as sensor networks and smart buildings. One of the most essential requirements of such systems is high gain antenna which is desirable as it will balance high path loss at mmWave frequency and decrease the system cost. The other desirable properties for such antenna design are as follows:

- High-efficiency and stable radiation patterns over the entire desired band
- . Compact size and low profile with simplicity of integration with other elements
- Multi-antenna technology

The increase in the gain and efficiency of an antenna are counterpoise by higher propagation loss at high frequencies, so the received signal level needs to be higher. Multi-antenna technology increases the receiving signal quality by producing high gain steerable beams to maintain the link. The miniaturization of RF front end and system integration on-package or on-chip without compromising its radiation efficiency, bandwidth and achievable gain are required for high frequency system design. The designed system capacity can be increased by using multiplexing techniques based on baseband signal processing.

Another important design consideration is the feeding structure as the types of feeding arrangement are of great importance in the design of antenna array at mmWave frequencies. Traditional planar feeding arrangements such as microstrip lines and coplanar waveguides experience conduction and radiation losses at mm-wave frequencies, which reduce the overall radiation efficiency and restrict the realizable gain of antenna arrays. The waveguide structure with lower losses is preferred in compare with the microstrip line for the designing of high-gain millimeter-wave antenna arrays, but not suitable for large-scale production due to huge fabrication costs and bulky volume. Therefore, Substrate integrated waveguide (SIW) has attracted as alternate choice for millimeter-wave applications which has low-loss characteristics, with planar structure, and low fabrication costs.

4. 60 GHz antenna technology and comparative analysis

The typical antennas for mmWave communication systems are reflector, lens and horn antennas [13]. These kinds of antennas possess high gain. However, these antennas are not attractive for commercial 60-GHz radios due to high cost, massive size, as a result not possible to integrate on a chip or in a package. Thus, researchers have switched to printed antenna arrays for mmWave systems. Printed antennas arrays for example microstrip patch or dipole arrays possess various distinct and attractive features, such as—low profile, small mass, compact and conformable in structure, and ease of fabrication and integration on a chip or in a package. As a result, they are much attractive for commercial 60-GHz radios and hard work is now being commenced for mass market deployment. In [14], a 60-GHz horn-type antenna array is presented which can be made of a multilayered structure by applying multilayer PCB technology. The other designs for 60 GHz antenna technology include patch with Substrate Integrated Waveguide (SIW), multi-layer and multi-patch designs, and different shape with multi slotted patch and so on [15]–[33]. Out of these antennas, different shapes of slotted antenna are normally used to improve the antenna performances due to their geometrical simplicity. In this section, various types of mmWave antennas for 60 GHz band that show huge flexibility and design capability for low-cost, low-profile, low-loss (L3) are illustrated in Table 2 & 3 for comparison. The selection of the antenna element for constructing the antenna array influences the design and characteristics of millimeter-wave antenna array and the fabrication complexity of the array is directly affected by the geometry of the single element. Table 2 shows the type of antenna used in the open literature and their characteristics such as, impedance bandwidth, gain, fabrication technology and overall dimensions of antenna with linear polarization for the 60 GHz band. Few selected antennas are presented here as reference.

Table 2: Linear polarization for 60 GHz applications

Published literature	Type	No. of elements	BW%	Fabrication technology	Substrate type	Gain[dBi]	Antenna size dimension (mm^3)
Ref.[21]	Grid	60	18.7	LTCC*	-	17.7	15×15×0.6
Ref.[22]	Patch with embedded cavity	16	9.5	LTCC	-	18.2	18.6×18.6×0.6
Ref.[23]	L-probe patch with soft surface	16	29%	LTCC	-	17.5	14.4×14.4×1
Ref.[24]	Cavity	64	17.1	SIW, LTCC	Ferro A6-M	22.1	24.6×31×2
Ref.[25]	Loop-loaded dipole	14	22.1	PCB*	Duroid 5880	20.1	20×20×0.254
Ref. [3]	Cavity-backed Patch	16	22.6	SIW, PCB	Rogers 5880	19.6	16.3×17.1×2.3
Ref. [26]	Slot	256	12.1	PCB	-	32	75×76×6.3
Ref. [27]	Slot	144	4.1	SIW, PCB	Rogers RT/Duroid 6002	22	30.7×30.7×0.508
Ref. [28]	Cavity-backed wide slot	8	11.6	SIW, PCB	RO3006	12.2	14×13.5×0.635
Ref. [39]	Dipole antenna	16	1.63	LTCC	-	15.6	N/A
Ref. [40]	Microstrip grid	N/A	26.83	LTCC	-	15	15×15×1
Ref. [24]	Aperture antenna	64	17	LTCC	-	22.1	N/A
Ref. [41]	Patch antenna	16	22.6	LTCC	-	17	N/A

Table 3: Circular polarization for 60 GHz applications

Published literature	Type	No. of elements	BW%	Fabrication technology	Substrate type	Gain[dBi]	Antenna size dimension (mm^3)
Ref. [46]	Grid	4	16.4			14.3	15×15×0.9
Ref. [43]	U-slot patch	16	28.1	LTCC	-	16	14×16×1.1
Ref. [45]	Helical antenna	16	22	LTCC	-	15.2	12×10×2
Ref. [44]	Hexagonal cavity	256	5.7			33.3	67.2×67.2
Ref. [19]	L-probe patch	16	17.8	CPW, PCB	Rogers Duroid 5880	14.5	14×15.2
Ref. [42]	Aperture coupled patch	4	6.7	SIW, PCB	Rogers	12.2	6.8×6.9
Ref. [38]	Slot-coupled rotated dipole	16	14.4% (-6 dB)	SIW, LTCC	Ferro A6-M	12.5	15.2×15.2
Ref. [31]	ME dipole	64	18.2	PCB	Rogers 5880	26.1	30.6×34×2.361
Ref. [47]	Patch antenna	16	19.67	LTCC	-	17.1	13×13×0.9
Ref. [48]	Patch antenna	16	20.44	LTCC	-	35	13×20×1.4

Studies on the propagation at 60 GHz demonstrate that the polarization of antenna plays a crucial role in mmWave band. The wave with circular polarization can provide more promising channel performance compared with the linearly polarized wave. Circular polarized high-gain antenna array is a desirable candidate at 60 GHz. A list of different designs with circular polarization for 60 GHz spectrum is given (table 3).The applications of circular polarized antenna include secured communication in space mission, high resolution sensor, portable imaging device and microwave energy harvesting.

5. Technologies for Integrated mmWave antennas

This section focuses on two solutions in regards to the antenna integration for 60 GHz which are -antennas on chip (AoC) and antenna in package (AiP). The 60-GHz radios to be adopted for 5G and to cover mass market products and to convene consumer demands, the cost, size and power consumption of antenna-on-chip or antenna-in-package solution must be kept as small as possible. These suggests silicon rather than GaAs as a better choice and the integrated circuit(IC) using silicon technology offers the greatest cost and power savings, especially while considering packaging, integration, and interconnect issues. Due to the latest advancement of integrated circuits (ICs), the complete integration of RF components on a single chip can be achieved except the antenna which often remains off-chip. Because, integrated antennas on chip exhibit quit low gain and poor radiation efficiency due to high permittivity and low resistivity of silicon substrate. The performance can be improved using a high resistivity (HR) silicon substrate. Therefore, to get a good-performance low-cost SoC, the antenna and ICs need to be integrated on HR Silicon-on-Insulator (SOI) CMOS.

However, the antenna array designs on Si substrate suffer from large insertion losses into the planar feeding arrangement at mmwave frequencies. Therefore, the crossbreed integration of the antenna on an additional substrate is an innovative technology, which exploits packaging (AiP) and coupling possibilities within such limited space. The desirable trend for front-end miniaturization and system integration on-package or on chip raises the challenge for antenna integration without sacrificing its radiation efficiency, bandwidth and achievable gain. The advantages and disadvantages of AiP and AoC are listed in table 4.

Fabrication process is employed to realize the design and low fabrication cost with good performance mmWave antenna arrays that are attractive and affordable for future 5G wireless communications. To meet the requirements for compact and high performance 5G wireless systems, Low-Temperature Cofired Ceramic (LTCC) can be used for packaging. LTCC owns the merits of multilayer fabrication capability, stability, and relatively low cost [34], it has become a good choice. On the other hand, Printed circuit board (PCB) technology encounters some problems at very high frequency, that severely distress the system performance and causes reduced efficiency [35]. Compared with PCB technology, LTCC technology is easier to grasp mmWave antenna array structures. The LTCC technology gets preference for most of arrays with multilayered structure and a lot of research papers have been published on compact antenna array for 60 GHz radio applications [36-38].

Table 4: Advantages and disadvantages of AiP and AoC

	Advantages	Disadvantages
AoC	Integration simplicity and compactness	Low gain, low efficiency and degrade the overall system's signal to noise ratio (S/N)
AiP	High performance antenna with low loss substrate	Integration and packaging complexity. Potential performance degradation due to hybrid interconnection.

5.1. Fabrication processing

The mmWave antenna designs using low temperature co-fired ceramic (LTCC) process are getting increasing attention due to the flexibility in realizing arbitrary number of layers, cross-layer vias, open and embedded cavities [50]. On the other hand, multi-layer PCB technology incurs high mechanical manufacturing cost due to the usage of blind or buried vias. Moreover, PCB technology faces difficulties in the very high frequency band, which brutally affect the system performance and result in reduced efficiency. Therefore, the LTCC technology is the choice of most of arrays with multilayered structures and in general, it can improve antenna performance. Apart from these fabrication technologies, Die-sink electrical discharge machining (EDM) process offers new opportunities for fabrication of cost effective mmWave antennas. Few examples are given in this paper.

a. PCB Process

The traditional printed circuit board (PCB) process offers low cost design. However, PCB based mmWave antenna design encounters few challenges including fabrication tolerance and reliability of the process. In [20], a center-fed patch antenna array is presented which is derived from the inset dielectric waveguide (IDW) using traditional PCB technology. The presented series-fed patch array antenna can realize comparatively large gain for mmWave applications in compare to the parallel-fed antenna arrays. It also provides a broad bandwidth in compare with the conventional series -fed slot arrays.

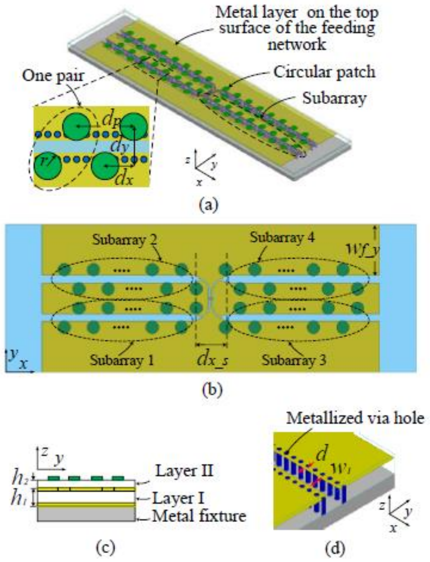

Figure 1: 3D-view, top view and side view of IDW fed patch antenna array [20]

b. LTCC process

It is mentioned earlier that LTCC is a multilayer technology which is being exploited for packaging integrated circuits (ICs) and applied to modern wireless communications for single-chip transceiver with comparatively low cost and mass productivity. Figure 2 shows an example of antenna design using LTCC process.

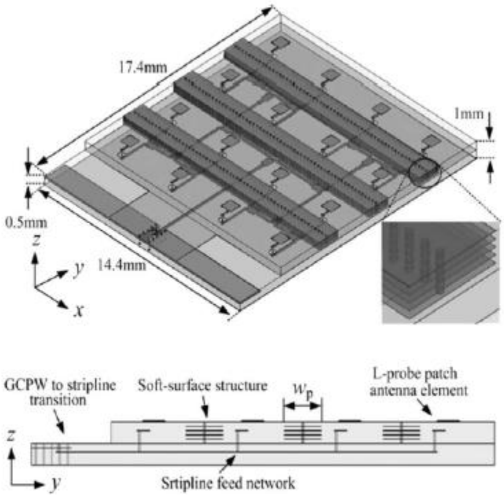

Figure 2: The L-probe patch array antenna [23]

c. Die-sink Electrical Discharge Machining (EDM)

Die-sink electrical discharge machining (EDM) process is a thermoelectric phenomenon which is widely applied in die and mold industries. Recently, this process is used in mmWave antenna design. In [49], a 8×8-slot planar array is designed from a fully corporate distribution network in ridge gap waveguide technology. This design process introduces new fabrication method called die-sink EDM or die forming which can offer low-cost millimeter wave antennas for 5G wireless systems.

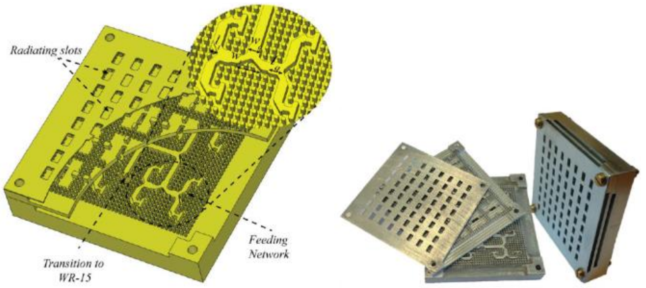

Figure 3: Corporate-fed planar slot antenna array for 60 GHz [49]

6. Conclusions

Due to attractive features of mmWave technology, researchers explore this technology for potential applications in 5G wireless systems. The mmWave antennas affect or control the overall performance of such system. The aim of this article is to investigate the recent development made in mmWave antennas. It also highlights the feasibility of antenna in package (AiP) and antenna on chip (AoC) using LTCC and PCB technology.

References

[1] R. A. Alhalabi, Y.-C. Chiou, and G. M. Rebeiz, ―Self-shielded high-efficiency Yagi-Uda antennas for 60GHz communications," *IEEE Trans. on Antennas and Propagat.*, Vol. 59, No. 3, 742–750, 2011.

[2] W. T. Sethi, H. Vettikalladi, B. K. Minhas, and M. A. Alkanhal, ―High gain and wide-band aperture-coupled microstrip patch antenna with mounted horn integrated on FR4 for 60GHz communication systems," *IEEE Symposium on Wireless Technology and Applications (ISWTA)*, 359–362, 2013.

[3] Y. Li and K.-M. Luk, ―Low-cost high-gain and broadband substrate integrated-waveguide-fed patch antenna array for 60-GHz band," *IEEE Trans. on Antennas and Propagat.*, Vol. 62, No. 11, 2014.

[4] O. Kramer, T. Djerafi, and K. Wu, ―Very small footprint 60 GHz stacked Yagi antenna array," *IEEE Trans. on Antennas and Propagat.*, Vol. 59, No. 9, 3204–3210, 2011.

[5] M. Sun, Y. P. Zhang, K. M. Chua, L. L. Wai, D. Liu, and B. P. Gauche, ―Integration of Yagi antenna in LTCC package for differential 60-GHz radio," *IEEE Trans. on Antennas and Propagat.*, Vol. 56, No. 8, 2008.

[6] A. Dadgarpour, B. Zarghooni, B. S. Virdee, and T. A. Denidni, ―Millimeter-wave high-gain end-fire bow-tie antenna," *IEEE Trans. on Antennas and Propagat.*, Vol. 63, No. 5, 2337–2342, 2015.

[7] P. Cabrol and P. Pietraski, ―60 GHz patch antenna array on low cost liquid crystal polymer (LCP) substrate," *IEEE Systems, Applications and Technology Conference (LISAT)*, 1–6, 2014.

[8] M. Sun, X. Qing, and Z. N. Chen, ―60-GHz end-fire Fan-like antennas with wide beamwidth," *IEEE Trans. on Antennas and Propagat.*, Vol. 61, No. 4, 1616–1622, 2013.

[9] W. M. Abdel-Wahab, S. Safavi-Naeini, ―Wide bandwidth 60 GHz aperture-coupled microstrip patch antennas (MPAs) fed by substrate intergrated waveguide", *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1003–1005, 2011.

[10] H.-T. Hsu and T.-J. Huang, ―A koch-shaped log-periodic dipole array (LPDA) antenna for universal ultra-high-frequency (UHF) radio frequency identification (RFID) handheld reader," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 9, pp. 4852–4856, 2013.

[11] Ning Wang and PengGao, ―A 60GHz End-Fire High-Gain Tapered Slot Antenna with Side-Lobe Suppression" *Progress In Electromagnetics Research Letters*, Vol. 55, 2015.

[12]A. I. Sulyman, A. T. Nassar, M. K. Samimi, G. R. Maccartney, T. S. Rappaport, and A. Alsanie, ―Radio propagation path loss models for 5G cellular networks in the 28 GHZ and 38 GHZ millimeter-wave bands," *IEEE Commun. Mag.*, vol. 52, no. 9, pp. 78-86, 2014.

[13] R. B. Dybdal, ―Millimeter wave antenna technology," *IEEE J. Sel. Areas Commun*., vol. 1, no. 4, pp. 633–644, Sep. 1983.

[14] A. Enayati, G. A. E. Vandenbosch, and W. D. Raedt, ―Millimeter-wavehorn-type antenna-in-package solution fabricated in a teflon-basedmultilayer PCB technology," *IEEE Trans. Antennas Propag*., vol. 61,no. 4, pp. 1581–1589, Apr. 2013.

[15] Z. Nasimuddin, and N. Chen, ―Multipatchs multilayered UWB microstrip antennas", *IET Microwaves, Antennas & Propagation*, vol. 3, no. 3, pp. 379–386, 2009. [Online]. Available: http://dx.doi.org/10.1049/iet-map.2008.0181

[16] W. M. Abdel-Wahab, and S. Safavi-Naeini, ―Wide bandwidth 60 GHz aperture-coupled microstrip patch antennas (MPAs) fed by substrate integrated waveguide", *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 1003–1005, 2011. [Online]. Available: http://dx.doi.org/10.1109/LAWP.2011.2168373.

[17] Y. Sung, ―Bandwidth enhancement of a microstrip line-fed printed wide-slot antenna with a parasitic center patch", *IEEE Trans. Antennas and Propagation*, vol. 60, pp. 1712–1716, 2012.[Online]. Available: http://dx.doi.org/10.1109/TAP.2012.2186224

[18] J. J. Tiang, M. T. Islam, N. Misran, ―Slot loaded circular microstrip antenna with meandered slits", Journal of Electromagnetic Waves and Applications, vol. 25, no. 13, pp. 1851–1862, 2011. [Online]. Available: http://dx.doi.org/10.1163/156939311797454042

[19] M. J. Li and K. M. Luk, ―Low-cost wideband microstrip antenna array for 60-GHz applications,"

IEEE Trans. Antennas Propag., vol. 62, no. 6, pp. 3012–3018, Jun. 2014.

[20] X Bai, S-W Qu, K B Ng, ―Center-fed patch antenna array excited by an inset dielectric waveguide for 60-GHz applications, *IEEE Trans. Antennas Propag.*, May 2016.

[21] B. Zhang and Y. P. Zhang, ―Grid array antennas with subarrays and multiple feeds for 60-GHz radios," *IEEE Trans. Angtennas Propag.*, vol. 60, no. 5, pp. 2270–2275, May 2012.

[22] A. Lamminen, J. Saily, and A. R. Vimpari, ―60 GHz patch antennas and arrays on LTCC with embedded cavity substrates," *IEEE Trans. Angtennas Propag.*, vol. 56, no. 9, pp. 2865–2874, Sep. 2008.

[23] 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 Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1802–1809, Apr. 2013.

[24] J. F. Xu, Z. N. Chen, X. M. Qing, and W. Hong, ―Bandwidth enhancement for a 60 GHz substrate integrated waveguide fed cavity array antenna on LTCC," *IEEE Trans. Antennas Propag.*, vol. 59, no. 3, pp. 826–832, Mar. 2011.

[25] M. J. Li and K. M. Luk, ―A low-profile unidirectional printed antenna for millimeter-wave applications," *IEEE Trans. Angtennas Propag.*, vol. 62, no. 3, pp. 1232–1237, Mar. 2014.

[26] Y. Miura, J. Hirokawa, M. Ando, Y. Shibuya, and G. Yoshida, ―Double-layer full-corporate-feed hollow-waveguide slot array antenna in the 60-GHz band," *IEEE Trans. Antennas Propag.*, vol. 59, no. 8, pp. 2844–2854, Aug. 2011.

[27] X. P. Chen, K. Wu, L. Han, and F.He, ―Low-cost high gain planar antenna array for 60-GHz band applications," *IEEE Trans. Antennas Propag.*, vol. 58, no. 6, pp. 2126–2129, June 2010.

[28] K. Gong, Z. N. Chen, X. M. Qing, P. Chen, and W. Hong, ―Substrate integrated waveguide cavity-backed wide slot antenna for 60-GHz bands," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp.6023–6026, Dec. 2012.

[29] Y Wanlan, M Kaixue, K S. Yeo, and W M Lim, ―A compact high-performance patch antenna array for 60-GHz applications" *IEEE Antennas Wireless Propag. Lett.*, vol.15, pp. 313-316, Feb. 2016.

[30] M O Sallam, M Serry, S Sedky, and A Shamim, ―Micromachined On-Chip Dielectric resonator Antenna operating at 60 GHz" ," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3410-3416, Aug. 2015.

[31] Y Li, and K M Luk, ―A 60-GHz wideband circularly polarized aperture coupled magneto-electric dipole antenna array" *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1325–1333, April 2016.

[32] H. Vettikalladi, O. Lafond, and M. Himdi, ―High-efficient and high gain superstrate antenna for 60-GHz indoor communication," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1422–1425, 2009.

[33] A. Lamminen, J. Saily, and A. R. Vimpari, ―60-GHz patch antennas and arrays on LTCC with embedded-cavity substrates," *IEEE Trans. Antennas Propag.*, vol. 56, no. 9, pp. 2865–2874, Sep. 2008.

[34] K. Lim, S. Pinel, M. F. Davis, A. Sutono, C.-H.Lee, D.Heo, A. Obatoynbo, J. Laskar, E.M. Tentzeris, and R. Tummala, ―RF system- on-package (SOP) for wireless communications," *IEEE Microwave Magazine*, Vol.3, No.1, pp.88-99, Mar. 2002.

[35] Y. Imanaka, ―Multilayered Low Temperature Cofired Ceramics (LTCC) Technology". Berlin, Germany: Springer-Verlag, 2005.

[36] J. F. Xu, Z. N. Chen, X. M. Qing, and W. Hong, ―Bandwidth enhancement for a 60 GHz substrate integrated waveguide fed cavity array antenna on LTCC," *IEEE Trans. Antennas Propag.,* vol. 59, no. 3, pp. 826–832, Mar. 2011.

[37] J. F. Xu, Z. N. Chen, X. M. Qing, and W. Hong, ―140-GHz TE20- mode dielectric-loaded SIW slot antenna array in LTCC," *IEEE Trans. Angtennas Propag.,* vol. 61, no. 4, pp. 1784–1793, Apr. 2013.

[38] Y. Li, Z. N. Chen, X. M. Qing, Z. J. Zhang, J. F. Xu, and Z. H. Feng, ―Axial ratio bandwidth enhancement of 60-GHz substrate integrated waveguide-fed circularly polarized LTCC antenna array," *IEEE Trans. Angtennas Propag.,* vol. 60, no. 10, pp. 4619–4626, Oct. 2012.

[39] C. Hui, Y.-X.Guo, and Z. Wang, ―60-GHz LTCC wideband vertical off-center dipole antenna and arrays," *IEEE Trans. Antennas Propag.,* vol. 61, no. 1, pp. 153–161, Jan. 2013.

[40] Z. Bing, D. Titz, F. Ferrero, C. Luxey, and Z. Zhang, ―Integration of quadruple linearly-polarized microstrip grid array antennas for 60-GHz antenna-in-package applications," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 3, no. 8, pp. 1293–1300, Aug. 2013.

[41] L. Duixian, J. A. G. Akkermans, H.-C.Chen, and B. Floyd, ―Packages with integrated 60-GHz aperture-coupled patch antennas," *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3607–3616, Oct. 2011.

[42] A. B. Guntupalli and K. Wu, ―60-GHz circularly polarized antenna array made in low-cost fabrication process," *IEEE Antennas Wireless Propag. Lett.,* vol. 13, pp. 864–867, 2014.

[43] H. C. Sun, Y. X. Guo, and Z. L. Wang, ―60-GHz circularly polarized U-slot patch antenna array on LTCC," *IEEE Trans. Antennas Propag.,* vol. 61, no. 1, pp. 430–435, Jan. 2013.

[44] Y. Miura, J. Hirokawa, M. Ando, K. Igarashi, and G. Yoshida, ―A circularly-polarized aperture array antenna with a corporate-feed hollow waveguide circuit in the 60 GHz-band," *2011 IEEE AP-S Int. Sym.,* Session: 429.2, July 2011.

[45] C. Liu, Y. X. Guo, X. Bao, and S. Q. Xiao, ―60-GHz LTCC integrated circularly polarized helical antenna

array," *IEEE Trans. Antennas Propag*., vol. 60, no. 3, pp. 1329–1335, Mar. 2012.

[46] B. Zhang, Y. P. Zhang, D. Titz, F. Ferrero, and C. Luxey, ―A circularly-polarized array antenna using linearly-polarized sub grid arrays for highly-integrated 60-GHz radio," *IEEE Trans. Antennas Propag*., vol. 61, no. 1, pp. 436–439, Jan. 2013.

[47] W. Zhang, Y. P. Zhang, M Sun, C Luxey, D Titz and F Ferrero, ―A 60-GHz circularly-polarized array antenna-in package in LTCC technology," *IEEE Trans. Antennas Propag.,* vol. 61, no. 12, pp. 6228–6232, Dec. 2013.

[48] M. Sun, Y. Q. Zhang, Y. X. Guo, M. F. Karim, O. L. Chuen, M. S. Leong, ―Integration of circular polarized array and LNA in LTCC as a 60-GHz active receiving antenna," *IEEE Trans. Antennas Propag.*, vol. 59, no. 8, pp. 3083–3089, Aug. 2011.

[49] A. Vosoogh, P. Kildal, "Corporate-Fed Planar 60 GHz Slot Array Made of Three Unconnected Metal Layers Using AMC pin surface for the Gap Waveguide". *IEEE Antennas Wireless Propag. Lett.,* vol.pp, 1-4, no. 99, Dec. 2015.

[50] Z. N. Chen, X. Qing, M. Sun, K. Gong, and W. Hong, "60-GHz antennas on PCB", proc. of 8th European Conference on Antennas and Propagation (EuCAP 2014), pp. 643-646, 6-11 April, 2014.