A multiple-input-multiple-output on-chip Quasi-Yagi-Uda antenna for multigigabit communications: Preliminary study

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Abstract
This article presents a solution for the low gain and the poor efficiency of the on-chip antennas (OCA). The four elements of Quasi-Yagi-Uda antennas (QYUA) are introduced based on the diversity technique to reduce the interference between the elements. In addition, these antennas achieve high isolations between them due to the use of reflector for each antenna. The QYUA is selected to improve the radiation properties of the end-fire radiator in the millimeter-wave range for on-chip systems. The proposed MIMO antenna is used for the point to point communications. The complementary metal-oxide semiconductor with 180 nm standard is used in the antenna design with six metal layers. The QYUA combines three parts (driven element, reflector, and director); the driven consists of two meander lines fed by coplanar-slot and operates as a dipole, the reflector is an arc like a semicircle to prevent the back radiation and increase the front to back ratio, and the director is a meander line to directive the radiation into the proposed direction (front end-fire direction). All MIMO parameters such as envelope correlation coefficient, channel capacity loss, diversity gain, and total active reflection coefficient in addition to the different configurations of the MIMO are presented. All results are verified by computer simulation technology and high-frequency structure simulator. The contribution of this article is the MIMO antenna design for point to point communications to serve multigiga communications systems with high data rate and high gain. This MIMO system is considered here to solve the problems of OCA designs.

KEYWORDS
antenna on chip, CMOS, end-fire, meander line, millimeter wave, multiinput multioutput, Quasi Yagi-Uda
1 \ | INTRODUCTION

Nowadays, with the fast development of communication techniques, wireless short-range communications require broadband, higher data rates, and compact size systems. The low-frequency bands are very crowded.\(^1\) Therefore, the millimeter-wave band at 60 GHz has attracted more and more attention in order to meet the required demands as it has unlicensed bandwidth (from 57 to 64 GHz) for several applications such as video streaming, wireless gaming, imaging, bacteria detection, and indoor networking.\(^2-9\) One of the new applications that are a candidate to use the on-chip antennas (OCA) is the 5G (future wireless communication systems).\(^10\) The antenna at this frequency band is the key component of the system on chip. Therefore, several studies are reported to improve the features of the antennas at this band, because these reported antennas suffer from the low gain, low efficiency, small transmission distance, high coupling between array elements, and complicated structures.\(^5,7,10-13\)

The aforementioned requirements have been led the companies to tend toward the on-chip technology because the links between RF circuits and off-chip antennas in the 60-GHz band produce parasitic elements, loss of radiation, decreasing circuit efficiency, and difficulty in the designs. Moreover, the off-chip antennas significantly increase the size of the devices. Fortunately, the antennas on-chip do not suffer from the aforementioned problems. On the other hand, compared with the low resistivity of the silicon substrate used in complementary metal-oxide semiconductor (CMOS) systems, the OCA usually have bad radiation efficiency as a result of extensive research to solve this problem.\(^5,11,12,14,15\) The literature reported six different approaches to solve these problems. The first approach depends on the antenna configuration: a slot antenna as an elliptical shape in Reference 16, a ring shape with quartz superstrates loaded in Reference 14 and slotted patch antenna (three different shapes: rectangular, diamond, and circular) in Reference 13 are introduced to enhance the radiation performance of the OCA, in addition to the micromachining techniques\(^17,18\) that need significant postfabrication steps to result in an additional cost. The second approach depends on the auxiliary structures: an artificial magnetic conductor (AMC), electromagnetic bandgap (EBG) structures, high impedance surface (HIS), and frequency selective surface (FSS) are used to reduce the radiation inside the CMOS substrate by reflecting the wave toward the antenna, but those methods faced difficulties in nanoscale fabrications.\(^10\) Different shapes of AMC, EBG, HIS, and FSS such as rectangular, squares, I-shapes, H-shapes, rings, and disks are introduced in the literature,\(^19-24\) but they still require a significant space or area in the chip to implement their structures in the presence of the other components of the proposed system. But it still requires significant space in the presence of embedded active circuitry to implement the necessary AMC structures.\(^10,24\)

The third approach depends on end-fire radiator: Zhang et al\(^25\) introduce Yagi-Uda-antenna (YUA) that consists of one dipole operates as a driver, two director, and truncated ground plane acts as a reflector, this is the conventional shape of YUA on standard silicon substrate with low resistive (10 $\Omega \text{cm}$) and fabricated with specific BEOL technology. This antenna has a total size (1300 $\times$ 426 $\mu$m) to achieve 10 GHz bandwidth from 55 to 65 GHz, $-12.5$ dBi gain, and 5.6% radiation efficiency. In addition, Gutierrez et al\(^26\) introduce four different antennas (dipole, Yagi antenna, loop, and rhombic), but the achieved gain still poor. Where the achieved gains are $-6.7$, $-3.5$, $-1.2$, and $-0.2$ dBi for dipole, Yagi, loop, and rhombic antennas, respectively.

The fourth approach depends on the combination between two or more from previous approaches: to improve the Yagi-Uda efficiency and gain, Bao et al\(^23\) use the AMC with the differential YUA on the 180 nm CMOS technology. The AMC improve the gain to $-2.64$ dBi and 16.6 dB front to back ratio with a total size of the antenna 2.45 $\times$ 1.8 mm\(^2\).

The fifth approach depends on the antenna array: Baniya et al\(^27\) introduce an antenna array 2$\times$2 elements to operate at 60 GHz (5 GHz bandwidth from 58 to 63 GHz) with a directional beam. This array introduces high gain due to using four elements, but still needs to solve the problems to communicate with multineighbors at the same time in different directions.

The six approach depends on multiple antenna: a multiple-input-multiple-output (MIMO) has been established through the last few years to be an essential technique in most wireless communications systems to provide the best use of communication channels either to increase system throughput or to improve channel gain. Moreover, the MIMO technology is used to enhance the reliability of communications, data rate, and capacity improvement without exhaustion of transmitted power and bandwidth. The antenna developers face two primary issues in any MIMO design; the first issue is the installation of many antennas in the small size of the proposed systems, while the second issue is the isolation between the antennas in this small area.\(^28-32\)

In this article, a compact MIMO diversity Quasi-Yagi-Uda antennas (QYUA) based on CMOS technology is introduced in this article for millimeter applications. The proposed MIMO based on diversity techniques achieves a very small mutual
coupling between the elements. This antenna is introduced to solve the inherent low gain of the OCA by using four elements MIMO antenna based on diversity topology. The antenna performs good impedance bandwidth from 50 to 68 GHz. The suggested QYUA combines of driver, reflector, director, and ground based on meander lines to reduce the physical size of the proposed antenna. Four elements MIMO antenna is introduced in order to decrees the channel capacity loss (CCL) than 0.3 bit/s/Hz.

This article is organized into four sections. Section 2 demonstrates a single element Yagi-Uda antenna design procedures and presents its results, whereas Section 3 describes the different MIMO antenna configurations and studies the performance of each configuration in addition to studying the MIMO parameters. The article is concluded in Section 4.

2 | QUASI-YAGI-UDA ANTENNA DESIGN

We introduced the single element of QYUA in Reference 5. We optimized the antenna dimension and the optimized geometry of the proposed antenna is shown in Figure 1. The QYUA is based on 180 nm CMOS technology that shown in Figure 1A. This technology consists of a base substrate from silicon (Si) with a thickness of 200 μm and thin silicon oxide layer (SiO₂) with a thickness of 10.34 μm. The SiO₂ layer consists of six metal layers, the thickness of each layer from M₁ to M₅ is 0.53 μm and the thickness of layer M₆ is 2.34 μm. Moreover, the area of 180 nm CMOS is 5 × 5 mm². The occupied size of the QYUA is 631 × 460 μm.

The QYUA combines of a driven element, a reflector element, a director element, and a ground plane. All the component of the proposed antenna is implemented on the sixth metal layer M₆. To reduce the physical size of the proposed antenna the driver element and the director element are designed as a mender line. The input feed of the proposed antenna is a coplanar-waveguide (CPW). Therefore, there is a request for a transition from CPW to coplanar-slot. The methodology of this transition introduced in Reference 33. The CPW is used for

![Figure 1: Yagi antenna geometry](image)
ground-signal-ground feeding standard in the millimeter-wave circuits. This antenna uses two reflectors, the first reflector is the ground plane when increasing its length \( W_g \) and the second reflector is the arc shape is used to avoid any back radiation and direct the full power to the front direction. All the optimized dimensions of QYUA are shown in Table 1.

The proposed antenna is designed and optimized by using two simulators to verify the results. We used computer simulation technology (CST) microwave studio version 2018 and high-frequency structure simulator (HFSS) version 15. The performance of the antenna is studied in two cases; using planar arc as the main reflector at width \( W_g = 0.18 \) mm and using the ground plane as the main reflector without the arc. The obtained return losses from CST and HFSS are close together as shown in Figure 2. The proposed QYUA covers the band from 50 to 68 GHz.

Figures 3 and 4 show the gain and radiation efficiency of the proposed QYUA with and without the arc, respectively. We notice that the arc enhance the value of gain by 0.8 dBi because it reflects the back radiation from the Yagi antenna. Furthermore, the gain of the antenna is verified by using HFSS in the two cases and there is good agreement between the results. Furthermore, the antenna efficiency is increased by using the arc to be 45%. Figure 5 illustrates the radiation pattern of the antenna in the XY plane and ZY plane at 60 and 65 GHz. There is a good agreement between the simulated radiation patterns from CST and HFSS as depicted in Figure 5. In addition, we noted that the radiation patterns of the antenna in the direction of Y-axis to ensure that the antenna has end-fire radiation. Table 2 shows the comparison between the proposed QYUA and published articles. Low profile, low complexity, compact size, high gain, high efficiency, and high front to back ratio are achieved.

![Graph of Reflection Coefficient](image1)

**TABLE 1** Optimized parameters of Quasi-Yagi-Uda antennas (μm)

| \( L_g \) | \( L_p \) | \( L_c \) | \( L_f \) | \( L_1 \) | \( L_2 \) | \( L_3 \) | \( L_4 \) | \( R_1 \) | \( R_2 \) |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 120       | 30        | 80        | 30        | 170       | 110       | 80        | 180       | 200       | 230       |
| \( W_g \) | \( W_c \) | \( W_1 \) | \( W_2 \) | \( W_3 \) | \( W_4 \) | \( W_5 \) | \( D \) | \( S \) |
| 120       | 60        | 30        | 85        | 16        | 16        | 6         | 50        | 40        |

![Graph of Gain](image2)

**FIGURE 2** Reflection coefficient of proposed Quasi-Yagi-Uda antennas with and without arc

**FIGURE 3** Gain of the Yagi-Uda antenna
3 MIMO ANTENNA

3.1 Two elements

This part introduces three different configurations of the MIMO on-chip (MOC) for two elements. Configuration I (Conf. I) introduces two elements side by side configuration with gap = 90 μm, Conf. II introduces two elements side by back configuration, and Conf. III introduces two elements back by back configuration. The three configurations of MIMO
antenna structure have two elements that provide better isolation between them without using any additional technique or decoupling circuit. The optimized geometry of the proposed three different configurations is shown in Figure 6. In this design, the ground plane and the arc play a significant role in the isolation performance of the proposed antenna. Furthermore, the diversity of the antenna positions helps to reduce coupling and achieve better isolation among them. The CST microwave studio and HFSS are used together to verify the simulated results for the S-parameters as shown in Figure 7. In this figure, only $S_{11}$ and $S_{21}$ are simulated because of the symmetrical arrangement of antenna elements in the structure. A good agreement between the simulated results of CST and HFSS is obtained. All three configurations offer good matching and high isolation because using arc as reflector between the elements. The isolation between elements is more than 40 dB that provides an enhancement in the radiation properties of antennas.

Table 3 shows a comparison between the three aforementioned configurations one can notice that all three configurations offer good matching and high isolation because using arc as reflector between the elements. The isolation between elements is more than 40 dB that provides an enhancement in the radiation properties of antennas. We notice that Conf. II has low isolation because the distance between its ports (1 and 2) is small compared with the other configuration, but it still has isolation 40 dB. On the other hand, Conf. II, and Conf. III achieve diversity in the radiation pattern and this diversity is the main factor in the MIMO designs.

3.2 | Multiple elements

In this section, a four- and eight-elements MIMO antenna are introduced as shown in Figure 8. The provided MIMO consists of two back by back and two side by back antennas. This configuration is introduced to provide high isolation between all elements. Moreover, the antennas in the proposed configuration are orthogonal together and this gives diversity in the radiation patterns. These properties of proposed MIMO indicate that antenna can be used for spatial multiplexing or pattern diversity. Figure 9 illustrates the S-parameters of the proposed MIMO antenna to ensure that the antenna covers the band from 50 to 68 GHz with good matching and high isolation. All the results are verified by CST in addition to HFSS. From 3D radiation patterns of four elements, that is, introduced in Figure 10, we notice that the radiation pattern of four elements are in a different direction because of the diversity between elements.

The configuration of eight elements MIMO antenna is introduced as shown in Figure 11. The eight elements are designed on the top layer of CMOS chip. The MIMO antenna compatibles with the chip size and achieves end-fire radiation from all elements. The good impedance matching from each port and the high isolation between ports are achieved as shown in Figure 12. This configuration can be used for multigigabit communication systems because it is based on the diversity between its elements. The eight elements are positioned in diversity to improve the isolation coefficients between elements and to achieve the high diversity gain (DG).

3.3 | MIMO parameters

Each MIMO antenna has four distinct parameters that should be tested to ensure that the MIMO gives a good performance. The MIMO parameters are applied for four-element MIMO antenna and the different MIMO configurations are similar.
**FIGURE 7** S-parameters of different configurations of two elements MIMO Yagi-Uda antenna. MIMO, multiple-input-multiple-output.

**TABLE 3** Comparison between three configurations of MIMO antennas

| Parameters     | Conf. I | Conf. II | Conf. III |
|----------------|---------|----------|-----------|
| $|S_{11}|$ (dB)   | 32      | 27       | 27        |
| $|S_{21}|$ (dB)   | 43      | 40       | 43        |
| Diversity      | No      | Yes      | Yes       |
| BW (GHz)       | 51.67   | 51.5-67  | 51.5-67   |

Abbreviation: MIMO, multiple-input-multiple-output.
Figures:

**Figure 8** Configuration of four elements MIMO antenna. MIMO, multiple-input-multiple-output

**Figure 9** S-parameters of proposed four elements MIMO antenna. MIMO, multiple-input-multiple-output

**Figure 10** Radiation pattern of proposed MIMO antenna at different ports at 60 GHz. MIMO, multiple-input-multiple-output
**FIGURE 11** Configuration of eight elements MIMO antenna. MIMO, multiple-input-multiple-output

**FIGURE 12** S-parameters of proposed eight elements MIMO antenna. MIMO, multiple-input-multiple-output

- **Envelope correlation coefficient (ECC)**

The ECC is one of the key parameters used to characterize MIMO antenna efficiency. Where it measures the relationship between the performance of the antennas in other words its value depends on the similarity of the radiation pattern and coupling between antenna elements. The following Equation (1) clarify the expression of ECC in case S-parameters:

\[
\rho_{nn} = \frac{|S_{nn}^*S_{mn} + S_{mn}^*S_{mm}|^2}{(1 - (|S_{nn}|^2 + |S_{mn}|^2)) (1 - (|S_{mm}|^2 + |S_{nm}|^2))},
\]  

where \(\rho\): ECC between the antenna elements, S: refers to the S-parameters, \(S^*\): refers to the conjugate of S-parameters, \(m\), and \(n\) are port number (\(m = 1:4, n = 1:4\)).

The value of ECC should be less than 0.5 over the operating band according to the published standards. Whereas the lower values of ECC mean that the two antennas are good isolated. Figure 13 shows the ECC between MIMO elements. It is obvious from the figure that the ECC is less than 0.0003 within the operating band.

- **Diversity gain**

The second parameter is a DG, where the DG can be expressed as.

\[
DG = 10\sqrt{1 - \text{ECC}^2}.
\]
As shown in Figure 14, the DG has 10 dBi over the impedance bandwidth, this high value of DG during the operating band due to the fact that ECC is extremely low (ECC ≅ 0).

- Total active reflection coefficient

The third parameter indicating the coupling between ports is the total active reflection coefficient (TARC). Its minimum value is 0, meaning that all incident energy is radiated, whereas the highest value is 1 meaning that all incident power is reflected. The TARC has a major impact on the MIMO antenna system's impedance bandwidth.\cite{32} The TARC is calculated by the following equations:

\[
\Gamma_a = \frac{\sqrt{\sum_{i=1}^{N} |b_i|^2}}{\sqrt{\sum_{i=1}^{N} |a_i|^2}},
\]

(3)

\[
[b] = [S][a],
\]

(4)

where \(a_i\), \(b_i\) refer to the amplitude of incident and reflected signals, respectively. \([S]\), \([a]\), and \([b]\) depict scattering matrix, vector of excitation signal, and scattered antenna vector, respectively.

To study the TARC of MIMO QYUA, we excite the MIMO antenna at port one by \(1e^{j0}\) and excite port2, port 3, and port 4 with the same amplitude, but with different excitation phases \((1e^{j\theta})\). Figure 15 shows the study of TARC at different values of excitation phases for ports 2, 3, and 4. We noted that the impedance bandwidth of the proposed MIMO still the same with varying of excitation phase. Therefore, we can observe that the operating BW of the proposed antenna is not affected by different excitation phase of the other ports.
The fourth diversity MIMO parameters is the CCL that must be has value according to this standard; CCL < 0.4 b/s/Hz. The capacity of MIMO system grow up with the increase of antenna numbers

\[ \text{CLL} = -\log_2 \det(\psi^R), \]  

(5)

\[ \psi^R = \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{bmatrix}, \quad \rho_{mn} = 1 - \left| \sum_{n=1}^{4} S_{mn} S_{nm} \right|^2, \quad \rho_{mp} = -\left| \sum_{n=1}^{4} S_{mn} S_{np} \right|, \text{ for } m, P = 1, 2, 3, \text{ or } 4. \]

Figure 16 illustrates the simulation results of the CLL for MIMO antenna by using HFSS and CST simulators. The HFSS results and CST results of CLL are less than 0.3 bits/s/Hz through the impedance bandwidth.

4 | CONCLUSION

The MIMO QYU A is proposed in this article based on 0.18 μm CMOS technology. The MIMO is introduced to increase the capacity and data rate for short range communications at 60 GHz. Furthermore, the MOC is introduced to solve the problems of low gain and low efficiency of OCA. A four elements are introduced with overall size 1.722 × 1.262 mm². Moreover, the MIMO parameters of the proposed antenna are introduced such as ECC, CCL, DG, and TARC to ensure that the MOC antenna has good performance over the full impedance bandwidth. The proposed antenna operates with good impedance matching from 50 to 68 GHz. All the simulated results are offered by tow simulators (CST and HFSS) to verify the results. The novelty of this work is underlined in providing MOC end-fire antenna with high gain and high efficiency.
compared with the related published articles, in addition to providing high-performance MIMO antenna to serve high gigabit communication systems. Currently, we work on the complete indoor communication level and its fabrication. However, the antenna design carried out in this article has effectively solved a number of significant problems in the short-range communications, but some proposed works may be recommended to further enhance for these applications by using metasurface to increase the gain and efficiency of proposed antenna in addition to using characteristic mode analysis to investigate the properties of metasurface before applying it with the OCA.

CONFLICT OF INTEREST
Authors have no conflict of interest relevant to this article.

AUTHOR CONTRIBUTIONS
Kamel Sultan Conceptualization-Lead, Methodology-Lead, Software-Lead, Writing-original draft-Lead, Writing-review & editing-Supporting; Esmat Abdallah Conceptualization-Supporting, Formal analysis-Supporting, Methodology-Supporting, Supervision-Lead, Writing-original draft-Supporting, Writing-review & editing-Equal; Hadia El hennawy Conceptualization-Supporting, Formal analysis-Supporting, Methodology-Supporting, Software-Supporting, Supervision-Lead, Validation-Equal, Writing-review & editing-Equal.

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REFERENCES
1. Huang F, Lee C, Kuo C, Luo C. MMW antenna in IPD process for 60-GHz WPAN applications. IEEE Antennas Wirel Propag Lett. 2011;10:565-568.
2. Liu Y, Agrawal A, Natarajan A. Millimeter-wave IC-antenna cointegration for integrated transmitters and receivers. IEEE Antennas Wirel Propag Lett. 2016;15:1848-1852.
3. Hsu S, Wei K, Hsu C, Ru-Chuang H. A 60-GHz millimeter-wave CPW fed Yagi antenna fabricated by using 0.18-μm CMOS technology. IEEE Electron Device Lett. 2009;29(6):625-627.
4. Kim Y, Tam S, Itoh T, Chang MF. A 60-GHz CMOS transceiver with on-chip antenna and periodic near field directors for multi-Gb/s contactless connector. IEEE Microw Compon Lett. 2017;27(4):404-406.
5. Sultan KS, Basha MA, Abdullah HH, Abdallah EA, El-Hennawy H. A 60-GHz CMOS quasi-Yagi antenna with enhanced radiation properties. Paper presented at: 12th European Conference on Antennas and Propagation (EuCAP 2018); London; 2018:1-3.
6. Sultan KS, Abdullah HH, Abdallah EA, Basha MA, El-Hennawy HH. A 60-GHz gain enhanced Vivaldi antenna on-chip. Paper presented at: 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting; Boston, MA; 2018:1821-1822.
7. Sultan KS, Ali TA, Fahmy NA, El-Shibiny A. Using millimeter-waves for rapid detection of pathogenic bacteria in food based on bacteriophage. 2019;1(1):e1026.
8. Sultan KS, Basha MA. High gain CPW coupled disc resonator antenna for THz applications. Paper presented at: 2016 IEEE International Symposium on Antennas and Propagation (APSURSI); Fajardo, Puerto Rico; 2016:263-264.
9. Sultan KS, Basha MA, Safavi-Naeini S. High gain disc resonator antenna array with CPW coupled for THz applications. Paper presented at: 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting; Boston, MA; 2018:603-604.
10. Hedayati MK, Abdipour A, Shirazi RS, et al. Challenges in on-chip antenna design and integration with RF receiver front-end circuitry in nanoscale CMOS for 5G communication systems. IEEE Access. 2019;7:43190-43204.
11. Sun Y, Babakhani A. A wirelessly powered injection-locked oscillator with on-chip antennas in 180-nm SOI CMOS for spectroscopy application. IEEE Sens J. 2019;19(7):1-4.
12. Sun Y, Babakhani A. Wirelessly-powered dielectric sensor with on-chip antennas in 180 nm SOI CMOS process. IEEE Sens J. 2019;19(7):2613-2620.
13. Xu L, Tong F, Bai X, Li Q. Design of miniaturised on-chip slot antenna for THz detector in CMOS. IET Microw Antennas Propag. 2018;12(8):1324-1331.
14. Ou Y, Rebeiz GM. Differential microstrip and slot-ring antennas for Millimeter-wave silicon systems. IEEE Trans Antennas Propag. 2012;60(6):2611-2619.
15. Singh H, Mandal S, Mandal SK, Karmakar A. Design of miniaturised meandered loop on-chip antenna with enhanced gain using shorted partially shield layer for communication at 9.45 GHz. IET Microw Antennas Propag. 2019;13(7):1009-1016.
16. Edwards JM, Rebeiz GM. High-efficiency elliptical slot antennas with quartz superstrates for silicon RFICs. IEEE Trans Antennas Propag. 2012;60(11):5010-5020.
17. Jeong-Geun K, Hyung Suk L, Ho-Seon L, Jun-Bo Y, Hong S. 60-GHz CPW-fed post-supported patch antenna using micromachining technology. IEEE Microw Wirel Compon Lett. 2005;15(10):635-637.
18. Sallam MO, Serry M, Shamim A, Sedky S, Soliman EA. Novel micromachined on-chip 10-elements wire-grid array operating at 60 GHz. Paper presented at: 2017 11th European Conference on Antennas and Propagation (EUCAP); Paris, France; 2017;202-206.

19. Hedayati MK, Abdipour A, Shirazi RS, John M, Ammann MJ, Staszewski RB. A 38 GHz on-chip antenna in 28-nm CMOS using artificial magnetic conductor for 5G wireless systems. Paper presented at: 2016 Fourth International Conference on Millimeter-Wave and Terahertz Technologies (MMWaTT); Tehran, Iran; 2016;29-32.

20. Barakat A, Allam A, Elsadek H, Kanaya H, Pokharel RK. Small size 60 GHz CMOS antenna-on-chip: gain and efficiency enhancement using asymmetric artificial magnetic conductor. Paper presented at: 2014 44th European Microwave Conference; Rome, Italy; 2014;104-107.

21. Barakat A, Allam A, Elsadek H, Abdel-Rahman AB, Hanif SM, Pokharel RK. Miniaturized 60 GHz triangular CMOS antenna-on-chip using asymmetric artificial magnetic conductor. Paper presented at: 2015 IEEE 15th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems; San Diego, CA; 2015;92-94.

22. Bao X, Guo Y, Xiong Y. 60-GHz AMC-based circularly polarized on-chip antenna using standard 0.18 μm CMOS technology. IEEE Trans Antennas Propag. 2012;60(5):2234-2241.

23. Bao X, Guo Y, Hu S. A 60-GHz differential on-chip Yagi antenna using 0.18-μm CMOS technology. Paper presented at: 2012 IEEE Asia-Pacific Conference on Antennas and Propagation; Singapore; 2012;277-278.

24. Khan MS, Tahir FA, Meredov A, Shamim A, Cheema HM. A W-band EBG-backed double-rhomboid bowtie-slot on-chip antenna. IEEE Antennas Wirel Propag Lett. 2019;18(5):1046-1050.

25. Zhang YP, Sun M, Guo LH. On-chip antennas for 60-GHz radios in silicon technology. IEEE Trans Electron Dev. 2005;52(7):1664-1668.

26. Gutierrez F, Agarwal S, Parrish K, Rappaport TS. On-chip integrated antenna structures in CMOS for 60 GHz WPAN systems. IEEE J Selected Areas Commun. 2009;27(8):1367-1378.

27. Baniya P, Bisognin A, Melde KL, Luxey C. Chip-to-chip switched beam 60 GHz circular patch planar antenna array and pattern considerations. IEEE Trans Antennas Propag. 2018;66(4):1776-1787.

28. Lin YY, Li WK, Wu PA, et al. A 2x2 MIMO 802.11 b/g/n WLAN SOC in 55 nm CMOS for AP/router application. Paper presented at: 2013 IEEE Asian Solid-State Circuits Conference (A-SSCC); Singapore; 2013;197-200.

29. Guermandi D, Shi Q, Dewilde A, et al. A 79GHz 2x2 MIMO PMCW radar SoC in 28 nm CMOS. Paper presented at: 2016 IEEE Asian Solid-State Circuits Conference (A-SSCC); Toyama, Japan; 2016;105-108.

30. Guermandi D, Shi Q, Dewilde A, et al. A 79-GHz 2x2 MIMO PMCW radar SoC in 28-nm CMOS. IEEE J Solid-State Circuits. 2017;52(10):2613-2626.

31. Ng HJ, Kissinger D. Highly miniaturized 120-GHz SIMO and MIMO radar sensor with on-chip folded dipole antennas for range and angular measurements. IEEE Trans Microw Theory Tech. 2018;66(6):2592-2603.

32. Sultan KS, Abdullah HHI. Planar UWB MIMO-diversity antenna with dual notch characteristics. Prog Electromag Res C. 2019;93:119-129.

33. Elsaidy E, Barakat A, Abdel-Rahman AB, Allam A, Pokharel RK. Radiation performance enhancement of a 60 GHz CMOS Quasi-Yagi antenna. Paper presented at: 2016 IEEE 17th Annual Wireless and Microwave Technology Conference (WAMICON); Clearwater, FL; 2016;1-4.

34. Huo Y, Dong X, Bornemann J. A wideband artificial magnetic conductor Yagi antenna for 60-GHz standard 0.13-μm CMOS applications. Paper presented at: 2014 12th IEEE International Conference on Solid-State and Integrated Circuit Technology (ICSICT); Gulin, China; 2014;1-3.

35. Shamim MS, Mansoor N, Narde RS, Kothandapani V, Ganguly A, Venkataraman J. A wireless interconnection framework for seamless inter and intra-Chip communication in multichip systems. IEEE Trans Comput. 2017;66(3):389-402.

36. Burasa P, Djerafi T, Constantin NG, Wu K. On-chip dual-band rectangular slot antenna for single-chip millimeter-wave identification tag in standard CMOS technology. IEEE Trans Antennas Propag. 2017;65(8):3858-3868.

37. Ahmad WA, Kucharski M, Serio AD, Ng HJ, Waldschmidt C, Kissinger D. Planar highly efficient high-gain 165 GHz on-chip antennas for integrated radar sensors. IEEE Antennas Wire Propag Lett. 2019;18(11):2429-2433.

38. Chandel R, Gautam AK, Rambabu K. Tapered fed compact UWB MIMO-diversity antenna with dual band-notched characteristics. IEEE Trans Antennas Propag. 2018;66(4):1677-1684.

39. Zhao P, He S, Wei X, Xu Z, Wang N, Zheng Y. Compact printed UWB diversity slot antenna with 5.5-GHz band-notched characteristics. IEEE Trans Antennas Wire Propag Lett. 2014;13:376-379.

40. Tripathi S, Mohan A, Yadav S. A compact Koch fractal UWB MIMO antenna with WLAN band-rejection. IEEE Antennas Wire Propag Lett. 2015;14:1565-1568.

41. Li Y, Sim C-Y-D, Luo Y, Yang G. 12-port 5G massive MIMO antenna array in sub-6GHz mobile handset for LTE bands 42/43/46 applications. IEEE Access. 2018;6:344-354.

42. Jha KR, Sharma SK. Combination of MIMO antennas for handheld devices. IEEE Antennas Propag Mag. 2018;60(1):118-131.
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