xIlkogretim Online - Elementary Education Online,2021; Vol 20 (Issue 1): pp.2383-2390
http://ilkogretim-online.org
doi: 10.17051/ilkonline.2021.01.266

Developments And Challenges In The Design Of Active Integrated Antennas

T Ravi Kumar Naidu, Department of ECE, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, India
M. Susila, Department of ECE, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, India Associate professor of Islamic studies, Lahore College for Women University Lahore.
T V S Gowtham Prasad, Department of ECE, Sree Vidyanikethan Engineering College, A.P, India

Abstract- This paper provides a deep look into various solid-state devices and active elements that can be integrated with antenna to improve the efficiency of transmitting and receiving signals. After close look in to historical remarks and classification, the paper emphasis the research efforts on last two decades how the integration has impacted the performance and change in the dimensions and losses of the system. Also, this Paper focused on application of active integrated antennas especially in 5G communications and beyond. This paper also contributed towards the research gaps, which gives possible insight for the researchers for further development is various areas of active integrated antenna and its application..

Keywords: Active integrated antennas, Power amplifiers, Transceivers, Beam forming Patch Antennas, MIMO, Phased Arrays, 5G Communications.

I. INTRODUCTION

The active antennas concept was introduced in early 1920's. At First electron tube with a small antenna which was operating at 1 MHz were designed for Radio Broadcast Receivers, which was operative and well-known those days.

Active antenna is not a new one; it has been in operation for many decades of years. After the breakthrough of high frequency transistors, the researchers focused much attention towards active antennas and several ground-breaking works were reported in 1960's and 1970's [16]. In wireless communication to achieve better performance, the radiating element can be configured with guided wave circuits which include passive and active devices. Because of the combination of guided-wave components and radiating element may leads to performance tradeoffs [13]. Additionally, functions of the components directly are connected to free space which leads to non quasi- optical processing or filtering and also degrades the component's performance due to the antenna's radiation [2]. Active integrated antennas overcome the difficulty and meets requirements of the system. Latest Advancements in quasi-optical power combiners has become key driving forces for progressing research on Active Integrated Antennas during 1990's [1].

Active Antennas integrates active devices (amplifier, oscillator, mixer, diodes) within the Antenna have receives prodigious attention due to their cost reduction and higher gains [3], better power transfer, increased efficiencies, smaller design footprints and adaptability to phased array antenna systems [4]. The active integrated antennas allow monolithic implementation by fabricating both active devices and radiating element on a single semiconductor substrate, which aided in using Active Integrated Antenna (AIA) over the conventional sub-system designs of various terminal circuits. One important feature of the active integrated antennas is that, the radiating element and active device are considered as a one unit., which are also referred as quasi-optical transmitters [6]. Advancements in MMIC's technology leads to active phased array antennas, to provide control on amplitude and phase in each array element [11]. Active Integrated Antennas (AIA's) have a mechanism to control the characteristics of a device such as shape of radiation pattern, peak gain, axial ratio and its physical size. It used to control the dynamic radiation patterns in mobile communications [12], active tunable printed dipoles [14]. Integrating a slot antenna and a high-electron-mobility transistor on opposite sides of a GaAs substrate exhibit good radiation efficiency and high relative dielectric constant due to the thinness of the substrate ($< 0.05\lambda$) [15]. Majorly, this paper focuses on the classification of AIA's based on the integrating elements and how these AIA's leads the 5G mobile communication technology. The rest of paper outlined the classification of AIA's and role of AIA's in the 5G Communication [4].

II. CLASSIFICATION OF ACTIVE ANTENNA

In general the active components such as Diode, Transistor, Silicon Controlled Rectifiers (SCRs) etc., can be used for RF signal amplification, rectification, frequency conversions and energy conversions.
Passive antennas are antennas that have no inbuilt amplification stages.

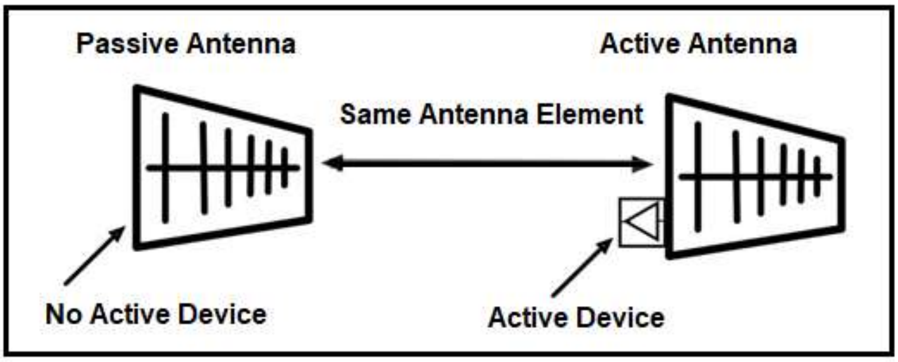


Figure 1. Comparison of Passive Antenna and Active Antenna

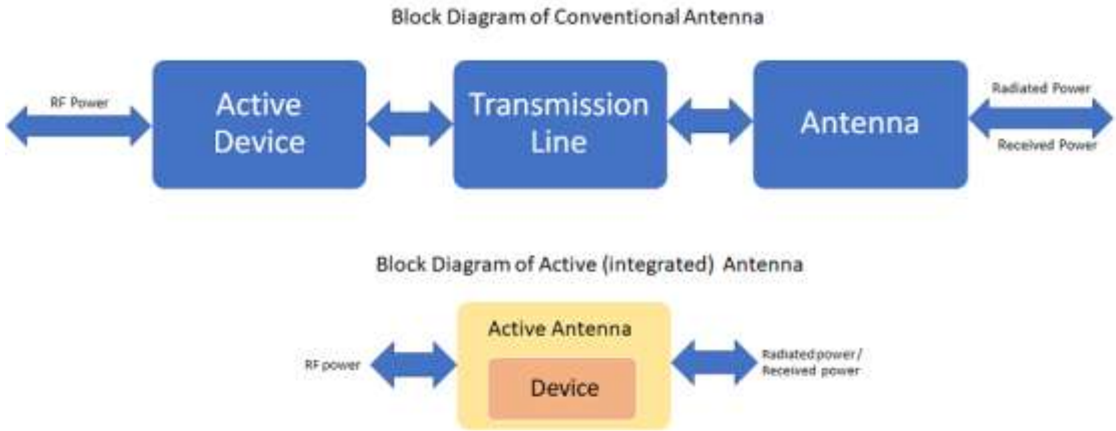
AIA has significant advantages over traditional amplifying antenna such as high power efficiency, compact configuration, low noise and high gain [5]. Depending on active device function, the AIA were categorized into four different types: diode integrated, transistor integrated, oscillator type and amplifier type AIA's. Furthermore, these four types of active antennas may be combined further to generate versatile functions in a single module such as the active transceiver, transponders, repeaters, and so on. The Amplifier Type AA is defined as a passive antenna integrated with Amplifying element at its I/O port for RF signal amplification [17]. The Figure 1 Comparison of Passive Antenna and Active Antenna

A. Diode- Integrated Active Patch Antenna

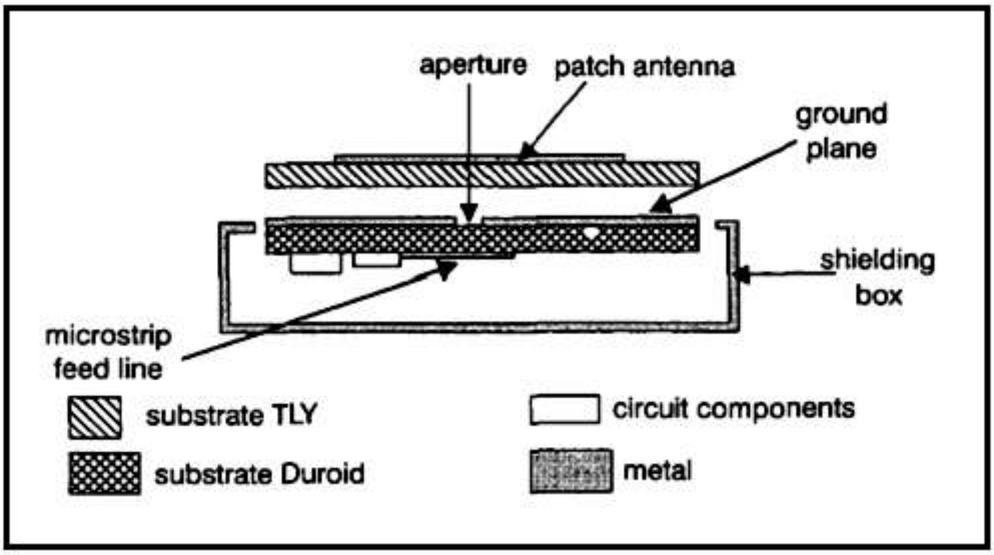
The Diode is a two terminal device used for rectifications, it converts ac to dc and acts as a uncontrolled switch. In the beginning of 19th century vacuum tubes (electron tube) were used in almost all electronic applications such as radios, televisions, sound systems and instrumentation. Various research works has been published related to diode integrated active patch antennas. Siang Ping Kwok and Kenneth P. Weller developed a self-mixing oscillator by using BARITT MIC circuit incorporated with micro strip antenna for Doppler-Sensing Applications in 1979 [18]. In 1996 Stiller et al. developed an Radiating Monolithic Integrate Planar Oscillator by using An IMPATT diode and planar resonant antenna for various applications like low-cost sensors [19]. M. Yeddes et al. analyzed tunnel diode antenna based on iterative method and wave concept technique in 2006 to achieve the frequency tenability in the millimeter range [20]. In 2012, Inam et al. developed an Active Reflect array Antenna by integrating PIN diodes with the slotted patch elements for beam steering applications [21]. Ruonan et al. Schottky-barrier diodes fabricated in CMOS for active THz imaging applications in 2013 [22].

B. Transistor Integrated Active Patch Antenna

The transistor invented in 1947, it is a three terminal device acts as a controlled switch used for switching apparatus, amplifiers and as a regulator. At the beginning Ge BJTs were used around 1 GHz, later Si BJTs and GaAs BJTs were developed for high-frequency applications [25].
In 1971, Ramsdale and Maclean used BFY 90 transistor and active loop-dipole aerials for transmitting applications [23]. In 1999 G. Ma et al, Designed an AIA to suppress the local oscillator radiated power by integrating the device with monolithic microwave integrated circuit (MMIC) package chip as shown in the Figure 2a and Figure 2b [24].



(a)



(b)

Figure 2. (a) Block Diagram of AIA; (b) Aperture-coupled integrated active antenna [24]

In 2007, M. Jalali et al. implemented an AIA by integrating Low Noise Amplifier with radiating element for Ultra Wide band (UWB) applications [26]. In 2008, Carl H. Mueller, Robert R. Romanofsky et al. has designed small size X band AIA with feedback loop for attaining high power radiations and efficiency [28]. In 2011, Leung chiu et al [8], has given a new concept of 4-Element Balanced Retrodirective Array for Direct Conversion Transmitter and designed a active integrated direct conversion receiver to recover the two individual baseband signals [29].

In 2016, S. K. Dhar, M. S. Sharawi et al. introduced an UWB active integrated MIMO antenna (AIA) design to provide wideband antenna matching for Improved radiation efficiency and diversity performance[30]. In 2018, Ramya et al, introduced a penta-band (1.2, 1.5, 2.4, 3.3, and 5.8 GHz) Active Integrated Antenna for wireless communication applications [31].

C. Oscillator Type Active Integrated Antenna

The oscillator-type of AIA is comprised of a oscillator, feed, and radiating element. The active solid-state device such as diodes (IMPATT, Gunn, BRITT, etc.,), transistors (MESFET, HEMT, and HBT) integrated with an antenna to form an AIA oscillator [7]. The Micro strip patch antenna was first integrated with a FET to form an active antenna element by Chang et al. in 1988 [9].In 1988 Stephan and Young has designed Radiation-Coupled Interinjection-Locked Oscillators for Integrated Phased Arrays to achieve Mode Stability and better phase noise [32]. In 1996, Chou and Tzuang has designed active- integrated leaky-mode antenna by using monolithic-microwave integrated circuit for better radiation patterns [33].

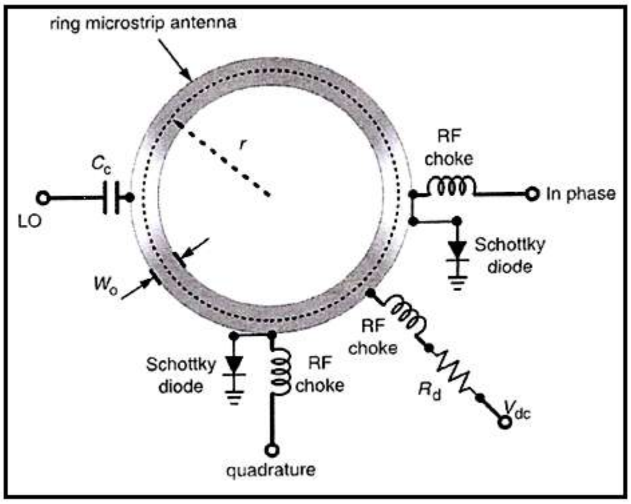


Figure 3. AIA with ring structure [35]

In 2006, Yi Qin et al. has proposed linearly polarized (LP) AIA and circularly polarized AIA to achieve a high power-added efficiency over a broad bandwidth, for LP AIA they used a ring-slot coupled micro strip patch antenna and for CP AIA they used a single-feed cross-slot-coupled micro strip patch antenna [34].

In 2011, J. Verhaevert et, al. has designed active ring antenna with tunable local oscillator shown in the Figure.3 [35]. In 2012, Jag tap and Minot have given a new concept of integrated active patch antenna for semiconductor super lattice THz oscillators [36]. In 2013, Upadhayay, M. D. and Koul has designed AIA using BJT with floating base for Optical control and Sensing applications [37]. In 2018, Rakhi Kumari, Ananjan Basu and Shiban K Koul has demonstrated A GaN HEMT based HPA type AIA which was operating at 2.4GHz to achieve highest Equivalent Isotropic ally Radiated Power (EIRP) [38]. In 2019, Elena I. Shirokova and B. Shirokov has designed Active Receiver-Transmitter Antenna by integrating regenerative amplifier with radiating element called micro strip antenna to improve overall efficiency of the entire antenna array system and it's widely used for the design of RFID systems in communications [39].

D. Amplifier Type Active Integrated antenna

In general transistor acts as an amplifier, if it integrates with radiating element at the input or output port to perform functions as receiver or transmitter. In 1999, author introduces a Compact AIA Transceiver for System Applications of two-way communications [40]. In 2007, Author has designed Wideband Integrated Transmitter to achieve high PAE and better output power operated at the entire 5-GHz band [41]. In 2011, Maryam Tabesh et al. has proposed the design of 60 GHz CMOS Phased-Array Transceiver to achieve a high power efficiency [42]. The recent developments in quasi-optical amplifiers motivated the researchers to work on Amplifier Type Active Integrated antenna to increase the operating frequency and speed of RF transistors [10].

III. ACTIVE INTEGRATED ANTENNAS ROLE IN MILLIMETER-WAVE COMMUNICATION

The 5G wireless communication systems need to be designed to support high speed and high data rates with maximum coverage for different applications. 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 [27].

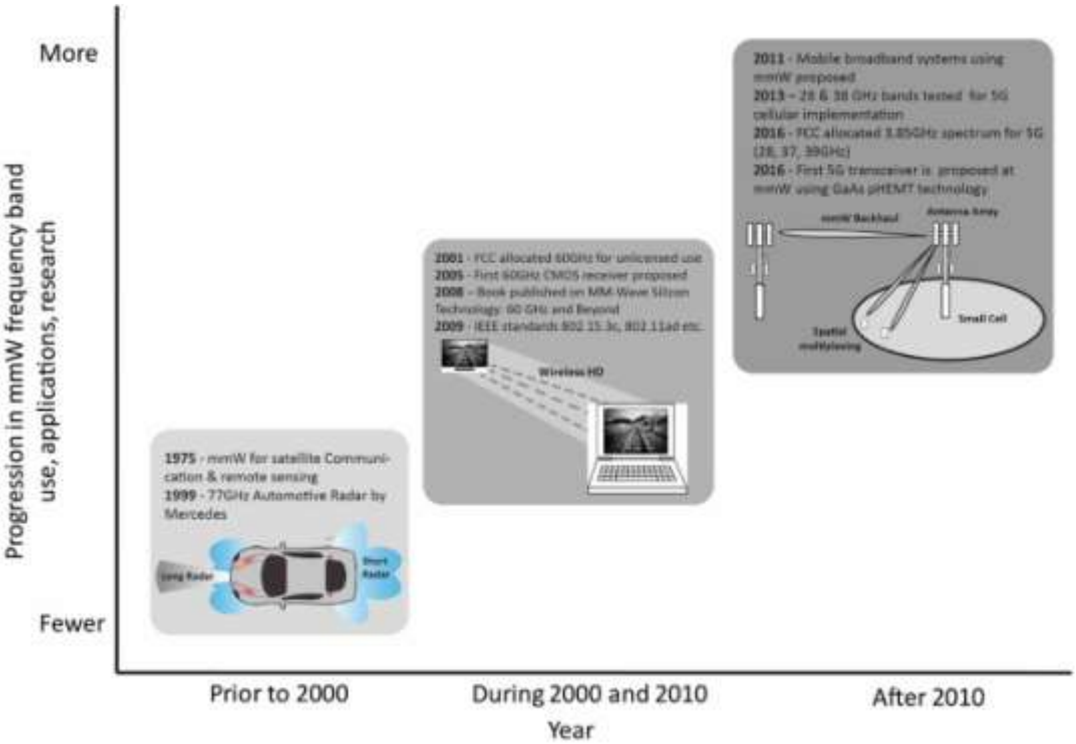


Figure. 4 Progression in understanding and use of mmW frequency band by research community [53]

Today, MIMO and Beam forming are the buzzwords commonly used in the telecom industry when referring to 5G and most recent advancements of LTE. Figure. 4 gives brief idea on usage of mmW frequency bands over few decades by the researchers. In 2014, Wonil Roh et, al. designed a mmWave prototype and produces results which features large system bandwidth at 28 GHz. Finally suggested that 28 GHz band is a feasible for wideband low power 5G systems [43]. In 2016, Shakib et al. has designed a Linear and highly efficient Power Amplifier for mmWave(28-GHz) 5G integrated phased array transceivers in 28 nm bulk CMOS and in 40nm CMOS [44]. In 2018, Kerim Kibarogluetal has designed an optimal phase array antenna that operates at 28GHz frequency for 5G Communication [46]. In 2018, Luca Aluigi et. Al designed a integrated patch antenna at 28 GHz for automotive beam forming systems for 5G Automotive Connectivity [47]. In 2018, Hong-Teuk et al, developed a 28-GHz CMOS direct conversion transceiver with low EVM, high EIRP, and Controlled beamforming capability [48]. In 2018, Hong-Teuk et.al, developed an active phased array antenna (APAA) by integrating GaAs RF frontend module with PA, LNA and switch at 28GHz-band for better spectral efficiency [49]. In 2019, Hanieh Aliakbari et al. has presented a Far-Field-Based Nonlinear Optimization of mmWave (28/38GHz), Active Antenna with circular polarization for 5G Services [50].

In 2020, QING-QIANG HE et al. developed a integrated phased array Ka-band active antenna for 5G wireless communications [51]. In 2020, Junho Parketal developed Systematically Integrated Array Antenna with Multiple Phase at 28 GHz, which Enhances Beam Coverage Efficiency of mmWave 5G systems [52].

As mmWave spectrum is very wide, high data rates can be achieved at an order of Gbps but it has more propagation losses because path loss is proportional to square of the distance and the modulated carrier frequency [45]. The major issue with integrating of passive component is, it leads high insertion loss which may decrease antenna gain therefore choosing passive component place a major role in the performance of active integrated antennas. Other parameters such as efficiency and radiation pattern are also affected by interfacing passive components with active device and its packaging. Therefore many investigators are looking in to AoC (Antenna-on-Chip) and AiP (Antenna-in-Package) for emphasizing gain, bandwidth, power radiations and efficiency of active devices [54].

IV. CONCLUSION

This paper inspects the developments and challenges in implementation and design of Active integrated antennas. One of the most important challenge is designing active integrated antenna with perfect impedance matching between radiating element and amplifier otherwise it may depreciate the performance of the integrated devices. Few more parameters that normally researcher focuses in designing integrated devices are compactness of the device, cost of the equipment and effective radiation with high power efficiency. More specifically, in the microwave and millimeter wave application, performance of active integrated devices depends on the selection of appropriate material and the fabrication technology. Another issue is undesired radiations due the active devices which can be suppressed by integrating a filter to the radiating element.

From the literature, it is known that the AIA will be most important element in future generations of communication applications in radar, satellite communications and mobile communications, currently used in RFID readers, sensor networks, GPS receivers, wireless LAN and collision avoidance radars and also in the field of spatial and quasi-optical power combiners, short range personnel sensors, transport control and monitoring etc. This paper will help the readers to figure out the requirements in millimeter-wave 5G communications.

Another important observation was that many of the researchers are working on designing of active integrated 28GHz multiphase array antennas to emphasize the beam steering and phase control Efficiencies of mmWave 5G Applications. In Millimeter-wave 5G wireless communication services, low latency and high data rate accelerated further research in developing 5G radio frequency systems.

REFERENCES

1. L. Wandinger and V. Nalbandian, "Millimeter-wave power combining using quasioptical techniques," IEEE Trans. Microwave Theory Tech., vol. MTT-31, pp. 189–193, Feb. 1983.
2. J. W. Mink, "Quasi-optical power combing of solid-state millimeter- wave sources," IEEE Trans. Microwave Theory Tech., vol. MTT-34, pp. 273–279, Feb. 1986.
3. R. A. Flynt, L. Fan, J. A. Navarro, and K. Chang, "Low cost and compact active integrated antenna transceiver for system applications," IEEE Trans. Microw. Theory Tech., vol. 44, pp. 1642–1649, 1996.
4. G. Forma and L. M. Laheurte, "CPW-fed oscillating microstrip antennas," IEEE Antennas and Propagation Society International Symposium. 1996 Digest, Baltimore, MD, USA,pp.526-529.
5. G. Forma and L. M. Laheurte, "CPW-fed oscillating microstrip antennas," Electron. Lett., vol. 32, pp. 85–86, 1996.
6. M. M. Kaleja, P. Heide, and E. M. Biebl, "An active integrated 24-GHz antenna using a flip-chip mounted HEMT," IEEE Microw. Guided Wave Lett., vol. 9, pp. 34–36, 1999.
7. K. Chang, R. York, P. Hall, and T. Itoh, "Active integrated antennas," IEEE Trans. Microw. Theory Tech., vol. 50, pp. 937–944, 2002.
8. K. H. Y. Ip, T. M. Y. Kan, and G. V. Eleftheriades, "A single-layer CPW-fed active patch antenna," IEEE Microw. Guided Wave Lett., vol. 10, pp. 64–66, 2000.
9. K. Chang, K. A. Hummer, and G. K. Gopalakrishnan, "Active radiating element using FET source integrated with microstrip patch antenna," Electron. Lett., vol. 24, pp. 1347–1348, 1988.
10. Ying Shen, Russ Fralich, Chen Wu, John Litva, "Active Radiating Element Using FET Source Integrated with a Multilayer Slot Coupled Patch Antenna," IEEE Antennas and Propagation Society International Symposium 1992 Digest, Chicago, IL, USA,pp.1052-55.
11. D. J. Roscoe, A. Ittipiboon and L. Shafai, "The Development ofan Active Integrated Microstrip Antenna," 1991 IEEE International Antennas and Propagation Symposium Digest, London, Ontario, Canada, pp. 48-51.
12. D J Roscoe, AIttipiboon and L Shafai, "The Application of a Circuit Simulator to the Design and Analysis of Passive and Active Microstrip Antenna,'' International IEEE Antennas and Propagation Society International Symposium 1992 Digest, Chicago, Illinois, pp. 1439-1443.
13. D J Roscoe, A Ittipiboon, L Shafai, and M Cuhaci, "Noise Analysis of an Integrated Travelling Wave Antenna,'' Electronics Letters, 29, 6, 1993, pp. 544-545
14. D J Roscoe, L Shafai, A Ittipiboon, M Cuhaci and R Douville, "Tunable Dipole Antennas," 1993 IEEE international Antennas and Propagation Symposium Digest, Ann Arbor, Michigan, pp 672-675.
15. L. Roy, M. G. Stubbs, and J. S. Wight, "Slot Antennas on GaAs for Integrated Array Applications," 1992 Symposium on Antenna Technology and Applied Electromagnetics, ANTEM'92 Digest, Winnipeg, Manitoba, Canada, pp. 637-642.

16. L Roy, M G Stubbs, and J S Wight, “A 30 GHz, HEMT, Active Antenna Structure in MMIC Technology,” 22nd European Microwave Conference Proceedings, 1992 Helsinki, Finland, pp. 236-241.
17. JenshanLin, and Tatsuo Itoh, “Active IntegratedAntennas,”IEEE. Transactions on Microwave Theory and Techniques. Vol 12. No 12. December 1994.
18. Kwok, S. P. and Weller, K. P.: Low cost X-band MIC BARITT Doppler sensor, IEEE Trans. Microwave Theory Tech., Vol. 27, No. 10, 1979, pp. 844-847.
19. Stiller, A. and Strohm, K. M.: A radiating monolithic integrated planar oscillator at 55 GHz, IEEE Microwave Guided Wave Lett., Vol. 6, No. 2, 1996, pp.100-102.
20. Yeddes, M. and Kharsallah, A.: Analysis of tunnel diode antenna using iterative method, International journal of electronics, 2006, pp. 559-566.
21. Inam, M. and Ismail, M. Y.: Integration of PIN diodes with slot embedded patch elements for active reflectarray antenna design, International symposium on telecommunication technologies, 2012, pp. 151-155.
22. Ruonan, H., Yaming, Z. and Kim, Y.: Active terahertz imaging using schottky diodes in CMOS array and 860-GHz pixel, IEEE Journal of Solid-State Circuits, Vol. 48, No. 10, 2013, pp. 2296-2308.
23. Ramsdale, P. A. and MacLean, T. S. M.: Active loop-dipole aerials, proceedings of the IEE, Vol. 118, No. 12, 1971, pp. 1698-1710.
24. G. Mal, P. S. Hall , P. Gardner, M. Hajian.: “Local oscillator radiation from active integrated antennas,” IEEE Antennas and Propagation Society International Symposium. 1999 Digest. Held in conjunction with: USNC/URSI National Radio Science Meeting (Cat. No.99CH37010) Orlando, FL, USA pp. 2378-2381.
25. Hall, P. S., Gardner, P. and Ma, G.: Local oscillator radiation from activeintegrated antennas, Electronics Letters, Vol. 35, No. 25, 1999, pp. 2163-2164.
26. M. Jalali, A. Abdipour, A. Tavakoli and G. Moradi, “An Active Integrated Spiral Antenna System for UWB Applications,” 2006 IEEE International Conference on Semiconductor Electronics (ICSE2006 Proc.), Kuala Lumpur, Malaysia, 29 Oct.-1 Dec. 2006,pp.102-105.
27. M. Jalali, A. Abdipour, A. Tavakoli and G. Moradi, “Performance Amelioration of an Active Integrated Spiral Antenna System for UWB Applications,” International workshop on Antenna Technology: Small and Smart Antennas Metamaterials and Applications, Cambridge, UK, 21-23 March 2007, pp.323-326.
28. Mueller, C. H. and Lee, R. Q.: Small-size X-band active integrated antenna with feedback loop, IEEE Transaction on antenna and propagation, Vol. 56, No. 5 , 2008, pp. 1236-1241.
29. Leung, C., Quan, X. and Chi, H.: A 4-element balanced retrodirective array for direct conversion transmitter, IEEE Transaction on antenna and propagation, Vol. 59, No. 4, 2011, pp. 1185-1190.
30. S. K. Dhar, M. S. Sharawi, O. Hammi, and F. M. Ghannouchi,“An Active Integrated Ultra-Wideband MIMO Antenna,” IEEE Transactions on Antennas and Propagation, Volume: 64 , Issue: 4 , April 2016, pp.1573 - 1578.
31. Ramya Vijay, Thipparaju Rama Rao,“Design of penta-band antenna with integrated LNA circuit for vehicular communications”, IET Circuits Devices Syst., 2018, Vol. 12 Iss. 3, pp. 221-225.
32. K.D. Stephan and S.L. Young, “Mode stability of Radiation-Coupled Inter injection-Locked Oscillators for Integrated Phased Arrays,” IEEE Tans. On Microwave Theory and Techniques, Vol.36, No. 5, pp. 921-924, May 1988.
33. Guang-Jong Chou and Ching-Kuang C. Tzuang, “Oscillator-Type Active-Integrated Antenna: The Leaky-Mode Approach,” IEEE Transactions on Microwave Theory and Techniques, VOL 44, NO 12, DECEMBER 1996, pp.2265-2272.
34. Yi Qin, Steven Gao and Alistair Sambell, “Broadband high-efficiency linearly and circularly polarized active integrated antennas,” IEEE Transactions on Microwave Theory and Techniques, Volume: 54 , Issue: 6 , June 2006,pp. 2723-2732.
35. Verhaevert, J. and Van Torre, P.: Active ring antenna with tunable local oscillator, IEEE Conference Publications, 2011, pp. 142-147.
36. Vishal S. Jagtap , Christophe Minot.: Internally integrated active-type patch antenna for semiconductor superlattice THz oscillators, IEEE Transactions on Terahertz Science and Technology, Vol. 2, No. 1, 2012, pp. 131-136.
37. Upadhayay, M. D., Basu, A., Abegaonkar, M. P. and Koul, S. K.: Active integrated antenna using BJT with floating base, IEEE microwave and wireless component letter, Vol. 23, No. 4, 2013, pp. 202-204.

38. RakhiKumari, AnanjanBasu and Shiban K Koul, "Development of GaN HEMT based High Power Active Integrated Antenna," 2018 IEEE MTT-S International Microwave and RF Conference (IMaRC), 28-30 Nov. 2018, Kolkata, India.
39. Elena I. Shirokova , Igor B. Shirokov, "New Approach to Active Antennas Design," 2019 Antennas Design and Measurement International Conference (ADMInC), 16-18 Oct. 2019, St. Petersburg, Russia, Russia, pp.18-22.
40. Flynt, R. A. and Lu Fan, J. A.: Low cost and compact active integrated antenna transceiver for system applications, IEEE Trans. on MTT, Vol. 44, No. 10, 1996, pp. 1642-1649.
41. Kim, H. and Yoon, Y. J.: Wideband design of the fully integrated transmitterfront-end with high power-added efficiency, IEEE Trans. on MTT, Vol. 55, No. 5, 2007, pp. 916-924.
42. Maryam Tabesh, Lingkai Kong, Ali M. Niknejad.: A 65 nm CMOS 4-element sub-34 mW/element 60 GHz phased array transceiver, IEEE J. Solid-State Circuits, Vol. 46, No. 12, 2011, pp. 3018-3032.
43. W. Roh et al., "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," IEEE Commun. Mag., vol. 52, no. 2, pp. 106–113, Feb. 2014.
44. S. Shakib, H.-C. Park, J. Dunworth, V. Aparin, and K. Entesari, "A highly efficient and linear power amplifier for 28-GHz 5G phased array radios in 28-nm CMOS," IEEE J. Solid-State Circuits, vol. 51, no. 12, pp. 3020–3036, Dec. 2016.
45. Sherif Shakib, Mohamed Elkholy, Jeremy Dunworth, Vladimir Aparin, Kamran Entesari, "A Wideband 28GHz Power Amplifier Supporting 8×100MHz Carrier Aggregation for 5G in 40nm CMOS," 2017 IEEE International Solid-State Circuits Conference (ISSCC),San Francisco, CA, USA,5-9 Feb. 2017.
46. K. Kibaroglu, M. Sayginer and G. M. Rebeiz, "A Low-Cost Scalable 32Element 28-GHz Phased Array Transceiver for 5G Communication Links Based on a 2×2 Beam former Flip-Chip Unit Cell," in IEEE Journal of Solid-State Circuits, vol. 53, no. 5, pp. 1260-1274, May 2018.
47. Luca Aluigi, Giulia Orecchini and Luca Larcher, "A 28 GHz Scalable Beamforming System for 5G Automotive Connectivity: an Integrated Patch Antenna and Power Amplifier Solution" 2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G), Dublin, Ireland, 30-31 Aug. 2018.
48. Hong-Teuk Kim, Byoung-Sun Park, Seong-Sik Song, Tak-Su Moon, So-Hyeong Kim, Jong-Moon Kim, Ji-Young Chang, and Yo-ChulHoA, "28-GHz CMOS Direct Conversion Transceiver With Packaged 2×4 Antenna Array for 5G Cellular System", IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 53, NO. 5, pp. 1245-1259, MAY 2018.
49. ShintaroShinjo, KeigoNakatani, Jun Kamioka, RyotaKomaru, Hifumi Noto, Hideyuki Nakamizo, Satoshi Yamaguchi, Shigeru Uchida, Akihiro Okazaki and Koji Yamanaka, "A 28GHz-band highly integrated GaAs RF frontend Module for Massive MIMO in 5G"2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G), Dublin, Ireland, 30-31 Aug. 2018.
50. HaniehAliakbari , AbdolaliAbdipour, Alessandra Costanzo, Diego Masotti , Rashid Mirzavand, and Pedram Mousavi, "Far-Field-Based Nonlinear Optimization of Millimeter-Wave Active Antenna for 5G Services," IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 67, NO. 7, pp. 2985-2997, JULY 2019.
51. QING-QIANG HE, SHUAI DING , CHEN XING, JUN-QUAN CHEN, GUO-QING YANG, and BING-ZHONG WANG, "Research on Structurally Integrated Phased Array for Wireless Communications," IEEE Access (Volume: 8), pp. 52359 – 52369, 13 March 2020.
52. Junho Park, Jaehyun Choi,Wonbin Hong, "Systematically Integrated Phased-Array Antenna Configuration to Enhance Beam Coverage Efficiencies of Millimeter-wave 5G Mobile Devices,"2020 International Workshop on Antenna Technology (iWAT), Bucharest, Romania, 25-28 Feb. 2020.
53. Sagar Juneja , Rajendra Pratap , Rajnish Sharma, "Semiconductor technologies for 5G implementation at millimeter wave frequencies – Design challenges and current state of work" Engineering Science and Technology, an International Journal, 2020. ISSN 2215-0986.
54. LI Lianming, NIU Xiaokang, CHAI Yuan, CHEN Linhui, ZHANG Tao, CHENG Depeng, XIA Haiyang, WANG Jiangzhou, CUI Tiejun, YOU Xiaohu, "The path to 5G: mmWave aspects" Journal of Communications and Information Networks, Vol.1, No.2, pp. 1-18, Aug. 2016