JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Multi-Band MM-Wave Wearable Antenna For Different Wireless Application - A Review

[1]Parul Pandey, [2]Prakash Saxena, [3]Saurabh Gupta
[1]M.tech Student , [2]Head of department, [3]Assistant Professor,
[1,2,3]Department of Electronics and Communication Engineering (E.C.)
[1,2,3]Bansal Institute of Science & Technology, Bhopal (M.P.), India, INDIA,

Abstract : The rapid growth of wireless communication systems and the increasing demand for higher data rates have fueled the development of millimeter-wave (MM-wave) technology for 5G and other wireless applications. In this review paper discuss the different multi-band MM-wave wearable antenna. Millimeter wave (mm Wave) bands attract large research interest as they can potentially lead to data rate of almost 10Gbits/sec and huge available bandwidth where as the microwave frequencies are limited to 1Gbits/s. This paper presents a comprehensive review of millimeter wave communications, frequency bands proposed by ITU, applications of mm Waves, advantages, limitations, challenges and research directions. Various antennas proposed by researchers for mm Wave applications are described in detail. The described models are analyzed and compared with common antenna parameters.

Keywords— Frequency reconfigurability, polarization reconfigurability, axial ratio bandwidth (AR B.W.), tuning range (TR), fractional bandwdith change (FBWC), PIN diodes, varactors.

I. INTRODUCTION

The rapid advancement of wireless communication technologies has led to the emergence of fifth-generation (5G) networks, which promise to revolutionize the way we connect and communicate. 5G networks operate in higher frequency bands, including the millimeter-wave (mm-wave) range, to accommodate the increasing demand for higher data rates and low-latency applications [9]. Designing antennas for mm-wave frequencies presents unique challenges due to the shorter wavelengths and increased path loss.

Conformal multi-band mm-wave variable antennas play a vital role in realizing the potential of 5G networks. These antennas are capable of dynamically adapting their operating frequency bands, enabling efficient utilization of available spectrum and supporting various use cases[10]. The conformal nature of these antennas allows them to seamlessly integrate into curved surfaces, such as vehicles, drones, or building facades, without compromising their performance.

The design of such antennas requires careful consideration of factors such as frequency bands, antenna types, conformal structure, variable mechanisms, matching networks, radiation patterns, and performance evaluation. By addressing these aspects, designers can create antennas that meet the stringent requirements of 5G applications while maintaining high performance and flexibility [28].

In this paper, we delve into the design principles and considerations for conformal multi-band mm-wave variable antennas tailored specifically for 5G applications [10] [11]. We will discuss each step of the design process, starting from the selection of frequency bands and antenna types suitable for mm-wave operation. We will explore the challenges associated with conformal integration, including maintaining optimal performance in curved surfaces or within conformal radomes[12].

Furthermore, the paper will explore the concept of variable antennas and different mechanisms that can be employed to dynamically tune the operating frequency bands. We will discuss the advantages and limitations of various tuning methods, such as varactor diodes, MEMS switches, or other reconfigurable techniques.

To ensure efficient power transfer and minimize reflections, we will explore the design and optimization of matching networks for the antenna. Additionally, the paper will cover techniques for shaping the radiation pattern of the antenna to meet specific coverage and gain requirements.

Finally, we will highlight the importance of fabrication and testing, both in controlled environments and real-world scenarios. Field testing and performance evaluation will validate the antenna's functionality, considering factors like antenna placement, interference, and environmental conditions.

By understanding the design considerations and challenges associated with conformal multi-band mm-wave variable antennas for 5G applications, engineers and researchers can contribute to the development of robust and efficient wireless communication systems. These antennas have the potential to revolutionize 5G networks by enabling high-capacity, low-latency connectivity in diverse environments, paving the way for the realization of advanced applications such as autonomous vehicles, smart cities, and Internet of Things (IoT) ecosystems [13].

II. LITERATURE SURVEY

Arebu Dejen et.al.(2023) - This research work presented, a dualband microstrip antenna optimization for mm-wave mobile applications.The engineered antenna was resonated at 39.1 GHz and 50.2 GHz whereas the reference model was resonated only at 39.0 GHz. To that purpose, a genetically modified microstrip antenna performed admirably in the operating band of interest. The optimized antenna have achieved 1.6 GHz bandwidth and 7.6 dB gain at 39.1 GHz and 3.3 GHz bandwidth, 7.4 dB gain at 50.2 GHz center frequency. This work can also compared with other related works and the proposed reference antenna in mmwave frequency. The proposed antenna performs brilliantly in terms of bandwidth and other far-field properties, which makes the antenna practical for mm-wave communication [01].

R. Krishnamoorthy et.al. (2023) - This research work presented, a metamaterial-inspired four-port dual-band MIMO antenna is suggested for use in applications operating at mm-wave frequencies at 38 GHz. In a design with a common ground plane, the antenna achieves a measured port isolation of greater than 25 decibels without the need of any decoupling device. In addition to this, it achieves acceptable antenna gains at both frequency bands while also achieving satisfactory ECC and CCL diversity performance values. In addition, the suggested tiny MIMO antenna is planar and has dimensions of 15 mm X 15 mm, making it suitable for incorporation into many 5G wireless devices [02].

Amandeep Kaur Sidhu et. al. (2023) - This research work presented ,A hybrid fractal shaped two-port MIMO antenna with stub loaded ground plane has been presented in this manuscript for 5G wireless applications. The performance of the proposed hybrid MIMO antenna with different ground planes has been compared and it found that the antenna with a modified ground plane is better in terms of improved bandwidth, reflection coefficient, and reduction in mutual coupling. The proposed MIMO antenna reveals the wider impedance bandwidth of 20. 4GHz (1. 0 to 21. 4GHz) and 6. 10GHz (23. 9 to 30GHz) with a fractional bandwidth of 182. 14% and 22. 63% respectively. Diversity performance parameters such as CCL, DG, ECC, and TARC are within reasonable limits. The proposed hybrid fractal MIMO antenna is a proficient candidate for 5G 3. 5GHz band (3. 4 – 3. 6GHz), 5G NR (New Radio) frequency bands (3. 3 – 5. 0GHz), LTE band 46 (5. 15 – 5. 925GHz), EU (European Union) 5G frequency band (5. 9 – 6. 4GHz), UWB applications (3. 1 – 10. 6GHz), 5G 26GHz frequency band, and the other applications in the obtained operational frequency range (1 – 21. 4GHz and 23. 9 – 30GHz) [03].

Muhammad Aamer Shahzad et.al. (2021) - This research work presented, A dual-band AMC-backed miniaturized antenna was designed for ISM frequency bands of 2.45 and 5.8 GHz. Roger 3003C (3, 0.0019) is used as a substrate to utilize its flexibility. The proposed antenna was designed with smaller dimensions of 28.81 × 19.22 × 1.58 mm^3. The antenna demonstrated an almost identical performance on a smart watch strap. A unit cell was designed having a size of 19.19 × 19.19 ×1.58 mm^3 to mitigate the effect of back radiation and to increase gain. The antenna's SAR value was tested and found to be within the FCC and ICINPR acceptable limits to ensure that the proposed antenna is safe to be used as wearable device. Because the antenna was designed to be wearable, the effect of bending was also evaluated and found to be an insignificant influence on antenna performance. The antenna is compact and has high gain, making it suitable for wireless data transfer and wearable electronics. The SAR values were calculated to be 0.19 and 1.18 W/kg at the designed ISM frequencies, and are less than the limits set by the FCC and ICINPR. Results of the bended analysis proved that bending along the x- and y-axes had a negligible effect on the antenna's performance, and the antenna showed excellent performance in the test of human proximity. The measured results of the fabricated antenna were comparable with the simulated results. Furthermore, the antenna achieved good measurement results and is a perfect candidate for smart watch wireless IoT applications. The antenna can be used to wirelessly transmit and receive data in wearable applications [04].

Bowen Lyu et.al. (2021) - This research work presented, A quasi-Yagi antenna for ultra-wideband mm-wave operation has been designed and analyzed numerically in this paper. The proposed antenna makes use of a relatively simple structure and small size to offer a huge -10 dB bandwidth ranging from 24-70 GHz. The antenna employs a flexible LCP substrate to ensure human body conformity while achieving good radiation coverage, high gain (greater than 6 dBi in most of the operating bandwidth) and greater than 70% of efficiency. These features make the proposed antenna a good candidate solution for ultra-wideband operation for 5G and beyond systems working at mm-wave frequencies [05].

Achilles D. Boursianis et.al, (2021) - In this research work presented, Three emerging swarm intelligence algorithms, namely the GWO, the WOA, and the SSA were investigated. To this end, several well-known test functions were utilized to assess the performance of the selected algorithms. Moreover, two different design cases, the design of a 50-element linear antenna array and the design of an aperture-coupled E-shaped patch antenna, were carried out to evaluate the operation of the SI algorithms. To further estimate their effectiveness, two independent statistical tests were applied, the Friedman test and the Wilcoxon signed-rank test. Numerical results demonstrated that the WOA outperforms the other algorithms in terms of average ranking as well as in 8 out of 10 well-known test functions. From the design case of the linear antenna array, we concluded that the best pSLL value was achieved by the GWO algorithm; yet the other SI algorithms exhibited satisfactorily competitive results. The employment of the WOA to the optimization problem of an aperture-coupled E-shaped antenna revealed the capability of the algorithm to design complex (a large number of parameters to be optimized) and compact (small size) structures as applications in antenna design optimization problems [06].

Arpan Desai et.al. (2021) - In this research work presented, A flexible transparent wideband four-element MIMO antenna with a connected ground plane is proposed with numerical computation and experimental measurement studies. The optical transparency is obtained using flexible conductive oxide material AgHT-4 and Melinex substrate. The radiating elements are in the form of circular stub-loaded C-shaped resonators, which are positioned in a carefully structured flexible Melinex substrate with an interconnected partial ground plane structured in the form of an L-shaped resonator, attaining an overall antenna size of 0.33λ× 0.48λ at the lowest operating frequency. The proposed antenna spans over a −10 dB impedance bandwidth of 2.21-6 GHz (92.32%) with an isolation level greater than 15dB among all elements. The maximum gain is 0.53dBi with a minimum efficiency of 41%, respectively which is satisfactory considering flexible structure and sheet impedance of 4 • /sq. MIMO antenna parameters in terms of the envelope correlation coefficient (ECC) and diversity gain (DG) are also extracted where all the values are satisfactory for MIMO applications. The bending analysis of the proposed transparent MIMO antenna along the X and Y axis has revealed good performance in terms of scattering parameters and radiation pattern along with MIMO diversity performance. All of these technical points make the flexible MIMO antenna suitable for smart devices using sub-6 GHz 5G and WLAN band in IoT applications where visual clutter and co-site location issues need to be mitigated with the integration ease of conformal placement on the curved component/device surfaces [07].

***Shahid M. Ali et.al. (2020)* -** In this research work presented, The demand for wearable technologies has grown tremendously in recent years. Wearable antennas are used for various applications, in many cases within the context of wireless body area networks (WBAN). In WBAN, the presence of the human body poses a significant challenge to the wearable antennas. Specifically, such requirements are required to be considered on a priority basis in the wearable antennas, such as structural deformation, precision, and accuracy in fabrication methods and their size. Various researchers are active in this field and, accordingly, some significant progress has been achieved recently. This article attempts to critically review the wearable antennas especially in light of new materials and fabrication methods, and novel designs, such as miniaturized button antennas and miniaturized single and multi-band antennas, and their unique smart applications in WBAN. Finally, the conclusion has been drawn with respect to some future directions **[**08].

III. MM-WAVE ANTENNAS FOR 5G APPLICATIONS

5G communication applications are mainly divided into two categories (in view of the operating frequency): 1. communication systems in the sub-6 GHz frequency range (microwave frequencies) and 2. Communication systems above 6 GHz frequency range (mm-wave frequency). A comparison between mm-wave and the microwave frequency band has been given in Table 1. There exist some frequency bands where the atmospheric attenuation is comparatively lower. These frequency bands are 35, 94, 140, and 220 GHz. These frequency bands are the obvious choice for long-distance communication. There are other frequency bands in the mm-wave regime where the atmospheric attenuation is severe. These frequency bands are 60, 120, and 180 GHz. They are used for short-distance communication [28]. As far as transmitters and receivers are concerned, potential candidates in this frequency band are horn antenna, reflector antenna, and lens antenna. Printed antennas are flexible and easily accommodated in a comparatively smaller space. Compared to the earlier mentioned bulk antennas, the only disadvantage is low gain. There are four fundamental types of printed antennas in the mm-wave frequency bands[30]. These four are monopole, dipole, Yagi-Uda, and loop antenna. Of course, the choice of these antennas depends on the application and operational environment. A comparative study of bulk and printed antennas has been given in Table 2. Antennas designed in this frequency band are mainly used for 5G communication and antenna on-chip applications.

A. *Discrete mm-Wave Antennas for 5G Communication*

Other than the sub 6 GHz band, higher frequency bands for 5G communication systems are 24.25–27.5 GHz, 26.5–27.5 GHz, 26.5–29.5 GHz, 27.5–28.28 GHz, 27.5– 28.35 GHz, 37.0–40.0 GHz, and 37.0–43.5 GHz. Other frequency bands higher than 40.0 GHz for 5G communications are 53.3–66.5 GHz, 55.4–66.6 GHz, 56.6 –64.8 GHz, 57.0–64.0 GHz and 57.0–65.0 GHz. The frequency band 25–40 GHz is very popular for 5G communications and has been implemented by many countries like China, Korea, Japan, etc. Over the years, many research groups worldwide developed different antennas in these frequency bands[29]. Glimpses of these antennas whose band of operation is below 40 GHz are referred. A variety of substrates have been used for the fabrication of these antennas. As mentioned earlier, other than 60 GHz, there is another frequency band ranging from 57 GHz –70 GHz, where a lot of antenna development has taken place for 5G related applications [27]. As most of these antennas are MIMO, they were developed with unique techniques for low mutual coupling.

IV. MAJOR CHALLENGES IN THE DESIGN OF MM-WAVE ANTENNAS

Due to several inherent advantages, mm-wave communication systems are becoming more and more popular in the present era. These advantages are ultra-wide bandwidth, high speed, compact size, etc [14] [16]. Despite these advantages, a few disadvantages make the mm-wave communication systems, vis-à-vis mm-wave antenna technology, more challenging to implement. These challenges include high path loss, the requirement of ultra-broadband and multi-band antenna, gain enhancement using a large antenna array, etc. In this section, we briefly discuss a few of these challenges.

A. Design of Broadband and Multiband Antennas

Typical bandwidth for mm-wave antennas ranges from several tens of GHz to a few THz. Designing an antenna with a specified gain for such broadband naturally imposes a challenge, as it is challenging to maintain constant gain even in a low-frequency regime. A horn or parabolic dish is a natural choice for a broadband antenna in the mm-wave band [17]. These antennas provide almost 10% bandwidth in and around their frequency of operation. Due to their bulky structure, these antennas are not suitable for on-chip applications. Other alternatives are log periodic or sinuous antennas [26]. The sinuous antenna provides the largest bandwidth compared to other antennas in the mm-wave range. In the case of multiband antenna design, often it is observed that there is a variation of gain in the different frequency bands. This non-uniform gain may give rise to the design complexity of the overall system. A system has to be designed with variable gain to compensate for the non-uniform gain of the antenna.

B. Design of Antenna Array

As the single element provides a low gain in mm-wave (mainly due to its small size) frequencies, it is essential to design an antenna array to enhance the antenna gain. Generally, in the mm-wave frequency band, large antenna arrays are designed and implemented. Designing a large antenna array in mm-wave frequencies imposes a tough challenge [24]. In mm-wave applications (particularly for on-chip applications), available space is limited; hence it is challenging to accommodate a very large antenna array. In addition to that, it is also tough to integrate the array with other components. Due to space limitations, inter-element spacing in the array is also comparatively small. This small inter-element spacing gives rise to a critical mutual coupling problem. There are two sources of mutual coupling [25]. The first is through freespace radiation, and the second is through surface wave propagation. Antenna arrays with low mutual coupling are crucial in the mm-wave regime. Many methods have been adopted over the years by researchers and scientists to reduce the mutual coupling in large antenna arrays. The majority of them are based on the usage of artificial materials (known as metamaterials) in the substrate to reduce the coupling Some other reported methods to reduce the mutual coupling includes electromagnetic band-gap (EBG) structures and array-antenna decoupling surface (ADS) structures. A dual-layer EBG mushroom structure proposed in was used to restrain the surface wave in the microstrip antenna to decrease the electromagnetic coupling effect. The ADS structure presented in, making use of simple broken metal strips to avoid resonances, aims to reflect electromagnetic waves with equal amplitude but opposite phase to compensate for mutual coupling effect between elements of a quasi-Yagi antenna arrays. Traditional decoupling methods such as the wideband neutralization line proposed in offset the mutual coupling of a two-port MIMO antenna. A Tshaped decoupling network enhanced the isolation between two strongly coupled antennas. Innovel FSS was used to reduce the near-field mutual coupling between circularly polarized antennas.

Another challenge in mm-wave antenna array design is to have a large bandwidth in large antenna arrays. Classical phased array antenna cannot provide large bandwidth. State of the art array schemes like MIMO (multiple inputs multiple outputs) are adopted to meet this goal [21] [22]. Depending on the application scenario, different MIMO array schemes can be adopted. Some of these MIMO array sachems are SUSB (single user single beam), SUMB (single user multi-beam), MUSB (multiuser single beam), and MUMB (multi-user multi-beam). Implementation of MIMO in communication applications having complex algorithms and hardware poses several challenges in design[23].

C. Design of High Gain Antennas

In the mm-wave frequency band, the antenna’s gain is limited by its small size. As we go up in frequency, the problem becomes more and more severe. A natural choice for a high gain antenna in the THz regime is reflector antennas like reflector array, Gregorian reflector, Cassegrain reflector, etc. But these antennas have their own disadvantages, like bulky nature, difficult to fabricate, incompatibility with on-chip applications, high cost, etc [20]. Although printed antennas overcome many of these disadvantages, they too have some drawbacks. Printed antennas often underperform due to their high substrate loss, low metal conductivity, rough surface finish in antenna surface, etc. Another approach to increase the gain of the mm-wave antenna is to adopt the Fabri-Parrot cavity approach. This approach usually provides high directivity, but the challenges in designing these high gain antennas are low radiation efficiency and narrow bandwidth [19].

V. CONCLUSION

In this survey paper discusses survey. The multi-band MM-Wave variable antenna proposed in this study offers a promising solution for 5G and wireless applications. Its ability to operate in multiple frequency bands, combined with its adjustable parameters, provides versatility and adaptability to evolving communication needs. Further research and development in this area may lead to the practical implementation of such antennas in next-generation wireless systems, enhancing network performance and user experience. Further research and development can be pursued to refine and enhance the design, considering real-world deployment scenarios and practical implementation challenges.

REFERENCES

[1] Arebu Dejen, Jaume Anguera, Jeevani Jayasinghe4 and Murad Ridwan “Bandwidth Improvment of Dualband mm-wave Microstrip Antenna Using Genetic Algorithm” ISSN (2210-142X) 2023.

[2] R. Krishnamoorthy, Ushus.S.Kumar, GundalaSwathi, M. Amina Begum, B.Nancharaiah, K.V.DayaSagar “Metamaterial Inspired Quad-port Multi-Antenna System for Millimeter Wave 5G Applications” 2023.

[3] Amandeep Kaur Sidhu and Jagtar Singh Sivia “Design of Wideband Fractal MIMO Antenna using Minkowski and Koch Hybrid Curves on Half Octagonal Radiating Patch with High Isolation and Gain for 5G Applications” Vol. 12, No. 1, March 2023.

[4] Muhammad Aamer Shahzad 1,Kashif Nisar Paracha,Salman Naseer,Sarosh Ahmad,Muhammad Malik,Muhammad Farhan 1ORCID,Adnan Ghaffar,Mousa Hussien andAbu Bakar Sharif “An Artificial Magnetic Conductor-Backed Compact Wearable Antenna for Smart Watch IoT Applications” 24 November 2021.

[5] Bowen Lyu, Ghazanfar A. Safdar, Muhammad Ali Jamshed, and Masood Ur-Rehman “Flexible Ultra-Wideband Antenna for 5G and Beyond Wearable Applications” 2021.

[6] Achilles D. Boursianis, Maria S. Papadopoulou , Marco Salucci , Alessandro Polo, Panagiotis Sarigiannidis, Konstantinos Psannis, Seyedali Mirjalili, Stavros Koulouridis and Sotirios K. Goudos “Emerging Swarm Intelligence Algorithms and Their Applications in Antenna Design: The GWO, WOA, and SSA Optimizers” Volume 11, Issue 18 2021.

[7] Arpan Desai, Merih Palandoken, Jayshri Kulkarni, Gangil Byun And Truong Khang Nguyen “Wideband Flexible/Transparent Connected-Ground MIMO Antennas for Sub-6 GHz 5G and WLAN Applications” November 4, 2021.

[8] Shahid M. Ali, Cheab Sovuthy, Muhammad A. Imran, Soeung Socheatra, Qammer H. Abbasi and Zuhairiah Zainal Abidin “Recent Advances of Wearable Antennas in Materials, Fabrication Methods, Designs, and Their Applications: State-of-the-Art” 24 September 2020.

[9] Syeda Iffat Naqvi, Niamat Hussain,Amjad Iqbal,MuhibUr Rahman,Masoud Forsat,Seyed Sajad Mirjavadi andYasar Amin “Integrated LTE and Millimeter-Wave 5G MIMO Antenna System for 4G/5G Wireless Terminals” 15 July 2020.

[10] Muhammad Kamran Shereen, Muhammad Irfan Khattak and Mu’ath Al-Hasan “A Frequency and Radiation Pattern Combo-Reconfigurable Novel Antenna for 5G Applications and Beyond” 25 August 2020.

[11] Abdul Rahim, Dr.Praveen Kumar Malik and Dr.V.A.Sankar Ponnapalli “Design and Analysis of Multi Band Fractal Antenna for 5G Vehicular Communication” Page No. 26487 – 26497 April 2020.

[12] Yan-Yan Wang , Yong-Ling Ban And Yanhui Liu “Sub-6GHz 4G/5G Conformal Glasses Antennas” 13, 2019,

[13] Syeda Fizzah Jilani, Max Munoz, Qammer H. Abbasi, and Akram Alomainy “Millimeter-wave Liquid Crystal Polymer Based Antenna Array for Conformal 5G Applications” July 7, 2018.

[14] C. Zhang, S. L. Ariyavisitakul, and M. Tao, ‘‘LTE-advanced and 4G wireless communications [guest editorial],’’ IEEE Commun. Mag., vol. 50, no. 2, pp. 102–103, Feb. 2012.

[15] J.-H. Lu and J.-L. Guo, ‘‘Small-size octaband monopole antenna in an LTE/WWAN mobile phone,’’ IEEE Antennas Wireless Propag. Lett., vol. 13, pp. 548–551, 2014.

[16] N. O. Parchin, H. J. Basherlou, Y. I. A. Al-Yasir, A. M. Abdulkhaleq, and R. A. Abd-Alhameed, ‘‘Reconfigurable antennas: Switching techniques—A survey,’’ Electronics, vol. 9, no. 2, p. 336, Feb. 2020.

[17] H. Dildar, F. Althobiani, I. Ahmad, W. U. R. Khan, S. Ullah, N. Mufti, S. Ullah, F. Muhammad, M. Irfan, and A. Glowacz, ‘‘Design and experimental analysis of multiband frequency reconfigurable antenna for 5G and Sub-6 GHz wireless communication,’’ Micromachines, vol. 12, no. 1, p. 32, Dec. 2020.

[18] W. Pan, C. Huang, P. Chen, M. Pu, X. Ma, and X. Luo, ‘‘A beam steering horn antenna using active frequency selective surface,’’ IEEE Trans. Antennas Propag., vol. 61, no. 12, pp. 6218–6223, Dec. 2013.

[19] M. W. Young, S. Yong, and J. T. Bernhard, ‘‘A miniaturized frequency reconfigurable antenna with single bias, dual varactor tuning,’’ IEEE Trans. Antennas Propag., vol. 63, no. 3, pp. 946–951, Mar. 2015.

[20] N. Nguyen-Trong, A. Piotrowski, and C. Fumeaux, ‘‘A frequencyreconfigurable dual-band low-profile monopolar antenna,’’ IEEE Trans. Antennas Propag., vol. 65, no. 7, pp. 3336–3343, Jul. 2017.

[21] S. Gao, A. Sambell, and S. S. Zhong, ‘‘Polarization-agile antennas,’’ IEEE Antennas Propag. Mag., vol. 48, no. 3, pp. 28–37, Jun. 2006.

[22] L. Kang, H. Li, J. Zhou, and S. Zheng, ‘‘An OAM-mode reconfigurable array antenna with polarization agility,’’ IEEE Access, vol. 8, pp. 40445–40452, 2020.

[23] M. N. Osman, M. K. A. Rahim, M. R. Hamid, M. F. M. Yusoff, and H. A. Majid, ‘‘Compact dual-port polarization-reconfigurable antenna with high isolations for MIMO application,’’ IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 456–459, 2016.

[24] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, ‘‘Reconfigurable antennas for wireless and space applications,’’ Proc. IEEE, vol. 100, no. 7, pp. 2250–2261, Jul. 2012.

[25] I. Ahmad, H. Dildar, W. U. R. Khan, S. A. A. Shah, S. Ullah, S. Ullah, S. M. Umar, M. A. Albreem, M. H. Alsharif, and K. Vasudevan, ‘‘Design and experimental analysis of multiband compound reconfigurable 5G antenna for sub-6 GHz wireless applications,’’ Wireless Commun. Mobile Comput., vol. 2021, pp. 1–14, Apr. 2021.

[26] R. L. Haupt and M. Lanagan, ‘‘Reconfigurable antennas,’’ IEEE Antennas Propag. Mag., vol. 55, no. 1, pp. 49–61, Feb. 2013.

[27] N. O. Parchin, H. J. Basherlou, Y. I. Al-Yasir, R. A. Abd-Alhameed, A. M. Abdulkhaleq, and J. M. Noras, ‘‘Recent developments of reconfigurable antennas for current and future wireless communication systems,’’ Electronics, vol. 8, no. 2, p. 128, 2019.

[28] R. Shanmugam, ‘‘Design and analysis of a frequency reconfigurable pentaband antenna for WLAN and 5G applications,’’ J. Electromagn. Eng. Sci., vol. 21, no. 3, pp. 228–235, Jul. 2021.

[29] F. Zadehparizi and S. Jam, ‘‘Increasing reliability of frequencyreconfigurable antennas,’’ IEEE Antennas Wireless Propag. Lett., vol. 17, no. 5, pp. 920–923, May 2018.

[30] M. M. Fakharian, P. Pezaei, A. A. Orouji, and M. Soltanpur, ‘‘A wideband and reconfigurable filtering slot antenna,’’ IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 1610–1613, 2016.

[31] L. Pazin and Y. Leviatan, ‘‘Reconfigurable slot antenna for switchable multiband operation in a wide frequency range,’’ IEEE Antennas Wireless Propag. Lett., vol. 12, pp. 329–332, 2013.

[32] G. Jin, C. Deng, J. Yang, Y. Xu, and S. Liao, ‘‘A new differentially-fed frequency reconfigurable antenna for WLAN and sub-6GHz 5G applications,’’ IEEE Access, vol. 7, pp. 56539–56546, 2019.

[33] T. Li, H. Zhai, L. Li, and C. Liang, ‘‘Frequency-reconfigurable bow-tie antenna with a wide tuning range,’’ IEEE Antennas Wireless Propag. Lett., vol. 13, pp. 1549–1552, 2014.

[34] Z. Zhang and Z. Pan, ‘‘Design of reconfigurable bandwidth filtering antenna and its applications in IR/UWB system,’’ Electronics, vol. 9, no. 1, p. 163, Jan. 2020.

[35] P. F. Hu, Y. M. Pan, X. Y. Zhang, and B.-J. Hu, ‘‘A filtering patch antenna with reconfigurable frequency and bandwidth using F-shaped probe,’’ IEEE Trans. Antennas Propag., vol. 67, no. 1, pp. 121–130, Jan. 2019.

[36] N. Ojaroudi, S. Amiri, and F. Geran, ‘‘A novel design of reconfigurable monopole antenna for UWB applications,’’ Appl. Comput. Electromagn. Soc. J., vol. 28, no. 7, pp. 633–639, 2013.

[37] J. Deng, S. Hou, L. Zhao, and L. Guo, ‘‘Wideband-to-narrowband tunable monopole antenna with integrated bandpass filters for UWB/WLAN applications,’’ IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2734–2737, 2017.

[38] P. Y. Qin, F. Wei, and Y. J. Guo, ‘‘A wideband-to-narrowband tunable antenna using a reconfigurable filter,’’ IEEE Trans. Antennas Propag., vol. 63, no. 5, pp. 2282–2285, May 2014.

[39] M.-C. Tang, Z. Wen, H. Wang, M. Li, and R. W. Ziolkowski, ‘‘Compact, frequency-reconfigurable filtenna with sharply defined wideband and continuously tunable narrowband states,’’ IEEE Trans. Antennas Propag., vol. 65, no. 10, pp. 5026–5034, Oct. 2017.

[40] [27] I. F. Da Costa, S. A. Cerqueira, D. H. Spadoti, L. G. Da Silva, J. A. J. Ribeiro, and S. E. Barbin, ‘‘Optically controlled reconfigurable antenna array for mm-Wave applications,’’ IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2142–2145, 2017.