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Metamaterials in 5G Antenna Designs: A Bibliometric Survey

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Abstract: The demand of high gain and wideband compact antenna designs are gaining importance to fulfil the need of 5G communication systems. This has opened the doors for the researchers to explore 5G antennas incorporating metamaterials as they can meet the requirement of high gain and wideband compact antennas. Overview of various metamaterial-based antenna designs including Electromagnetic Band Gap (EBG), artificial Magnetic Conductor (AMC), Frequency Selective Surface (FSS) and Partially Reflective Surface (PRS) are discussed in the paper. The paper primarily focuses on bibliometric survey of various types of 5G metamaterial antennas in terms of number of documents published, leading universities actively involved in the related research, distribution of documents in different areas, major contribution of authors and leading journal publishing the documents. Scopus database from 1st September 2014 till date is used to carry out this bibliometric survey. The statistical data presented in this paper can provide the prerequisite for the researchers to work in this area.

Keywords: Metamaterials; 5G antenna; Bibliometric; Scopus; VOS viewer tool

1. Introduction

The demand of compact, high gain, wideband antenna designs capable of enhancing channel capacity is gaining importance to meet the requirements of 5G technology. Also, extensive Bibliometric surveys are done in 5G and millimeter wave applications to enable the researchers to explore novel ideas to improve the overall antenna performance [Malekar et al. 2020, Shevada et al. 2020, Dixit et al. 2020]. The dipole antennas can provide enhanced gain, bandwidth, and stable radiation pattern [Zheng et al. 2017, Wang et al. 2018, Cui et al. 2013]. Multilayer PCB antenna structures can provide multiband operations along with wideband by simply exciting the resonant modes [Tang et al. 2018, Huang et al. 2018]. Likewise, the use of parasitic elements in antenna design along with different coupling techniques can enhance various antenna parameters like bandwidth, isolation, and radiation pattern isolation [Ding et al. 2018, Zhang et al. 2018, Chu et al. 2015, Ding et al. 2018, Cui et al. 2018]. Also, the design of resonant cavity antennas (RCA) can further enhance the gain, front to back ratio and directivity [Liang et al. 2018]. The use of corrugated structures in 5G applications can further improvise the antenna performance in terms of size and front to back ratio. Hence, Antipodal Vivaldi antenna inclusive of corrugated structures can enhance the antenna gain and is one of the important factors to be considered in design of antenna for 5G [Dixit et al. 2021]. The use of Dolph Chebyshev current distribution in design of antenna array can reduce side lobes and improve the radiation characteristics [Bhadoria et al. 2018]. Recently metamaterial (MTM) based 5G antenna designs are widely noticed by the researchers because of their unique features of providing enhanced gain, bandwidth, and compact size [Kumar et al. 2021, Dixit et al. 2020a, Dixit et al. 2020b, Gunjal et al. 2020]. An extensive review is carried out in 5G antenna designs which includes various metamaterial-based antenna structures and their applications in multiple input multiple output (MIMO) systems [Kumar et al. 2020]. In recent years 5G antenna designs including artificial magnetic conductor (AMC), high impedance surface (HIS), reactive impedance surface (RIS), partially reflecting surface (PRS), electromagnetic band gap (EBG) and metasurface are explore to improve the overall antenna performance. Like perfect magnetic or electric conducting surfaces, RIS can also reflect the total power and has the capability to conserve magnetic and electric energy simultaneously. Further, RIS enhances bandwidth and reduces antenna size. [Jagtap et al. 2018]. Antenna structures incorporating multilayer PRS, AMC or HIS can also improve the gain and bandwidth requirement [Wang et al. 2015]. EBG based antenna structure provides better isolation and is best suited for 5G MIMO antenna designs [Kumar et al. 2020].

2. Classification of Metamaterials based on Permittivity and Permeability

The electromagnetic properties of any material are governed by its permittivity (ε) and permeability (μ). Based on the values of ε and μ the classification of metamaterials was first proposed by Veselago. When both permittivity and permeability are negative some unusual phenomena occur like reversal of Snell Law and Doppler Shift. The relation between permittivity, permeability, and refractive index (n) is given by

$$n = \pm\sqrt{\varepsilon_r \mu_r}$$

Where μ_r and ε_r are relative permeability and relative permittivity of a medium. Therefore, based on the value of ε and μ in addition to the sign metamaterials are broadly classified in to four distinct categories as shown in the figure 1. Each class represents different metamaterial structure [Picchio et al. 2020].

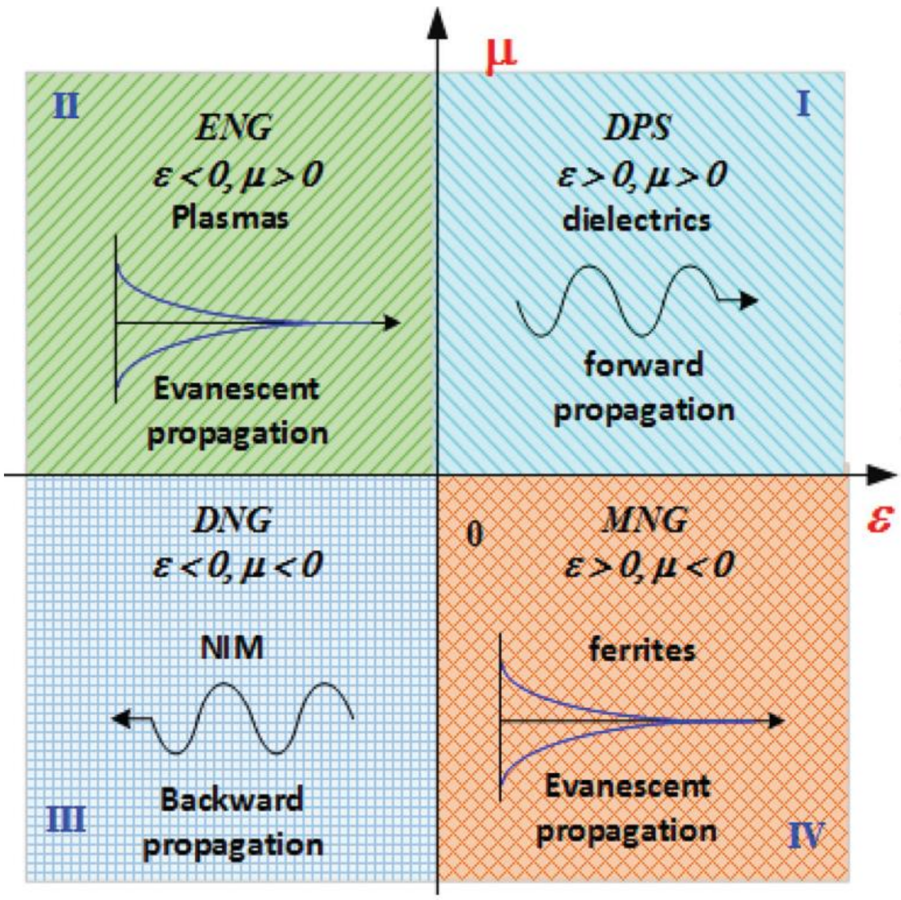

Figure 1: Classification of metamaterials based on refractive index (n), permittivity (ε) and permeability (μ).

The first quadrant represents double positive (DPS) materials as both μ and ε are positive. The material is also called as right-handed medium and EM waves can propagate. These materials are easily found in nature. In second quadrant the value of $\varepsilon < 0$ and $\mu > 0$ hence, these materials are referred as epsilon negative (ENG) materials and represents electric plasma. The third quadrant represents double negative (DNG) materials as both μ and ε are negative and are also referred as left-handed medium. The EM waves can propagate through left-handed medium and such materials are not found in nature. In fourth quadrant $\varepsilon > 0$ and $\mu < 0$ hence these materials are referred as mu negative (MNG) and represents ferrite materials [Kumar et al. 2021].

3. Metamaterials in antenna design

Electromagnetic metamaterials generally referred to as metamaterials are artificial materials found in nature with unusual properties. MTMs are composed of microstructures usually called as unit cells. These structures can be antisymmetric or symmetric [Picchio et al. 2020]. The geometry and size of each unit cell determines the value of permittivity, permeability, and resonant frequencies [Phan et al. 2016]. The unit cell size is a function of frequency and varies with respect to the resonant frequency (f_r). As represented in figure 2 the size of a unit cell is less than 1/10 of the wavelength. As per the available literature the basic designs used in most of the metamaterials are electric dipoles and split ring resonators (SRRs). As shown in figure 2, it is observed that as the size of the inclusion decreases the order of Hilbert fractal curve increases [Krzysztofik et al. 2014a, Krzysztofik et al. 2013b, Krzysztofik et al. 2017c].

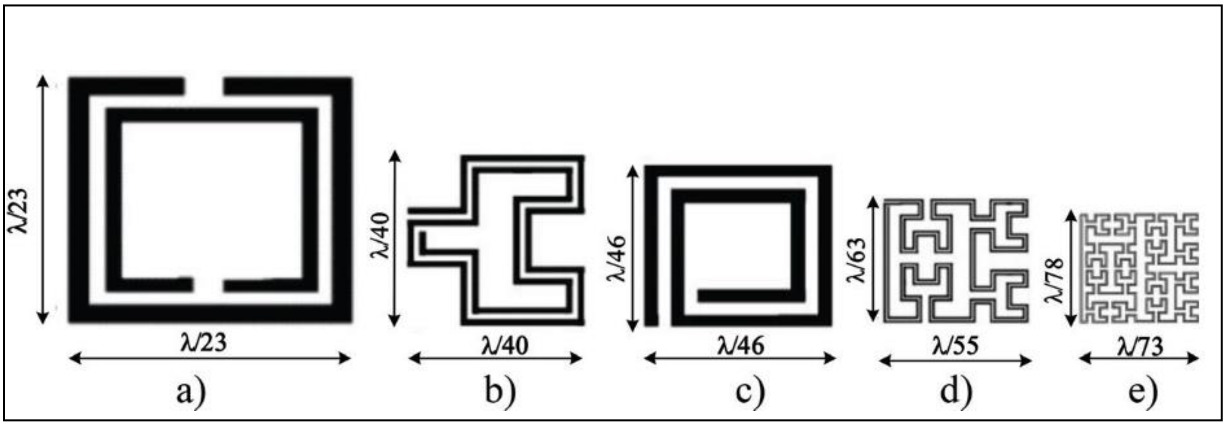

Figure 2. (a) SSR based unit cell, (b) 2nd order Hilbert fractal inclusion, (c)square spiral, (d) 3rd order Hilbert fractal inclusion, (e) 4th order Hilbert fractal inclusion [Krzysztofik et al. 2014a, Krzysztofik et al. 2013b, Krzysztofik et al. 2017c].

The antenna performance such as high gain [Wu, et al. 2016, Bhaskar et al. 2016], multiband structures [Si L et al. 2015a, Si L et al. 2015b] along with beam steering [Dadgarpour et al. 2016, Li J et al. 2017] can be enhanced using metamaterials in antenna designs. A 5G mmWave metamaterial-based antenna design capable of providing high gain is discussed [Jiang et al. 2019]. The shared-aperture MTM antenna design can also provide orthogonal pattern diversity and enhanced mutual coupling. Also, the design is suitable for 5G base stations as it can provide wide frequency band [Sadananda et al. 2019]. The negative refractive index metamaterial (NRIM) along with dielectric resonators (DRA) provides dual polarization and enhance bandwidth [Li J et al. 2017]. The MTM based AVA design with and without corrugated structures are designed and shows that the design with corrugation provides better bandwidth and is suitable for 5G applications [Dixit et al 2020c].

4. Metamaterial Induced Antenna Gain and Bandwidth Enhancement

The available literature highlights that low profile antenna structures exhibits low gain and narrow bandwidth. There are multiple methods available so as to enhance the antenna gain and bandwidth [Hema et al. 2021, Shevada et al. 2021, Gunjal et al. 2020]. Over last few years 5G antenna designs incorporating metamaterial structures are widely explored. A planar MTM based antenna design capable of providing impedance bandwidth of 3.08 – 11.7 GHz and 13.6 – 36.4 GHz respectively with peak gain of 8.02 dBi is presented in [Yuan et al. 2017]. A DNG based dual band antenna design can provide a gain of 7.45 dBi and bandwidth of 6 GHz [Urul et al. 2020]. Antenna design using split ring resonator (SSR) with and without corrugated structures can provide a gain upto 7dBi and bandwidth of 230 – 420 MHz [Patel et al. 2016]. In addition, a Fabry Perot Cavity (FPC) antenna structure incorporating partially reflective surface (PRS) can provide 8.2 dBi gain with impedance bandwidth of 2.2 GHz [Meriche et al. 2019]. Further, antenna designs based on electromagnetic band gap (EBG) [Verma et al. 2020, Alibakhshikenari et al. 2019], Frequency selective surfaces [Thummaluru et al 2018, Hassan et al. 2018, Akbari et al. 2017], artificial magnetic conductors [Zhu et al 2018] can also be incorporated in 5G antenna designs to enhance gain and bandwidth.

5. Metamaterial Based Compact Antenna Designs

Antenna miniaturization deals with reduced size antenna designs capable of providing desired gain and bandwidth. Traditional method of designing miniaturized antenna includes use of high permittivity and permeability materials. A complimentary SRR based antenna structure can provide a compact antenna of size 23 mm x 29 mm that can cover a wide band of 3 - 12 GHz

[Khan et al. 2016]. EBG based low profile wearable antenna design exhibits a compact size of 20 mm x 25 mm within the frequency band of 3.1 - 10.6 GHz [Sambandam et al. 2020]. Metamaterial based antenna design suitable for biomedical application has a size of 7 mm × 6 mm [Zada et al. 2020]. A compact antenna design inclusive of metamaterial is suitable for 5G application and has a size of 31 mm x 31 mm [Gulur et al 2019]. In addition, various structures incorporating metamaterials include loops, leaky-wave, and dipoles [Bonefacic et al. 2012, Xi et al 2019].

6. Bibliometric Analysis of Metamaterial Based 5G Antennas

The amount of research work displayed in the field of metamaterial based 5G antenna designs can be quantified by means of Bibliometric survey. Scopus database from 2014 till date is analysed and summarized in this section via line charts, bar charts, tables, and VOS viewer tool. The main aim of this quantitative analysis is to explore the amount of work done and to enable the researchers to decide his/her boundary of research.

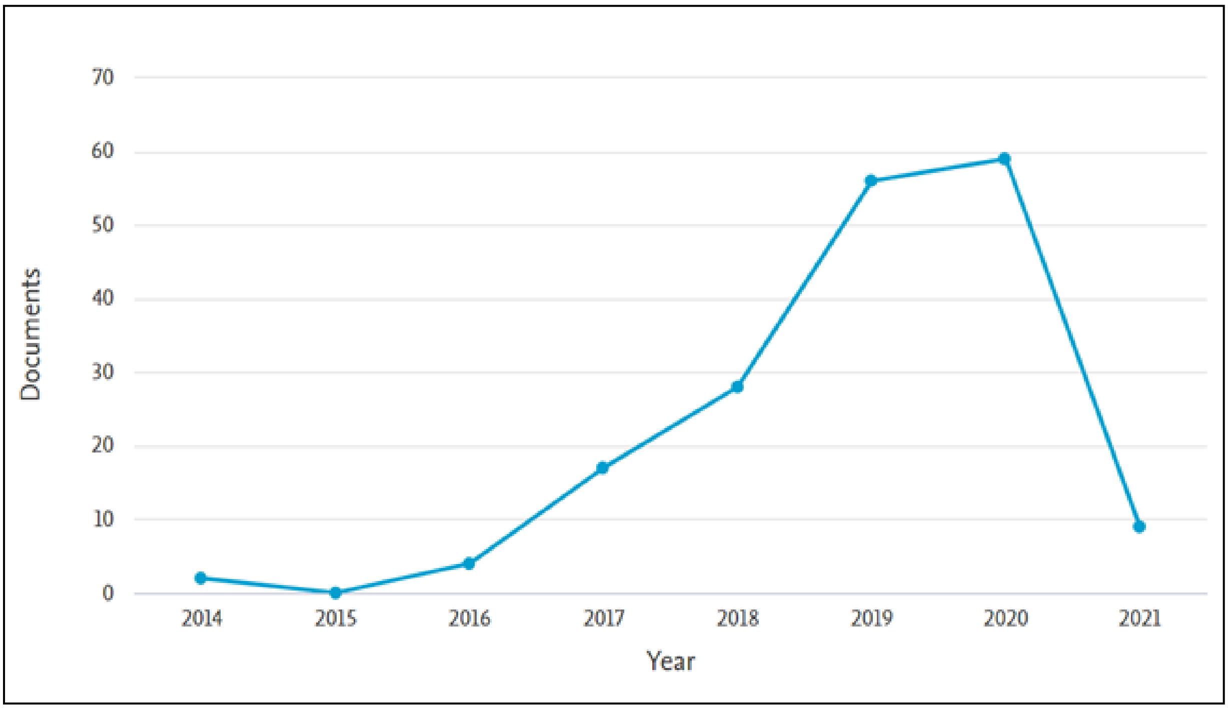

Figure 3: Number of documents published per year

Figure 3 represents year wise statistical data highlighting the number of documents published in the field of metamaterial based 5G antenna designs. As per the statistics the research work was primarily reported in 2014 with 2 documents. The research work shows a rising profile from 2015 onwards till date with a maximum of 59 documents in the year 2020. The total number of documents published from 2014 till date are 175 as per Scopus database thereby indicating the thrust of research work in 5G communication.

The distribution of metamaterial based 5G antenna document types include conference papers, articles, conference reviews and review papers as shown in figure 4. According to the quantitative data represented it is observed that out of 175 documents 78 are conference papers (44.6%), followed by 73 articles (41.7%), 20 conference review papers (11.4%) with merely 4 review papers (2.3%). A majority of research work carried out by is published in conferences.

The bar chart of the number of documents published by top 10 universities across the world is represented in figure 5. The Indian Institute of Technology Delhi tops the chart with a maximum of 11 documents published followed by University Tecknologi Malaysia and Xidian University with 10 and 6 documents, respectively. As per the Scopus database from 2014 till date, total 160 universities worldwide have contributed to the field of metamaterial based 5G antenna designs indicating its significance.

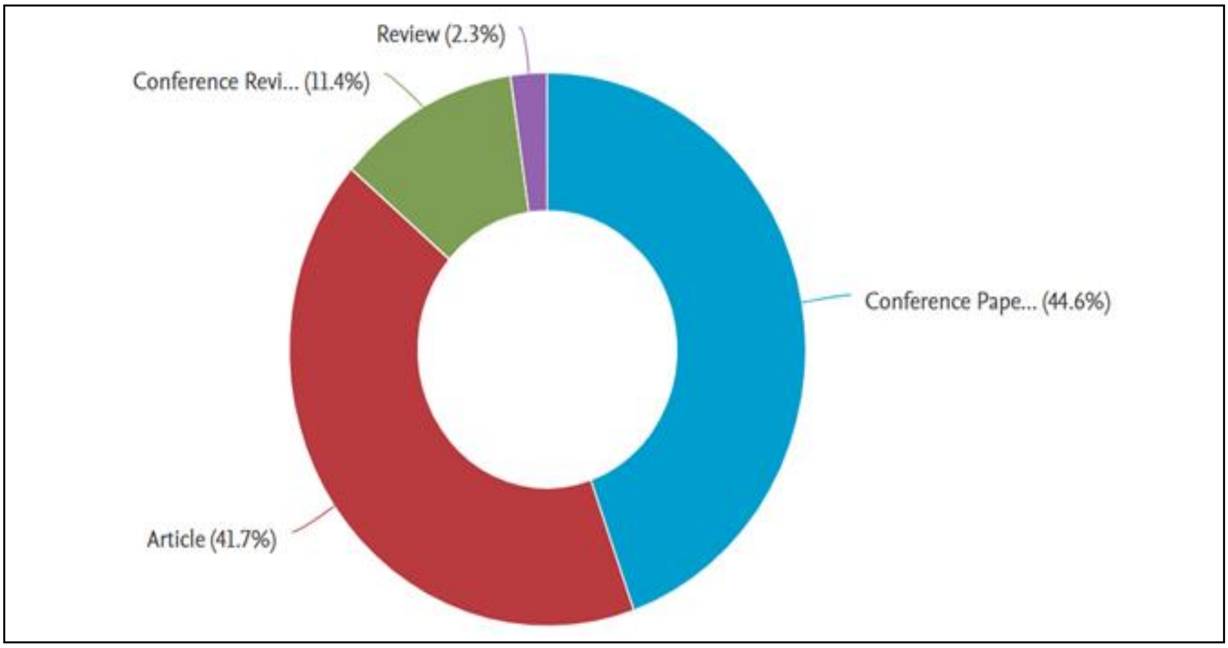

Figure 4: Distribution of metamaterial based 5G antenna documents by its type

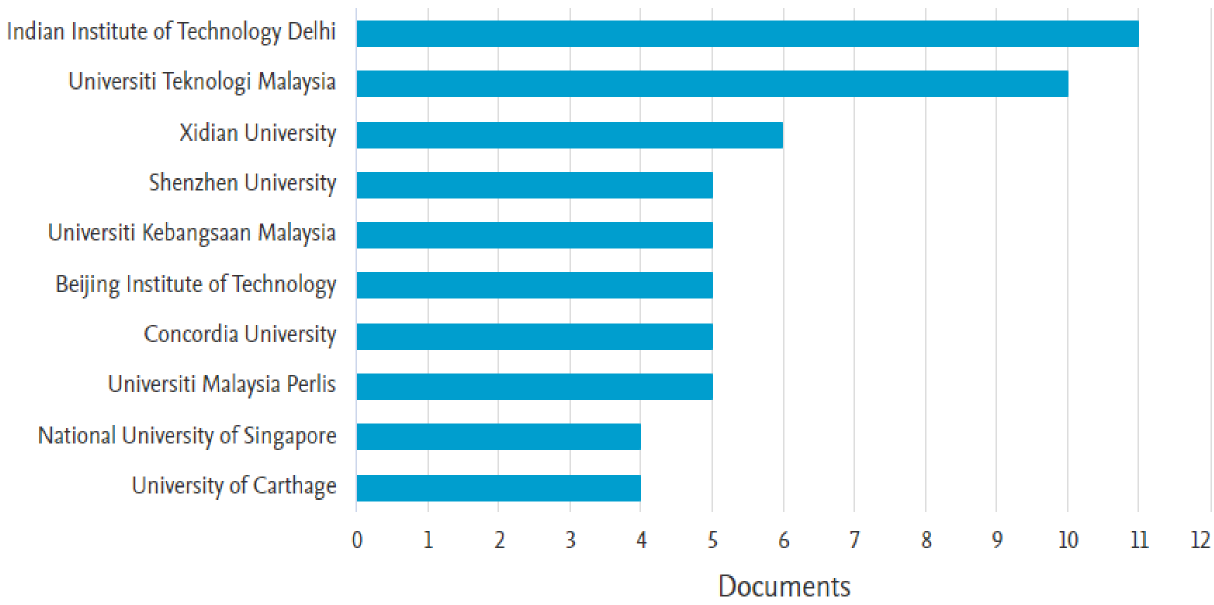

Figure 5: Bar chart of number of documents published by top ten universities

Figure 6 highlights year wise publications in top five journals indicating a maximum count of 8 documents in IEEE Access followed by International Journal Of RF And Microwave Computer Aided Engineering and Microwave and Optical Technology Letters with 7 documents each. Journals namely Lecture Notes in Electrical Engineering published 6 documents and IEEE Transactions on Antennas and Propagation published 5 documents.

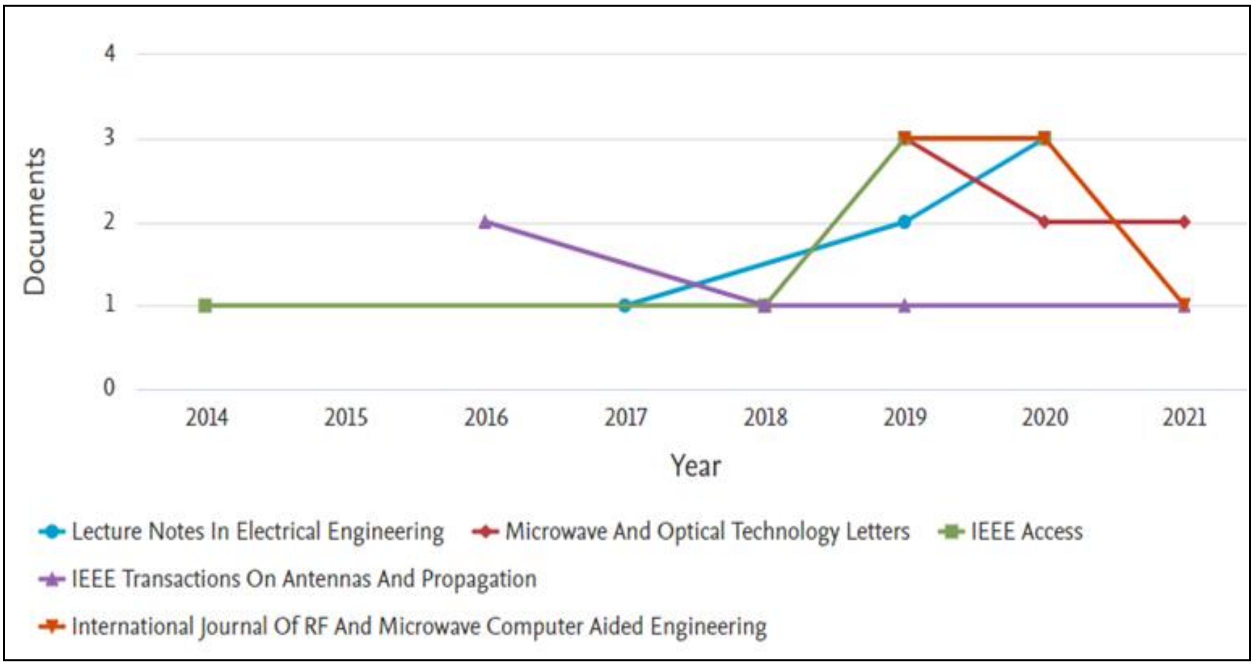

Figure 6: Number of documents published per year in various journals

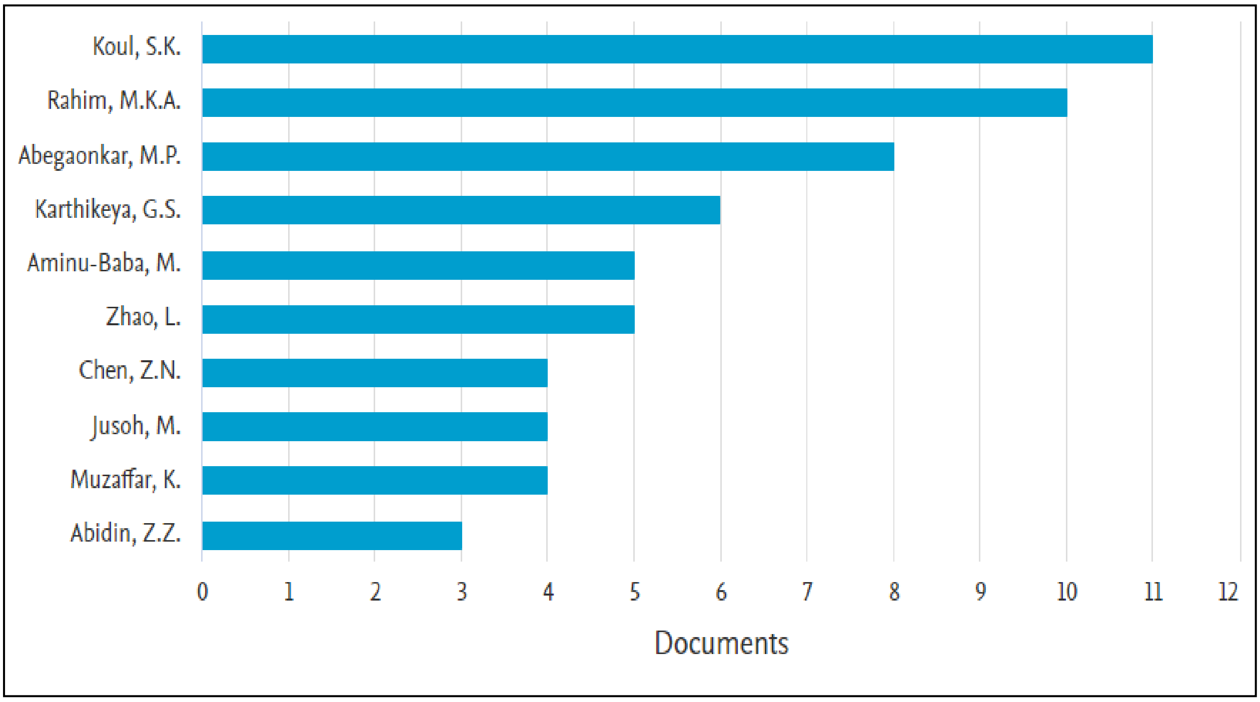

Figure 7: The bar chart of research contribution by top ten authors

Lot of researchers are working in 5G antenna designs incorporating metamaterials since 2014. A quantitative analysis is represented in figure 7 indicating research contribution by top 10 authors. According to Scopus database total 159 research scholars are working in the field of metamaterial based 5G antenna designs with a maximum count of 11 documents published by author Koul, S.K. followed by Rahim, M.K.A.with 10 publications, Abegaonkar, M.P. with 8 publications, Karthikeya, G.S. with 6 publications and 5 publications by Aminu-Baba, M. and Zhao, L. respectively.

The design of 5G antennas using different types of metamaterials with variations in unit cell structures is available in the literature survey. This research work is not only restricted to the field of Engineering but includes various other fields like computer science, physics and Astronomy, Material Science, Mathematics, Decision Science, Energy, Medicine, Social Science, Biochemistry and others. The distribution of 175 documents by subject area is illustrated in figure 8 emphasizing a maximum of 117 documents (28.4%) in Engineering, 103 documents (25%) in Computer Science and 78 documents (18.9%) in the field of Physics and Astronomy.

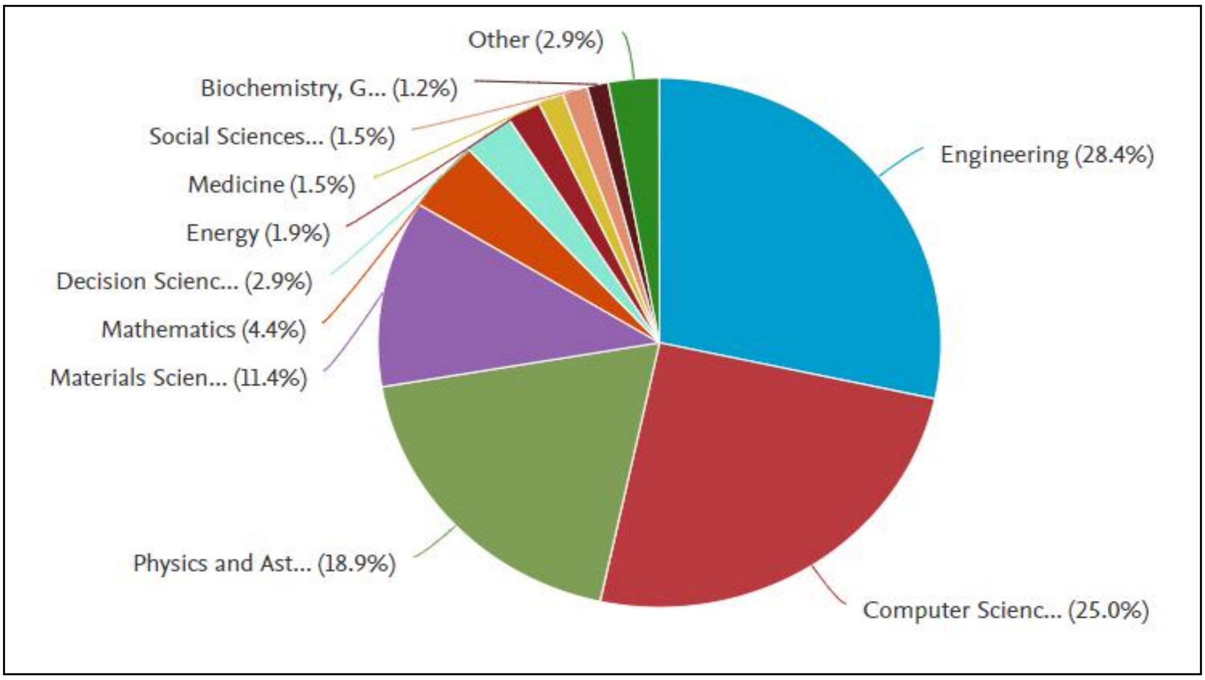

Figure 8: Distribution of documents by subject area

The researchers all over the world are contributing to the field of 5G antenna designs integrating various types of metamaterials. Table 1 throws light on the number of documents published in the first 10 countries/territories. Figure 9 illustrates network visualization depicting the interlinkage of indexed keywords and the source titles using the VOS viewer tool. Different keywords of the source titles like 5G communication systems, metamaterial antennas, metamaterials, etc are indicated by circles in the network and the curved lines interconnecting the circles represents linkage between the keywords.

Table 1: Number of documents published by Countries/Territories

Country/Territory	Number of documents published in Scopus
India	41
China	30
Malaysia	18
Canada	11
United Kingdom	11

Egypt	10
United States	9
Pakistan	7
South Korea	7
Saudi Arabia	6

Table 2 displays highly cited top five publications in the field of metamaterial 5G antennas along with year of publication, authors name and Journal title. As mentioned in the table the article published by author Haraz O.M in IEEE Access (2014) was cited 94 times by the researchers. This paper presented a design of 5G antenna incorporating EBG structure capable of providing improved radiation characteristics.

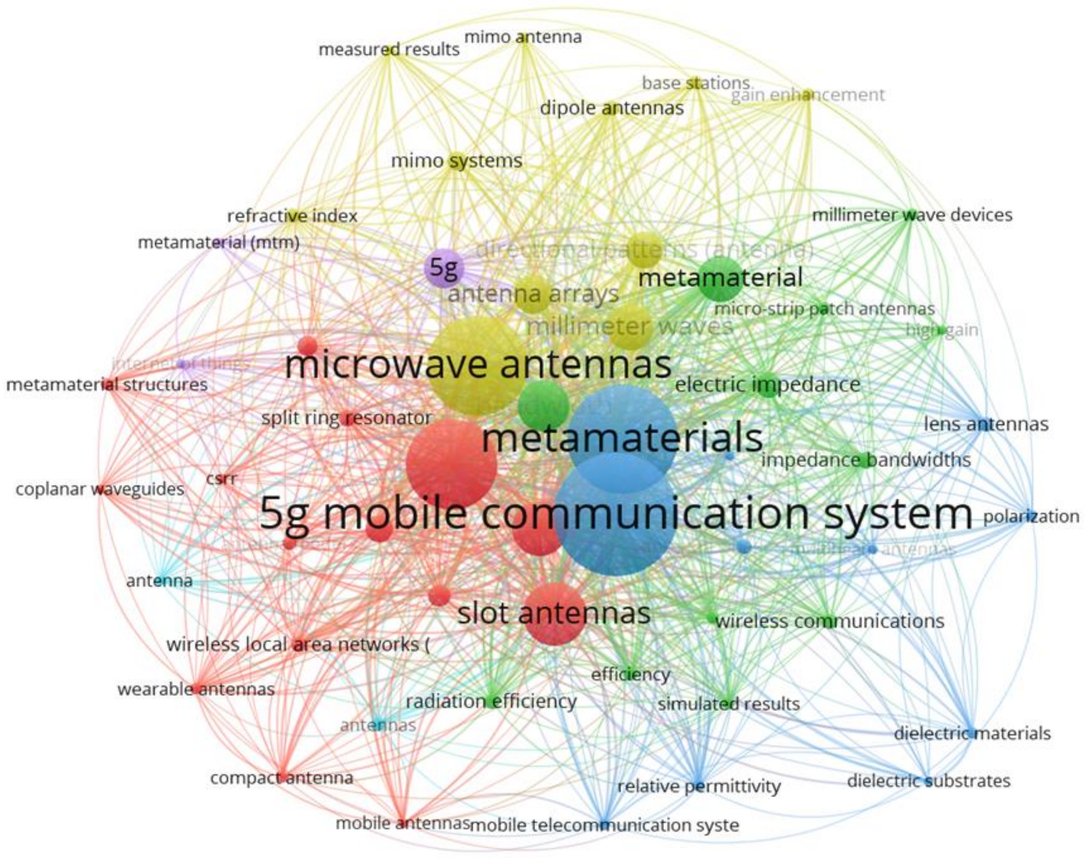

Figure 9: Network visualization depicting the inter linkage of indexed keywords

Table 2. Top five highly cited documents in the field of metamaterial based 5G antennas

Sr. No.	Document Title	Authors	Year of publication	Journal Title	Citation Count
1	Dense dielectric patch array antenna with improved radiation characteristics using ebg ground structure and dielectric superstrate for future 5G cellular networks	Haraz O.M., Elboushi A., Alshebeili S.A., Sebak A.-R.	2014	IEEE Access	94
2	A flat dual-polarized transformation-optics beam scanning luneburg lens antenna using PCB-Stacked gradient index metamaterials	Su Y., Chen Z.N.	2018	IEEE Transactions on Antennas and Propagation	37
3	A Meta-Surface Decoupling Method for Two Linear Polarized Antenna Array in Sub-6 GHz Base Station Applications	Liu F., Guo J., Zhao L., Shen X., Yin Y.	2019	IEEE Access	36

4	Single End-Fire Antenna for Dual-Beam and Broad Beamwidth Operation at 60 GHz by Artificially Modifying the Permittivity of the Antenna Substrate	Dadgarpour A., Zarghooni B., Virdee B.S., Denidni T.A.	2016	IEEE Antennas and Wireless Propagation Letters	34
5	A 28-GHz antenna for 5G MIMO applications	Wani Z., Abegaonkar M.P., Koul S.K.	2018	Progress in Electromagnetics Research Letters	32

7. Conclusion

The bibliometric paper presented explores the statistical data in the field of metamaterial 5G antenna design. The quantitative analysis is carried out based on the Scopus database from 2014 till date including a total of 175 papers published in various journals, by different researcher scholars from all over the world working with different universities. Some of the noteworthy facts that can be summarized are Indian Institute of Technology Delhi ranks 1st and had publish a total of 11 documents and also amongst all the countries/territories India holds 1st rank in publishing documents with 41. This indicates a massive research work carried out by the researchers in the field of 5G antenna designs incorporating metamaterials in India. In addition, network visualization depicting the inter linkage of indexed keywords like metamaterials, 5G mobile communication system and microwave antennas is viewed in the paper using VOS viewer tool. Finally, the bibliometric paper will help the researchers to narrow down the spectrum of research thereby helping them to focus on the research area by finding out the research gaps.

References:

Zheng D.Z, and Chu Q.X. 2017 ‘‘A wideband dual-polarized antenna with two independently controllable resonant modes and its array for base- station applications,’’ IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2014–2017.

Wang, C., Chen, Y., and Yang, S. 2018. ‘‘Dual-band dual-polarized antenna array with flat-top and sharp cutoff radiation patterns for 2G/3G/LTE cellular bands,’’ IEEE Trans. Antennas Propag., vol. 66, no. 11, pp. 5907–5917.

Cui, Y., Li, R., and Wang, P. 2013. ‘‘Novel dual-broadband planar antenna and its array for 2G/3G/LTE base stations,’’ IEEE Trans. Antennas Propag., vol. 61, no. 3, pp. 1132–1139.

Tang, Z., Liu, J., Cai, M., Wang, J., and Yin, Y. 2018. ‘‘A wideband differentially fed dual-polarized stacked patch antenna with tuned slot excitations,’’ IEEE Trans. Antennas Propag., vol. 66, no. 4, pp. 2055–2060.

Huang, H., Li, X., and Liu, Y. 2018. ‘‘A novel vector synthetic dipole antenna and its common aperture array,’’ IEEE Trans. Antennas Propag., vol. 66, no. 6, pp. 3183–3188.

Ding, C., Sun, H., Ziolkowski, R., and Guo, Y. 2018. ‘‘A dual layered loop array antenna for base stations with enhanced cross- polarization discrimination,’’ IEEE Trans. Antennas Propag., vol. 66, no. 12, pp. 6975–6985.

Zhang, Q., and Gao, Y. 2018. ‘‘A compact broadband dual-polarized antenna array for base stations,’’ IEEE Antennas Wireless Propag. Lett., vol. 17, no. 6, pp. 1073–1076.

Chu, Q., Wen, D., and Luo, Y. 2015. ‘‘A broadband ±45◦ dual-polarized antenna with Y-Shaped feeding lines,’’ IEEE Trans. Antennas Propag., vol. 63, no. 2, pp. 483–490.

Ding, C., Zhang, X., Zhang, Y., Pan, Y., and Xue, Q. 2018 ‘‘Compact broadband dual-polarized filtering dipole antenna with high selectivity for base-station applications,’’ IEEE Trans. Antennas Propag., vol. 66, no. 11, pp. 5747–5756.

Cui, Y., Wu, L., and Li, R. 2018. ‘‘Bandwidth enhancement of a broadband dual- polarized antenna for 2G/3G/4G and IMT base stations,’’ IEEE Trans. Antennas Propag., vol. 66, no. 12, pp. 7368–7373.

Liang Z., Lu, C., Li, Y., Liu, J., and Long, Y. 2018. ‘‘A broadband dual-polarized antenna with front-to-back ratio enhancement using semicylindrical side- walls,’’ IEEE Trans. Antennas Propag., vol. 66, no. 7, pp. 3735–3740.

Kumar, P., Ali, T., Pai, M.M.M., 2021. “Electromagnetic Metamaterials: A New Paradigm of Antenna Design,” IEEE Access.

Dixit, Amruta S., and Sumit Kumar. 2020a. “A Survey of Performance Enhancement

Techniques of Antipodal Vivaldi Antenna.” IEEE Access 8: 45774–96.

Dixit, Amruta S, and Sumit Kumar. 2020b. “A Miniaturized Antipodal Vivaldi Antenna for 5G Communication Applications.” In 7th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, 800–803.

Kumar S., Dixit A., Malekar R., Raut H., Shevada L. 2020. “Fifth Generation Antennas : A Comprehensive Review of Design and Performance Enhancement Techniques.” IEEE Access 8: 163568–93.

Picchio, V., Cammisotto V., Pagano F., Carnevale R., and Chimenti. 2020. “Metamaterials in Application to Improve Antenna Parameters,” in: Intechopen. pp. 1–15.

Phan DT., Phan HL., and Nguyen TQH. 2016. “A miniaturization of microstrip antenna using negative permittivity metamaterial based on CSRR loaded ground for WLAN applications,” Journal of Science and Technology. Pp. 689-697.

Krzysztofik WJ., 2014a. “Antenna properties improvement by means of modern technology—Metamaterials as a modified substrate and/or superstrate,” In 20th International Conference on Microwave, Radar and Wireless Communications. Vol. 2. Gdansk, Poland: MIKON. pp. 637-640.

Krzysztofik WJ. 2013b. “Fractal geometry in electromagnetics applications—From antenna to metamaterials,” Microwave Review., 19(2):3-14.

Krzysztofik WJ., 2017c. “Fractals in antennas and metamaterials applications,” INTECHopen science, open minds. In: Brambila F, editor. Fractal Analysis–Applications in Physics, Engineering and Technology. Rijeka, pp. 45-81.

Wu S., Yi Y., Yu Z., Huang X., and Yang H. 2016. “A zero-index metamaterial for gain and directivity enhancement of tapered slot antenna,” J Electromagn Waves Appl 30(15): pp 1993– 2002

Bhaskar M., Johari E., Akhter Z., and Akhtar M J. 2016. “Gain enhancement of the Vivaldi antenna with band notch characteristics using zero-index metamaterial,” Microw Opt Techn Lett 58(1):233– 238.

Si L., Zhu W., and Sun H. 2015a. “A compact, planar, and CPW-fed metamaterial-inspired dual-band antenna,” IEEE Antennas Wireless Propag Lett vol 12, pp 305–308.

Si L., 2015b. “A uniplanar triple-band dipole antenna using complementary capacitively loaded loop,” IEEE Antennas Wireless Propag Lett vol 14, pp 743–746.

Dadgarpour A., Zarghooni B., Virdee S., Denidni A., 2016. “Single end-fire antenna for dualbeam and broad beamwidth operation at 60 GHz by artificially modifying the permittivity of the antenna substrate,” IEEE Trans Antennas Propag 64(9):4068–4073.

Li J., Zeng Q., Liu R., Denidni TA., 2017. "Beam-tilting antenna with negative refractive index metamaterial loading," IEEE Antennas Wireless Propag Lett 16, pp 2030–2033.

Jiang H., Si L-M., Hu W., Lv X. 2019. "A symmetrical dual-beam Bowtie antenna with gain enhancement using metamaterial for 5G MIMO applications," IEEE Photonics J 11(1).

Sadananda G., Abegaonkar P., Koul K. 2019. "Gain equalized shared-aperture antenna using dual-polarized ZIM for mmWave 5G base stations," IEEE Antennas Wireless Propag Lett 18(6), pp 1100–1104.

Dixit A., Kumar S. 2020c. "The enhanced gain and cost-effective antipodal Vivaldi antenna for 5G communication applications," Microw Opt Technol Lett 62, pp 2365–2374.

Shevada L., Raut H.D., Malekar R., Kumar S. 2021."Comparative Study of Different Beamforming Techniques for 5G: A Review." In: Ranganathan G., Chen J., Rocha Á. (eds) Inventive Communication and Computational Technologies. Lecture Notes in Networks and Systems, vol 145. Springer, Singapore.

Raut H.D., Shevada L., Malekar R., Kumar S. 2021. "High Gain Wideband Antennas for 5G Applications: A Review." In: Ranganathan G., Chen J., Rocha Á. (eds) Inventive Communication and Computational Technologies. Lecture Notes in Networks and Systems, vol 145. Springer, Singapore.

Yuan B., Zheng Y., Zhang X.,, You B., and Luo G., 2017. ''A bandwidth and gain enhancement for microstrip antenna based on metamaterial,'' Microw. Opt. Technol. Lett., vol. 59, no. 12, pp. 3088–3093.

Urul B., 2020. ''Gain enhancement of microstrip antenna with a novel DNG material,'' Microw. Opt. Technol. Lett., vol. 62, no. 4, pp. 1824–1829.

Patel S., and Argyropoulos C., 2016. ''Enhanced bandwidth and gain of compact microstrip antennas loaded with multiple corrugated split ring resonators,'' J. Electromagn. Waves Appl., vol. 30, no. 7, pp. 945–961.

Meriche M., Attia H., Messai A., Mitu S., and Denidni T., 2019.''Directive wideband cavity antenna with single-layer meta-superstrate,'' IEEE Antennas Wireless Propag. Lett., vol. 18, no. 9, pp. 1771–1774, Sep. 2019.

Verma A., Singh A., Srivastava N., Patil S., and Kanaujia B., 2020. ''Hexagonal ring electromagnetic band gap-based slot antenna for circular polarization and performance enhancement,'' Microw. Opt. Technol. Lett., vol. 62, no. 7, pp. 2576–2587.

Alibakhshikenari M., Khalily M., Virdee B., See C., Abd-Alhameed R., and Limiti E., 2019. ''Mutual coupling suppression between two closely placed microstrip patches using EM-bandgap metamaterial fractal loading,'' IEEE Access, vol. 7, pp. 23606–23614, 2019.

Thummaluru S., Kumar R., and Chaudhary R., 2018‘‘Isolation enhancement and radar cross section reduction of MIMO antenna with frequency selective surface,’’ IEEE Trans. Antennas Propag., vol. 66, no. 3, pp. 1595–1600.

Hassan T., Khan M., Attia H., and Sharawi M., 2018‘‘An FSS based correlation reduction technique for MIMO antennas,’’ IEEETrans. Antennas Propag., vol. 66, no. 9, pp. 4900–4905.

Akbari M., Ali M., Farahani M., Sebak A., and Denidni T., 2017 ‘‘Spatially mutual coupling reduction between CP-MIMO antennas using FSS superstrate,’’ Electron. Lett., vol. 53, no. 8, pp. 516–518.

Zhu J., Li S., Liao S., and Xue Q., 2018. ‘‘Wideband low-profile highly isolated MIMO antenna with artificial magnetic conductor,’’ IEEE AntennasWire- less Propag. Lett., vol. 17, no. 3, pp. 458–462.

Khan M., Capobianco A., Asif S., Anagnostou D., Shubair R., and Braaten B., 2017 ‘‘A compact CSRR-enabled UWB diversity antenna,’’ IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 808–812.

Sambandam P., Kanagasabai M., Ramadoss S., Natarajan R., Alsath M., Shanmuganathan S., Sindhadevi M., and Palaniswamy S., 2020. ‘‘Compact monopole antenna backed with fork- slotted EBG for wearable applications,’’ IEEE AntennasWireless Propag. Lett., vol. 19, no. 2, pp. 228–232.

Zada M., Shah I., and Yoo H., 2020. ‘‘Metamaterial-loaded compact high- gain dual-band circularly polarized implantable antenna system for mul- tiple biomedical applications,’’ IEEE Trans. Antennas Propag., vol. 68, no. 2, pp. 1140–1144.

Gulur Sadananda, K., Abegaonkar, M.P., Koul, S.K., 2019. “Gain Equalized Shared-Aperture Antenna Using Dual-Polarized ZIM for mmWave 5G Base Stations,” IEEE Antennas and Wireless Propagation Letters 18, pp. 1100–1104.

Bonefacic D., and Bartolic J., 2012. ‘‘Small antennas: Miniaturization tech- niques and applications,’’ Automatika, vol. 53, no. 1, pp. 20–30.

Xi B., Li Y., and Long Y., 2019. ‘‘A miniaturized periodic microstrip leaky wave antenna with shorting pins,’’ Int. J. Antennas Propag., pp. 1–7.

Jagtap S., Chaudhari A., Chaskar N., Kharche S., and Gupta R K.,2018. “A Wideband Microstrip Array Design Using RIS and PRS Layers,” IEEE Antennas and Wireless Propagation Letters vol. 17, pp. 509–512.

Wang, N., J. Li, G. Wei, L. Talbi, Q. Zeng, and J. Xu, 2015. “Wideband Fabry-Perot resonator antenna with two layers of dielectric superstrates," IEEE Antennas and Wireless Propagation Letters, Vol. 14, pp. 229–232.

Dixit, A. S., Kumar, S., Urooj, S., and Malibari, A., 2021. "A Highly Compact Antipodal Vivaldi Antenna Array for 5G Millimeter Wave Applications", Sensors, 21, 2360.

Malekar R., Shevada L K., Raut, H D., Dixit A S., and Kumar S., 2020. "MIMO antenna for Fifth Generation mm-Wave Applications: A Bibliometric Survey". Library Philosophy and Practice (e-journal). 4854.

Shevada L K., Raut, H D., Malekar, R, R., Dixit A, S., and Kumar, S., 2020. "A Bibliometric Survey on Ultra Wideband Multiple Input Multiple Output Antenna with Improved Isolation". Library Philosophy and Practice (e-journal). 4841.

Dixit A, S., Shevada L K., Raut, H D., Malekar, R, R., and Kumar, S., 2020. "Fifth Generation Antennas: A Bibliometric Survey and Future Research Directions" (2020). Library Philosophy and Practice (e-journal). 4575.

Gunjal A., and Kumar S., 2020. "Gain Enhancement in U-Slotted Broadband Dual Circularly Polarized Antenna for S-Band Radar Applications." International Conference on Emerging Smart Computing and Informatics (ESCI), Pune, India, pp. 124-128.

Bhadoria B., Kumar S., 2018. "A Novel Omnidirectional Triangular Patch Antenna Array Using Dolph Chebyshev Current Distribution for C-Band Applications," Progress In Electromagnetics Research M, Vol. 71, pp. 75-84.