A MILLIMETER WAVE REFLECTARRAY ANTENNA WITH TILTED SIDE PATCH ELEMENTS FOR FIFTH GENERATION COMMUNICATION SYSTEMS

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DEDICATION

Sincerely dedicated to my beloved mother and late father

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ABSTRACT

A flat surface reflectarray antenna is becoming an impending competitor for fifth generation (5G) communications among the generally known conventional antenna systems. Its narrow bandwidth and high loss performance lead to restrict its gain and efficiency at millimeter wave frequencies. Additionally, high design sensitivity is also an issue at millimeter waves that can trigger the problem of imperfect fabrications. Therefore, a simple design of reflectarray patch element is required with wide reflection phase range to achieve wideband and high gain performance. Efficiency of reflectarray antenna is also needed to be formulated properly to acquire polarization diversity. In this work, a new reflectarray patch element with a tilted side is recommended for a wideband dual resonance operation within 24 GHz to 28 GHz frequency range. Dual resonance of the tilted side patch element offers a reflection phase range of more than 600° and a reflection loss of 1.6 dB with a novel design. Simulated results of the patch element have been verified by the scattering parameter measurements using a waveguide simulator. Additionally, a mathematical relationship has been formulated to predict the efficiency of the reflectarray antenna based on its aperture shape and feed distance. It has been found that, a circular aperture reflectarray attains 21.46% higher efficiency than its equivalent square aperture reflectarray of the same feed distance. Consequently, a circular aperture reflectarray consisting of 332 variable size tilted side patch elements has been designed and tested at 26 GHz with various possible configurations. The high cross polarization issue due to the asymmetric design of the tilted side patch element has been tackled by mirroring the orientations of the elements on the surface of reflectarray. Moreover, circular ring slots with variable radius have been embedded in reflectarray ground plane for gain improvement. Experimental results show that, the slotted ground reflectarray antenna offers a 3.5 dB higher gain with 22.9% higher efficiency and 3% wider bandwidth than a full grounded reflectarray antenna. A maximum of 26.1 dB gain with 41.3% efficiency and 11.5% (3 GHz) bandwidth has been acquired with the slotted ground reflectarray antenna. The tilted side patch reflectarray has offered dual linear polarization when its elements are mirrored to each other and dual circular polarization when its elements are not mirrored to each other. Its main beam has been numerically steered up to ±20° by a progressive phase shift of 80°. The acquired parameters of the tilted side patch reflectarray antenna fit within the requirements of the 5G communication systems.

ABSTRAK

Antena *reflectarray* yang mempunyai permukaan yang rata menjadi pesaing untuk komunikasi generasi kelima (5G) di antara sistem antena konvensional yang diketahui umum. Lebar jalurnya yang sempit dan prestasi kehilangannya yang tinggi menjurus kepada kekangan gandaan dan kecekapan pada frekuensi gelombang milimeter. Di samping itu, kepekaan reka bentuk yang tinggi merupakan masalah pada gelombang millimeter yang akan mencetuskan masalah pada ketidak sempurnaan fabrikasi. Oleh itu, reka bentuk yang ringkas pada elemen tampalan *reflectarray* diperlukan dengan pelbagai julat fasa pantulan yang luas dan prestasi gandaan yang tinggi. Kecekapan untuk antena *reflectarray* juga diperlukan untuk dirumus dengan baik untuk memperolehi kepelbagaian polarisasi. Di dalam kerja ini, elemen tampalan *reflectarray* baru dengan sisi condong disyorkan untuk dual operasi jalur lebar dari julat frekuensi 24 GHz sehingga 28 GHz. Dual resonans bagi elemen tampalan sisi condong memberikan pelbagai fasa pantulan lebih daripada 600° dan 1.6 dB kehilangan pantulan dengan reka bentuk yang novel. Hasil simulasi bagi elemen tampalan telah disahkan oleh pengukuran parameter berselerak menggunakan simulator pandu gelombang. Di samping itu, hubungan matematik telah dirumuskan untuk menjangkakan kecekapan antena *reflectarray* berdasarkan bentuk bukaan dan jarak masukan. Telah diperolehi bahawa bukaan bulatan *reflectarray* mencapai kecekapan yang tinggi iaitu 21.46% berbanding dengan bukaan empat segi *reflectarray* pada jarak masukan yang sama. Oleh itu, bukaan bulatan *reflectarray* terdiri daripada 332 kepelbagaian saiz tampalan elemen condong direka bentu dan diuji pada 26 GHz dengan pelbagai konfigurasi. Isu polarisasi menyilang yang tinggi disebabkan oleh reka bentuk asimetri elemen tampalan sisi yang condong telah ditangani dengan pencerminan orientasi elemen pada permukaan *reflectarray*. Selain itu, slot cincin bulatan dengan pelbagai radius sudah dibenamkan pada satah bumi *reflectarray* untuk meningkatkan gandaan. Keputusan eksperimen menunjukkan bahawa, antena *reflectarray* yang mempunyai satah bumi memberikan gandaan 3.5 dB dengan 22.9% kecekapan dan 3% lebar jalur yang lebih tingi berbanding antena *reflectarray* yang tiada slot. Gandaan maksimum 26.1 dB dengan 41.3% kecekapan dan 11.5% (3 GHz) lebar jalur telah diperolehi dengan antena *reflectarray* yang mempunyai berslot. Pada sisi *reflectarray* tampalan condong menawarkan polarisasi dua linear apabila unsur-unsurnya dicerminkan antara satu sama lain, manakala dua bulatan diperolehi apabila unsur-unsurnya tidak dicerminkan pada satu sama lain. Alur utamanya telah dikemukakan secara berperingkat sehingga ±20° oleh pergerakan fasa progresif sebanyak 80°. Parameter-parameter yang diperolehi daripada antena *reflectarray* sisi condong adalah sangat bersesuaian dengan apa yang diperlukan untuk sistem komunikasi 5G.

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LIST OF ABBREVIATIONS

5G	–	Fifth Generation
AF	–	Array Factor
AR	–	Axial Ratio
AUT	–	Antenna Under Test
CST	–	Computer Simulation Technology
dB	–	Decibel
DR	–	Dual Resonance
EF	–	Element Factor
FBR	–	Front to Back Ratio
FEM	–	Finite Element Method
FIM	–	Finite Integral Method
GHz	–	Giga Hertz
HFSS	–	High Frequency Structure Simulator
HP	–	Horizontal Polarization
LHCP	–	Left Hand Circular Polarization
LP	–	Linear Polarization
RHCP	–	Right Hand Circular Polarization
SNR	–	Signal to Noise Ratio
SR	–	Single Resonance
TE	–	Transverse Electric
VNA	–	Vector Network Analyzer
VP	–	Vertical Polarization
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LIST OF SYMBOLS

f	–	Frequency
c	–	Speed of Light
λ	–	Wavelength
φ	–	Reflection Phase
S	–	Element Spacing
G	–	Gain
D	–	Directivity
E	–	Electric Field
A	–	Area
η	–	Efficiency
q	–	Exponent of Feed Pattern Function
L	–	Length
d	–	Diagonal
ε	–	Dielectric Constant
J	–	Surface Current
k	–	Wave Number
σ	–	Conductivity
β	–	Progressive Phase Shift
	–	

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CHAPTER 1

INTRODUCTION

Fifth Generation (5G) communications are currently represented as a future technology, which is supposed to meet the high data rate goals, roughly 1000 times faster than the current systems. The peak data rate in the order of Gbps will require fast switching mechanism which is possible at short wavelengths of millimeter waves (mm-waves). The mm-waves are considered with the wavelengths ranging from 1 mm to 100 mm, occupying the frequency range from 3 GHz to 300 GHz [1]. However, due to congested frequency spectrum at lower frequencies, the frequencies over 20 GHz have a good potential to be considered for 5G communications [2]. Consequently, different frequency bands were proposed for 5G starting from 24.25 GHz up to 86 GHz in World Radiocommunication Conference (WRC-15) [3]. The data rate requirements of 5G can be met by enhancing the bandwidth and efficiency of the antenna systems at mm-waves [2, 4]. However, the mm-wave frequencies have some propagation limitations in terms of high path loss and very short communication distances. Massive improvements in the architecture of current communication systems are desperately required in order to adopt 5G technology [1].

The propagation issues related with mm-waves can be avoided by selecting a suitable type of antenna for 5G systems. Array antennas are considered as a good candidate to compensate the issues regarding path loss for short range communications [5]. Two dimensional planar arrays with large electrical apertures can provide narrow beamwidth, which is essential for 5G base station operations [1]. Large electrical aperture at mm-waves for 5G, does not affect the physical profile of the antenna due to short wavelengths. Massive MIMO systems have also been suggested for 5G due to their possible integrity with small cells [1, 6]. However, as compared to array antennas massive MIMO are not the potential candidate for 5G systems due to their design complexity and less adaptability with shorter wavelengths [1, 2]. There are many other types of antennas, which can be found in the literature for proposed 5G operation

[7, 8, 9]. Their main purpose is to achieve wide bandwidth to support high throughput of 5G systems [10]. The operation of antenna systems for 5G compatibility largely depends on the enhancement of its bandwidth performance. A massive bandwidth is required in mm-wave range to support high data requirements [11]. Bandwidth of the order of GHz is attainable at mm-wave frequency range, but some extra design efforts are still required to fully utilize it with other requirements.

However, by just enhancing the bandwidth of proposed antenna does not solve all issues regarding 5G compatibility. Significant improvements in some other parameters like gain, efficiency, polarization diversity and adaptive beamsteering are also considered as a need of time [11, 12, 1]. It is because, the antenna performance for 5G can directly depend on the mode of antenna operation. Antenna used for transmission or reception can significantly affect its required parameters for 5G operation. It is widely believed that the requirement of improvement in antenna parameters for transmission is higher than the same parameters for reception. An improved gain performance can ensure the strong transmission capabilities for antenna [11]. In the case of 5G, when antenna systems are required to work at mm-waves, their communication distances significantly decrease due to the short wavelength. In this case, a high gain antenna can radically improve the path loss performance, without disturbing its original power consumption [7].

A high aperture efficiency of antenna systems ensures the best utilization of maximum gain value for the reduction of path loss [12]. On the other hand, the data rate can also be increased by enhancing the spectral efficiency of antenna systems [2]. Polarization diversity can be achieved when a single antenna is used with two or more different polarizations [13]. The concept of frequency reuse also emerges from polarization diversity, where a single frequency can be dually utilized with different polarizations of the signal. Frequency reuse is useful for 5G systems, where wide bandwidth is essentially required. The mm-wave antennas support fixed narrow beam operation for high gain performance, which enables the need of adaptive beamsteering [1]. Moreover, the highly directional nature of mm-waves can produce blockage of signals, which can be countered by performing adaptive beamsteering [2]. These described parameters of a potential 5G antenna, are attainable with a reflectarray antenna.

The array of elements combined together on a flat dielectric surface to reflect the incidence signals coming from a properly distant feed defines the main architecture of a reflectarray antenna [14]. Figure 1.1 distinguishes between the basic operational characteristics of a reflectarray antenna, parabolic reflector and phased array antenna. As demonstrated in Figure 1.1, the reflection of the signals can be directed like a parabolic reflector with an additional advantage of a plane and light weighted surface. Moreover, reflectarray can also perform beam scanning like a phased array antenna, but without the aid of any power divider or additional phase shifters [15]. The less complex design of reflectarray makes it more cost effective and competitive, especially for beam scanning applications. The bulky and curvy design of parabolic antenna is not a good candidate for high frequency applications [14]. Alternatively a reflectarray antenna can easily be designed from as low as Microwave [16] to as high as Terahertz frequency range [17]. The adaptability of reflectarray to high frequencies makes it suitable for high gain and high bandwidth operation.

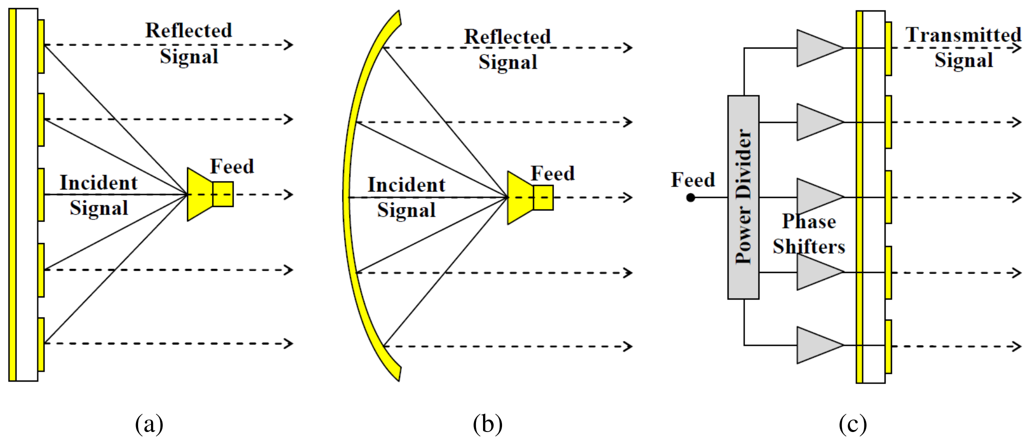

Figure 1.1 Operational layout of (a) Reflectarray antenna (b) Parabolic reflector (c) Phased array antenna

Phased array antenna is the nearest possible competitor of reflectarray antenna for 5G operation, but it faces efficiency lacking problems at mm-waves due to its additional loss performance at high frequencies [18]. Moreover, its design complexity and power consumption are also major issues at mm-wave frequencies. On the other hand, the discussed antenna parameters for possible 5G application are inevitable with reflectarray antenna. Its bandwidth can be enhanced by optimizing its unit cell designs with different substrate thicknesses [19]. The high gain performance can be obtained by increasing the size of the reflectarray, which can produce sharp beams [14]. Its reflection loss performance along with its feeding mechanism can be optimized for efficiency enhancement. Different design configuration of patch elements can be utilized for various polarization combinations. Furthermore, the incident signal from feed or the reflection phase of the reflectarray can be dynamically tuned to get adaptive beamsteering [20].

There are a lot of techniques mentioned in the literature for the enhancement of each discussed parameters of reflectarray. In this work, the emphasis has been given specially on the design configuration needed for reflectarray bandwidth and gain enhancement as a 5G base station antenna. Improvement in the bandwidth performance surely reduces the gain of the reflectarray antenna. Therefore, various techniques have been implemented in the reflectarray comprised of the proposed elements for high gain and high efficiency performance. The finalized design of the reflectarray antenna has also been realized for the possibility of acquiring polarization diversity and electronic beamsteering at mm-wave frequency range.

1.1 Problem Statement

High reflection loss and narrow bandwidth are the two main performance degradation of reflectarray antenna, which also limit its gain and efficiency. The losses in the reflectarray are associated with the design of its unit cell element and the material used to construct it. A wide patch element, such as a square patch, reflects back most of the incident signals and offers low loss performance. However, it also provides narrow bandwidth performance due to its limited reflection phase range. In order to coincide with the 5G high data rate requirements, a wide bandwidth reflectarray antenna is required with high gain and high efficiency at mm-wave frequency range. The main problem associated with mm-wave is its high design sensitivity due to shorter wavelengths. It means that, a slight change in the dimension of reflectarray element would drastically affect its performance. This slight change in the dimension is unavoidable in the case of an imperfect fabrication. Alternatively, the high performance parameters of 5G reflectarray antenna come with increasing design complexity. The high design complexity also increases the chances of imperfect fabrication at mm-wave frequencies due to very short physical dimensions. The bandwidth of the reflectarray antenna can be improved by introducing extra resonances at its unit cell level. However, this may trigger extra losses with a possibility of mutual coupling between the elements and degradation in gain performance. This effect of mutual coupling can alter the resonant behavior, increase the cross polarization level and limit the efficiency of reflectarray antenna. Gain and efficiency of the reflectarray antenna are largely dependent on its aperture size and feeding mechanism. The spillover and illumination efficiencies can be optimized by selecting a proper feed distance in front of the reflectarray. A suitable feed distance also eliminates the chances of high side lobe formation that limits the gain performance. The mm-wave array antennas produce highly directional narrow beams, which shrink down their coverage area and limit the full bandwidth utilization by introducing signal blockage problem. The signal blockage can be avoided by introducing electronic beamsteering, whereas the diversity in the polarization can be utilized as an efficient tool for frequency reuse. Therefore in this work, a novel reflectarray unit cell with simple design and extended reflection phase range has been proposed to avoid the design complexity issue at mm-waves. The mutual coupling and hence the high cross polarization issue of the proposed unit cells has been tackled by selecting the proper orientation of the elements on the surface of constructed reflectarray. The gain and efficiency of the constructed reflectarray have been optimized by a suitable aperture size with a proper feed distance. The reflectarray antenna comprising the new unit cells has also been realized with the available possibilities of polarization diversity and beamsteering.

1.2 Research Objectives

There are four main research objectives of this work, which are listed below;

1. To design and investigate the performance of a wideband tilted side reflectarray patch element with wide reflection phase range.
2. To numerically analyze the relationship between the efficiency, aperture size and feeding mechanism of the reflectarray antenna.
3. To develop a wideband reflectarray antenna with improved gain and reduced cross polarization.
4. To implement a technique for the realization of polarization diversity and beamsteering in the reflectarray antenna.

1.3 Research Scope

The main scope of this research work comprises of the designing of a reflectarray antenna that could satisfy the requirements for the 5G communications systems. Unit cell patch element of the reflectarray antenna has been characterized in order to obtain dual resonance response operating at 26 GHz for bandwidth enhancement. The unit cell simulations has been performed using CST MWS and Ansys HFSS simulations tools, while measurements have been done by waveguide simulator approach. Rogers 5880 material has been selected as the substrate for the reflectarray antenna with 0.254 mm thickness. A full reflection phase span of 720° and 360° is selected for the realization of a proper full reflectarray antenna design. Far-field measurements of the full reflectarray antenna have been performed in anechoic chamber. Three different horn feeds with different gains are used to analyze the effect of variable feed distance on the performance of the reflectarray antenna. A mathematical relation has been derived to estimate the efficiency of the reflectarray antenna by considering its aperture shape and feeding mechanism characteristics within the frequency range of 24 GHz to 28 GHz. Gain enhancement in the reflectarray antenna is characterized by embedding circular ring slots in its ground plane. Reduction in the cross polarization of the reflectarray antenna has been optimized by selecting different element orientations on its surface. Different polarization operation of the reflectarray antenna has been tested by 90° rotating its aperture, while keeping the same feed orientation. Finally, Matlab software is used to numerically obtain the maximum possible beamsteering by the finalized reflectarray antenna design.

1.4 Thesis Organization

The second chapter of the thesis discusses the main techniques available in the literature for the performance enhancement of reflectarray antenna. The performance parameters of reflectarray antenna in terms of its bandwidth, gain, efficiency, polarization diversity and adaptive beamsteering are thoroughly analyzed in this chapter. Importance of each of these parameters is also explored for their plausible compatibility with 5G communication systems.

The conventional tactics and procedures involving the design and analysis of a reflectarray antenna are provided in the third chapter. Detailed design analyses of a unit cell element with its proper boundary conditions and excitation is included. The step by step process involving the design of a full reflectarray antenna is mentioned in this chapter. The methods of performing simulations, fabrication and measurements of the reflectarray antenna are also thoroughly discussed.

Chapter four studied the efficiency characteristics of reflectarray antenna in conjunction with its feeding mechanism. Mathematical equations for the aperture efficiency of reflectarray antenna are formulated and analyzed by performing far-field simulations and measurements of a square path reflectarray antenna. Total efficiency of the reflectarray antenna is also estimated by the developed equations and the results are validated by the conventional gain-directivity relation.

The tilted side patch element and its full reflectarray configuration are thoroughly analyzed in chapter five. Process of the evaluation of the tilted side patch element from a square patch element is defined in this chapter. The wide reflection phase range of the tilted side patch element is then utilized to study different configurations of the reflectarray antenna for its performance improvement. The main techniques for the enhancement of bandwidth and gain, and reduction of the cross polarization of developed reflectarray antenna are also provided in this chapter. The

REFERENCES

1. Boccardi, F., Heath, R., Lozano, A., Marzetta, T. L. and Popovski, P. Five disruptive technology directions for 5G. *IEEE Communications Magazine*, 2014. 52(2): 74–80. ISSN 01636804. doi:10.1109/MCOM.2014.6736746.

2. Andrews, J. J. G., Buzzi, S., Choi, W., Hanly, S. V. S., Lozano, A., Soong, A. C. K. and Zhang, J. J. C. What will 5G be? *IEEE Journal on Selected Areas in Communications*, 2014. 32(6): 1065–1082. ISSN 0733-8716. doi: 10.1109/JSAC.2014.2328098.

3. ITU. Final Acts WRC-15. *World Radiocommunication Conference*. Geneva. 2015.

4. Rappaport, T. S., Mayzus, R., Azar, Y., Wang, K., Wong, G. N., Schulz, J. K., Samimi, M. and Gutierrez, F. Millimeter Wave Mobile Communications for 5G Cellular: It Will Work! *IEEE Access*, 2013. 1: 335–349.

5. Malkowsky, S., Vieira, J., Liu, L., Harris, P., Nieman, K., Kundargi, N., Wong, I. C., Tufvesson, F., Owall, V. and Edfors, O. The World's First Real-Time Testbed for Massive MIMO: Design, Implementation, and Validation. *IEEE Access*, 2017. 5: 9073–9088. ISSN 2169-3536. doi:10.1109/ACCESS.2017.2705561.

6. Zhao, X., Li, S., Wang, Q., Wang, M., Sun, S. and Hong, W. Channel Measurements, Modeling, Simulation and Validation at 32 GHz in Outdoor Microcells for 5G Radio Systems. *IEEE Access*, 2017. 5: 1062–1072. ISSN 2169-3536. doi:10.1109/ACCESS.2017.2650261.

7. Haraz, O. M., Elboushi, A., Alshebeili, S. A. and Sebak, A. R. Dense Dielectric Patch Array Antenna With Improved Radiation Characteristics Using EBG Ground Structure and Dielectric Superstrate for Future 5G Cellular Networks. *Access, IEEE*, 2014. 2: 909–913. ISSN 2169-3536. doi: 10.1109/ACCESS.2014.2352679.

8. Elsharkawy, R., Sebak, A. R., Hindy, M., Haraz, O. M., Saleeb, A. and El-Rabaie, E. S. Single layer polarization independent reflectarray antenna for future 5G cellular applications. *IEEE International Conference on*

information and Communication Technology Research (ICTRC). IEEE. 2015. 9–12. doi:10.1109/ICTRC.2015.7156408.

9. Ban, Y. L., Li, C., Sim, C. Y. D., Wu, G. and Wong, K. L. 4G/5G Multiple Antennas for Future Multi-Mode Smartphone Applications. *IEEE Access*, 2016. 4: 2981–2988. ISSN 2169-3536. doi:10.1109/ACCESS.2016.2582786.

10. Ka Ming, M., Hau Wah, L., Kwai Man, L. and Chi Hou, C. Circularly Polarized Patch Antenna for Future 5G Mobile Phones. *IEEE Access*, 2014. 2: 1521–1529. ISSN 2169-3536. doi:10.1109/ACCESS.2014.2382111.

11. Roh, W., Seol, J. Y., Park, J., Lee, B., Lee, J., Kim, Y., Cho, J., Cheun, K. and Aryanfar, F. Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results. *IEEE Communications Magazine*, 2014. 52(2): 106–113.

12. Dinh Thuy, P. H., Sternad, M. and Svensson, T. Making 5G Adaptive Antennas Work for Very Fast Moving Vehicles. *IEEE Intelligent Transportation Systems Magazine*, 2015. 7(2): 71–84. doi:10.1109/MITS.2015.2408151.

13. Guo, L., Tan, P. K. and Chio, T. H. A simple approach to achieve polarization diversity in broadband reflectarrays using single-layered rectangular patch elements. *Microwave and Optical Technology Letters*, 2015. 57(2): 305–310. doi:10.1002/mop.28833.

14. Huang, J. and Encinar, J. *Reflectarray antennas*. USA: Wiley Inter Science. 2007.

15. Huang, J. *Analysis of microstrip reflectarray antenna for microspacecraft applications*. Technical report. Spacecraft Telecommunications Equipment Section: TDA Progress Report. 1995.

16. Yu, A., Yang, F., Elsherbeni, A. Z., Huang, J. and Kim, Y. An offset-fed X-band reflectarray antenna using a modified element rotation technique. *IEEE Transactions on Antennas and Propagation*, 2012. 60(3): 1619–1624.

17. Chang, Z., You, B., Wu, L. S., Tang, M., Zhang, Y. P. and Mao, J. F. A Reconfigurable Graphene Reflectarray for Generation of Vortex THz Waves.

IEEE Antennas and Wireless Propagation Letters, 2016. 15: 1537–1540. doi: 10.1109/LAWP.2016.2519545.

18. Hum, S. V. and Perruisseau Carrier, J. Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review. *IEEE Transactions on Antennas and Propagation*, 2014. 62(1): 183–198.

19. Abbasi, M. I. and Ismail, M. Y. Reflection loss and bandwidth performance of X-band infinite reflectarrays: Simulations and measurements. *Microwave and Optical Technology Letters*, 2011. 53(1): 77–80. doi:10.1002/mop. 25662.

20. Nayeri, P., Yang, F. and Elsherbeni, A. Z. Beam-Scanning Reflectarray Antennas: A technical overview and state of the art. *IEEE Antennas and Propagation Magazine*, 2015. 57(4): 32–47. ISSN 1045-9243. doi: 10.1109/MAP.2015.2453883.

21. Kishor, K. K. and Hum, S. V. An amplifying reconfigurable reflectarray antenna. *IEEE Transactions on Antennas and Propagation*, 2012. 60(1): 197–205.

22. Pozar, D. M. and Metzler, T. A. Analysis of a reflectarray antenna using microstrip patches of variable size. *Electronics Letters*, 1993. 29(8): 657–658. ISSN 00135194. doi:10.1049/el:19930440.

23. Jamaluddin, M. H., Gillard, R., Sauleau, R. and Milon, M. A. Perturbation Technique to Analyze Mutual Coupling in Reflectarrays. *IEEE Antennas and Wireless Propagation Letters*, 2009. 8: 697–700. ISSN 1536-1225.

24. Pozar, D. M. and Metzler, T. A. Analysis of a reflectarray antenna using microstrip patches of variable size. *Electronics Letters*, 1993. 29(8): 657–658. ISSN 00135194.

25. Huang, J. and Pogorzelski, R. A Ka-band microstrip reflectarray with elements having variable rotation angles. *IEEE Transactions on Antennas and Propagation*, 1998. 46(5): 650–656.

26. Ismail, M. Y. and Inam, M. Resonant Elements for Tunable Reflectarray Antenna Design. *International Journal of Antennas and Propagation*, 2012. 2012: 1–6. doi:10.1155/2012/914868.

27. Chang, D. C. and Huang, M. Multiple-polarization microstrip reflectarray antenna with high efficiency and low cross-polarization. *IEEE Transactions on Antennas and Propagation*, 1995. 43(8): 829–834.

28. Chang, D. C. and Huang, M. C. Microstrip reflectarray antenna with offset feed. *Electronics Letters*, 1992. 28(16): 1489–1491. ISSN 00135194. doi: 10.1049/el:19920946.

29. Yi, M., Lee, W., Yoon, Y. J. and So, J. Non-resonant conductor reflectarray element for linear reflection phase. *Electronics Letters*, 2015. 51(9): 669–671. doi:10.1049/el.2015.0194.

30. Jamaluddin, M. H., Gillard, R., Sauleau, R., Le Coq, L., Castel, X., Benzerga, R. and Koleck, T. A dielectric resonator antenna (DRA) reflectarray. *European Microwave Week 2009, EuMW 2009: Science, Progress and Quality at Radiofrequencies - 39th European Microwave Conference, EuMC 2009*. 2009. doi:10.1109/EUMC.2009.5296579.

31. Abd Elhady, M., Hong, W. and Zhang, Y. A Ka-band reflectarray implemented with a single-layer perforated dielectric substrate. *IEEE Antennas and Wireless Propagation Letters*, 2012. 11: 600–603.

32. Wenxing An, W., Shenheng Xu, S. and Fan Yang, F. A Metal-Only Reflectarray Antenna Using Slot-Type Elements. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 1553–1556. doi:10.1109/LAWP.2014.2342376.

33. Polenga, S. V., Stankovsky, A. V., Krylov, R. M., Nemshon, A. D., Litinskaya, Y. A. and Salomatov, Y. P. Millimeter-wave waveguide reflectarray. *2015 International Siberian Conference on Control and Communications, SIBCON 2015 - Proceedings*. Institute of Electrical and Electronics Engineers Inc. 2015.

34. Berry, D. C., Malech, R. G. and Kennedy, W. A. The reflectarray antenna. *IEEE Transactions on Antennas and Propagation*, 1963. 11(6): 645 – 651.

35. Huang, J. Microstrip reflectarray. *Antennas and Propagation Society Symposium 1991 Digest*, 1991: 612–615. doi:10.1109/APS.1991.174914.

36. Gohil, A., Modi, H. and Patel, S. K. 5G technology of mobile

communication: A survey. *2013 International Conference on Intelligent Systems and Signal Processing, ISSP 2013*. Ieee. 2013. ISBN 9781479903160. 288–292. doi:10.1109/ISSP.2013.6526920.

37. Han, S., I, C. L., Xu, Z. and Rowell, C. Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G. *IEEE Communications Magazine*, 2015. 53(January): 186–194. ISSN 0163-6804. doi:10.1109/MCOM.2015.7010533.

38. Rajagopalan, H. and Samii, Y. R. Loss quantification for microstrip reflectarray: Issue of high fields and currents. *2008 IEEE Antennas and Propagation Society International Symposium*. 2008. ISBN 9781424420414. 1–4. doi:10.1109/APS.2008.4619755.

39. Pozar, D. M. Bandwidth of reflectarrays. *Electronics Letters*, 2003. 39(21): 1490–1491.

40. Misran, N., Cahill, R. and Fusco, V. Design optimisation of ring elements for broadband reflectarray antennas. *IEE Proceedings - Microwaves, Antennas and Propagation*, 2003. 150(6): 440–444.

41. Sayidmarie, K. and Bialkowski, M. Fractal unit cells of increased phasing range and low slopes for single-layer microstrip reflectarrays. *IET Microwaves, Antennas & Propagation*, 2011. 5(11): 1371.

42. Li, Q. Y., Jiao, Y. C. and Zhao, G. A novel microstrip rectangular-patch/ring-combination reflectarray element and its application. *IEEE Antennas and Wireless Propagation Letters*, 2009. 8: 1119–1122.

43. Li, L., Chen, Q., Yuan, Q., Sawaya, K., Maruyama, T., Furuno, T. and Uebayashi, S. Novel broadband planar reflectarray with parasitic dipoles for wireless communication applications. *IEEE Antennas and Wireless Propagation Letters*, 2009. 8: 881–885.

44. Li, Y., Bialkowski, M. E. and Abbosh, A. M. Single layer reflectarray with circular rings and open-circuited stubs for wideband operation. *IEEE Transactions on Antennas and Propagation*, 2012. 60(9): 4183–4189.

45. Venneri, F., Costanzo, S., Di Massa, G., Venneri, F., Costanzo, S. and Di Massa, G. Bandwidth Behavior of Closely Spaced Aperture-Coupled

Reflectarrays. *International Journal of Antennas and Propagation*, 2012. 2012: 1–11. doi:10.1155/2012/846017.

46. Xue, F., Wang, H. J., Yi, M. and Liu, G. A broadband KU-band microstrip reflectarray antenna using single-layer fractal elements. *Microwave and Optical Technology Letters*, 2016. 58(3): 658–662. doi:10.1002/mop.29637.

47. Zhao, J. J., Gong, S. X., Xu, Y. X. and Ren, L. S. Design of a broadband reflectarray using meander-shaped elements. *Microwave and Optical Technology Letters*, 2012. 54(2): 500–503. doi:10.1002/mop.26563.

48. Wu, W. W., Qu, S. W. and Zhang, X. Q. Single-layer reflectarray with novel elements for wideband applications. *Microwave and Optical Technology Letters*, 2014. 56(4): 950–954. doi:10.1002/mop.28208.

49. Yoon, J. H., Yoon, Y. J., Lee, W. S. and So, J. H. Broadband microstrip reflectarray with five parallel dipole elements. *IEEE Antennas and Wireless Propagation Letters*, 2015. 14: 1109–1112.

50. Derafshi, I., Komjani, N. and Mohammadirad, M. A single-layer broadband reflectarray antenna by using quasi-spiral phase delay line. *IEEE Antennas and Wireless Propagation Letters*, 2015. 14: 84–87.

51. Pan, Y., Zhang, Y. R. and Yu, X. A X/Ku dual-band reflectarray design with cosecant squared shaped beam. *Microwave and Optical Technology Letters*, 2014. 56(9): 2028–2034. doi:10.1002/mop.28525.

52. Hamzavi Zarghani, Z. and Atlasbaf, Z. A New Broadband Single-Layer Dual-Band Reflectarray Antenna in X- and Ku-Bands. *IEEE Antennas and Wireless Propagation Letters*, 2015. 14: 602–605. doi:10.1109/LAWP.2014.2374351.

53. Malfajani, R. S. and Atlasbaf, Z. Design and Implementation of a Dual-Band Single Layer Reflectarray in X and K Bands. *IEEE Transactions on Antennas and Propagation*, 2014. 62(8): 4425–4431. doi:10.1109/TAP.2014.2327137.

54. Oh, S., Ahn, C. and Chang, K. Reflectarray element using variable ring with slot on ground plane. *Electronics Letters*, 2009. 45(24): 1206.

55. Pochiraju, T. and Fusco, V. Amplitude and phase controlled reflectarray element based on an impedance transformation unit. *IEEE Transactions on*

Antennas and Propagation, 2009. 57(12): 3821–3826.

56. Yoon, J. H., So, J. h., Yoon, Y. J., Kim, J. s. and Lee, W. s. Single-layer reflectarray with combination of element types. *Electronics Letters*, 2014. 50(8): 574–576. doi:10.1049/el.2014.0435.

57. Tienda, C., Encinar, J. A., Arrebola, M., Barba, M. and Carrasco, E. Design, manufacturing and test of a dual-reflectarray antenna with improved bandwidth and reduced cross-polarization. *IEEE Transactions on Antennas and Propagation*, 2013. 61(3): 1180–1190.

58. Nayeri, P., Liang, M., Sabory Garcia, R., Tuo, M., Yang, F., Gehm, M., Xin, H. and Elsherbeni, A. High gain dielectric reflectarray antennas for THz applications. *2013 IEEE Antennas and Propagation Society International Symposium (APSURSI)*. IEEE. 2013. ISBN 978-1-4673-5317-5. 1124–1125. doi:10.1109/APS.2013.6711222.

59. Yi, M., Lee, W. and So, J. Design of cylindrically conformed metal reflectarray antennas for millimetre-wave applications. *Electronics Letters*, 2014. 50(20): 1409–1410. doi:10.1049/el.2014.2206.

60. Mohammadirad, M., Komjani, N., Chaharmir, M. R., Shaker, J. and Sebak, A. R. Phase error analysis of the effect of feed movement on bandwidth performance of a broadband X-Ku band reflectarray. *International Journal of RF and Microwave Computer-Aided Engineering*, 2013. 23(5): 517–526. doi:10.1002/mmce.20685.

61. Park, J. H., Choi, H. K. and Kim, S. H. Design of Ku-band reflectarray using hexagonal patch with crossed slots. *Microwave and Optical Technology Letters*, 2012. 54(10): 2383–2387. doi:10.1002/mop.27095.

62. Tahseen, M. M. and Kishk, A. A. Ka-Band Circularly Polarized High Efficiency Wide Band Reflectarray Using Cross Bow-Tie Elements. *Progress In Electromagnetics Research*, 2015. 153: 1–10. doi:10.2528/PIER15072305.

63. Florencio, R., Boix, R. R., Carrasco, E., Encinar, J. A., Barba, M. and Pérez-Palomino, G. Broadband reflectarrays made of cells with three coplanar parallel dipoles. *Microwave and Optical Technology Letters*, 2014. 56(3):

748–753. ISSN 08952477. doi:10.1002/mop.28171.

64. Chen, H. W., Zhang, G. Q., Lei, X. and Wu, J. M. A slotted hollow ring element for Ku-band high-efficiency circularly polarized reflectarrays. *Microwave and Optical Technology Letters*, 2015. 57(11): 2629–2632.

65. Deng, R., Mao, Y., Xu, S. and Yang, F. A Single-Layer Dual-Band Circularly Polarized Reflectarray With High Aperture Efficiency. *IEEE Transactions on Antennas and Propagation*, 2015. 63(7): 3317–3320. doi:10.1109/TAP.2015.2429684.

66. Hasani, H., Kamyab, M. and Mirkamali, A. Low cross-polarization reflectarray antenna. *IEEE Transactions on Antennas and Propagation*, 2011. 59(5): 1752–1756.

67. Kim, D. and Park, I. Y. A Miniaturized Reflectarray Antenna for Scanned Beam Applications. *IEEE Transactions on Antennas and Propagation*, 2016. 64(3): 960–967. doi:10.1109/TAP.2016.2517676.

68. Zhong, X. J., Chen, L., Shi, Y. and Shi, X. W. A Dual-Frequency Single Layer Circularly Polarized Reflectarray with Frequency Selective Surface Backing. *Progress In Electromagnetics Research C*, 2014. 51: 87–93. doi:10.2528/PIERC14040103.

69. Lim, E. H. and Leung, K. W. *Compact Multifunctional Antennas for Wireless Systems*. John Wiley & Sons, Inc. 2012. ISBN 978-0-470-40732-5.

70. Martinez Lopez, L., Rodriguez Cuevas, J., Martynyuk, A. E. and Martinez Lopez, J. I. Wideband-reconfigurable reflectarrays based on rotating loaded split rings. *Journal of Electromagnetic Waves and Applications*, 2016. 29(2): 218–232. doi:10.1080/09205071.2014.993770.

71. Encinar, J., Boix, R. R., Perez Palomino, G. and Florencio, R. Dual-polarisation reflectarray made of cells with two orthogonal sets of parallel dipoles for bandwidth and cross-polarisation improvement. *IET Microwaves, Antennas & Propagation*, 2014. 8(15): 1389–1397. doi:10.1049/iet-map.2014.0202.

72. Pereira, R., Gillard, R., Sauleau, R., Potier, P., Dousset, T. and Delestre, X. Four-state dual polarisation unit-cells for reflectarray applications.

Electronics Letters, 2010. 46(11): 742.

73. Chaharmir, M. R., Shaker, J., Gagnon, N. and Lee, D. Design of broadband, single layer dual-band large reflectarray using multi open loop elements. *IEEE Transactions on Antennas and Propagation*, 2010. 58(9): 2875–2883. ISSN 0018926X. doi:10.1109/TAP.2010.2052568.

74. Mener, S., Gillard, R., Sauleau, R., Bellion, A. and Potier, P. Dual Circularly Polarized Reflectarray With Independent Control of Polarizations. *IEEE Transactions on Antennas and Propagation*, 2015. 63(4): 1877–1881. doi: 10.1109/TAP.2015.2398458.

75. Visser, H. J. *Array and Phased Array Antenna Basics*. England: John Wiley & Sons Ltd. 2005. ISBN 13 978-0-470-87117-1.

76. Askeland, D., Fulay, P. and Wendelin, W. *The Science and Engineering of Materials*. Cengage Learning. 2010.

77. Kelly, S. M. and O'Neill, M. Liquid Crystals for Electro-Optic Applications. In: Nalwa, H. S., ed. *Handbook of Advanced Electronic and Photonic Materials and Devices*. California: Academic Press, chap. Liquid Cry. 1–66. 2000.

78. Bildik, S., Dieter, S., Fritzsch, C., Menzel, W. and Jakoby, R. Reconfigurable Folded Reflectarray Antenna Based Upon Liquid Crystal Technology. *IEEE Transactions on Antennas and Propagation*, 2015. 63(1): 122–132. ISSN 0018-926X. doi:10.1109/TAP.2014.2367491.

79. Perez Palomino, G., Barba, M., Encinar, J., Cahill, R., Dickie, R., Baine, P. and Bain, M. Design and Demonstration of an Electronically Scanned Reflectarray Antenna at 100 GHz Using Multi-Resonant Cells Based on Liquid Crystals. *IEEE Transactions on Antennas and Propagation*, 2015. (99): 1–6. ISSN 0018-926X. doi:10.1109/TAP.2015.2434421.

80. Karnati, K. K., Shen, Y., Trampler, M. E., Ebadi, S., Wahid, P. F. and Gong, X. A BST-Integrated Capacitively Loaded Patch for Ka and X-band Beamsteerable Reflectarray Antennas in Satellite Communications. *IEEE Transactions on Antennas and Propagation*, 2015. 63(4): 1324–1333. doi: 10.1109/TAP.2015.2389252.

81. Velu, G., Blary, K., Burgnies, L., Marteau, A., Houzet, G., Lippens, D. and Carru, J. C. A 360 degree BST phase shifter with moderate bias voltage at 30 GHz. *IEEE Transactions on Microwave Theory And Techniques*, 2007. 55(2): 438–444. ISSN 00189480. doi:10.1109/TMTT.2006.889319.

82. Carrasco, E. and Perruisseau-Carrier, J. Reflectarray antenna at terahertz using graphene. *IEEE Antennas and Wireless Propagation Letters*, 2013. 12: 253–256. ISSN 15361225. doi:10.1109/LAWP.2013.2247557.

83. Chang, Z., Wu, L. S., Tang, M., Zhang, Y. P. and Mao, J. F. Generation of THz wave with orbital angular momentum by graphene patch reflectarray. *2015 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*. IEEE. 2015. ISBN 978-1-4799-6450-5. 1–3. doi:10.1109/IMWS-AMP.2015.7325042.

84. Carrasco, E., Michele, T. and Carrier, J. P. Tunable Graphene-Based Reflectarray Element for Reconfigurable Beams. *7th European Conference on Antennas and Propagation (EUCAP 2013)*. Gothenburg: IEEE. 2013. 1779–1782.

85. Montori, S., Cacciamani, F., Gatti, R. V., Sorrentino, R., Arista, G., Tienda, C., Encinar, J. A. and Toso, G. A Transportable Reflectarray Antenna for Satellite Ku-band Emergency Communications. *IEEE Transactions on Antennas and Propagation*, 2015. 63(4): 1393–1407.

86. Abbosh, A. and Li, Y. Reconfigurable reflectarray antenna using single-layer radiator controlled by PIN diodes. *IET Microwaves, Antennas & Propagation*, 2015. 9(7): 664–671. doi:10.1049/iet-map.2014.0227.

87. Hajian, M., Kuijpers, B., Buisman, K., Akhnoukh, A., Pelk, M., de Vreede, L. C. N., Zijdeveld, J., Ligthart, L. P., Spitas, C., Hajian, M., Kuijpers, B., Buisman, K., Akhnoukh, A., Pelk, M., de Vreede, L. C. N., Zijdeveld, J., Ligthart, L. P. and Spitas, C. Passive and Active Reconfigurable Scan-Beam Hollow Patch Reflectarray Antennas. *ISRN Communications and Networking*, 2012. 2012: 1–10. doi:10.5402/2012/290534.

88. Tayebi, A., Tang, J., Paladhi, P. R., Udpa, L., Udpa, S. S. and Rothwell, E. J. Dynamic Beam Shaping Using a Dual-Band Electronically Tunable

Reflectarray Antenna. *IEEE Transactions on Antennas and Propagation*, 2015. 63(10): 4534–4539. doi:10.1109/TAP.2015.2456939.

89. Venneri, F., Boccia, L., Angiulli, G., Amendola, G. and Di Massa, G. Analysis and design of passive and active microstrip reflectarrays. *International Journal of RF and Microwave Computer-Aided Engineering*, 2003. 13(5): 370–377.

90. Carrasco, E., Barba, M., Arrebola, M., Encinar, J. A., Carrasco, E., Barba, M., Arrebola, M. and Encinar, J. A. Recent Developments of Reflectarray Antennas for Reconfigurable Beams Using Surface-Mounted RF-MEMS. *International Journal of Antennas and Propagation*, 2012. 2012: 1–12. doi: 10.1155/2012/386429.

91. Bayraktar, O., Civi, O. A. and Akin, T. Beam switching reflectarray monolithically integrated with RF MEMS switches. *IEEE Transactions on Antennas and Propagation*, 2012. 60(2): 854–862.

92. Pozar, D. M. *Microwave Engineering*. 3rd ed. USA: John Wiley and sons. 2005.

93. Balanis, C. A. *Antenna; Theory Analysis and Design*. 3rd ed. John Wiley and sons. 2005.

94. Huang, J. *Analysis of microstrip reflectarray antenna for microspacecraft applications*. Technical report. Spacecraft Telecommunications Equipment Section: TDA Progress Report. 1995.

95. Rajagopalan, H. and Rahmat Samii, Y. On the reflection characteristics of a reflectarray element with low-loss and high-loss substrates. *IEEE Antennas and Propagation Magazine*, 2010. 52(4): 73–89. ISSN 10459243. doi:10.1109/MAP.2010.5638237.

96. Haraz, O. M. and Ali, M. M. M. A millimeter-wave circular reflectarray antenna for future 5G cellular networks. *IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*. Institute of Electrical and Electronics Engineers Inc. 2015, vol. 2015-Octob. 1534–1535.

97. Yang, X., Xu, S., Yang, F., Li, M., Hou, Y., Jiang, S. and Liu, L. A Broadband High-Efficiency Reconfigurable Reflectarray Antenna Using Mechanically

Rotational Elements. *IEEE Transactions on Antennas and Propagation*, 2017. 65(8): 3959–3966. ISSN 0018-926X. doi:10.1109/TAP.2017.2708079.

98. Vosoogh, A., Keyghobad, K., Khaleghi, A. and Mansouri, S. A High-Efficiency Ku-Band Reflectarray Antenna Using Single-Layer Multiresonance Elements. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 891–894. doi:10.1109/LAWP.2014.2321035.

99. Rajagopalan, H. and Samii, Y. R. Dielectric and conductor loss quantification for microstrip reflectarray: simulations and measurements. *IEEE Transactions on Antennas and Propagation*, 2008. 56(4): 1192–1196. ISSN 0018926X. doi:10.1109/TAP.2008.919225.

100. Milligan, T. A. *Modern Antenna Design*. 2nd ed. John Wiley and sons, Hoboken, New Jersey. 2005.

101. R. Zhou, H. X., D. Liu. A Wideband Circularly Polarized Patch Antenna for 60 GHz Wireless Communications. *Wireless Engineering and Technology*, 2012. 3: 97–105.