DESIGN OF REFLECTARRAY ANTENNA USING DIFFERENT UNIT CELL ELEMENT AT KU-BAND

CHRISTELLE UWIZEYE

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Universiti Teknologi Malaysia

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To my parents, brothers, family and friends for their love, prayers and blessings.

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ABSTRACT

Reflectarray antenna offers several advantages over parabolic and phased array antennas, such as low weight, low profile, low cost, small size and low transmission losses due to the feeding mechanism. However, reflectarray antennas require the use of element shapes which are able to meet the requirements of modern technologies. This has led to the use of several unit cell designs by different researchers. However there is no specific shape which meets all specifications and design requirements. Therefore is a need to investigate several element shapes in the unit cell design to provide a quick reference guide for researchers. In this project, six different unit cells which are rectangular, circular, triangle, ring, rectangular with slot and cross shapes at 12 GHz are investigated through simulation. Each of the shape is then used in the complete antenna design of 11×11 reflectarray elements fed by a center feed horn antenna. The antenna results shows circular shapes gives the best performances with higher gain of 20.6 dB and low side lobes level in E and H planes. The outcome of this study provide insight in the development of high performance antenna.

ABSTRAK

Antena *reflectarray* mempunyai beberapa kelebihan berbanding antena *parabolic* dan antena *phased array*. Seperti, ringan, profil yang rendah, murah dan kadar kehilangan maklumat yang rendah disebabkan mekanisma suapan. Walau bagaimanapun, antena *reflectarray* memerlukan penggunaan bentuk elemen yang mampu memenuhi keperluan teknologi moden. Ini telah membawa kepada penggunaan beberapa reka bentuk sel unit oleh penyelidik yang berbeza. Walaubagaimanapun, tidak ada bentuk tertentu yang dapat memenuhi semua spesifikasi dan keperluan reka bentuk. Oleh itu, terdapat keperluan untuk mengenalpasti beberapa bentuk elemen dalam reka bentuk sel unit untuk dijadikan panduan untuk penyelidik. Dalam projek ini, enam sel unit yang berbeza seperti segi empat tepat, bulat, segi tiga, cincin, segi empat tepat dengan slot dan tanda tambah pada 12 GHz telah dikenalpasti melalui simulasi. Setiap bentuk kemudian digunakan dalam reka bentuk lengkap antena *reflectarray* yang berdimensi 11×11 dengan suapan pusat antena *horn*. Keputusan menunjukkan bentuk bulat memberikan prestasi yang terbaik dengan kearahan yang lebih tinggi iaitu 20.6 dB dan tahap paras cuping sisi yang rendah dalam plan E dan H. Hasil dari kajian ini dapal memberi panduan untuk menghasilkan antena yang berprestasi tinggi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

RF	-	Radio frequency
BW	-	Bandwidth
CST MWSF	-	Computer Simulation Technology Microwave Studio
DBS	-	Direct Broadcast Satellite
HPBW	-	Half Power Bandwidth
MEMS	-	Microelectro mechanical systemsRadio frequency
WR	-	Rectangular Waveguide
IEEE	-	Institute of Electrical and Electronics Engineering
GHz	-	Giga Hertz
dB	-	Decibel
dBi	-	Decibel Isotropy

LIST OF SYMBOLS

λ	-	Wavelength
ε_r	-	dielectric constant
π	-	radial measure

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Antenna serves a very important role in any wireless communication system. They are basically used in the transmission and reception of radio frequency (RF) signals between devices. Antenna are usually designed to receive or transmit RF signals in certain directions which is dependent on the application for which the antenna is designed. This can be observed from the antenna's radiation pattern [1]. Antenna have been integrated into several applications. For example personal communications and wireless connection. Direct communication links can employ antenna with narrow beams. Its usually refer to as pencil beams.

On the other hand, antenna which is mounted on satellites could shape their beam pattern so that it will provide wireless coverage to a specific geographic area. High gain antenna are usually required for many applications; such as radar and satellite communications. This is because the power radiated from the communication system can be focused at a specific direction to achieve maximum signal to noise ratio at the receivers. The high gain provided by parabolic reflector antenna has made them attractive in microwave point-to-point links and satellite communication [2]. Parabolic reflector antenna and constrained-fed planar array antenna were for a long time the only options available to the designer to achieve such performance [3]. Moreover, high gain antenna can be achieved either by the use of a big antenna aperture, or an array of small size antenna [4]. For the first case when big antenna aperture is implemented, high gain can be achieved from aperture antenna by forming a large illuminated apertures. The directivity can be made much larger by having a larger aperture, higher uniform field phases and larger amplitude on the aperture. A system which generally produce such performance is the combination of the horn antenna and the reflectors [5]. However, the aperture antennas provides much larger dimension and physical area, and therefore

requires a structure for support [6]. However, the limiting factor for this type of antenna is the weight and size of the aperture antenna [7]. This make them less compatible with modern communication systems. In the case where an array of small antennas are used, each element has it specific phase angle. This enables the antenna array to create a uniform field and provides a large aperture to achieve similar high gain provided by the parabolic antenna. Another advantage of the array antenna is that the phase can be reconfigured since each element can be electrically tuned by exciting specific element separately [8,9]. In addition, the array of small antenna is usually less bulky compared with the parabolic antenna because the element can be conformal or planner arrays. This make it suitable for modern communication systems.

In spite of the advantages provided by phased arrays antennas, they also posses some drawbacks. This can be observed in the feeding network design complexities and in their losses [10]. The feeding network complexities arise from the fact that each element of the array needs to be excited independently by a network of transmission line. As the array size increases, the losses on the transmission line also increases. This losses and feeding network complexities become the limiting factor militating against the advantages provided by the phased array of small antenna.

To exploit the advantages of both phased array and parabolic antenna, spatial techniques can be used. It can be achieved by exciting a phase array antenna using a single feed antenna such as a horn antenna. The array acts as passive scatterers [11,12]. A reflectarray antenna comprises of two main parts namely 1) the array of elements printed on a substrate, and 2) a feed antenna such as a horn antenna usually placed at the arrays focal point. Each elements of the reflectarray are designed with a specific size [13]. This will provide a phase difference to compensate for the difference in path from the feed to each element. Thus enable collimated beams with uniform phase to be created in the far-fields region of the reflectarray antenna. Moreover, placing the primary feeding source at the focal point of the reflectarray eliminates the use of complex transmission line feeding and the losses associated with phase array antennas [14].

Reflectarray antennas provides several advantages such as high gain, low-cost, low profile and they also poses a planer design which allows them to be easily integrated into structures such as roofs and walls [15]. Compared to parabolic antenna, reflectarray are usually more portable. In addition, It posses beam-scanning capabilities that can be achieved by integrating Micro-ElectroMechanical Systems control devices or solid state devices. This project is concerned with the design and

comparison of linear polarized reflectarray antenna. The comparison is made for different patch shapes which radiates at 12 GHz in the Ku-band. It is expected that the designed antenna is useful for direct broadcasting satellite application.

1.2 Problem Statement

To achieve better performance such as gain and bandwidth, researchers have investigate the phase characteristics, bandwidth and gain using various types of element shapes such as rectangular, dual square rings, circular ring, square ring, dual circular rings [16] and [17]. Element shapes with slots such as ring and rectangular slots are known to provide wider phase range [17], while patch elements without slots provides high gains. One can use variable size patches, dipoles or rings elements to achieve different scattering impedance and thus different phases to compensate for the different feed path delay [18]. However, there is no specific element shape that has been highlighted to meet specific application requirement particularly gain and bandwidth. Therefore there is a need to investigate the performance of reflectarray antenna with different element shapes. The study will provide researchers a reference guide on how each element shape affects the reflectarray antenna performance.

1.3 Objectives

The objectives of the project are as follows:

1. To design a unit cell with different element shapes at 12GHz.
2. To design and simulate reflectarray antenna with different unit cell.
3. To compare the results from different reflectarray antennas with various shape.

1.4 Scope of Work

The scope of this work includes

1. The design and simulation of six different unit cell shapes (rectangular, rectangular with slot, circular, circular ring, cross and triangle).
2. The horn antenna is designed to feed the reflectarray antenna.
3. Each shape is implemented in the design and simulation of reflectarray antenna.
4. The performance comparison for each shape in the reflectarray antenna are reflected phase response, radiation pattern, return loss and gain.

1.5 Organization of the Project

This project consist of 5 chapters. In Chapter 1, an introduction to the work is presented, where the project background is discussed. This is followed by the problem statement, objective and the scope of the project. In chapter 2, a review of recent work related to the theories and design of the reflectarray antenna are given so as to obtain a clear direction of the project. The methodology on how the project is carried out is presented in chapter 3, where the design specifications are highlighted. The results achieved from the return loss, the gain and the radiation patterns are given in chapter 4. Comparison of all the designed reflectarray antenna are made and its performance analysis in included. Finally, summary and conclusions are drawn from the entire project, recommendations based on how the project can be improved are stated in chapter 5.

1.6 Summary

The overview of reflectarray antenna is presented in this chapter, the problem statement, objectives, and scope of the project are also highlighted so as to present the direction of the project. In the next chapter, the literature review related to this project is given.

REFERENCES

1. Balanis, C. A. Antenna theory analysis and design, 1997. *John Wily & Sons inc*.

2. Caverly, R., Silver, W., Katz, A., Franco, M. and Campbell, R. RF and Microwave Links: The MTT Society and the Amateur Radio Community. *Microwave Magazine, IEEE*, 2015. 16(1): 50–63.

3. Rudge, A. W. and Adatia, N. A. Offset-parabolic-reflector antennas: a review. *Proceedings of the IEEE*, 1978. 66(12): 1592–1618.

4. Feresidis, A. P. and Vardaxoglou, J. C. High gain planar antenna using optimised partially reflective surfaces. *IEE Proceedings - Microwaves, Antennas and Propagation*, 2001. 148(6): 345–350. ISSN 1350-2417. doi: 10.1049/ip-map:20010828.

5. Hasselmann, F. J. and Felsen, L. B. Asymptotic analysis of parabolic reflector antennas. *Antennas and Propagation, IEEE Transactions on*, 1982. 30(4): 677–685.

6. Imbriale, W. A., Ingerson, P. G. and Wong, W. C. Large lateral feed displacements in a parabolic reflector. *Antennas and Propagation, IEEE Transactions on*, 1974. 22(6): 742–745.

7. Hansen, R. C. Fundamental limitations in antennas. *Proceedings of the IEEE*, 1981. 69(2): 170–182. ISSN 0018-9219. doi:10.1109/PROC.1981.11950.

8. Cheng, Y. J., Guo, Y. X. and Liu, Z. G. W-Band large-scale high-gain planar integrated antenna array. *Antennas and Propagation, IEEE Transactions on*, 2014. 62(6): 3370–3373.

9. Ghassemi, N., Wu, K., Claude, S., Zhang, X. and Bornemann, J. Low-cost and high-efficient W-band substrate integrated waveguide antenna array made of printed circuit board process. *Antennas and Propagation, IEEE Transactions on*, 2012. 60(3): 1648–1653.

10. Speciale, R. A. Advanced design of phased-array beam-forming networks. *IEEE Antennas and Propagation Magazine*, 1996. 38(4): 22–34. ISSN 1045-9243. doi:10.1109/74.537363.

11. Hu, W., Cahill, R., Encinar, J. A., Dickie, R., Gamble, H., Fusco, V. and Grant, N. Design and measurement of reconfigurable millimeter wave reflectarray cells with nematic liquid crystal. *Antennas and Propagation, IEEE Transactions on*, 2008. 56(10): 3112–3117.

12. Shaker, J., Chaharmir, M. R. and Ethier, J. *Reflectarray Antennas: Analysis, Design, Fabrication, and Measurement*. Artech House. 2013.

13. Qin, P. Y., Guo, Y. J. and Weily, A. R. Broadband Reflectarray Antenna Using Subwavelength Elements Based on Double Square Meander-Line Rings. *IEEE Transactions on Antennas and Propagation*, 2016. 64(1): 378–383. ISSN 0018-926X. doi:10.1109/TAP.2015.2502978.

14. Elsherbeni, A. Z., Nayeri, P. and Yang, F. Reflectarray antennas for space applications. *2012 IEEE International Conference on Ultra-Wideband*. 2012. ISSN 2162-6588. 362–365. doi:10.1109/ICUWB.2012.6340389.

15. Moharram, M. A. and Kishk, A. A. Optically Transparent Reflectarray Antenna Design Integrated With Solar Cells. *IEEE Transactions on Antennas and Propagation*, 2016. 64(5): 1700–1712. ISSN 0018-926X. doi:10.1109/TAP.2016.2539379.

16. Karnati, K. K., Yusuf, Y., Ebadi, S. and Gong, X. Theoretical Analysis on Reflection Properties of Reflectarray Unit Cells Using Quality Factors. *IEEE Transactions on Antennas and Propagation*, 2013. 61(1): 201–210. ISSN 0018-926X. doi:10.1109/TAP.2012.2214753.

17. Bialkowski, M. E. and Sayidmarie, K. H. Investigations Into Phase Characteristics of a Single-Layer Reflectarray Employing Patch or Ring Elements of Variable Size. *IEEE Transactions on Antennas and Propagation*, 2008. 56(11): 3366–3372. ISSN 0018-926X. doi:10.1109/TAP.2008.2005470.

18. Kiyani, A. and Ismail, M. Y. Numerical model for phase distribution characterization of reflectarray elements. *Telecommunication Technologies (ISTT), 2012 International Symposium on*. IEEE. 2012. 160–163.

19. Huang, J. *Reflectarray antenna*. Wiley Online Library. 2007.

20. Jorgensen, D., Loadman, C. and Chen, Z. D. Retrodirective antenna systems for wireless communications. *Proceedings of the 1st Annual Communication Networks and Services Research Conference (CNSR'03)*. 2003. 20–23.

21. Pozar, D. M., Targonski, S. D. and Syrigos, H. D. Design of millimeter wave microstrip reflectarrays. *IEEE Transactions on Antennas and Propagation*, 1997. 45(2): 287–296. ISSN 0018-926X. doi:10.1109/8.560348.

22. Berry, D., Malech, R. and Kennedy, W. The reflectarray antenna. *IEEE Transactions on Antennas and Propagation*, 1963. 11(6): 645–651. ISSN 0018-926X. doi:10.1109/TAP.1963.1138112.

23. Pozar, D. M. and Targonski, S. D. A microstrip reflectarray using crossed dipoles. *Antennas and Propagation Society International Symposium, 1998. IEEE*. 1998, vol. 2. 1008–1011 vol.2. doi:10.1109/APS.1998.702120.

24. Javor, R. D., Wu, X.-D. and Chang, K. Design and performance of a microstrip reflectarray antenna. *IEEE Transactions on Antennas and Propagation*, 1995. 43(9): 932–939. ISSN 0018-926X. doi:10.1109/8.410208.

25. Yusoff, M. and Fairus, M. *Low-profile antennas at millimeter waves: study of micromachined Fabry-Perot cavity antennas and folded reflectarray antennas*. Ph.D. Thesis. Rennes 1. 2012.

26. Encinar, J. A. and Zornoza, J. A. Three-layer printed reflectarrays for contoured beam space applications. *IEEE Transactions on Antennas and Propagation*, 2004. 52(5): 1138–1148. ISSN 0018-926X. doi:10.1109/TAP.2004.827506.

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

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

29. Munson, R. E., Haddad, H. A. and Hanlen, J. W. Microstrip reflectarray for satellite communication and radar cross-section enhancement or reduction, 1987. US Patent 4,684,952.

30. Targonski, S. and Pozar, D. Analysis and design of a microstrip reflectarray using patches of variable size. *Antennas and Propagation Society International Symposium, 1994. AP-S. Digest*. IEEE. 1994, vol. 3. 1820–1823.

31. Huang, J. Microstrip reflectarray. *Antennas and Propagation Society International Symposium, 1991. AP-S. Digest*. IEEE. 1991. 612–615.

32. Huang, J. Capabilities of printed reflectarray antennas. *Phased Array Systems and Technology, 1996., IEEE International Symposium on*. 1996. 131–134. doi:10.1109/PAST.1996.565950.

33. Guo, Y. J. and Barton, S. K. Phase correcting zonal reflector incorporating rings. *IEEE Transactions on Antennas and Propagation*, 1995. 43(4): 350–355. ISSN 0018-926X. doi:10.1109/8.376031.

34. Han, C., Huang, J. and Chang, K. A high efficiency offset-fed X/ka-dual-band reflectarray using thin membranes. *IEEE Transactions on Antennas and Propagation*, 2005. 53(9): 2792–2798. ISSN 0018-926X. doi:10.1109/TAP.2005.854531.

35. Perruisseau-Carrier, J. Dual-Polarized and Polarization-Flexible Reflective Cells With Dynamic Phase Control. *IEEE Transactions on Antennas and Propagation*, 2010. 58(5): 1494–1502. ISSN 0018-926X. doi:10.1109/TAP.2010.2044333.

36. Pozar, D. M., Targonski, S. D. and Pokuls, R. A shaped-beam microstrip patch reflectarray. *IEEE Transactions on Antennas and Propagation*, 1999. 47(7): 1167–1173. ISSN 0018-926X. doi:10.1109/8.785748.

37. Colin, J.-M. Phased array radars in France: present and future. *Phased Array Systems and Technology, 1996., IEEE International Symposium on*. IEEE. 1996. 458–462.

38. Tolkachev, A., Denisenko, V., Shishlov, A. and Shubov, A. High gain antenna systems for millimeter wave radars with combined electronical and mechanical beam steering. *Phased Array Systems and Technology, 1996., IEEE International Symposium on*. IEEE. 1996. 266–271.

39. Javor, R. D., Wu, X.-D. and Chang, K. Design and performance of a microstrip reflectarray antenna. *Antennas and Propagation, IEEE Transactions on*, 1995. 43(9): 932–939.

40. 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. ISSN 1536-1225. doi:10.1109/LAWP.2014.2374351.

41. 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. ISSN 0018-926X. doi:10.1109/TAP.2014.2327137.

42. Qu, S. W., Chen, Q. Y., Xia, M. Y. and Zhang, X. Y. Single-Layer Dual-Band Reflectarray With Single Linear Polarization. *IEEE Transactions on Antennas and Propagation*, 2014. 62(1): 199–205. ISSN 0018-926X. doi:10.1109/TAP.2013.2287517.

43. Ahmadi, F., Forooraghi, K. and Atlasbaf, Z. Circular polarized reflectarray antenna. *20th Iranian Conference on Electrical Engineering (ICEE2012)*. 2012. ISSN 2164-7054. 1135–1139. doi:10.1109/IranianCEE.2012.6292525.

44. Yang, F., Kim, Y., Yu, A., Huang, J. and Elsherbeni, A. A Single Layer Reflectarray Antenna for C/X/Ka Bands Applications. *Electromagnetics in Advanced Applications, 2007. ICEAA 2007. International Conference on*. 2007. 1058–1061. doi:10.1109/ICEAA.2007.4387492.

45. 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. ISSN 0018-926X. doi:10.1109/TAP.2015.2398128.

46. Huang, J. Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept. *Antennas and Propagation Society International Symposium, 1995. AP-S. Digest*. 1995, vol. 1. 582–585 vol.1. doi:10.1109/APS.1995.530086.

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

48. Encinar, J. A. Design of a dual frequency reflectarray using microstrip stacked patches of variable size. *Electronics Letters*, 1996. 32(12): 1049–1050. ISSN 0013-5194. doi:10.1049/el:19960710.

49. Encinar, J. A. and Zornoza, J. A. Broadband design of three-layer printed reflectarrays. *IEEE Transactions on Antennas and Propagation*, 2003. 51(7): 1662–1664.

50. Croq, F. and Pozar, D. M.

51. Pozar, D. Wideband reflectarrays using artificial impedance surfaces. *Electronics Letters*, 2007. 43(3): 1.

52. Tienda, C., Encinar, J. A. and Arrebola, M. Contoured-beam dual-reflectarray antenna for DBS application. *Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on*. 2011. ISSN 1522-3965. 109–112. doi:10.1109/APS.2011.5996652.

53. Hodges, R. E., Hoppe, D. J., Radway, M. J. and Chahat, N. E. Novel deployable reflectarray antennas for CubeSat communications. *2015 IEEE MTT-S International Microwave Symposium*. 2015. ISSN 0149-645X. 1–4. doi:10.1109/MWSYM.2015.7167153.

54. Zhang, Y., Jiang, M., Shunhua, Y. and Hong, W. Integration design of high efficiency reflectarray and transmitarray for millimeter wave wireless communications. *Communication Problem-Solving (ICCP), 2014 IEEE International Conference on*. 2014. 250–253. doi:10.1109/ICCPS.2014.

7062265.

55. Huang, J., Feria, V. A. and Fang, H. Improvement of the three-meter Ka-band inflatable reflectarray antenna. *Antennas and Propagation Society International Symposium, 2001. IEEE*. 2001, vol. 1. 122–125 vol.1. doi: 10.1109/APS.2001.958808.

56. Zawadzki, M. and Huang, J. Integrated RF antenna and solar array for spacecraft application. *Phased Array Systems and Technology, 2000. Proceedings. 2000 IEEE International Conference on*. 2000. 239–242. doi: 10.1109/PAST.2000.858948.

57. Huang, J. and Zawadzki, M. Antennas integrated with solar arrays for space vehicle applications. *Antennas, Propagation and EM Theory, 2000. Proceedings. ISAPE 2000. 5th International Symposium on*. 2000. 86–89. doi:10.1109/ISAPE.2000.894730.

58. Boccia, L., Venneri, F., Amendola, G. and Di Massa, G. Application of varactor diodes for reflectarray phase control. *IEEE Antennas and Propagation Society International Symposium*. IEEE; 1999. 2002, vol. 3. 132–135.

59. Metzler, T. Stub loaded microstrip reflectarrays. *Antennas and Propagation Society International Symposium, 1995. AP-S. Digest*. IEEE. 1995, vol. 1. 574–577.

60. Huang, J. Microstrip reflectarray. *Antennas and Propagation Society International Symposium, 1991. AP-S. Digest*. 1991. 612–615 vol.2. doi: 10.1109/APS.1991.174914.

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

62. Chaharmir, M. R., Shaker, J., Cuhaci, M. and Sebak, A. Circularly polarised reflectarray with cross-slot of varying arms on ground plane. *Electronics Letters*, 2002. 38(24): 1492–1493. ISSN 0013-5194. doi:10.1049/el: 20021051.

63. Chaharmir, M., Shaker, J., Cuhaci, M. and Sebak, A. Reflectarray with variable slots on ground plane. *IEE Proceedings-Microwaves, Antennas and Propagation*, 2003. 150(6): 436–439.

64. Cadoret, D., Laisne, A., Gillard, R. and Legay, H. A new reflectarray cell using microstrip patches loaded with slots. *Microwave and optical technology letters*, 2005. 44(3): 270–272.

65. Krachodnok, P. and Wongsan, R. Phase-bandwidth enhancement of microstrip patch reflectarray with cross slot loads. *Microwave Conference, 2007. APMC 2007. Asia-Pacific*. IEEE. 2007. 1–4.

66. Chaharmir, M. R., Shaker, J., Cuhaci, M. and Ittipiboon, A. A broadband reflectarray antenna with double square rings as the cell elements. *2006 First European Conference on Antennas and Propagation*. 2006. ISSN 2164-3342. 1–4. doi:10.1109/EUCAP.2006.4584613.

67. Chaharmir, M., Shaker, J., Cuhaci, M. and Ittipiboon, A. A broadband reflectarray antenna with double square rings as the cell elements. *Antennas and Propagation, 2006. EuCAP 2006. First European Conference on*. IEEE. 2006. 1–4.

68. Costanzo, S., Venneri, F. and Massa, G. D. Bandwidth enhancement of aperture-coupled reflectarrays. *Electronics Letters*, 2006. 42(23): 1320–1321. ISSN 0013-5194. doi:10.1049/el:20062492.

69. Encinar, J. A. Design of two-layer printed reflectarrays using patches of variable size. *IEEE Transactions on Antennas and Propagation*, 2001. 49(10): 1403–1410. ISSN 0018-926X. doi:10.1109/8.954929.

70. Wan, C. and Encinar, J. A. Efficient computation of generalized scattering matrix for analyzing multilayered periodic structures. *Antennas and Propagation, IEEE Transactions on*, 1995. 43(11): 1233–1242.

71. Encinar, J. Design of a dual frequency reflectarray using microstrip stacked patches of variable size. *rn*, 1996. 1(12): 1–4.