COMPACT ULTRA-WIDEBAND DIELECTRIC RESONATOR ANTENNAS

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To my beloved parents, who their enthusiasm and encouragement, I would never step in this way

and

To my beloved, mindful understanding wife, Shadi, who supported me each step of the way.

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ABSTRACT

UWB communication systems were newly regenerated when the Federal Communications Commission (FCC) defined the 3.1-10.6 GHz unlicensed band for UWB applications. Based on an investigation in designing UWB antennas, researchers have encountered more difficulties compared to a narrow band antenna. UWB antennas should have extremely wide impedance bandwidth while preserving high radiation efficiency with compact size. In some cases, a band-notched function should have been created to avoid electromagnetic interference between nearby existing systems and UWB systems. In this research, various promising UWB Dielectric Resonator Antennas (DRAs) have been demonstrated to overcome several challenges. The impedance bandwidth of the UWB DRAs has been improved for more than 110% by using some techniques such as connecting a strip to the ground plane and modifying structure of Dielectric Resonator (DR). The efficiency issue of UWB antennas is overcome by implementing DR as a resonator element which is excited by various shape structures feed lines to achieve more than 90% efficiency. The electromagnetic interferences between UWB systems and nearby existing systems in the frequency bands of 3.22-4.06 GHz, 4.84-5.96 GHz and 5.71-6.32 GHz are eliminated by using a stub connected to the hollow centre of feed line, an inverted-T shape parasitic strip near DR and modified metallic sheet underneath the DR, respectively. Compared with UWB monopole antennas, UWB DRAs obviate the problem of radiation pattern by utilizing dielectric resonator characteristics. In parallel, the broadside radiation pattern is obtained by implementing various shapes of microstrip feed line at a proper location to excite the DRA that provides symmetry radiation patterns with a consistent stability across the desired bandwidth.

ABSTRAK

Sistem komunikasi UWB adalah baru tumbuh semula apabila Suruhanjaya Komunikasi Persekutuan (FCC) mentakrifkan 3.1-10.6 GHz *band* yang tidak berlesen untuk aplikasi UWB. Berdasarkan kajian di dalam mereka bentuk antena UWB, para penyelidik menghadapi lebih kesukaran berbanding dengan mereka bentuk antena jalur sempit. Antena UWB harus mempunyai lebar jalur galangan masukan yang sangat luas di samping kecekapan pada radiasi tinggi dengan saiz yang kompak. Dalam beberapa kes, fungsi jalur-bertakuk dicipta untuk mengelakkan gangguan elektromagnet di antara sistem sedia ada dan sistem UWB. Di dalam kajian ini, pelbagai UWB bentuk Antena Penyalun Dielektrik (DRAs) dicipta bagi mengatasi beberapa cabaran berkaitan UWB. Lebar jalur galangan masukan daripada DRAs UWB dipertingkatkan dengan lebih daripada 110% menggunakan beberapa teknik seperti menghubungkan jalur dengan satah tanah dan mengubah suai struktur Penyalun Dielektrik. Isu kecekapan antena UWB diatasi dengan melaksanakan DR sebagai elemen resonator yang teruja dengan pelbagai struktur bentuk talian untuk mencapai kecekapan yang lebih daripada 90%. Gangguan elektromagnetik antara sistem UWB dan sistem sedia ada yang berdekatan dalam jalur frekuensi 3.22-4.06 GHz, 4.84-5.96 GHz, dan 5.71-6.32 GHz dapat dikurangkan dengan menggunakan puntung yang dihubungkan dengan pusat berongga talian makanan bentuk-T terbalik jalur parasit berhampiran DR dan lembaran logam diubah suai bawahnya DR, masing-masing. Berbanding dengan UWB antena *monopole*, DRAs UWB menyelesaikan masalah corak sinaran dengan menggunakan ciri-ciri resonator dielektrik. Pada masa yang sama, corak sinaran selebaran diperolehi dengan melaksanakan pelbagai bentuk garis jalur mikro di lokasi yang betul, untuk merangsang DRA yang menyediakan corak sinaran simetri dengan kestabilan yang konsisten di seluruh lebar jalur yang dikehendaki.

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LIST OF ABBREVIATIONS

AR	–	Axial Ratio
BW	–	Bandwidth
CDR	–	Cylindrical Dielectric Resonator
CDRA	–	Cylindrical Dielectric Resonator Antenna
CRP	–	Circular Ring Patch
CPW	–	Co-Planar Waveguide
CST	–	Computer Simulation Software
dB	–	decibel
dBi	–	decibel (isotropic)
DIG	–	Dielectric Image Guide
DR	–	Dielectric Resonator
DRA	–	Dielectric Resonator Antenna
DWM	–	Dielectric Waveguide Model
EDC	–	Effective Dielectric Constant
EM	–	Electromagnetic
ESCSRR	–	Elliptic Single Complementary Split-Ring Resonator
FCC	–	Federal Communication Commission
FDTD	–	Finite Difference Time Domain
FEM	–	Finite Element Method
FSS	–	Frequency Selective Surface
GHz	–	Giga Hertz
HCLR	–	Hollow-Cross-Loop Resonator
HDR	–	Hemispherical Dielectric Resonator
HDRA	–	Hemispherical Dielectric Resonator Antenna
HFSS	–	High Frequency Structural Simulator
Hz	–	Hertz
IDCLLR	–	Interdigital Capacitance Loading Loop Resonator
IEEE	–	Institute of Electrical and Electronic Engineers

mm	–	Millimeter
MoM	–	Method of Moment
MSDRA	–	Multi-Segment Dielectric Resonator Antenna
MWM	–	Magnetic Waveguide Model
PCB	–	Printed Circuit Boards
PIN	–	Positive-Intrinsic-Negative
Q factor	–	Quality factor
RDR	–	Rectangular Dielectric Resonator
RDRA	–	Rectangular Dielectric Resonator Antenna
RF	–	Radio Frequency
RL	–	Return Loss
RSRR	–	Rectangular Split-Ring Resonator
SIR-DGS	–	Stepped Impedance Resonator-Defected Ground Structure
SRR	–	Split-Ring Resonator
TE	–	Transverse Electric
TLM	–	Transmission Line Matrix
TM	–	Transverse Magnetic
TSDRA	–	Two-Segment Dielectric Resonator Antenna
UWB	–	Ultra-wideband
VSWR	–	Voltage Standing Wave Ratio
WiMAX	–	Worldwide Interoperability for Microwave Access
WLAN	–	Wireless Local Area Network
	–	

LIST OF SYMBOLS

f_c – Center frequency

ε – Dielectric constant

ε_{eff} – Effective permittivity

$E - plane$ – Electric plane

δ – Fraction of a half-of-field cycle variation

G – Gain of antenna

$H - plane$ – Magnetic plane

$\geq$ – More than

f_n – Notched frequency

ϕ – Phi angle

λ – Wavelength

λ_n – wavelength at the notched resonant frequency

π – pi

Γ – Reflection coefficient

f_0 – Resonant frequency

c – Speed of light

θ – Theta angle

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The Ultra-Wideband (UWB) systems have developed intensely in the past two decades which are implemented for both academic and industrial communities of telecommunication applications. These antennas generally strive to be compatible the Federal Communications Commission (FCC) which support an impedance bandwidth of 7.5 GHz, i.e. from 3.1 GHz to 10.6 GHz in 2002 [1]. There are several advantages of UWB communications compare to other technologies which make them excellent candidate to present a further eloquent solution for wireless broadband applications as follow [2–6].

First of all, the UWB systems can obtain an immense capacity of several Gbps with a short range of 1 to 10 meters due to proportion of channel capacity to bandwidth. Secondly, the UWB facilitates an extremely reliable communication and secure solution due to possessing a spectral density in low power level, noise-like, which causes slightly electromagnetic interference with longer-range existing narrow-band systems. Thirdly, in UWB systems, a sufficient spatial resolution is achieved by applying a short duration impulse. This characteristic is used in target imaging to provide a potential capability to distinct targets from background clutter. Fourthly, since the UWB signals have short duration pulse waveforms, no multi-path cancellation will occurred because of passing the direct path signal through the system before attaining the reflected path signal. Lastly, UWB systems compared to conventional radio systems have an intrinsic capability for integration in low complexity, low power, and low cost due to propagating without the requirement of an additional RF components which providing considerably short time domain pulse.

On the other hands, dielectric resonators (DRs) have been applied in the microwave circuits design such as oscillators and filters due to their high Q-factor characteristic. Moreover, it is found that the DRs with low dielectric constant can be used in antenna design as radiating element because of their low radiating Q-factor [7]. In the last two decades, dielectric resonator antennas (DRAs) have received agreeable consideration for UWB antennas due to remarkable characteristics such as different excitation mechanisms [8–11], high radiation efficiency [12], nearly constant gain [13, 14], and compact antenna size [15, 16]. The DRAs compared to microstrip patch antennas (MPAs)have wider impedance bandwidth because of having very small dielectric losses and lack of conductor losses, and also higher efficiency and less radiation pattern distortions due to lack of existing surface wave phenomena. In addition, DRAs compared with printed antenna provide small size ate expense of thickness due to decreasing the maximum path length in a certain direction to other directions.

1.2 Problem Statement

Based on investigation on ultra-wideband DR antenna, the researchers encountered some difficulties. One of the main challenges is obtaining wide impedance bandwidth more than around 91% with high radiation efficiency more than 90% while sustaining compact size. For example, the DRA impedance bandwidth is mostly below 10% for a single-mode excitation, which is not sufficient for UWB applications. On the other hands, existing electromagnetic interference of some narrow bands system such as wireless local area network (WLAN) and worldwide interoperability for microwave access (WiMAX) is a serious problem for UWB application systems. Some design techniques have been developed for the band rejection UWB DRA antenna. However, most of these approaches suffer from increasing size of antenna and lack of the flexibility and separately of each band rejection with control the width of the band-notch across the stop-band.

1.3 Research Objective

The objectives of this work focus on simulate and fabricate of a novel UWB DRA which are :

i. Design of compact UWB DRA with high radiation efficiency while sustaining wide bandwidth over whole desired frequencies.
ii. Design of UWB DRA with sufficient band rejection for existing electromagnetic interference of nearby wireless communication systems such as WiMAX (3.3-3.8 GHz) and WLAN (5.15-5.825 GHz).

1.4 Scopes of Project

This work focuses on the design of the UWB DRA which operates within the frequency range from 3.1 GHz to 10.6 GHz. The development of the UWB DRA is comprised by avoiding the electromagnetic interference of nearby narrow band systems such as the worldwide interoperability for microwave access (WiMAX) system operating at 3.3-3.8 GHz and wireless local area network (WLAN) system operating at 5.15-5.85 GHz.

The rectangular DR with dielectric constant less than 15 is used to achieve wide impedance bandwidth. The compact UWB DRAs is simulated and verified by CST and HFSS in terms of return loss, gain, efficiency, and radiation pattern to improve its performance. A parametric study of the different design of UWB DRAs was carried out. The UWB DRA is optimized and fabricated with good agreement between the measured results with simulated results.

1.5 Contribution of the Research

For this work, four contributions are introduced which include:

1. Design of a new compact two-segment Z-shaped DRA with different permittivity excited by a U-shaped feed-line for ultra-wideband application that the combination mechanism of the U-shaped feed-line and two-segments DR (TSDR) characteristics provide firm omnidirectional radiation pattern and high radiation efficiency with compact size while sustaining wide impedance bandwidth.
2. Design of a new simple compact rectangular dielectric resonator antenna (RDRA) for ultra-wideband application that by applying a combination of simple parasitic strip connected to the ground plane, microstrip feed line and inserted RDR characteristic, a compact antenna size with a wide impedance bandwidth, high radiation efficiency, nearly constant gain and consistent omnidirectional radiation pattern over desired frequency range are achieved.
3. Design of a new compact DRA with band rejection of 5.71-6.32 GHz (upper WLAN band) using a modified metallic sheet for ultra-wideband application that the combination mechanism of L-Shape strip connected to the ground plane, proper position of microstrip feed line, inserted DR characteristic, and metallic sheet underneath DR provide a wide impedance bandwidth and compact antenna with consistent omnidirectional radiation pattern.
4. Design of a new compact UWB DRA with dual band rejection of 3.22-4.06 GHz (WiMAX) and 4.84-5.96 GHz (WLAN) that by intently implementing a combination mechanism of two inserted identical DRs, U-shaped excitation performance, stub, inverted T-shaped parasitic strip, and slot in the ground plane, ultra wideband characteristic with efficient dual band-notched and miniature size of about $0.124\lambda \times 0.31\lambda \times 0.062\lambda$ at 3.1 GHz are achieved simultaneously.

1.6 Signification of the Research

Dielectric resonator antennas would be chosen by more system engineers when designing their wireless products due to possessing their considerable characteristics, flexibility in design and easily available commercially at very low cost. Therefore, DRAs have proved themselves to be ideal candidates for UWB antenna applications such as local and personal area networks (LAN/PAN), roadside info-station, short range radios and military communications.

1.7 Thesis Outlines

This thesis is organized in six chapters, which each chapter will describe on the different aspects of the work. The outlines of the dissertation for each 6 chapter are organized as follows.

Chapter 1 introduces an introduction of UWB system and a brief history about the dielectric resonator antenna and also makes some view about the problem statements, objective, and scope of this work.

Chapter 2 describes most prevalently used shapes of DRA and focuses on surveys of coupling mechanisms, bandwidth enhancement techniques, and compact techniques of DRAs through the literature to obtain some idea and achieve proper design.

Chapter 3 focuses on the methodology of project and steps of design. Moreover, the steps of the fabrication process and measurement procedure are illustrated.

Chapter 4 depicts simulated and measured results of an ultra-wideband dielectric resonator antenna design. Discussions about comparisons between simulated and measured result through the diagram are illustrated.

Chapter 5 demonstrates a design of ultra-wideband dielectric resonator antenna with WiMAX/WLAN band rejections. Parametric studies and discussions with experimental results are illustrated.

Chapter 6 concludes this project and indicates some possible future works.

REFERENCES

1. FCC. *Federal Communications Commission Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission System from 3.1 to 10.6 GHz*. Federal Communications Commission. 2002.
2. Dowla, F. *Handbook of RF and Wireless Technologies*. Elsevier Science. 2003.
3. Wayarles, K. and Rahman, T. A. Reconfigurable Ultra Wideband Antenna Design and Development for Wireless Communication. 2008.
4. Lim, E. G., Wang, Z., Lei, C.-U., Wang, Y. and Man, K. Ultra Wideband Antennas-Past and Present. *IAENG International Journal of Computer Science*, 2010. 37(3): 304–314.
5. Oppermann, I., Hämäläinen, M. and Iinatti, J. *UWB: theory and applications*. John Wiley & Sons. 2005.
6. Roy, S., Foerster, J. R., Somayazulu, V. S. and Leeper, D. G. Ultrawideband radio design: The promise of high-speed, short-range wireless connectivity. *Proceedings of the IEEE*, 2004. 92(2): 295–311.
7. Long, S. A., McAllister, M. W. and Shen, L. C. The resonant cylindrical dielectric cavity antenna. *IEEE Transactions on Antennas and Propagation*, 1983. 31: 406–412.
8. Guo, Y.-X. and Luk, K.-M. On improving coupling between a coplanar waveguide feed and a dielectric resonator antenna. *IEEE Transactions on Antennas and Propagation*, 2003. 51(8): 2144–2146.
9. Al Salameh, M., Antar, Y. M. and Séguin, G. Coplanar-waveguide-fed slot-coupled rectangular dielectric resonator antenna. *IEEE Transactions on Antennas and Propagation*, 2002. 50(10): 1415–1419.
10. Danesh, S., Abdulrahim, S., Abedian, M., Khalily, M. and Hamid, M. Frequency Reconfigurable Rectangular Dielectric Resonator Antenna. *IEEE Antennas and Wireless Propagation Letters*, 2013. 12: 1331–1334.
11. Sulaiman, M. I. and Khamas, S. K. A singly fed rectangular dielectric

resonator antenna with a wideband circular polarization. *IEEE Antennas and Wireless Propagation Letters*, 2010. 9: 615–618.

12. Ryu, K. S. and Kishk, A. A. Ultrawideband dielectric resonator antenna with broadside patterns mounted on a vertical ground plane edge. *IEEE Transactions on Antennas and Propagation*, 2010. 58(4): 1047–1053.

13. Ryu, K. S. and Kishk, A. A. UWB dielectric resonator antenna having consistent omnidirectional pattern and low cross-polarization characteristics. *IEEE Transactions on Antennas and Propagation*, 2011. 59(4): 1403–1408.

14. Ryu, K. S. and Kishk, A. A. Evaluation of dielectric resonator sensor for near-field breast tumor detection. *IEEE Transactions on Antennas and Propagation*, 2011. 59(10): 3738–3745.

15. Buerkle, A., Sarabandi, K. and Mosallaei, H. Compact slot and dielectric resonator antenna with dual-resonance, broadband characteristics. *IEEE Transactions on Antennas and Propagation*, 2005. 53(3): 1020–1027.

16. Huitema, L., Koubeissi, M., Mouhamadou, M., Arnaud, E., Decroze, C. and Monediere, T. Compact and multiband dielectric resonator antenna with pattern diversity for multistandard mobile handheld devices. *IEEE Transactions on Antennas and Propagation*, 2011. 59(11): 4201–4208.

17. IEEE Standard Definitions of Terms for Antennas. *IEEE Std 145-1993*, 2013: 1–32.

18. Lodge, O. Electric telegraphy, 1898. US Patent 609,154.

19. PS, C. Wideband, short wave antenna and transmission line system, 1939. US Patent 2,181, 870.

20. NE, L. Wide Band Antenna, 1941. US Patent 2,239,724.

21. LN, B. Broad Band Antenna, 1948. US Patent 2,454,766.

22. W, S. Broadband ellipsoidal dipole antenna, 1968. US Patent 3,364,491.

23. Gibson, P. The Vivaldi Aerial. *Microwave Conference, 1979. 9th European.* 1979. 101–105.

24. Liang, X. L. *Ultra-Wideband Antenna and Design, Ultra Wideband - Current Status and Future Trends, Dr. Mohammad Matin (Ed.).* InTech. 2012.

25. Agrawall, N., Kumar, G. and Ray, K. Wide-band planar monopole antennas. *IEEE Transactions on Antennas and Propagation*, 1998. 46(2): 294–295.

26. Kim, J., Yoon, T., Kim, J. and Choi, J. Design of an ultra wide-band printed monopole antenna using FDTD and genetic algorithm. *IEEE Microwave and*

Wireless Components Letters, 2005. 15(6): 395–397.

27. Chen, H.-D. Broadband CPW-fed square slot antennas with a widened tuning stub. *IEEE Transactions on Antennas and Propagation*, 2003. 51(8): 1982–1986.

28. Ruan, Y.-F., Guo, Y.-X. and Shi, X.-Q. Double annular-ring dielectric resonator antenna for ultra-wideband application. *Microwave and Optical Technology Letters*, 2007. 49(2): 362–366.

29. Okaya, A. and Barash, L. The dielectric microwave resonator. *Proceedings of the IRE*, 1962. 50(10): 2081–2092.

30. McAllister, M., Long, S. and Conway, G. Rectangular dielectric resonator antenna. *Electronics Letters*, 1983. 19(6): 218–219.

31. McAllister, M. and Long, S. Resonant hemispherical dielectric antenna. *Electronics Letters*, 1984. 20(16): 657–659.

32. Petosa, A. *Dielectric Resonator Antenna Handbook*. Artech House. 2007.

33. Luk, K. and Leung, K. *Dielectric Resonator Antennas*. Research Studies Press. 2003.

34. Maity, S. and Gupta, B. Effective wave guide model (EWGM) for resonant frequency computation of rectangular dielectric resonator antennas. *Progress In Electromagnetics Research C*, 2010. 16: 1–12.

35. Kumar Mongia, R. and Ittipiboon, A. Theoretical and experimental investigations on rectangular dielectric resonator antennas. *IEEE Transactions on Antennas and Propagation*, 1997. 45(9): 1348–1356.

36. McLevige, W., Itoh, T. and Mittra, R. New Waveguide Structures for Millimeter-Wave and Optical Integrated Circuits. *IEEE Transactions on Microwave Theory and Techniques*, 1975. 23(10): 788–794.

37. Marcatili, E. A. Dielectric rectangular waveguide and directional coupler for integrated optics. *Bell System Technical Journal*, 1969. 48(7): 2071–2102.

38. Guha, D., Gupta, B., Kumar, C. and Antar, Y. M. Segmented hemispherical DRA: New geometry characterized and investigated in multi-element composite forms for wideband antenna applications. *IEEE Transactions on Antennas and Propagation*, 2012. 60(3): 1605–1610.

39. Guha, D., Gupta, B. and Antar, Y. M. Hybrid monopole-DRAs using hemispherical/conical-shaped dielectric ring resonators: Improved ultrawideband designs. *IEEE Transactions on Antennas and Propagation*, 2012. 60(1): 393–398.

40. Mukherjee, B., Patel, P. and Mukherjee, J. A Novel Cup-shaped Inverted Hemispherical Dielectric Resonator Antenna for Wideband Applications. *IEEE Antennas and Wireless Propagation Letters*, 2013. 12: 1240–1243.

41. Lim, E. H. and Leung, K. W. Use of the dielectric resonator antenna as a filter element. *IEEE Transactions on Antennas and Propagation*, 2008. 56(1): 5–10.

42. Hady, L. K., Kajfez, D. and Kishk, A. A. Triple mode use of a single dielectric resonator. *IEEE Transactions on Antennas and Propagation*, 2009. 57(5): 1328–1335.

43. Zou, L., Abbott, D. and Fumeaux, C. Omnidirectional cylindrical dielectric resonator antenna with dual polarization. *IEEE Antennas and Wireless Propagation Letters*, 2012. 11: 515–518.

44. Rashidian, A. and Klymyshyn, D. M. On the two segmented and high aspect ratio rectangular dielectric resonator antennas for bandwidth enhancement and miniaturization. *IEEE Transactions on Antennas and Propagation*, 2009. 57(9): 2775–2780.

45. Petosa, A. and Thirakoune, S. Rectangular dielectric resonator antennas with enhanced gain. *IEEE Transactions on Antennas and Propagation*, 2011. 59(4): 1385–1389.

46. Collin, R. *Foundations for Microwave Engineering*. Wiley. 2001.

47. Li, B. and Leung, K. W. On the differentially fed rectangular dielectric resonator antenna. *IEEE Transactions on Antennas and Propagation*, 2008. 56(2): 353–359.

48. Rashidian, A., Shafai, L. and Klymyshyn, D. M. Compact wideband multimode dielectric resonator antennas fed with parallel standing strips. *IEEE Transactions on Antennas and Propagation*, 2012. 60(11): 5021–5031.

49. Haraz, O., Sebak, A.-R. and Denidni, T. Dual-polarised dielectric-loaded monopole antenna for wideband communication applications. *IET Microwaves, Antennas & Propagation*, 2012. 6(6): 663–669.

50. Petosa, A., Simons, N., Siushansian, R., Ittipiboon, A. and Cuhaci, M. Design and analysis of multisegment dielectric resonator antennas. *IEEE Transactions on Antennas and Propagation*, 2000. 48(5): 738–742.

51. Rezaei, P., Hakkak, M. and Forooraghi, K. Design of wide-band dielectric resonator antenna with a two-segment structure. *Progress In Electromagnetics Research*, 2006. 66: 111–124.

52. Denidni, T. A., Rao, Q. and Sebak, A. R. Broadband L-shaped dielectric resonator antenna. *Antennas and Wireless Propagation Letters, IEEE*, 2005. 4: 453–454.

53. Ge, Y., Esselle, K. and Bird, T. Compact Dielectric Resonator Antennas With Ultrawide $60\% - 110\%$ Bandwidth. *IEEE Transactions on Antennas and Propagation*, 2011. 59(9): 3445–3448.

54. Simeoni, M., Cicchetti, R., Yarovoy, A. and Caratelli, D. Plastic-based supershaped dielectric resonator antennas for wide-band applications. *IEEE Transactions on Antennas and Propagation*, 2011. 59(12): 4820–4825.

55. Yang, N., Leung, K. W. and Lim, E. H. Mirror-Integrated Dielectric Resonator Antenna. *IEEE Transactions on Antennas and Propagation*, 2014. 62(1): 27–32.

56. Dhar, S., Ghatak, R., Gupta, B. and Poddar, D. R. A Wideband Minkowski Fractal Dielectric Resonator Antenna. *IEEE Transactions on Antennas and Propagation*, 2013. 61(6): 2895–2903.

57. Gao, Y., Feng, Z. and Zhang, L. Compact CPW-fed dielectric resonator antenna with dual polarization. *IEEE Antennas and Wireless Propagation Letters*, 2011. 10: 544–547.

58. Lin, Y.-F., Chen, H.-M. and Lin, C.-H. Compact dual-band hybrid dielectric resonator antenna with radiating slot. *IEEE Antennas and Wireless Propagation Letters*, 2009. 8: 6–9.

59. Chang, T.-H. and Kiang, J.-F. Broadband dielectric resonator antenna with metal coating. *IEEE Transactions on Antennas and Propagation*, 2007. 55(5): 1254–1259.

60. Roslan, S., Kamarudin, M., Khalily, M. and Jamaluddin, M. An MIMO Rectangular Dielectric Resonator Antenna for 4G Applications. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 321–324.

61. Al-Zoubi, A. S., Kishk, A. A. and Glisson, A. W. A linear rectangular dielectric resonator antenna array fed by dielectric image guide with low cross polarization. *IEEE Transactions on Antennas and Propagation*, 2010. 58(3): 697–705.

62. Nikkhah, M. R., Rashed-Mohassel, J. and Kishk, A. A. High-Gain Aperture Coupled Rectangular Dielectric Resonator Antenna Array Using Parasitic Elements. *IEEE Transactions on Antennas and Propagation*, 2013. 61(7): 3905–3908.

63. Majeed, A., Abdullah, A., Elmegri, F., Sayidmarie, K., Abd-Alhameed, R. and Noras, J. Aperture-Coupled Asymmetric Dielectric Resonators Antenna for Wideband Applications. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 927–930.

64. Fang, X., Leung, K. W. and Lim, E. H. Singly-Fed Dual-Band Circularly Polarized Dielectric Resonator Antenna. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 995–998.

65. Chang, T.-H. and Kiang, J.-F. Dualband Split Dielectric Resonator Antenna. *IEEE Transactions on Antennas and Propagation*, 2007. 55(11): 3155–3162.

66. Chang, T.-H., Huang, Y.-C., Su, W.-F. and Kiang, J.-F. Wideband dielectric resonator antenna with a tunnel. *IEEE Antennas and Wireless Propagation Letters*, 2008. 7: 275–278.

67. Denidni, T. A., Weng, Z. and Niroo-Jazi, M. Z-shaped dielectric resonator antenna for ultrawideband applications. *IEEE Transactions on Antennas and Propagation*, 2010. 58(12): 4059–4062.

68. Zhang, L.-N., Zhong, S.-S. and Xu, S.-Q. Broadband U-shaped dielectric resonator antenna with elliptical patch feed. *Electronics Letters*, 2008. 44(16): 947–949.

69. Kishk, A. A., Chair, R. and Lee, K. F. Broadband dielectric resonator antennas excited by L-shaped probe. *IEEE Transactions on Antennas and Propagation*, 2006. 54(8): 2182–2189.

70. Chang, W. and Feng, Z. Investigation of a novel wideband feeding technique for dielectric ring resonator antennas. *IEEE Antennas and Wireless Propagation Letters*, 2009. 8: 348–351.

71. Saed, M. A. and Yadla, R. Microstrip-fed low profile and compact dielectric resonator antennas. *Progress In Electromagnetics Research*, 2006. 56: 151–162.

72. Chaudhary, R. K., Kumar, R. and Srivastava, K. V. Wideband ring dielectric resonator antenna with annular-shaped microstrip feed. *IEEE Antennas and Wireless Propagation Letters*, 2013. 12: 595–598.

73. Khalily, M., Rahim, M. K. A. and Kishk, A. A. Bandwidth enhancement and radiation characteristics improvement of rectangular dielectric resonator antenna. *IEEE Antennas and Wireless Propagation Letters*, 2011. 10: 393–395.

74. Denidni, T. and Weng, Z. Rectangular dielectric resonator antenna for

ultrawideband applications. *Electronics Letters*, 2009. 45(24): 1210–1212.

75. Petosa, A., Larose, R., Ittipiboon, A. and Cuhaci, M. Microstrip-fed array of multisegment dielectric resonator antennas. *IEE Proceedings - Microwaves, Antennas and Propagation*, 1997. 144(6): 472–476.

76. Long, R., Dorris, R., Long, S., Khayat, M. and Williams, J. Use of parasitic strip to produce circular polarisation and increased bandwidth for cylindrical dielectric resonator antenna. *Electronics Letters*, 2001. 37(7): 406–408.

77. Leung, K. W. and Ng, H. K. The slot-coupled hemispherical dielectric resonator antenna with a parasitic patch: Applications to the circularly polarized antenna and wide-band antenna. *IEEE Transactions on Antennas and Propagation*, 2005. 53(5): 1762–1769.

78. Kishk, A. A., Zhang, X., Glisson, A. W. and Kajfez, D. Numerical analysis of stacked dielectric resonator antennas excited by a coaxial probe for wideband applications. *IEEE Transactions on Antennas and Propagation*, 2003. 51(8): 1996–2006.

79. Guo, Y.-X., Ruan, Y.-F. and Shi, X.-Q. Wide-band stacked double annular-ring dielectric resonator antenna at the end-fire mode operation. *IEEE Transactions on Antennas and Propagation*, 2005. 53(10): 3394–3397.

80. Rocha, H., Freire, F., Sohn, R., da Silva, M., Santos, M., Junqueira, C., Cordaro, T. and Sombra, A. Bandwidth enhancement of stacked dielectric resonator antennas excited by a coaxial probe: an experimental and numerical investigation. *IET Microwaves, Antennas & Propagation*, 2008. 2(6): 580–587.

81. Walsh, A. G., DeYoung, C. S. and Long, S. A. An investigation of stacked and embedded cylindrical dielectric resonator antennas. *IEEE Antennas and Wireless Propagation Letters*, 2006. 5(1): 130–133.

82. Shum, S. and Luk, K. Stacked annular ring dielectric resonator antenna excited by axi-symmetric coaxial probe. *IEEE Transactions on Antennas and Propagation*, 1995. 43(8): 889–892.

83. Sangiovanni, A., Dauvignac, J. and Pichot, C. Embedded dielectric resonator antenna for bandwidth enhancement. *Electronics Letters*, 1997. 33(25): 2090–2091.

84. Chair, R., Kishk, A. and Lee, K. Low profile wideband embedded dielectric resonator. *Microwaves, Antennas & Propagation, IET*, 2007. 1(2): 294–298.

85. Kishk, A. A. Experimental study of broadband embedded dielectric resonator

antennas excited by a narrow slot. *IEEE Antennas and Wireless Propagation Letters*, 2005. 4: 79–81.

86. Ahmed, O., Sebak, A. and Denidni, T. Compact UWB printed monopole loaded with dielectric resonator antenna. *Electronics Letters*, 2011. 47(1): 7–8.

87. Esselle, K. P. and Bird, T. S. A hybrid-resonator antenna: Experimental results. *IEEE Transactions on Antennas and Propagation*, 2005. 53(2): 870–871.

88. Gupta, V., Sinha, S., Koul, S. K. and Bhat, B. Wideband dielectric resonator-loaded suspended microstrip patch antennas. *Microwave and Optical Technology Letters*, 2003. 37(4): 300–302.

89. Dong, Y.-D., Hong, W., Kuai, Z.-Q. and Chen, J. X. Analysis of Planar Ultrawideband Antennas With On-Ground Slot Band-Notched Structures. *IEEE Transactions on Antennas and Propagation*, 2009. 57(7): 1886–1893.

90. Yeo, J. and Mittra, R. A novel wideband antenna package design with a compact spatial-notch filter for wireless applications. *Microwave and Optical Technology Letters*, 2002. 35(6): 455–460.

91. Chu, Q.-X. and Yang, Y.-Y. A Compact Ultrawideband Antenna With 3.4/5.5 GHz Dual Band-Notched Characteristics. *IEEE Transactions on Antennas and Propagation*, 2008. 56(12): 3637–3644.

92. Zheng, Z.-A., Chu, Q.-X. and Tu, Z.-H. Compact Band-Rejected Ultrawideband Slot Antennas Inserting With $\lambda/2$ and $\lambda/4$ Resonators. *IEEE Transactions on Antennas and Propagation*, 2011. 59(2): 390–397.

93. Sarkar, D., Srivastava, K. and Saurav, K. A Compact Microstrip-Fed Triple Band-Notched UWB Monopole Antenna. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 396–399.

94. Aghdam, S. A Novel UWB Monopole Antenna With Tunable Notched Behavior Using Varactor Diode. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 1243–1246.

95. Gao, P., He, S., Wei, X., Xu, Z., Wang, N. and Zheng, Y. Compact Printed UWB Diversity Slot Antenna With 5.5-GHz Band-Notched Characteristics. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 376–379.

96. Badamchi, B., Nourinia, J., Ghobadi, C. and Valizade Shahmirzadi, A. Design of compact reconfigurable ultra-wideband slot antenna with switchable single/dual band notch functions. *IET Microwaves, Antennas &*

Propagation, 2014. 8(8): 541–548.

97. Eshtiaghi, R., Nourinia, J. and Ghobadi, C. Electromagnetically Coupled Band-Notched Elliptical Monopole Antenna for UWB Applications. *IEEE Transactions on Antennas and Propagation*, 2010. 58(4): 1397–1402.

98. Ma, T.-G. and Wu, S.-J. Ultrawideband Band-Notched Folded Strip Monopole Antenna. *IEEE Transactions on Antennas and Propagation*, 2007. 55(9): 2473–2479.

99. Ellis, M., Zhao, Z., Wu, J., Nie, Z. and Liu, Q.-H. A Novel Miniature Band-Notched Wing-Shaped Monopole Ultrawideband Antenna. *IEEE Antennas and Wireless Propagation Letters*, 2013. 12: 1614–1617.

100. Wang, J., Yin, Y., Liu, X. and Wang, T. Trapezoid UWB antenna with dual band-notched characteristics for WiMAX/WLAN bands. *Electronics Letters*, 2013. 49(11): 685–686.

101. Zhang, C., Zhang, J. and Li, L. Triple band-notched UWB antenna based on SIR-DGS and fork-shaped stubs. *Electronics Letters*, 2014. 50(2): 67–69.

102. Ryu, K. and Kishk, A. UWB Antenna With Single or Dual Band-Notches for Lower WLAN Band and Upper WLAN Band. *IEEE Transactions on Antennas and Propagation*, 2009. 57(12): 3942–3950.

103. Li, T., Zhai, H., Li, G., Li, L. and Liang, C. Compact UWB Band-Notched Antenna Design Using Interdigital Capacitance Loading Loop Resonator. *IEEE Antennas and Wireless Propagation Letters*, 2012. 11: 724–727.

104. Reddy, G., Kamma, A., Mishra, S. and MUKHERJEE, J. Compact Bluetooth/UWB Dual-Band Planar Antenna With Quadruple Band-Notch Characteristics. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 872–875.

105. Azim, R., Islam, M. and Mobashsher, A. Dual Band-Notch UWB Antenna With Single Tri-Arm Resonator. *IEEE Antennas and Wireless Propagation Letters*, 2014. 13: 670–673.

106. Liu, Y., Chen, Z. and Gong, S. Triple band-notched aperture UWB antenna using hollow-cross-loop resonator. *Electronics Letters*, 2014. 50(10): 728–730.

107. Ojaroudi, M. and Ojaroudi, N. Ultra-Wideband Small Rectangular Slot Antenna With Variable Band-Stop Function. *IEEE Transactions on Antennas and Propagation*, 2014. 62(1): 490–494.

108. Denidni, T. and Weng, Z. Hybrid ultrawideband dielectric resonator antenna

and band-notched designs. *IET Microwaves, Antennas & Propagation*, 2011. 5(4): 450–458.

109. Niroo-Jazi, M. and Denidni, T. A. Experimental investigations of a novel ultrawideband dielectric resonator antenna with rejection band using hybrid techniques. *IEEE Antennas and Wireless Propagation Letters*, 2012. 11: 492–495.

110. Shahine, M. A., Al-Husseini, M., Kabalan, K. and El-Hajj, A. An Ultra-wideband Dielectric Resonator Antenna with Reconfigurable Band Rejection. *Session 2A9*: 298.

111. kumari, P., Bisoyi, D. K. and Behera, S. K. Design of Dielectric Resonator antenna with band notched Characteristics for UWB applications. *International Journal of Scientific & Engineering Research*, 2013. 4(6): 2624–2628.

112. Sabouni, A. and Kishk, A. Single or multi notch bands applied to microstrip excited ultra-wideband antennas with dielectric resonator antenna case. *Microwave and Optical Technology Letters*, 2013. 55(5): 1066–1069.

113. Tseng, C.-F. and Lu, S.-C. Notch frequency of dielectric resonator-loaded monopole antenna for UWB application. *Microwave and Optical Technology Letters*, 2014. 56(5): 1189–1193.

114. Vashistha, V., Kartikeyan, M., Malik, J. and Maheshwari, R. Analysis of ultra wide band dielectric resonator antenna with band notch for WLAN communication. *Electrical, Electronics and Computer Science (SCEECS), 2014 IEEE Students' Conference on*. 2014. 1–3.

115. Wang, Y. F., Denidni, T., Zeng, Q. S. and Wei, G. Band-notched UWB rectangular dielectric resonator antenna. *Electronics Letters*, 2014. 50(7): 483–484.

116. Tseng, C.-F. and Lu, S.-C. A compact band-notched ultrawideband dielectric-loaded antenna. *Microwave and Optical Technology Letters*, 2014. 56(2): 456–462.

117. Liang, X.-L., Denidni, T. and Zhang, L.-N. Wideband L-Shaped Dielectric Resonator Antenna With a Conformal Inverted-Trapezoidal Patch Feed. *IEEE Transactions onAntennas and Propagation*, 2009. 57(1): 271–274.

118. Chen, Z. N., See, T. S. P. and Qing, X. Small Printed Ultrawideband Antenna With Reduced Ground Plane Effect. *IEEE Transactions onAntennas and Propagation*, 2007. 55(2): 383–388.