

FREQUENCY RECONFIGURABLE METAMATERIAL RESONANT ANTENNA

MOHAMMED MUSTAPHA GAJIBO

UNIVERSITI TEKNOLOGI MALAYSIA

FREQUENCY RECONFIGURABLE METAMATERIAL RESONANT ANTENNA

MOHAMMED MUSTAPHA GAJIBO

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical-Electronics & Telecommunications)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2015

To my beloved parents: Hon. Engr. Mustapha Alkali Gajibo and mothers Hajja
Yagana Mustapha and Hajja Safiya Tijjani.

ACKNOWLEDGEMENT

In the Name of Allah, Most Gracious, Most Merciful In this context, I would like to extend my gratitude to my supervisor, Professor Dr. Mohamad Kamal A. Rahim for his support, guidance, gentleness and patience. Without, his unwavering confidence and his genuine personal interest in me, I am sure I would never have completed this project. Also my sincere appreciation goes to Dr. Bashir D. Bala and Dr. Huda A. Majid for their fruitful discussions, contributions, support and motivation.

Finally, I am very grateful to my beloved parents and siblings, Binta M. G, Awal M.G, Kakagana M. G, Hadiza M. G, Ahmed M. G, Kaltum M. G, Muktar M. G, Amina M. G, Nafisa M. G, Yusuf M. G, Halima M. G and last but not the least Ahmed T. M. G for their endless prayers, love and encouragement.

ABSTRACT

New paradigm has been engineered to exhibit reverse electromagnetic properties. Novel composite and micro-structured materials (metamaterials) have been designed to control electromagnetic radiation. Such substances have been called as Left Handed Material (LHM) with simultaneous negative or positive permittivity, permeability and refractive index or mixed positive and negative. This engineered paradigm was used to implement the proposed antenna. The proposed frequency reconfigurable metamaterial antenna is a coplanar waveguide (CPW)-fed metamaterial antenna using an epsilon negative transmission line. The resonance frequencies are reconfigured and also reconfiguration from narrow to wideband was also implemented. The reflection coefficient, bandwidth and surface current of the designed antenna were studied and analyzed. The antenna configuration consists of a signal patch, coplanar ground planes, microstrip lines (switches) for varying or selecting frequencies. The switches connect the signal patch with the coplanar ground plane to realize increase in inductance L_L , which is proportional to the length of the patch, where the switch is located. Since it is very difficult to realize large inductance in microstrip lines, a coplanar waveguide was used. The shunt capacitor C_R , is obtained from the coupling between the signal patch. Reconfigurability functionality was realized with the help of switches (microstrip lines) incorporated into the antenna. The narrow to wideband configuration is realized by selecting various combinations of those switches. A measured radiation efficiency of more than 70% and gain greater than 1dB was obtained for the narrowband configuration. On the other hand, a measured radiation efficiency of more than 80% and gain greater than 1dB was obtained for the wideband configuration. Computer Simulation Technology (CST) microwave studio was employed as the simulation tool and measurement of the result were obtained via Vector network analyser (VNA).

ABSTRAK

Paradigma baru telah untuk mempamerkan sifat-sifat elektromagnet balikan. Komposit novel dan bahan bahan mikro-struktur tela dirancang untuk mengawal sinaran elektromagnet. Bahan bahan tersebut telah dipanggil sebagai metabahan tangan kiri (LHM) dengan ketelusan negatif atau positif serentak, keboleh telapan dan indeks pembiasain atau positif dan negatif campuran. Paradigma teraka bentuk ini telah digunakan untuk melaksanakan ialah antena metabahan frekuensi boleh konfigurasi semula yang dicadangkan ialah antena metabahan sesatah pandu gelombang (CPW) menggunakan garis transmisi negatif epsilon. Frekuensi gema dikonfigurasi semula dari sempit ke jalur lebar. Pantulan pekali, lebar jalur dan arus permukaan antena yang dirangcang telah diteliti dan diabalisis. Konfigurasi antena terdiri daripada isyarat tampal, satah bumi sesatah dan garis mikrojalur (suis) untuk membezakan atau memilih frekuensi. Suis menghubungkan antara isyarat tampal dengan satah bumi sesatah untuk merealisasikan peningkatan dalam aruhan L_L , yang berkadar kepada panjang tampal, dimana suis ditempatkan. Oleh sebab sukur untuk merealisasikan aruhan besar dalam garis mikrojalur, pandu gelombang sesatah telah digunakan. Kapasitor pengalih C_R , diperoleh daripada pengganding di antara isyarat tampal. Fungsi kebolehkongfigurasi telah direalisasi dengan bantuan suis-suis (garis mikrojalur), digabungkan ke dalam antena. Pengkonfigurasian sempit ke jalur lebar direalisasi dengan memilih pelbagai kombinasi suis-suis tersebut. Kecekapan pengukuran sinaram melenihi 70% dan gandaan melebihi 1dB telah diperoleh untuk konfigurasi jalur sempit. Pada masa yang sama, kecekapan pengukuran sinaran melebihi 80% dan gandaan melebihi 1dB telah diperoleh untuk konfigurasi jalur lebar. Gelombang mikro teknologi simulasi computer (CST) telah digunakan sebagai peralatan simulasi dan dapatan pengukuran telah diperoleh melalui penganalisis jaringan vector (VNA).

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	x
	LIST OF FIGURES	xi
	LIST OF ABBREVIATIONS	xiv
	LIST OF SYMBOLS	xv
1	INTRODUCTION	1
	1.1 Background of study	1
	1.2 Problem statement	1
	1.3 Research Objectives	2
	1.4 Scope of Works	3
	1.5 Project Report Outline	3
2	LITERATURE REVIEW	5
	2.1 Introduction	5
	2.2 Engineering negative ϵ and negative μ	6
	2.3 Non-resonant Approach to Metamaterial Antenna Designs	9
	2.4 Analysis of CRLH-TL	9
	2.5 Reconfigurations in metamaterials	11
	2.6 Previous work on other metamaterial antenna	12
	2.6.1 Metamaterial-based frequency reconfig- urable antenna	12

2.6.2	A Compact Frequency-Reconfigurable Metamaterial Inspired Antenna	14
2.6.3	Frequency Switchable Metamaterial Inspired Antenna for Software Defined Radio (SDR) Applications	16
2.6.4	A novel via less resonant type antenna based on composite right/left handed transmission line (CRLH-TL) unit cell with defected ground structure	19
2.6.5	Design of a compact ultra wideband metamaterial antenna based on modified Split-ring resonator and capacitively loaded strips unit cell	20
2.7	Summary	26
3	METHODOLOGY	27
3.1	Introduction	27
3.2	Design procedure	27
3.3	Design specification	29
3.4	Antenna Structure and Simulations	29
3.5	Parametric study of the Structure	30
3.5.1	Varying switch position Narrowband operation.	30
3.5.2	Varying switch position Wideband operation	32
3.5.2.1	Varying unit cell position Narrowband operation	34
3.5.3	Varying unit cell position Wideband operation.	37
3.5.4	Summary	39
3.6	Fabrication Process	40
3.7	Measurements	44
3.8	Summary	46
4	RESULTS AND DISCUSSIONS	47
4.1	Introduction	47
4.2	Narrowband Configuration	48
4.2.1	Narrowband Operations	48

4.2.2	Simulated and measured Reflection coefficient	49
4.2.3	Farfield narrowband 1.75 GHz	50
4.2.3.1	E-plane Co-polarization	50
4.2.3.2	H-plane Co-polarization	51
4.2.3.3	E-plane Cross-polarization	52
4.2.3.4	H-plane Cross-polarization	53
4.2.3.5	Narrowband configurations gain and efficiency	54
4.2.4	Surface current of Narrowband configurations at 1.75GHz	55
4.3	Wideband Configuration	56
4.3.1	Wideband Operations	56
4.3.2	Reflection coefficient	57
4.3.3	Farfield wideband 1.75 GHz	58
4.3.3.1	E-plane Co-polarization	58
4.3.3.2	H-plane Co-polarization	59
4.3.3.3	E-plane Cross-polarization	60
4.3.3.4	H-plane Cross-polarization	61
4.3.4	Wideband configurations gain and efficiency	62
4.3.5	Surface current of wideband configurations at 1.75GHz	63
4.3.6	Farfield wideband 3.5 GHz	64
4.3.6.1	E-plane Co-polarization	64
4.3.6.2	H-plane Co-polarization	65
4.3.6.3	E-plane Cross-polarization	66
4.3.6.4	H-plane Cross-polarization	67
4.3.7	Surface current of wideband configurations at 3.5GHz	68
4.4	Summary	68

5	CONCLUSION AND FUTURE WORK RECOMMENDATION	69
5.1	Conclusion	69
5.2	Future Work	70

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	list of other related works on metamaterials	24
2.2	continuation list of other related works on metamaterials	25
2.3	continuation list of other related works on metamaterials	26
3.1	Design Specifications for narrowband and wideband configuration	29
4.1	Summary of the possible combinations	47

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	A slip ring structure etched into a circuit board plus copper wire to negative permittivity and permeability (adapted from www.laserfocusworld.com).	8
2.2	Equivalent circuit models for ideal (a) Right Handed Transmission line (RH-TL) (b) Left Handed Transmission Line (LH-TL) (c) Composite Right Left Handed Transmission Line CRLH-TL [26].	10
2.3	Designed Antenna layout and dimensions	13
2.4	Fabricated Antenna vs. Coin	13
2.5	Reflection coefficients of the designed Antenna in various configurations	14
2.6	Designed Antenna layout	15
2.7	Fabricated Antenna layout and dimensions	15
2.8	Reflection coefficients at different capacitive values.	16
2.9	Designed Antenna layout and dimensions	17
2.10	Reflection coefficient of measured vs simulated at state one	18
2.11	Reflection coefficient of measured vs simulated at state two	18
2.12	Fabricated signal patch and ground plane	19
2.13	Reflection coefficient with different dimensions of ‘a’	20
2.14	Single spiral slot antenna layout	21
2.15	Reflection coefficients of the single-slot spiral slot antenna	22
2.16	Reflection coefficients of the single-slot spiral slot antenna	22
2.17	Reflection coefficients of the dual-slot spiral slot antenna	23
3.1	Main process flow chart	28
3.2	Schematics of the Antenna	28
3.3	Equivalent circuit model for ENG-TL unit cell.	29
3.4	4 Switches moved to the left on the unit cells (Narrowband Operations)	30
3.5	Switches moved to the right on the unit cells (Narrowband Operations)	31

3.6	Reflection coefficients when switches are moved to left and right	31
3.7	Switches moved to the left on the unit cells (wideband Operation)	32
3.8	Switches moved to the right on the unit cells (wideband operation)	33
3.9	Reflection coefficients when switches are moved to left and right	33
3.10	Unit cell 1 moved down (Narrowband Operations)	34
3.11	Unit cell 1 moved up (Narrowband Operations)	35
3.12	Unit cell 2 moved down (Narrowband Operations)	35
3.13	Unit cell 2 moved up (Narrowband Operations)	36
3.14	Reflection coefficients when unit cells are moved	36
3.15	Unit cell 1 moved down (Wideband Operations)	37
3.16	Unit cell 1 moved up (Wideband Operations)	38
3.17	Unit cell 2 moved down (Wideband Operations)	38
3.18	Unit cell 2 moved up (Wideband Operations)	39
3.19	Reflection coefficients when unit cells are moved	39
3.20	Laminating machine used to attach the photo resist layer to the microstrip board	40
3.21	Photopolymer dry film resist	41
3.22	Microstrip Board laminated with Photopolymer dry film resist	41
3.23	Ultra-violet (UV) expose machine	42
3.24	Dry Film Developer	42
3.25	Etching Machine	43
3.26	Substrate Cutter	43
3.27	Soldering Iron at soldering station	44
3.28	Layout of radiation pattern measurement.	45
3.29	Measurement of S_{11} from Vector Network Analyzer (VNA)	45
3.30	Anechoic chamber with absorbers	46
4.1	S-parameter Narrowband and Wideband	48
4.2	Schematics of Narrowband configuration	48
4.3	Fabricated Narrowband configuration	49
4.4	S-parameter of Narrow band configuration (measured and simulated)	49
4.5	Radiation pattern narrowband at 1.75GHz (E-co-polarization at 1.75GHz)	50
4.6	Radiation pattern narrowband at 1.75GHz (H co-polarization at 1.75GHz)	51

4.7	Radiation pattern narrowband (E-Cross-polarization at 1.75GHz)	52
4.8	Radiation pattern narrowband (H-Cross-polarization at 1.75GHz)	53
4.9	Narrowband configuration gain	54
4.10	Narrowband configuration efficiency	54
4.11	Simulated Surface current distribution (narrow band configuration 1.75GHz)	55
4.12	Schematics of narrowband configuration	56
4.13	Fabricated wideband configuration	57
4.14	S-parameter of Wide band configuration (measured and simulated)	58
4.15	Radiation pattern Wideband at 1.75GHz (E-co-polarization at 1.75GHz)	58
4.16	Radiation pattern wideband at 1.75GHz (H co-polarization at 1.75GHz)	59
4.17	Radiation pattern wideband (E-Cross-polarization at 1.75GHz)	60
4.18	Radiation pattern wideband (H-Cross-polarization at 1.75GHz)	61
4.19	Wideband configuration gain	62
4.20	Wideband configuration efficiency	62
4.21	Simulated Surface current distribution (wideband configuration 1.75GHz)	63
4.22	Radiation pattern wideband at 3.5GHz (E Co-polarization at 3.50GHz)	64
4.23	Radiation pattern wideband at 3.5GHz (H co-polarization at 3.5GHz)	65
4.24	Radiation pattern wideband (E-Cross-polarization at 3.5GHz)	66
4.25	Radiation pattern wideband (H-Cross-polarization at 3.5GHz)	67
4.26	Simulated Surface current distribution (wideband configuration 3.50 GHz)	68

CHAPTER 1

INTRODUCTION

1.1 Background of study

The evolution of metamaterial is from naturally occurring electromagnetic materials. A number of procedures were established in order to extract or combine useful substance from natural occurring ones. This is done by either splitting, combining, restructuring or rearranging their particles. This ability shown or developed by man to create or manipulate a naturally existing substance to form a new structure is an extraordinary achievement in human history.

Manipulation or tempering with the structural properties of these substances yields an unusual properties which could be desirable for a certain applications.

1.2 Prolem statement

In the modern world where technology has advanced and progressed, the demand for portable multi-functional mobile communication devices is at high rise. Antenna as a front component is required to have a wideband, good radiation performances and in some cases ability to switch operating frequency. The reconfigurable characteristics of antennas are very valuable for many modern wireless communication and radar system applications, such as object detection, secure communications, multi-frequency communications, vehicle speed tests and many more. Besides, the reconfigurable antenna can also operate within multiple systems by just using a single antenna. For example, a single antenna can be used for both WLAN 2.4 GHz and 5.8 GHz by reconfiguring their dual-band operation.

The ideology of using metamaterial for antenna design seems to be profitable in bid to achieve these desires because of its advantage in size reduction. The exotic property of CRLH unit cell that allows merging of independent resonant modes on a single pass-band is exploited. Furthermore, since the zeroth order mode of the CRLH unit cell supports an infinite wavelength, then a more compact size of the antenna can be realized with smaller footprint so that it can be integrated into small and compact size wireless devices.

1.3 Research Objectives

With the recent advancement in technology as mentioned earlier, devices tend to become even more and more smaller. In addition to that, more functionalities are integrated into these devices. These additional functionalities increases the complexity of these devices and give rises to the need for such devices to operate under various frequencies. It is not practical to have a separate antenna for each function or application on a device, instead, the idea of a single compact antenna with the ability to operate in different circumstances or for various applications in such device is being examined. Metamaterial is used in order to gain the compactness required but these devices.

Therefore the objectives of this project are summarized as follows:

- To design and simulate frequency reconfigurable metamaterial antennas.

- To integrate frequency reconfigurability into the antennas with the help of ideal switches.

- Fabricate the frequency reconfigurable antennas

- To compare and characterized the performance of the simulated and fabricated antennas.

1.4 Scope of Works

This project will focus on the study of frequency reconfigurable metamaterial antenna with more emphasis on its performance properties such as impedance bandwidth, gain and directivity under different selected frequencies.

- The first part involves obtaining the metamaterial antenna design structure and study the various characteristics and performance as listed above.
- The second part involve the realization of the frequency reconfigurability and carry out similar study on its characteristics and performance.
- The final part involves fabrication and testing of the antenna to ascertain the result.

Computer simulation tool (CST-MW studio) will be used for result simulation and Vector Network Analyzer (VNA) and Anechoic Chamber for results measurements.

1.5 Project Report Outline

Chapter 1 introduces metamaterial from antenna's point of view, it further elaborated or gave overview of the project work, problem statements, objective and scope of project.

In chapter 2, the basics of metamaterials, the unusual properties of metamaterials such as negative permittivity and permeability and the left handed phenomenon have been discussed. Also previous work done on metamaterials in relation to frequency reconfigurable antennas were discussed and summarized.

Chapter 3 discusses details on methodology and the flow of the project work. Here, more details were given on the structure of the antenna. In addition, detailed fabrication and measurements process used were discussed.

Chapter 4 describes the configurations and operating principles of the antenna. It discussed more on the narrowband and wideband operations. It compared Simulated

and measured results such as S_{11} and radiation patterns of the two. It gave insight of the current distribution in the various configurations.

Chapter 5 concludes the project report and gives recommendations for future work.

References

- [1] V.G Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ ", *sov. Phys.* Vol. 10, no.4, 509-504, February, 1968.
- [2] Smith, D.R., Padilla, W.J., Vier, D.C., Nemat-Nasser, S.C., and Schultz, S.: "Composite medium with simultaneously negative permeability and permittivity", *Phys, Rev. Lett.*, 2000, 84, pp 4184-4187.
- [3] Pendry, J.B., A. J. Holden, D. J. Robbins, and W. J. Stewart. "Magnetism From Conductors and Enhanced Nonlinear Phenomena." *IEEE Trans. Microwave Theory Tech.* 47 (11) (1999): 2075-2081.
- [4] Pendry, J. B., A. J. Holden, W. J. Stewart, and I. I. Youngs. "Extremely Low-Frequency Plasmons in Metallic Mesostructures. *Phys. Rev. Lett.* 76 (25) (1996): 4773-4776.
- [5] H. Cheribi, H. Kimouche, and F. Ghanem, "Metamaterial-based frequency reconfigurable antenna," *Electronics Letters*, vol. 49, no. 5, pp. 315–316, Feb. 2013.
- [6] H. Mirzaei and G. V Eleftheriades, "A Compact Frequency-Reconfigurable Metamaterial-Inspired Antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1154–1157, 2011.
- [7] I. Lim and S. Lim "Frequency Switchable Metamaterial Inspired Antenna for Software Defined Radio (SDR) Applications,"
- [8] X. Li, Q. Y. Feng and Q. Y. Xiang "A novel via less resonant type antenna based on composite right/left handed transmission line (CRLH-TL) unit cell with defected ground structure," *Progress In Electromagnetics Research Letters*, Vol. 38, 55-64, 2013

- [9] M. A. W. Nordin, M. T. Islam and N. Misran "Design of a compact ultra wideband metamaterial antenna based on modified Split-ring resonator and capacitively loaded strips unit cell," *Progress In Electromagnetics Research Letters*, Vol. 136, 157-173,, 2013
- [10] Richard W. Ziolkowski, *Design, Fabrication, and Testing of Double Negative Metamaterials*, *IEEE Transactions on Antennas and Wireless Propagation*, Vol. 51, No. 7, 2003.
- [11] F. Yang and Y. Rahmat-Samii, "Patch antennas with switchable slots(PASS) in wireless communications: concepts, designs and applications," *IEEE Antennas Propag. Mag.*, vol. 47, no. 2, pp. 13–29, Apr.2005.
- [12] S. Kawasaki and T. Itoh, "A slot antenna with electronically tunable length," *IEEE Antennas Propag. Symp. Dig.*, vol. 1, 1991,pp. 130–3.
- [13] D. J. Roscoe, L. Shafai, A. Ittipiboon, M. Cuhaci, and R. Douville, "Tunable dipole antennas," *IEEE Antennas Propag. Symp. Dig.*, vol. 2, 1972, pp. 672–5.
- [14] Y.-X. Guo, M.Y.W. Chia, and Z. N. Chen, "Miniature built-in multiband antennas for mobile handsets," *IEEE Antennas Propag. Mag.*, vol. 52, no. 8, pp. 1936–1944, Aug. 2004.
- [15] C. Puente-Baliarda, J. Romeu, and A. Cardama, "The Koch monopole: A small fractal antenna," *IEEE Trans. Antennas Propag.*, vol. 48, pp. 1773–1781, Nov. 2000.
- [16] A. Sanada, C. Caloz, and T. Itoh, "Zeroth order resonance in composite right/left-handed transmission line resonators," in *Proc. Asia-Pacific Microwave Conf.*, Seoul, Korea, vol. 3, pp. 1588-1592, Nov. 2003.
- [17] A. Lai, K.M.K. H. Leong, and T. Itoh, "Infinite wavelength resonant antennas with monopolar radiation pattern based on periodic structures," *IEEE Trans. Antennas Propag.*, vol. 55, no. 3, pp. 868–876, Mar. 2007.
- [18] Pendry, J.B.: "Negative refraction make a perfect lens", *Phys. Rev. Lett.*, 2000, 85, pp3966-3969.

- [19] C. Caloz and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*. Piscataway, NJ: Wiley-IEEE, 2005
- [20] H. Chen, J. Zhang, Y. Bai, Y. Luo, L. Ran, Q. Ji and J. A. Kong, "Experimental retrieval of the effective parameters of metamaterials based on the waveguide method," *Opt. Express*, Vol. 14, no 26, pp 12944-12949, Dec 2006.
- [21] D. R. Smith, D. C. Vier, N. Kroll and S. Schultz, "Direct calculation of permeability and permittivity for a Left-handed metamaterial," *App. Phys. Lett.* Vol. 77 no 14, pp 2246-2248, Oct 2000.
- [22] Lindell, I.V., and Sihvola, A.H., "Negative-definite media, a class of bi-anisotropic metamaterials", *Microwave Opt. Tech. Lett.*, 2006, 48, (3), pp 602-606.
- [23] Lindell, I.V., Tretykov, S.A., Nikoskinen, K.I., and Ilonen, S., "BW media with negative parameters, capable of supporting backward waves," *Micro Opt. Tech. Lett.*, 2001, 31 (2) pp 129-133.
- [24] D. M. Pozar and D. H. Schaubert. "Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays." New York, IEEE Press. 1995.
- [25] J. R. James and P. S. Hall, *Handbook of Microstrip Antennas* London, U.K, Peregrinus, 1989. [26] B. Wu, W. Wang, J. Pacheco, X. Chen, T. Grzegorzczak, J. A. Kong, and P. Art, "A Study of Using Metamaterials As Antenna Substrate To Enhance Gain," *Progress in Electromagnetics Research, PIER*, vol. 51, no. 2005, pp. 295-328, 2005.
- [27] D. R. Smith and N. Kroll, "Negative refractive index in left-handed materials.," *Physical review letters*, vol. 85, no. 14, pp. 2933-6, Oct. 2000.
- [28] C. Caloz, H. Okabe, T. Iwai, and T. Itoh, "Anisotropic PBG surface and its transmission line model," *URSI Digest, IEEE-AP-S USNC/URSI National Radio Science Meeting*, San Antonio, TX, vol. 224, 2002.
- [29] A. A. Oliner, "A periodic-structure negative-refractive index medium without resonant elements," in *URSI Digest, IEEE-AP-S USNC/URSI National Radio Science*

Meeting, 2002, p. 41.

[30] A. Grbic and G. V Eleftheriades, "A Backward-wave antenna based on negative refractive index LC networks," in IEEE-AP-S USNC/URSI National Radio Science Meeting., 2002, p. 224.

[31] A. K. Iyer, G. V Eleftheriades, and T. Edward, "Negative Refractive Index Metamaterials Supporting 2-D Waves," in IEEE MTT-S Digest, 2002, pp. 1067–1070.

[32] T. Kim and B. Lee, "Metamaterial-based compact zeroth-order resonant antenna," Electronics Letters, vol. 45, no. 1, 2009.

[33] C.-J. Lee, K. M. K. H. Leong, and T. Itoh, "Composite Right/Left-Handed Transmission Line Based Compact Resonant Antennas for RF Module Integration," IEEE Transactions on Antennas and Propagation, vol. 54, no. 8, pp. 2283–2291, Aug. 2006.

[34] M. S. Majedi and A. R. Attari, "A Compact and Broadband Metamaterial-Inspired Antenna," IEEE Antennas and Wireless Propagation Letters, vol. 12, pp. 345–348, 2013.

[35] C. Caloz and T. Itoh, Electromagnetic metamaterials: Transmission line theory and microwave applications. Wiley-IEEE Press, 2005.