



STUDY OF METAMATERIAL UNIT CELLS FOR
WIRELESS APPLICATION

BY

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A dissertation submitted in fulfilment of the requirement
for the degree of Master of Science (Communication
Engineering)

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MAY 2017

ABSTRACT

Metamaterials are artificial effectively-homogenous electromagnetic structures with properties those are not readily available in nature, metamaterials are generally periodic structures made up of unit cells. While the field of metamaterial is receiving much interest, not too many researches have been done to characterize the metamaterial. In this research work, characterization and synthesis of metamaterial unit cells for wireless applications are investigated. Eight metamaterial unit cells are chosen to characterize and investigate the propagation of EM waves inside the metamaterial. Eigenmode solver in Computer Simulation Technology Microwave studio (CST MWS) has been used to derive the dispersion diagram. From the analysis seven of the cells showed that they are pure left handed (PLH) while the remaining one is composite right/left handed (CRLH). Furthermore, based on the resonance frequencies four unit cell structures are found resonances occurred between 2 GHz to 5 GHz and suitable for wireless application. The unit cell which showed CRLH characteristics is further analyzed based on electric field and current distribution. Finally, an equivalent circuit has been derived based upon the field and current distributions of the CRLH unit cell structure. This analysis can be applied as a useful tool for developing metamaterial transmission line and antenna.

خلاصة البحث

Metamaterials هي عبارة عن هياكل كهرومغناطيسية متجانسة بشكل فعال وعادة تتكون هذه الهياكل من عدة خلايا وهي غير متاحة بسهولة في الطبيعة. لا يوجد الكثير من الابحاث التي تهتم بهذا المجال وتعمل على تحديد خصائص هذه الخلايا. في هذا البحث سيتم دراسة وتحليل خلايا Metamaterial للتطبيقات اللاسلكية. للتحقق من انتشار موجات EM داخل هذه الخلايا تم اختيار عينة من ثمانية خلايا. تم استخدام طريقة Eigenmode لعمل محاكاة بالحاسوب لتقنية الميكروويف (MWSCST) لقياس شكل التشتت. أظهرت النتائج إن سبعة خلايا من ثمانية أخذت جهة اليسار (PLH) في حين ان الخلية الثامنة بقت بين اليسار واليمين (CRLH). علاوة على ذلك، كان تردد الرنين لعدد أربعة خلايا ما بين 2GHz و 5GHz، ويعتبر هذا التردد مناسب للتطبيقات اللاسلكية. تم تحليل الخلية التي أظهرت خصائصها بين اليسار واليمين على اساس المجال الكهربائي وتوزيع التيار. أخيراً تم الحصول على الدائرة المكافئة على أساس توزيع التيار والمجال الكهربائي لهذه الخلية. يمكن الاستفادة من نتائج هذا البحث في تطوير الهوائي وخطوط النقل.

APPROVAL PAGE

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DECLARATION

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ACKNOWLEDGEMENTS

In the name of Allah, Most Gracious, Most Compassionate. All Praise be to Allah (S.W.T.), the Almighty for bestowing His Bounty and Mercy, Solawat and Salam to our beloved prophet (P.B.U.H).

First and foremost, all my du'a and gratitude make to Allah the Almighty for granting me the nikmah and abilities to pursue my post graduate studies. With His blessings, I am able to withstand all the obstacles and hardships throughout the journey in completing this research. With His favors, I am able to carry out and complete this dissertation.

I would like to express my sincere gratitude and respect to my supervisor Prof. Dr. Md. Rafiqul Islam for his constructive suggestions, guidelines and continuous supervision. Also, I like to give thank and respect to my co-supervisor Dr. Mimi Aminah Wan Nordin for her many invaluable suggestions, discussion and guidelines. Without her help it is really impossible for me to submit this thesis. I would like to pay my thanks to the Department of Electrical and Computer Engineering and the university, for various laboratory supports, and cooperation. Special thanks extended to all of my friends who have helped me through various suggestions and inspirations. Finally, I wish to express my love and gratitude to my beloved family members, my mother and my siblings especially for their understanding, continuous encourage and support me, and love throughout the study periods. Besides, I would like to acknowledge people in Post Graduate Lab and Electric Lab who have helped and encourage me a lot during the period of my studies. Their

encouragement and support have helped me a lot in increasing my self-esteem and all sort of challenge I encountered seemed bearable.

TABLE OF CONTENTS

Abstract	ii
Abstract in Arabic	iii
Approval Page.....	iv
Declaration.....	v
Copyright Page.....	vi
Acknowledgements.....	vii
Table of contents.....	ix
List of Tables	xi
List of Figures	xii
List of Abbreviations	xvii
CHAPTER ONE: INTRODUCTION	1
1.1 Background.....	1
1.2 Basic types of material elements	5
1.3 Problem statement	7
1.4 Research objective	7
1.5 Scope reseacrh	7
1.6 Research methodology.....	8
1.7 Dissertation outline	9
CHAPTER TWO: LITERATURE REVIEW.....	10
2.1 Introduction.....	10
2.2 Metamaterials	10
2.2.1 Left-Handed (LH) electromagnetic metamateria (mtm).....	12
2.2.2 Lh Structures.....	14
2.2.3 Left-Handed Transmission LINE.....	17
2.2.4 Composite Right/Left-Handed CRLH Trasnmission (TL).....	21
2.3 CRLH Theory	25
2.3.1 Homogeneous case	26
2.3.2 LC Network	32
2.4 Metamaterial Unit Cells Models	33
2.4.1 Pure Right-Handed (PRH).....	34
2.4.2 Pure Left-Handed (PLH)	34
2.4.3 Composite Right/Left Handed (CRLH)	35
2.5 Crlh-Tl Unit Cell	47
2.5.1 Configurations Available For Unit Cells.....	48
2.5.2 Advantages And Usages Of Crlh Unit Cells	50
2.6 Wave Propagation In Periodic Structures.....	52
2.6.1 Dispersion Diagram	54
2.6.2 The Need To Study The Dispersion Of Crlh Unit Cell	61
2.7 Equivalent Circuit Parameter	64
2.7.1 Capacitance Vs Voltage.....	64
2.7.2 Voltage Vs Electric Field	65
2.7.3 Inductor Vs Current	66
2.8 Summary.....	67

CHAPTER THREE: CHARACTERISTICS ANALYSIS OF METAMATERIAL UNIT CELLS	69
3.1 Introduction	69
3.2 Analysis Of Unit Cells.....	70
3.2.1 PLH Unit Cells	70
3.2.2 CRLH Unit Cell.....	78
3.3 Summary.....	80
CHAPTER FOUR: DISCUSSION AND CONCLUSION	82
4.1 Introduction	82
4.2 Field And Current Distributions Of The Unit Cell Structure	82
4.2.1 Excitation In The X-Direction.....	83
4.2.2 Excitation In The Y-Direction.....	85
4.3 Equivalent Circuit Model Of The Unit Cell Structure	88
4.3.1 Excitation In X And Y-Direction	88
4.3.1.1 Capacitance Derivation.....	88
4.3.1.2 Inductance Derivation.....	89
4.3.1.3 Circuit Model In X-Directions.....	89
4.3.1.4 Circuit Model In Y-Directions.....	93
4.4 Summary.....	96
CHAPTER FIVE: CONCLUSION AND SUGGESTIONS FOR FUTURE WORK.....	97
5.1 Conclusion.....	97
5.2 Future Work.....	98
REFERENCES.....	99
APPENDIX I	107
LIST OF PUBLICATIONS	109

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
2.1	The 8 Unit Cells and their Properties	45
3.1	Resonance frequencies at each mode of index, m obtained from sampling the dispersion diagram in figure 3.5	80
3.2	Resonance frequencies at each mode of index, m obtained from sampling the dispersion diagram of all the unit cell	81

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
1.1	The permittivity-permeability (ϵ - μ) diagram which shows the material classifications	4
1.2	A summary of the different metamaterial elements that have been used for metamaterial synthesis: (a) SRRs, (b) metal wire lines, (c) CSRRs, and (d) slot lines	6
2.1	Material parameter space characterized by electric permittivity (ϵ) and magnetic permeability (μ).	12
2.2	Metal thin wire (TW), producing ENG and (b): split-ring resonators (SRR), producing MNG	15
2.3	(a) Unit cell of the TW-SRR and (b): TW-SRR structure (Smith, et al., 2000)	16
2.4	(a) A conventional RH TL equivalent circuit, and (b): A purely LH TL equivalent circuit	18
2.5	(a) LH TL using interdigital caps and shorted stubs, and (b): LH TL using the 'mushroom structure'.	20
2.6	Composite Right/Left-Handed (CRLH) Transmission Line (TL) Model	22
2.7	CRLH TL Dispersion Diagram	24
2.8	1D CRLH (microstrip) metamaterial	25

2.9	2D Mushroom structure (a) Overall structure (b) Unit cell	25
2.10	Equivalent circuit model.(a) Homogeneous RH TL. (b) Homogeneous LH TL. (c) Homogeneous CRLH TL	27
2.11	Dispersion diagrams from the TLs of Figure 2.10. (a) Homogenous RH TL (C. Caloz & Itoh, 2006) (b)Homogenous LH TL(C. Caloz & Itoh, 2006) . (c) Homogenous CRLH TL (unbalanced).	29
2.12	Balanced form of figure 2.10(c). (a) Simplified equivalent circuit model. (b) Dispersion diagram showing continuous transition from LH to RH.	30
2.13	LC-based CRLH TL. (a) Unit cell. (b) LC periodic network equivalent to a homogeneous CRLH TL of length d for $p = \Delta z \rightarrow 0$ (C. Caloz & Itoh, 2006)	33
2.14	(a) PRH TL (b) Dispersion diagram	34
2.15	(a) PRH TL (b) Dispersion diagram.	35
2.16	Composite Right/Left-Handed (CRLH) Transmission Line (TL) Model of cascaded unit cells(Lee, Leong, & Itoh, 2006)	36
2.17	(a) CRL-TL Model (b) dispersion graph	36
2.18	Unit cell 1 Geometry	38
2.19	(a) Unit cell 2 Layout; (b) Equivalent circuit model extracted from the unit cell	40
2.20	(a) Unit cell 3; (b) Equivalent circuit model	41

2.21	(a) unit cell 5(Mushroom structure); (b) Perspective view	42
2.22	Unit cell 5 Layout	43
2.23	Unit cell 6 Geometry	43
2.24	Unit cell 7 design	44
2.25	Unit cell 8 Geometry	44
2.26	Composite Right/Left-Handed (CRLH) Transmission Line (TL) Model of cascaded unit cells	48
2.27	Sievenpiper unit cell	49
2.28	Equivalent circuit of Sievenpiper unit cell	50
2.29	(a): Unit cell of the mushroom structure, (b) Mushroom Structure	53
2.30	(a) one dimensional, and (b) two dimensional CRLH TL structure	56
2.31	Sample of a two dimensional dispersion diagram. Balanced unit cell is shown in solid line. Unbalanced unit cell is shown in dashed line	57
2.32	(a) Geometry of the unit cell (b) dispersion of the unit cell (Hanafi, Nordin, Islam, & Misran, 2013)	59
2.33	(a) Geometry of the unit cell (b) dispersion of the unit cell (Christophe Caloz, Lai, & Itoh, 2004)	59
2.34	Dispersion of the unit cell in figure 2.16(Lee, Leong, & Itoh, 2006)	60
2.35	(a) Geometry of the unit cell (b) dispersion of the unit cell (Rennings, Liebig, Otto, Caloz, & Wolff, 2007)	60

2.36	∇V between a and b can be calculated along any a-b path if the field is conservative	65
2.37	Current loop for the calculation of inductance	66
3.1	(a) Geometry (b) Dispersion diagram for unit cell-1	71
3.2	(a) Unit cell layout (b) Dispersion curve(a) Geometry (b) Dispersion curve for unit cell-2	72
3.3	(a) Geometry (the mushroom structure) (b) Dispersion diagram for unit cell-3	73
3.4	(a) Geometry (b) Dispersion diagram for unit cell-4	74
3.5	(a) Geometry (b) Dispersion diagram for unit cell-5	75
3.6	(a) Geometry (b) Dispersion diagram for unit cell-6	76
3.7	(a) Geometry (b) Dispersion diagram for unit cell-7	77
3.8	(a) Geometry (b) Dispersion diagram for unit cell-8.	78
4.1	(a) Electric field distribution of lower mode in x-direction, (b) Electric field distribution of upper mode in x-direction	83
4.2	(a) Surface current distribution of lower mode in x-direction (b) Surface current distribution of upper mode in x-direction	85
4.3	(a) Electric field distribution of lower mode in y-direction, (b) Electric field distribution of upper mode in y-direction	86
4.4	(a) Surface current distribution of lower mode in y-direction, (b) Surface current distribution of upper mode in y-direction	87
4.5	(a) Electric field distribution of lower mode in x-direction, (b)	90

	Surface current distribution of lower mode in xdirection, (c)	
	Equivalent circuit of lower mode in x-direction	
4.6	(a) Electric field distribution of upper mode in x-direction, (b)	92
	Surface current distribution of upper mode in xdirection, (c)	
	Equivalent circuit of upper mode in x-direction	
4.7	(a) Electric field distribution of lower mode in y-direction, (b)	94
	Surface current distribution of lower mode in ydirection, (c)	
	Equivalent circuit of lower mode in y-direction	
4.8	(a) Electric field distribution of higher mode in y-direction, (b)	95
	Surface current distribution of higher mode in direction, (c)	
	Equivalent circuit of higher mode in y-direction	

LIST OF ABBREVIATIONS

MTMs	Metamaterials
λ_g	Guided Wavelength
NRI	Negative Refractive Index
LH	Left Handed
RH	Right Handed
TL	Transmission Line
CRLH	Composite Right/Left Hand
SRRs	Split Ring-Resonators
CSRRs	Complementary SRRs
CST	Computer Simulation Technology
β	Propagation constant
Z_c	Characteristic impedance
V_p	Phase velocity
V_g	Group velocity
C_R	Right-handed capacitance
L_R	Right-handed inductance
C_L	Left-handed capacitance

L_L

Left-handed inductance

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Electromagnetism plays a major role in today's technology. However, it was recently noted that all the electromagnetic devices are using half of the possible electromagnetic medium i.e. the propagation in these media is right handed. The electric field, magnetic field and wave vector constitute a right handed coordinate system that limits the control of fundamental device properties. Another possible medium is left handed that excited many researchers and named it as metamaterial a material that has properties beyond the limits of the right handed material.

An electromagnetic metamaterial (MTM) is defined as artificial effectively-homogenous electromagnetic structures with properties that are not readily available in nature (C. Caloz & T. Itoh, 2005). In the year 1968 V. G. Veselago (a physicist from the Lebedjev Physical Institute in Moscow) published a paper (Veselago, 1968), in which he speculated about materials having double negative values of permittivity, ϵ and permeability, μ . The simultaneously negative for both the parameters results the occurrence of anti-parallel propagation for both phase velocity and the group velocity. There are several electromagnetic wave phenomena that can be withdrawn from the conditions stated in (Veselago, 1968). For the existence a negative-refractive-index (NRI) from the Snell's relation, the reversal of the Doppler Effect and the reversal of the Vavilov-Cerenkov radiation. All of the above mentioned features form new electromagnetic structures with novel characteristics.

The Veselago paper was in theory for 29 years after its publication in the year 1967, since then no one found such materials and constructed it. After 29 years elapsed, in 1996, a research group from the Imperial College London led by J. B. Pendry was able to construct a artificial structure that shows negative permittivity (Pendry, Holden, Stewart, & Youngs, 1996). Those structures proposed by Pendry were a thin-wire (TW) structure that only shows negative- ϵ / positive- μ and the splitting-ring-resonator (SRR) which exhibits the positive- ϵ / negative- μ characteristic. These structures however, were only able to show one negative parameter (either ϵ or μ) at a time, and not both simultaneously.

After the pioneering work did by Pendry, another group of researchers from the University of California, San Diego (UCSD) introduced a structure which was a combination TW and SRR structures (Smith, Padilla, Vier, Nemat-Nasser, & Schultz, 2000). They did experimental setup using their constructed metamaterial, in order to confirm the left-handed (LH) nature of the structure through the reversal of the Snell's law.

Though left-handed metamaterials can be realized by the combined structure of TW-SRR which was proposed by the group from UCSD, the nature resonance of the structure makes it difficult in practical for engineering applications (C. Caloz & T. Itoh, 2005). This is due to the resonating structures that display high loss and as well narrow bandwidths. This was the main motivation behind the introduction of the transmission line (TL) approach towards realizing the LH metamaterial. This effort was initiated by Eleftheriades et.al (Eleftheriades, Iyer, & Kremer, 2002) , Caloz and Itoh (C. Caloz, Sanada, & Itoh, 2004) and Oliner (Oliner, 2002). The TL approach has got a high superiority to that of the TW-SRR structures in the case of they do not

suffer from some of the limitations of the previously discussed TW-SRR structures, like high loss and narrow bandwidths. In 2003, Caloz introduced the concept of the composite right/left-handed (CRLH) transmission line (C. Caloz & Itoh, 2003) .

This concept generalizes the realistic model of a LH transmission line (TL). Due to the planar configuration of the CRLH TL, the model has been used to design many novel microwave devices, which include antennas. Antennas that were designed by employing the CRLH TL have been shown a novel characteristics.

As it is mentioned metamaterials are homogenous structures. An effectively homogeneous structure is a structure whose structural average cell size p is much smaller than the guided wavelength λ_g . Hence, this average cell size of the composite structure must be at least smaller than a quarter of wavelength, $p < \lambda_g/4$. The rule for homogeneity limit $p = \lambda_g/4$ is used in order to confirm that refractive phenomena will dominate over scattering/diffraction phenomena at the time the wave propagates inside the metamaterial medium. Once the condition of homogeneity is a achieved, the structure acts as a real material in the sense that electromagnetic waves are basically nearsighted to the lattice and only explore the average, or effective, macroscopic and well-defined constitutive parameters, which as well depend upon the nature of the unit cell; the structure become electromagnetically uniform along the direction of propagation. The constitutive parameters of the structure are the permittivity ϵ and the permeability μ , which are related to the refractive index n by (Yuandan, Itoh, T. ,2012)

$$n = \pm\sqrt{\epsilon_r\mu_r} , \quad (1.1)$$

Where ϵ_r and μ_r are the relative permittivity and permeability related to the free space permittivity (ϵ) and permeability (μ) by $\epsilon_0 = \frac{\epsilon}{\epsilon_r} = 8.854 * 10^{-12} F/m$ and $\mu_0 = \frac{\mu}{\mu_r} = 4\pi * 10^{-7} H/m$, respectively.

In (1.1), sign \pm for the double-valued square root function has been a priori admitted for generality. Four possible sign combinations can be drawn in the pair (ϵ , μ) and they are (+,+), (+,-), (-,+), and (-,-), as it shown in the ϵ - μ diagram of Figure 1.1 that shows the material classification (Yuandan & Itoh, 2012). The first three combinations are well known and can be found in conventional materials, the last pair [(-,-)], that has been characterized on double negative values of permittivity and permeability, corresponds to new class of left-handed (LH) materials, due to their double negative parameters, this left-handed materials are characterized by antiparallel phase and group velocities, or negative refractive index (NRI).

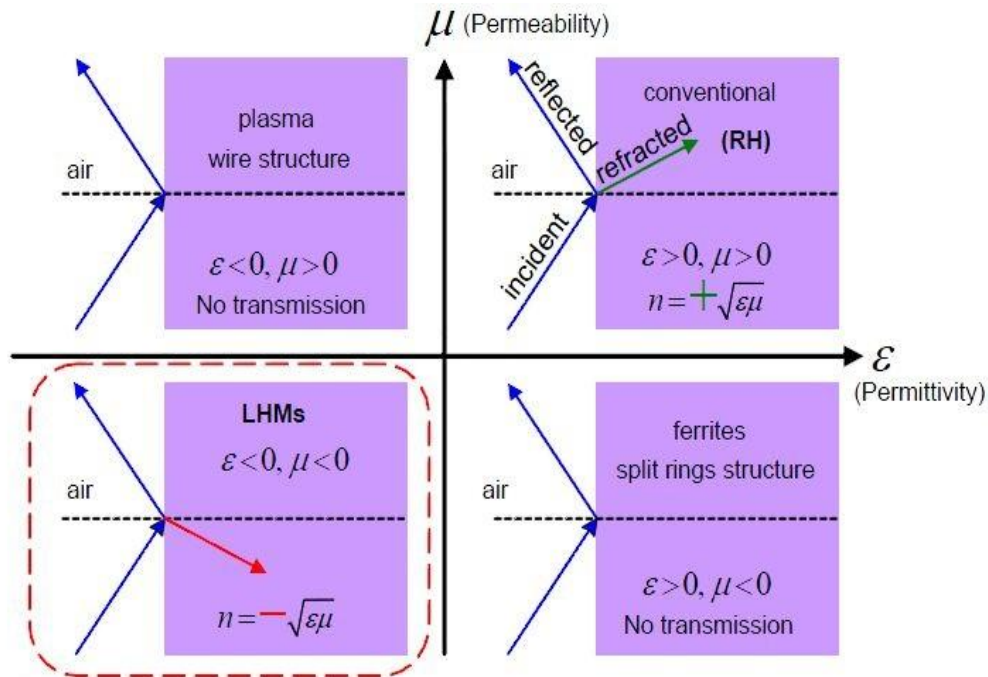


Figure 1.1: The permittivity-permeability (ϵ - μ) diagram which shows the material classifications (Yuandan & Itoh, 2012).

1.2 BASIC TYPES OF MATERIAL ELEMENTS

The original and well-known left-handed material was proposed by a research group in the University of California at San Diego (USCD) (R. A. Shelby, 2001; Sheeja, Dakhli, Sahu, & Behera, 2010). This material contains of the split-ring resonators (SRRs) and thin copper wires that provide negative values of permeability and permittivity, respectively. The SRRs act equally to the resonant magnetic dipoles that can be excited using the axial magnetic field (J. B. Pendry, A. J. Holden, D. J. Robbins, & W. J. Stewart, 1999), (Baena et al., 2005). In the year 2004, the start of a dual argument, complementary SRRs (CSRRs) were introduced by Falcone et al. considering as new metamaterial elements and it proves to show a negative permittivity (Falcone et al., 2004). It was realized that the thin copper wire can be reflected as an electric dipole. Furthermore, it has also a dual counterpart, which is the slot magnetic dipole. This slot has been used to produce transmission line (TL) metamaterials and delivers the LH capacitance instead of the consideration of a magnetic dipole. Basically, they work in the same way, and sometimes the slot is meandered in for the purpose of increasing its effective length. Figure 1.2 summarizes all the four metamaterial elements discussed above, which can be taken as two pairs of electric and magnetic dipoles (Yuandan & Itoh, 2012).

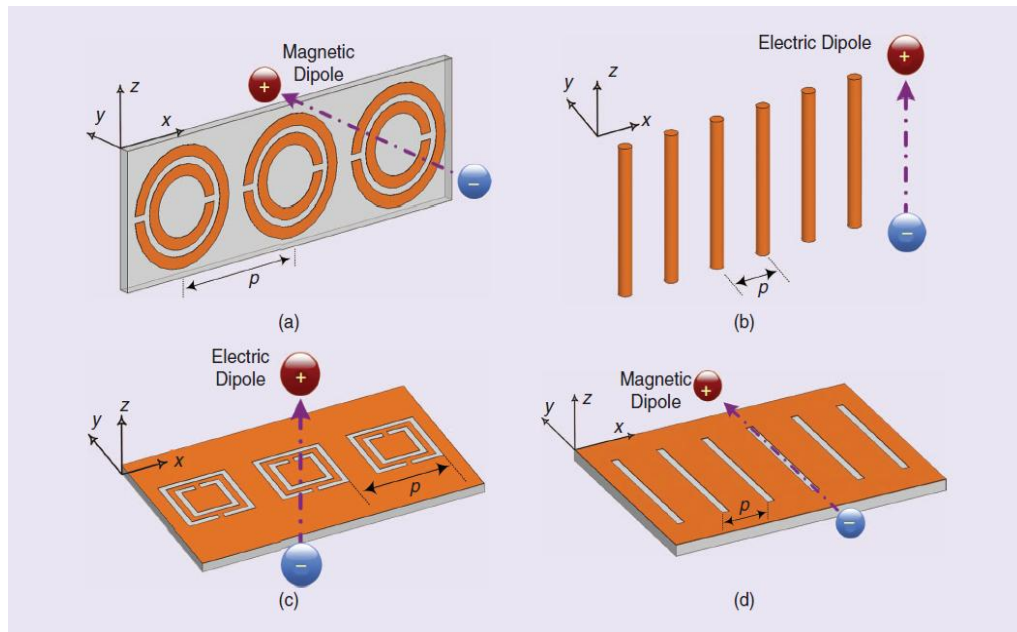


Figure 1.2: A summary of the different metamaterial elements that have been used for metamaterial synthesis: (a) SRRs, (b) metal wire lines, (c) CSRRs, and (d) slot lines (Yuandan & Itoh, 2012).

The following are different metamaterial elements that have been used for metamaterial synthesis:

- 1) SRR and Wire dipole: this is the most original combination mode that was broadly used (R. A. Shelby, 2001).
- 2) SRR and CSRR: an example using SRR and CSRR is illustrated in (Q.Zhang, 2009). This mode does not gain popularity because of the difficulty in arrangement.
- 3) Slot dipole and wire dipole: a structure known as mushroom structure was originally proposed by Sievenpiper et al. in (D. Sievenpiper, 1999) for the purpose of realizing an high-impedance surfaces. There are many papers that have been examined this structure using the CRLH TL theory (Lai, Leong, & Itoh, 2007), (M. A. Antoniades & Eleftheriades, 2008). the coupling slots can be generalized as slot dipoles that provides the negative μ , while the vias can be regarded as wire dipoles which displays a negative ϵ .