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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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 metamaerial 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 هى عبارة عن هياكل كهرومغناطيسية متجانسة بشكل فعال وعادة تتكون هذه الهياكل من عدة خلايا وهى غير متاحة بسهولة في الطبيعة. لايوجد 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 محاكاه 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 مابين 2GHz و 5GHz ، ويعتبر هذا التردد مناسب للتطبيقات اللاسلكية. تم تحليل الخلية التي أظهرت خصائصها بين اليسار واليمين على اساس المجال الكهربي وتوزيع التيار. أخيراً تم الحصول على الدائرة المكافئة على أساس توزيع التيار والمجال الكهربي لهذه الخلية. يمكن الاستفادة من نتائج هذا البحث في تطوير الهوائي وخطوط النقل.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of science (Communication Engineering)

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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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).

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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 split-ring-resonator (SRR) which exhibits the positive- ε / negative- μ characteristic. These structures however, were only able to show one negative parameter (either ε o rμ) 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 < λ_g/4. The rule for homogeneity limit p = λ_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)

$$n = \pm\sqrt{\mathrm{\varepsilon_r \mu_r}}\ , \qquad (1.1)$$

Where ε_r and μ_r are the relative permittivity and permeability related to the free space permittivity ($\in$) and permeability (μ) by $\varepsilon_0 = \frac{\in}{\in_r} = 8.854 * 10^{-12}\ F/m$ and $\mu_0 = \frac{\mu}{\mu_r} = 4\pi * 10^{-7}\ H/m$, respectively.

In (1.1), sign ± 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).

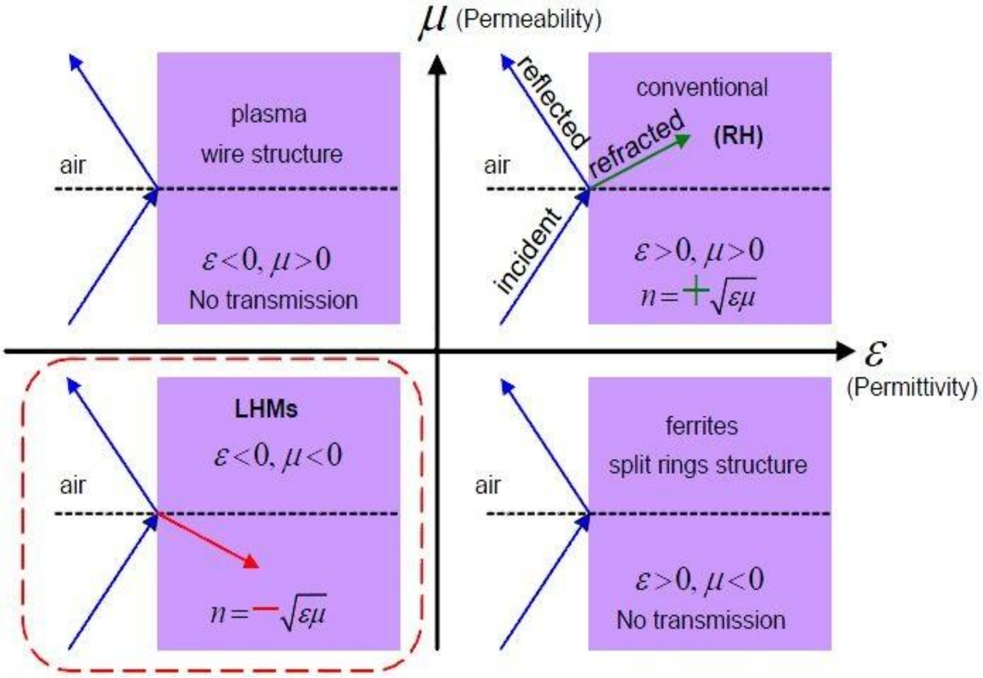

Figure 1.1: The permittivity-permeability (ε-μ) diagram which shows the material classifications (Yuandan & Itoh, 2012).

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).

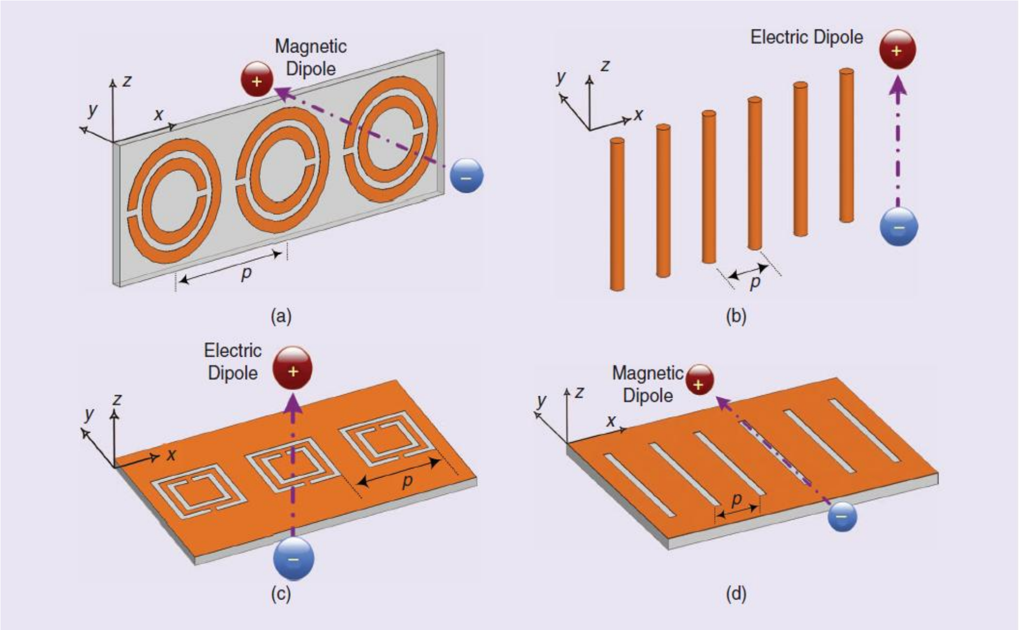

Figure 1.2: A summary of the different metamaterial elements that have been used for metamaterial synthesis: (a) SRRs, , (b) metal wire lines, , (c) CSRRs, and (d) slot lines (Yuandan & Itoh, 2012).

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.