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METAMATERIAL – BASED SENSOR FOR DETECTION OF BIOMOLECULES

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By

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METAMATERIAL - BASED SENSOR FOR DETECTION OF BIOMOLECULES

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July 2017

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Recently, the interest of microwave signals for biological detection applications using metamaterial structure as a biosensor element is tremendously increased due to high *Q* factor value and stronger electric field compared to the conventional microwave sensor. This research refers to a proof-of-concept study concerning the development of a metamaterial based sensor for biomolecule detection.

The first part of this thesis is focusing on the design and characterisation of two novel planar μ-negative metamaterial structure, called Aligned Gap Split Ring Resonator (AGSRR) and Centered-Gap Split Ring Resonator (CGSRR). AGSRR is a multi-ring split ring resonator that differs from conventional split ring resonator (SRR) where the split gaps of all rings are aligned towards the same directions to obtain stronger localization of electric field at particular spots. Furthermore, Centered-Gap SRR (CGSRR) is proposed as a second design, where it combines multiple SRRs in a compact design, thus being able to miniaturize the whole structure by 64% from AGSRR structure. An investigation of the electric field distribution is conducted for AGSRR and CGSRR at resonance frequency to identify the suitable location for sensing application. The simulation results show both structures are able to obtain approximately around 400 *Q* factor value which lead to a better sensitivity of a sensor.

In the second parts of the thesis, the proposed metamaterial structures are exploited in the designs of novel microwave sensors using Computer Simulation Technology (CST) Microwave Studio. All dimensions of the sensors are in miliscale and the operating resonance frequency is within C band. The sensing mechanism is based on perturbing the electromagnetic field around the spots, thus initiating a shift in resonance frequency that is used as an indicator of the sensor sensitivity. Sample loading with dielectric samples at these local spots is simulated and investigated in detail. By comparing to existing research works, the electric field at the occupied sensing area is strong and localized, yet required only small size of 1 mm^2 sample to induce a measureable frequency shift.

In the final part of this thesis, both sensors are fabricated and the sensitivity is characterised by loading several sample in solid and liquid form as well as biomolecules material with different concentrations. Both sensors demonstrate a maximum of 500 MHz frequency shift for liquid and solid sample compared to existing works by Wiwatcharagoses et al., which is around 350 MHz for maximum value of dielectric sample. Furthermore, the maximum values of frequency shifts obtained for these sensors are 70 MHz for ssDNA and 150 MHz for dsDNA compared to the reported literature by Lee et al., 20 MHz for ssDNA and 60 MHz for dsDNA. It can be concluded that, the sensitivity of these biosensors are up to 10 MHz/μMolar with the detection limit of 1μMolar are conducted during this experiment.

The experiments have demonstrated that the presence of DNA can be detected at microwave frequency. Due to its simplicity of fabrication, it is expected that the proposed microwave biosensor could be a candidate for exploring cost competitive, reusable or disposable bioanalysis system.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENDERIA BERASASKAN METAMATERIAL UNTUK PENGESANAN BIOMOLEKUL

Oleh

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Dewasa kini, minat terhadap isyarat gelombang mikro untuk aplikasi pengesanan biologi menggunakan struktur metamaterial sebagai elemen penderia bio semakin mendapat perhatian kerana mempunyai nilai faktor *Q* yang tinggi dan juga medan elektrik yang kuat berbanding dengan kebiasaan penderia gelombang mikro yang sedia ada. Oleh itu, penyelidikan ini adalah berkaitan bukti kajian pembinaan penderia berasaskan metamaterial untuk pengesanan biomolekul.

Bahagian pertama tesis ini memfokuskan tentang rekabentuk dan pencirian dua novel struktur metamaterial μ-negatif yang dinamakan sebagai ‘Aligned Gap Split Ring Resonator’ (AGSRR) and ‘Centered-Gap Split Ring Resonator’ (CGSRR). AGSRR merupakan pengalun berbilang gelang terpisah dan ia berbeza dari rekabentuk konvensional di mana sela pada setiap gelang disusun secara berjajar mengikut arah yang sama, bertujuan untuk mendapatkan medan elektrik yang kuat pada lokasi yang setempat. Tambahan pula, Centered-Gap Split Ring Resonator (CGSRR) dicadangkan sebagai rekabentuk yang kedua, di mana ia menggabungkan gelung berbilang menjadi rekabentuk yang padat, bertujuan mengecilkan keseluruhan struktur sebanyak 64% berbanding struktur AGSRR. Pemerhatian terhadap taburan medan elektrik dijalankan untuk AGSRR dan CGSRR pada frekuensi terayun bertujuan untuk mengenalpasti lokasi yang sesuai pengesanan bahan. Seterusnya, keputusan simulasi menunjukkan kedua-dua struktur berjaya mendapatkan nilai faktor *Q* sebanyak 400 untuk lebih kepekaan kepada penderia.

Dalam bahagian kedua tesis ini, struktur metamaterial yang dicadangkan sebelum ini telah digunakan dalam rekabentuk novel penderia gelombang mikro. Dimensi penderia ini adalah dalam skala mili dan ayunan frekuensi pengendalian adalah dalam jalur C. Mekanisma penderiaan adalah berdasarkan gangguan terhadap medan elektromagnet di kawasan tertentu dan seterusnya mengakibatkan anjakan pada frekuensi pengayun dan ia boleh digunakan sebagai penanda aras kepekaan sesebuah penderia. Simulasi terhadap

kehadiran sampel dielektrik di kawasan yang memiliki medan elektrik yang tinggi disiasat dengan lebih terperinci. Dengan membandingkan aktiviti penyelidikan yang sedia ada, didapati, medan elektromagnet di kawasan penderia yang dicadangkan ini adalah kuat dan setempat, jesteru hanya memerlukan saiz sampel yang sedikit untuk menghasilkan keputusan anjakan frekuensi yang agak jelas dan ketara.

Di bahagian terakhir tesis ini, kedua dua penderia telah terbikin dan kepekaan penderia dicirikan menggunakan beberapa sampel samada dalam bentuk pepejal mahupun cecair dan bahan biomolekul dengan kepekatan yang berbeza-beza. Kedua-dua penderia menunjukkan nilai maksimum anjakan frekuensi sebanyak 500 MHz untuk sampel pepejal dan cecair berbanding hanya sekitar 350 Mhz untuk kerja penyelidikan oleh Wiwatcharagoses et al, terhadap sampel yang memiliki nilai dielektrik yang tertinggi. Didapati untuk ujikaji penderiaan biomolekul, anjakan frekuensi yang maksima diperolehi sebanyak 70 MHz untuk ssDNA dan 150 MHz untuk dsDNA, dimana nilai tersebut agak tinggi berbanding dengan nilai yang telah dilaporkan oleh Lee et al, iaitu sebanyak 20 MHz untuk ssDNA dan 60 MHz untuk dsDNA. Dapat disimpulkan bahawa, kepekaan untuk kedua dua penderia ini adalah sehingga 10 MHz/µMolar bagi had pengesanan sebanyak 1µMolar sepanjang ujikaji ini dijalankan.

Walaupun dimensi dan saiz penderia yang dicadangkan adalah besar berbanding dengan saiz bahan biomolekul yang berskala nano, hasil ujikaji menunjukkan bahawa kehadiran DNA dapat dikenalpasti pada frekuensi gelombang mikro. Oleh kerana pembikinan penderia yang mudah, maka, adalah diharapkan penderia bio yang dicadangkan ini, mampu menjadi calon yang sesuai untuk mengasilkan penderia yang murah, boleh digunakan semula atau dibuang pakai untuk sistem analisis bio.

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I certify that a Thesis Examination Committee has met on 28 July 2017 to conduct the final examination of Izyani binti Mat Rusni on her thesis entitled "Metamaterial-Based Sensor for Detection of Biomolecules" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

aDSR	Asymmetric Double Split Ring Resonator
AFM	Atomic Force Microscope
AGSRR	Aligned Gap Split Ring Resonator
BCSRR	Broadside Split Ring Resonator
CGSRR	Centered Gap Split Ring Resonator
CST	Computer Simulation Technology
DNA	Deoxyribonucleic Acid
DNG	Double Negative
DPS	Double Positive
dsDNA	Double Stranded Deoxyribonucleic Acid
EM	Electromagnetic
ENG	Epsilon Negative
GHz	Gigahertz
LHM	Left Handed Material
LR	Labrynth Resonator
MHz	Megahertz
MNG	Miu Negative
MSRR	Multi Ring Split Ring Resonator
MTM	Metamaterial
MUT	Material Under Test
NRW	Nicolson Ross Weir
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Condition

RF	Radio Frequency
SMA	SubMiniature version A
ssDNA	Single Stranded Deoxyribonucleic Acid
SRR	Split Ring Resonator
TEM	Transverse Electromagnetic
THz	Terahertz
TOLRS	Triangular Open Loop Resonators
VNA	Vector Network Analyser

CHAPTER 1

INTRODUCTION

1.1 Research Background

In general, every material is a mixture of different sized molecules, where the permittivity of a material is determined by its molecular structure. Permittivity is an important material property to describe the characteristics of materials with respect to high frequency applications (Rabih et al., 2014). For microwave sensors, the permittivity of a material depends on the response of molecules towards electrical signals. Thus, studying the interaction of a material with applied electromagnetic fields provides valuable information of a material that has undergone physical or chemical changes. Therefore, the measurements of permittivity have gained importance in many applications such as in the biomedical field, military applications, agricultural and food industry.

Commonly, microwave biosensor can be employed in many scenarios where dielectric properties of a certain object are important. Several factors contribute towards sensing implementation such as sensitivity, selectivity, fast response time, and cost. A biosensor is defined as a compact analytical tool that integrates a biological sensing element with a transducer that converts the sensing event into a recordable signal (Solanki et al., 2011).

Figure 1.1 illustrates three major components in a biosensor that consist of an analyte, a bio-element, a detecting element, and a signal-processing element. Most biosensors are affinity-based, by using an immobilised capture probe to bind with the bio-molecule targe*t* or analyte (Jonathan S. Daniels and Pourmand, 2008). The bio-element directly interfaces to detecting element to transduce a signal which respond to the analyte variation and produce a measurable response. The common function of a biosensor is to produce either a digital or analog signal which is proportional to the amount of detected analyte. By choosing an appropriate bioreceptor and transducer, a sensitive biosensor could be developed. Therefore, a key part of the biosensor is the transducer and it is critical in determining the sensitivity of the biosensor.

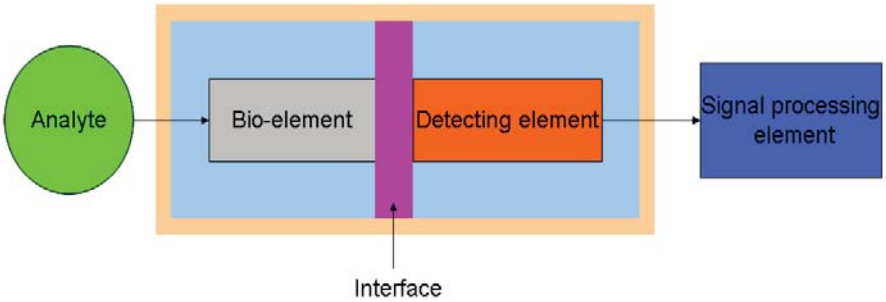

Figure 1.1: Block diagram of a Biosensor (Source:Zhou et al., 2012)

Recently, biosensors play an importance role in several aspects such as detection of disease, infectious agents, and monitoring of environmental toxins and many more (Mello and Kubota, 2002). Two categories that currently used in bio-sensing methods direct-labelling and label-free techniques (Iramnaaz et al., 2011). Direct-labeling technique involves attaching a special molecule to the bio elements such as radioactive, fluorescent, chemiluminescence and colormetric (Iramnaaz et al., 2011). The advantage of this method is it improves signal generation and ease distinguishing new targets. However, the disadvantages of this method are it involves lot of cost and additional time in preparing the sample (Jonathan S. Daniels and Pourmand, 2008). Therefore, label-free method is more tolerable and recognised due to the cost reduction and accuracy improvement. By implementing this method, the complexity in sample preparation is reduced and let to the platform of real-time measurement.

Recently, microwave biosensor based on metamaterials has been widely used for the characterization of biological matters because of their capability to provide cost efficient and label free detection. Furthermore, microwave biosensors do not need the bio samples to be optically or chemically altered, which is a huge advantage compared to optical and chemical biosensors. The detection of biological materials is because they have a distinct difference in their permittivity characteristics. In addition, most materials, either organic or inorganic will have their own specific frequency behaviour which can be related to the information about their structure and function.

To date, the use of metamaterial design has gained significant interest in the design of portable microwave biosensors due to several advantages such as label free and compact size. Metamaterial are artificial materials with structures that are smaller than the wavelength of incident electromagnetic wave. Therefore, the size of metamaterial sensors can be reduced compared to the conventional resonant structures, which is suitable for miniaturisation purposes. They are also very flexible in terms of operating frequency and geometry of the structures. Since the metamaterial structure can be modelled by an LC circuit, thus, the resonance frequency are sensitive to any value of capacitive and inductive. The capacitive effects are basically determined by the substrates parameters as well as the gap of the structure, while, the inductive effects are mainly determined by the dimension of metallic inclusions and their positions to each other. Another special behaviour of metamaterials is the ability to exhibit a strong localisation and enhancement of electric fields, which can be used to improve the sensor selectivity of detecting nonlinear substances and to enable the detection of extremely small amounts of analytes. These special properties make metamaterial a potential candidate for metamaterial sensor application.

1.2 Problem Statements

A biosensor is a device comprising an immobilised biological sensitive material (enzyme, antibody, antigen, DNA, cells, tissues) integrated within a transducer which ultimately translates a biological signal into a measurable electrical signal. An inexpensive and portable biosensor would be beneficial for on-site screening tests. However, most conventional biosensing techniques used to detect and analyse biomolecular binding, requires the usage of specific labels to enhance signal discrimination, such as fluorescent molecules (Tjong et al., 2013) , magnetic or gold particles (Csáki et al., 2001)(Park et al., 2009), or other surface treatments for antibodies attachment (Rissner et al., 2010)(Vahlberg et al., 2005). However, these specific labelling techniques induce some drawbacks such as the need for sophisticated equipment, rigorous sample preparation, off-site verification, and excessive time consumption. In response to these issues, metamaterial based biosensor is introduced for the characterisation of biological matters because of their cost efficient and label free biomolecule detection.

Another issue that needs to be considered in sensor design is the coupling technique of the electric field with the test material. Some of the existing sensor design requires bigger sample to uniformly cover the sensing area during measurement (Boybay and Ramahi, 2012a)(Faktorova et al., 2012). Efficient coupling of electric field with the material under test is therefore needed by utilising a region, which most electric field is concentrated. Thus, only a small volume of sample is required for detection purposes.

Furthermore, the biomolecular size is just a few nano-metres, the frequency deviation due to biomolecular binding is too small for detection (Lee et al., 2009)(Mason et al., 2013), thus a high sensitivity transducer needs to be designed by providing high Quality factor for better sensor selectivity and sensitivity towards material under test. In the detection area, finding a good method for molecule detection has become a hot issue. It is believed that sensitivity enhancement can be achieved by producing a strong and measurable read out signal with a sharp resonant behaviour to distinguish various types of material under test. In addition, none of these earlier studies have characterised the material electric permittivity, despite the fact that the exhibited resonance contains complete information on the dielectric constant of the material under test (Wiwatcharagoses, 2012) (Labidi et al., 2011)(Al-Naib et al., 2008).

Several types of microwave based sensor device (Cismaru et al., 2012)(Dragoman et al., 2011)(Iramnaaz et al., 2011)(H.-S. Lee et al., 2008) that exhibit the detection of the DNA sample have been proposed. However, the proposed designs faced complexities in the fabrication procedure with the introduction of nanomaterial such as graphene and carbon nanotube. In addition, the biomolecule sample is made to bind with the copper trace of the sensor where it needs to be immersed in a specific substance for a few hours in order to allow immobilisation and hybridisation of biomolecule to occur (Lee et al., 2009)(Lee et al., 2010) (Lee and Yook, 2008) (H.-J. Lee et al., 2012). Therefore, those activities will result in the oxidisation of metal traces and lead to the performance decrement of the sensor itself. Thus, the biomolecule sample should be dried because the resonant frequency is greatly influenced by the effect of solution.

1.3 Research Aim and Objectives

In recent activities of research, metamaterial structures have not been adequately exploited for microwave sensing applications. Therefore, the primary aim of this research is to develop a microwave planar biosensor using metamaterial as a transducer for chemical and biological detection. The aim can be broken down into three main objectives that comprised :

1. Developing two novel compact unit cells metamaterial structures that is efficiently capable in localising electric fields between the selected areas, which in turn can be used in the interrogation of small volumes of materials under test as well as providing a label free method for biomolecule detection as the sample is directly probed by the electric fields.

2. Proposing, simulating, evaluating and analysing metamaterials structure as a high sensitivity transducer in microwave planar sensor to provide an analysis of material under test with a single read out system.

3. Measuring the performance of fabricated sensors and characterised with various material under test such as liquids, solids and biomolecule sample to verify the function of the proposed sensor. An extraction technique by using the measured results of *S*-parameter; is proposed to derive the dielectric properties of material under test.

1.4 Research Scope

The scope of this research is to develop and analyse a novel unit of metamaterial structure to be used as a sensing element in microwave sensor. The use of miu negatives structures as the main elements for the development of planar microwave sensors provide sensitivity and specificity by having narrower and deeper resonance dip. The unit cell is designed to be easily fabricated on a single planar metal layer. For the unit cells that will be presented, a modified Split Ring Resonators (SRRs) were used as resonant structures coupled to the microstrip line. Microwave field region is chosen because it can provide label free operation by probing the electric field to the material under test. The principle operation is based on relative frequencies and magnitude shift of transmission coefficients. The S21 parameter is used in discriminating signal for material under test due to its resonant frequencies. The scope of this study is depicted in Figure 1.2. The scope to achieve the objectives of this study is indicated by continuous lines while the dashed lines represent the other research areas that are not discussed in this study.

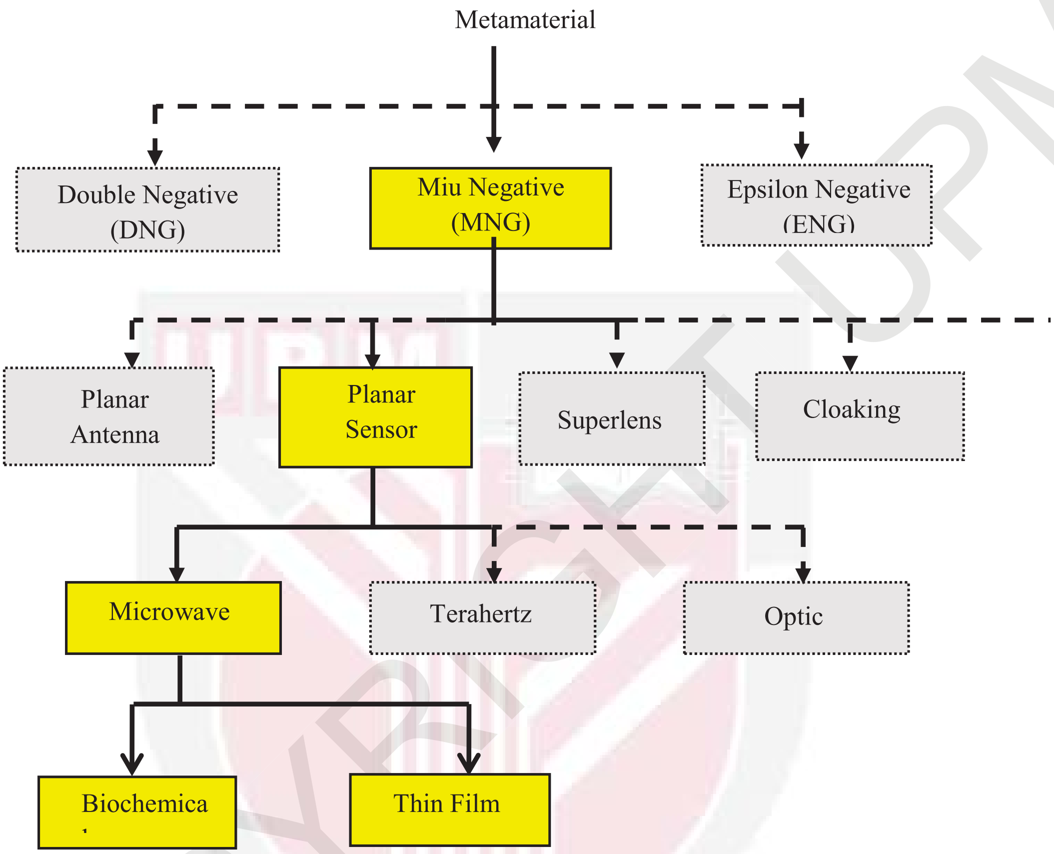

Figure 1.2: Scope of Research

1.5 Research Methodology

In general, the overall methodologies for this research comprised seven steps as shown in Figure 1.3 and briefly discussed as follows:

1. Literature Review of suitable unit cell of Metamaterial

A review of metamaterial structure type that can be operated in near field region as well as can be used as a microwave probe will be conducted.

2. Unit cell Design using full- wave EM simulator

Initially, the unit cell will be designed and analysed using full- wave EM simulator to be operated in microwave frequencies. A modified Split Ring Resonator may be considered in the design to enhance sensitivity and selectivity as well as to increase the localisation of electric field at selected area for the purpose of sample interrogation.

3. Metamaterial Sensor Fabrication

To validate the simulations that has been conducted in full- wave EM simulator, the sensor will be fabricated and the return loss, insertion loss, Q-factor and resonant frequency will be measured in comparison to the simulated ones.

4. Sample Preparation and Detection

A number of materials under test in the form of liquids and solid will be prepared in measuring the dielectric properties of the given sample. Therefore, a study will be conducted in identifying the interaction of material with electric field and in addition to that an approach to determine the permittivity of the sample will be suggested. Furthermore, a biomolecule detection through hybridisation activity of DNA will be conducted by measuring the transmission coefficient and the resonant frequency shift of the sensor using network analyser.

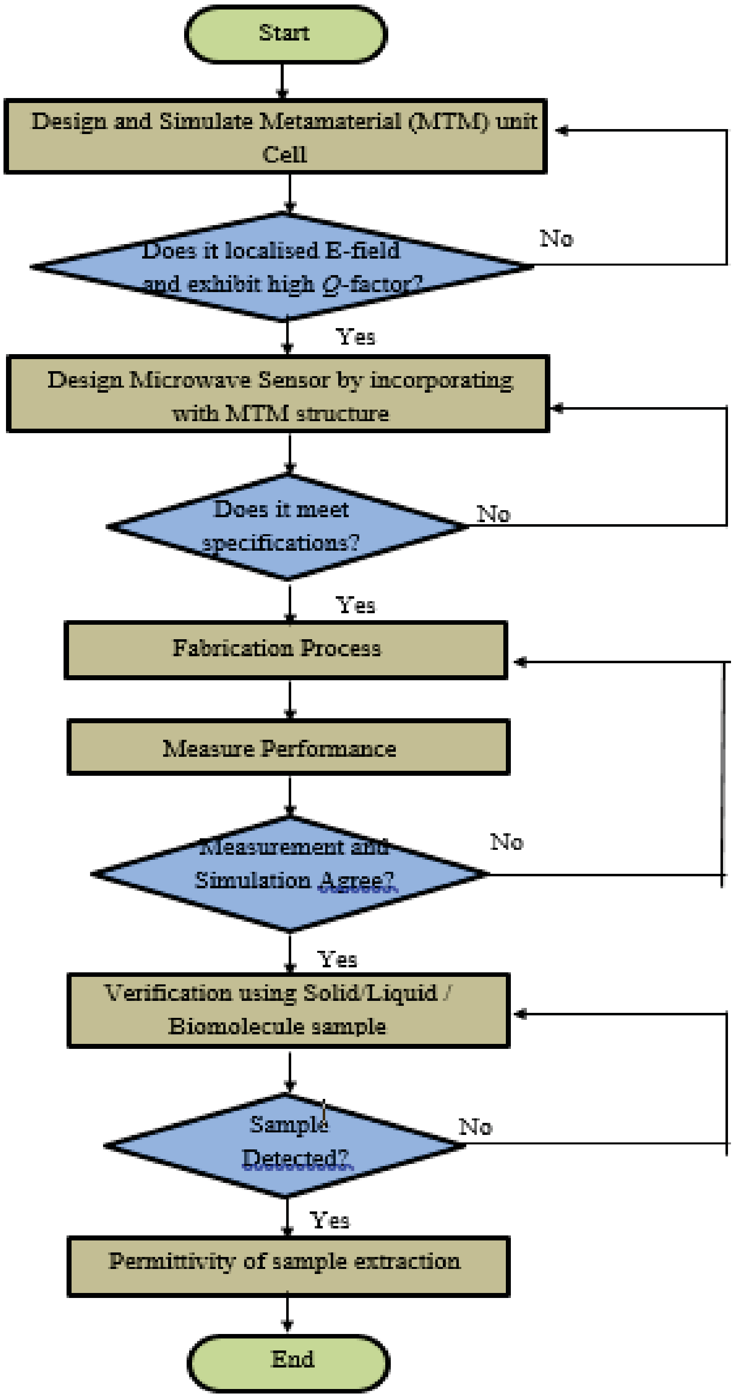

Figure 1.3: Methodology Design of Metamaterial based Sensor

1.6 Thesis Organisation

This thesis is organised into six chapters, which discussed topics as follows:

Chapter 1 introduces the research area, and identifies the current problems in designing metamaterial sensor that motivate this research. This chapter introduces the goal, objectives, methodology, scope of research as well as the organisation of the thesis writing.

Chapter 2 introduces the fundamentals of metamaterial structures. It provides a background and history of metamaterials. Furthermore, a few types of existing metamaterial structures were presented and discussed. In the same chapter, a few types of microwave sensor inspired by metamaterial structure were highlighted.

Chapter 3 presents a new design of metamaterial structures by using CST Microwave Studio 2014, which increased field confinement and thereby higher sensitivity for the sensing purposes. A calculation for parameter extraction of permeability value of both structures was presented to validate the μ-negative characteristics. Details of preliminary studies were performed to understand the dependence of proposed metamaterial structure parameters on the magnetic resonance frequency.

Chapter 4 covers the design and analysis of a metamaterial based sensor for detecting the presence of dielectric materials. The novel metamaterial unit cells that have been proposed in Chapter 3 were used in the construction of metamaterial based sensors. The design of the sensors were based on planar metamaterial inspired by modified split ring resonator. Comprehensive analyses were done throughout the chapter to validate the function of the sensor through simulation using Computer Simulation Technology (CST) Microwave studio software.

Chapter 5 presents and demonstrates two novel fabricated microwave sensors based metamaterial. The comparison between simulated and measured result of fabricated sensor is detailed out. Both sensors are characterised by examining the resonant shift and Q-factor of the sensor for different dielectric material such as solid, liquid and DNA sample. Measurement results of different materials tested by both sensors are presented and discussed in this Chapter. In addition, this chapter describe the methods used for attaching the DNA molecule to the electrode surface for immobilisation and hybridisation purposes. At the end of the chapter, results of Atomic Force Microscopy (AFM) are discussed to validate the presence of DNA sample in the sensor.

In Chapter 6, the entire thesis is summarised and concluded, followed by discussion of the major contributions of the work. Eventually, potential ideas for future work are also suggested.

The structure of this thesis is summarized as in Figure 1.4.

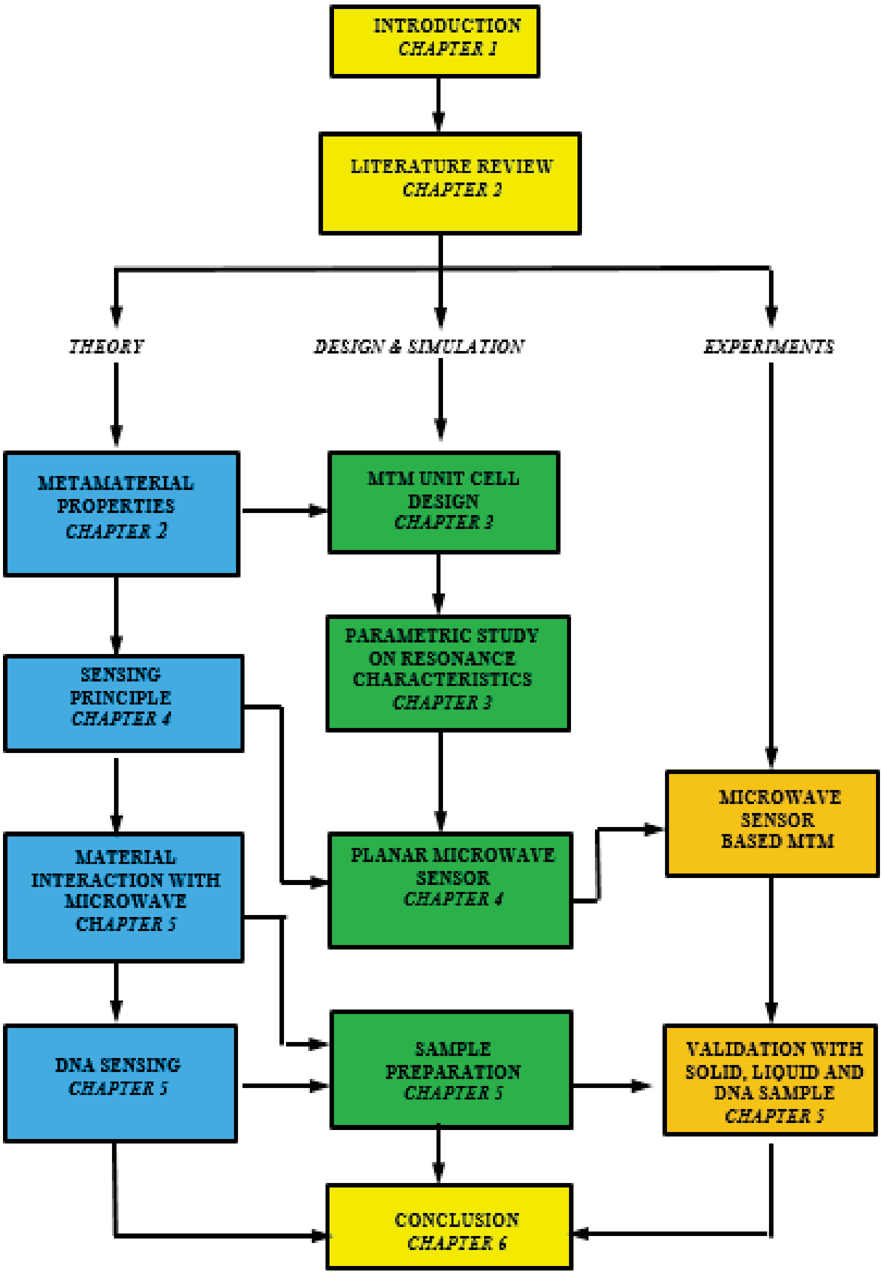

Figure 1.4: Structure of the Research and Thesis

1.7 Summary

This chapter introduced the background and motivation towards the development of metamaterial based sensor. Problem statements are discussed and the objectives of this research are formulated based on the statements. The research scope is identified as a guide for the research works. Furthermore, the methodology, which comprises the major works of this research, is thoroughly described in this Chapter. The novelty in the research works presented in this thesis is based on the designs of metamaterial unit cell that is capable to produce high Q factor and strong electric field for better sensitivity in sensing approach compared to the existing literature. Furthermore, a simple extraction techniques used to characterise several samples of material under test are proposed.

REFERENCES

Abdolrazzaghi, M., Abdolali, A., Hashemy, S., 2016. Improvements in DNA biosensors using joint split ring resonators coupled with thin film microstrip line. Appl. Comput. Electromagn. Soc. J. 31, 126–131.

Al-Naib, I. a. I., Jansen, C., Koch, M., 2009. High Q-factor metasurfaces based on miniaturized asymmetric single split resonators. Appl. Phys. Lett. 94, 153505. doi:10.1063/1.3122147

Al-Naib, I. a. I., Jansen, C., Koch, M., 2008. Thin-film sensing with planar asymmetric metamaterial resonators. Appl. Phys. Lett. 93, 83507. doi:10.1063/1.2976636

Al??, A., Engheta, N., 2008. Dielectric sensing in -near-zero narrow waveguide channels. Phys. Rev. B - Condens. Matter Mater. Phys. 78. doi:10.1103/PhysRevB.78.045102

Alici, K.B., Bilotti, F., Vegni, L., Ozbay, E., 2007. Miniaturized negative permeability materials. Appl. Phys. Lett. 91, 71121. doi:10.1063/1.2772672

Aydin, K., Bulu, I., Guven, K., Kafesaki, M., Soukoulis, C.M., Ozbay, E., 2005a. Investigation of magnetic resonances for different split-ring resonator parameters and designs. New J. Phys. 7, 168–168. doi:10.1088/1367-2630/7/1/168

Aydin, K., Bulu, I., Guven, K., Kafesaki, M., Soukoulis, C.M., Ozbay, E., 2005b. Investigation of magnetic resonances for different split-ring resonator parameters and designs. New J. Phys. 7. doi:10.1088/1367-2630/7/1/168

Aydin, K., Guven, K., Kafesaki, M., Zhang, L., Soukoulis, C.M., Ozbay, E., 2004. Experimental observation of true left-handed transmission peaks in metamaterials. Opt. Lett. 29, 2623–2625. doi:10.1364/OL.29.002623

Aznar-ballesta, F., Gil, M., Durán-sindreu, M., Bonache, J., Martin, F., 2012. Characterization of Metamaterial Transmission Lines with Coupled Resonators Through Parameter Extraction, in: Xun-Ya, J. (Ed.), Metamaterial. InTech. doi:10.5772/36542

Badaruzzaman, M., Shafit, H., 2014. Determination of salt content in raw beef burger using microwave technique. J. Trop. Agric. Fd. Sc 42, 9–17.

Baena, J.D., Bonache, J., Mart??n, F., Sillero, R.M., Falcone, F., Lopetegi, T., Laso, M.A.G., Garc??a-Garc??a, J., Gil, I., Portillo, M.F., Sorolla, M., 2005. Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines. IEEE Trans. Microw. Theory Tech. 53, 1451–1460. doi:10.1109/TMTT.2005.845211

Battocletti, J.H., 1995. Biomedical Applications of Microwave Engineering, in: Handbook of Microwave Technology. pp. 309–345.

Bilotti, F., Toscano, A., Vegni, L., 2007a. Design of Spiral and Multiple Split-Ring Resonators for the Realization of Miniaturized Metamaterial Samples. IEEE Trans.

Antennas Propag. 55, 2258–2267. doi:10.1109/TAP.2007.901950

Bilotti, F., Toscano, A., Vegni, L., Aydin, K., Alici, K.B., Ozbay, E., 2007b. Equivalent-Circuit Models for the Design of Metamaterials Based on Artificial Magnetic Inclusions. IEEE Trans. Microw. Theory Tech. 55, 2865–2873.

Boybay, M.S., Ramahi, O.M., 2012a. Material Characterization Using Complementary Split-Ring Resonators. IEEE Trans. Instrum. Meas. 61, 3039–3046.

Boybay, M.S., Ramahi, O.M., 2012b. Material characterization using complementary split-ring resonators. IEEE Trans. Instrum. Meas. 61, 3039–3046. doi:10.1109/TIM.2012.2203450

Caloz, C., Itoh, T., 2004. Transmission line approach of left-handed (LH) materials and microstrip implementation of an artificial LH transmission line. IEEE Trans. Antennas Propag. 52, 1159–1166.

Chen, H., Ran, L., Huangfu, J., Zhang, X., Chen, K., Grzegorczyk, T.M., Kong, J.A., 2004. Left-handed materials composed of only S-shaped resonators. Phys. Rev. E - Stat. Nonlinear, Soft Matter Phys. 70. doi:10.1103/PhysRevE.70.057605

Chen, L.F., Ong, C.K., Neo, C.P., Varadan, V. V., Varadan, V.K., 2004. Microwave Electronics. John Wiley & Sons, Ltd, Chichester, UK. doi:10.1002/0470020466

Chen, T., Li, S., Sun, H., Experimentation, B., 2012. Metamaterials Application in Sensing. Sensors 2742–2765. doi:10.3390/s120302742

Chou, Y., County, T., 2008. Properties and Losses. Electromagnetics 4, 139–148.

Cismaru, A., Dragoman, M., Radoi, A., Dinescu, A., Dragoman, D., 2012. The microwave sensing of DNA hybridization using carbon nanotubes decorated with gold nanoislands. J. Appl. Phys. 111, 76106. doi:10.1063/1.4704369

Csáki, a, Möller, R., Straube, W., Köhler, J.M., Fritzsche, W., 2001. DNA monolayer on gold substrates characterized by nanoparticle labeling and scanning force microscopy. Nucleic Acids Res. 29, E81.

Cuervo, A., Dans, P.D., Carrascosa, J.L., Orozco, M., Gomila, G., Fumagalli, L., 2014. Direct measurement of the dielectric polarization properties of DNA. Proc. Natl. Acad. Sci. 111, E3624–E3630. doi:10.1073/pnas.1405702111

Debus, C., Bolivar, P.H., 2007. Frequency selective surfaces for high sensitivity terahertz sensing. Appl. Phys. Lett. 91, 184102. doi:10.1063/1.2805016

Dei, D., Grazzini, G., Luzi, G., Pieraccini, M., Atzeni, C., Boncinelli, S., Camiciottoli, G., Castellani, W., Marsili, M., Lo Dico, J., 2009. Non-Contact Detection of Breathing Using a Microwave Sensor. Sensors 9, 2574–2585. doi:10.3390/s90402574

Dragoman, M., Cismaru, A., Radoi, A., Voicu, M., Dragoman, D., 2011. DNA hybridization detection in a miniaturized electromagnetic band gap resonator. Appl. Phys. Lett. 99, 253106. doi:10.1063/1.3671397

Ebrahimi, A., Withayachumnankul, W., Al-Sarawi, S., Abbott, D., 2014. High-Sensitivity Metamaterial-Inspired Sensor for Microfluidic Dielectric Characterization. IEEE Sens. J. 14, 1345–1351. doi:10.1109/JSEN.2013.2295312

Ekmekci, E., 2010. Design, Fabrication and Characterization of Novel Metamaterials in Microwave and Terahertz Regions: Multi-band, Frequency-Tunable and Miniaturized Structures.

Ekmekci, E., Turhan-Sayan, G., 2012. Multi-functional metamaterial sensor based on a broad-side coupled SRR topology with a multi-layer substrate. Appl. Phys. A 110, 189–197. doi:10.1007/s00339-012-7113-1

Ekmekci, E., Turhan-Sayan, G., 2009. Comparative investigation of resonance characteristics and electrical size of the double-sided SRR, BC-SRR and conventional SRR type metamaterials for varying. Prog. Electromagn. … 12, 35–62.

Engheta, N., Ziolkowski, R.W., 2006. Metamaterials: Physics and Engineering Explorations, Metamaterials: Physics and Engineering Explorations. John Wiley & Sons, Inc.

Faktorova, D., Savin, A., Grimberg, R., 2012. Enhancement of waveguide sensor for biological tissues dielectric properties investigation with metamaterials, in: International Conference on Telecommunications and Signal Processing. pp. 544–548.

García-García, J., Martín, F., Baena, J.D., Marqués, R., Jelinek, L., 2005. On the resonances and polarizabilities of split ring resonators. J. Appl. Phys. 98, 33103. doi:10.1063/1.2006224

Gregory, A.P., R N Clarke, 2012. Tables of Complex Permittivity of Dielectric Reference Liquids at Frequencies up to 5 GHz, AP Gregory, RN Clarke.

He, S., Jin, Y., Ruan, Z., Kuang, J., 2005. On subwavelength and open resonators involving metamaterials of negative refraction index. New J. Phys. 7. doi:10.1088/1367-2630/7/1/210

He, X., Qiu, L., Wang, Y., Geng, Z., Wang, J., Gui, T., 2011. A Compact Thin-Film Sensor Based on Nested Split-Ring-Resonator (SRR) Metamaterials for Microwave Applications. J. Infrared, Millimeter, Terahertz Waves 32, 902–913. doi:10.1007/s10762-011-9807-4

Horestani, A.K., Durán-Sindreu, M., Naqui, J., Fumeaux, C., Martín, F., 2014. S-shaped complementary split ring resonators and their application to compact differential bandpass filters with common-mode suppression. IEEE Microw. Wirel. Components Lett. 24, 149–151. doi:10.1109/LMWC.2013.2291853

Huang, M., Yang, J., 2011. Microwave sensor using metamaterials, in: Wave Propagation. pp. 13–36. doi:10.5772/14459

Huangfu, J., Ran, L., Chen, H., Zhang, X.M., Chen, K., Grzegorczyk, T.M., Kong, J.A., 2004. Experimental confirmation of negative refractive index of a metamaterial composed of ??-like metallic patterns. Appl. Phys. Lett. 84, 1537–1539. doi:10.1063/1.1655673

Iramnaaz, I., Xing, Y., Xue, K., Zhuang, Y., Fitch, R., 2011. Graphene based RF/microwave impedance sensing of DNA. 2011 IEEE 61st Electron. Components Technol. Conf. 1030–1034. doi:10.1109/ECTC.2011.5898636

Jakšić, Z., Vuković, S., Matovic, J., Tanasković, D., 2010. Negative refractive index metasurfaces for enhanced biosensing. Materials (Basel). 4, 1–36. doi:10.3390/ma4010001

Jaruwongrungsee, K., Withayachumnankul, W., Wisitsoraat, A., Abbott, D., Fumeaux, C., Tuantranont, A., 2012. Metamaterial-inspired microfluidic-based sensor for chemical discrimination. 2012 IEEE Sensors 2, 1–4. doi:10.1109/ICSENS.2012.6411237

JMPEE-Vol26-1-Pg45-Nelson.pdf, n.d.

Jonathan S. Daniels, Pourmand, N., 2008. Label-Free Impedance Biosensors:Opportunities and Challenges 19, 1239–1257.

Katsarakis, N., Konstantinidis, G., Kostopoulos, a, Penciu, R.S., Gundogdu, T.F., Kafesaki, M., Economou, E.N., Koschny, T., Soukoulis, C.M., 2005. Magnetic response of split-ring resonators in the far-infrared frequency regime. Opt. Lett. 30, 1348–1350. doi:10.1364/OL.30.001348

Katsarakis, N., Koschny, T., Kafesaki, M., Economou, E.N., Soukoulis, C.M., 2004. Electric coupling to the magnetic resonance of split ring resonators. Mater. Sci. 4. doi:10.1063/1.1695439

Kumar, N., Gupta, S., 2014. A planar microstrip metamaterial resonator using split ring dual at Ku-Band. Int. J. Phys. … 9, 26–33. doi:10.5897/IJPS2013.4088

La Spada, L., Bilotti, F., Vegni, L., 2011. Metamaterial resonator arrays for organic and inorganic compound sensing, in: Tománek, P., Senderáková, D., Páta, P. (Eds.), Proc. SPIE 8306, Photonics, Devices, and Systems V. p. 83060I. doi:10.1117/12.912267

Labidi, M., Tahar, J.B., Choubani, F., 2011. Meta-materials applications in thin- film sensing and sensing liquids properties. Opt. Express 19 Suppl 4, A733-9.

Lee, H.-J., Lee, H., Yoo, K., Yook, J., 2010. DNA sensing using split-ring resonator alone at microwave regime. J. Appl. Phys. 108, 1–6. doi:10.1063/1.3459877

Lee, H.-J., Lee, J.-H., Choi, S., Jang, I.-S., Choi, J.-S., Jung, H.-I., 2013. Asymmetric split-ring resonator-based biosensor for detection of label-free stress biomarkers. Appl. Phys. Lett. 103, 53702. doi:10.1063/1.4816440

Lee, H.-J., Lee, J.-H., Moon, H.-S., Jang, I.-S., Choi, J.-S., Yook, J.-G., Jung, H.-I., 2012. A planar split-ring resonator-based microwave biosensor for label-free detection of biomolecules. Sensors Actuators B Chem. 169, 26–31. doi:10.1016/j.snb.2012.01.044

Lee, H.-J., Yook, J.-G., 2007. Magnetic Coupling Effect of the Square Split-Ring Resonators Array using Microstrip Line. 2007 Asia-Pacific Microw. Conf. 1–4. doi:10.1109/APMC.2007.4554670

Lee, H.-S., Lee, H.-J., Choi, H.H., Yook, J.-G., Yoo, K.-H., 2008. Carbon-nanotube-resonator-based biosensors. Small 4, 1723–7. doi:10.1002/smll.200800382

Lee, H., Lee, H., Yoo, K., Yook, J., 2009. DNA Sensing Based on Single Element Planar Double Split-Ring Resonator. IEEE MTT-S Int. Microw. Symp. Dig. 1685–1688.

Lee, H., Lee, H., Yoo, K., Yook, J., 2008. On the possibility of Biosensors Based on Split Ring Resonators. 38th Eur. Microw. Conf. EuMC 1222–1225.

Lee, H., Yook, J., 2008. Biosensing using split-ring resonators at microwave regime. Appl. Phys. Lett. 254103, 2011–2014. doi:10.1063/1.2946656

Lee, H., Yoon, K.C., Lee, D.K., Jung, T.S., Lee, J., 2012. A New High-Q Resonator Using Combination of D-SR and S-SRR with μ -near Zero Metamaterial, in: Progress In Electromagnetics Research Symposium. pp. 1233–1236.

Lheurette, É., Houzet, G., Carbonell, J., Zhang, F., Vanbésien, O., Lippens, D., 2008. Omega-type balanced composite negative refractive index materials. IEEE Trans. Antennas Propag. 56, 3462–3469. doi:10.1109/TAP.2008.2005448

Li, D., Xie, Y.J., Wang, P., Yang, R., 2007. Applications of Split-Ring Resonances on Multi-Band Frequency Selective Surfaces. J. Electromagn. Waves Appl. 21, 1551–1563. doi:10.1163/156939307782000271

Liu, R., Degiron, A., Mock, J.J., Smith, D.R., 2007. Negative index material composed of electric and magnetic resonators. Appl. Phys. Lett. 90. doi:10.1063/1.2752120

Lubkowski, G., Schuhmann, R., Weiland, T., 2007. Extraction of effective metamaterial parameters by parameter fitting of dispersive models. Microw. Opt. Technol. Lett. 49, 285–288. doi:10.1002/mop.22105

M Pozar, D., 2005. Microwave Engineering, 3rd Edition, John Wiley and Sons Inc. doi:10.978.0471/448785

Marqués, R., Martin, F., Sorolla, M., 2007. Metamaterials with Negative Parameters: Theory, Design, and Microwave Applications, Metamaterials with Negative Parameters: Theory, Design, and Microwave Applications. John Wiley & Sons, Inc.

Marqués, R., Medina, F., Rafii-El-Idrissi, R., 2002. Role of bianisotropy in negative permeability and left-handed metamaterials. Phys. Rev. B 65, 1–6. doi:10.1103/PhysRevB.65.144440

Marqués, R., Mesa, F., 2003. Comparative analysis of edge-and broadside-coupled split ring resonators for metamaterial design-theory and experiments. … Propagation, IEEE … 51, 2572–2581.

Marques, R., Mesa, F., Martel, J., Medina, F., 2003. Comparative analysis of edge- and broadside- coupled split ring resonators for metamaterial design - theory and experiments. IEEE Trans. Ant. Propagat. 51, 2572–2581. doi:10.1109/TAP.2003.817562

Martín, F., 2012. Metamaterials for Wireless Communications, Radiofrequency Identification, and Sensors. ISRN Electron. 2012, 1–29. doi:10.5402/2012/780232

Mason, a., Korostynska, O., Ortoneda-Pedrola, M., Shaw, A., Al-Shamma'a, A., 2013. A resonant co-planar sensor at microwave frequencies for biomedical applications. Sensors Actuators A Phys. 202, 170–175. doi:10.1016/j.sna.2013.04.015

Melik, R., Unal, E., Perkgoz, N., 2010. Nested metamaterials for wireless strain sensing. IEEE J. Sel. Top. Quantum Electron. 16, 450–458.

Mello, L.D., Kubota, L.T., 2002. Review of the use of biosensors as analytical tools in the food and drink industries. Food Chem. 77, 237–256. doi:10.1016/S0308-8146(02)00104-8

Namba, A., Wada, O., Toyota, Y., Fukumoto, Y., Koga, R., Miyashita, T., Watanabe, T., 2001. A simple method for measuring the relative permittivity of printed circuit board materials. IEEE Trans. Electromagn. Compat. 43, 515–519. doi:10.1109/15.974630

O$rquot$Brien, S., Pendry, J.B., 2002. Magnetic activity at infrared frequencies in structured metallic photonic crystals. J. Phys. Condens. Matter 14, 6383–6394. doi:10.1088/0953-8984/14/25/307

Park, K.H., Kim, S., Yang, S.-M., Park, H.G., 2009. Detection of DNA Immobilization and Hybridization on Gold/Silver Nanostructures Using Localized Surface Plasmon Resonance. J. Nanosci. Nanotechnol. 9, 1374–1378. doi:10.1166/jnn.2009.C160

Patel, M.K., Solanki, P.R., Khandelwal, S., Agrawal, V. V, Ansari, S.G., Malhotra, B.D., 2012. Self-assembled monolayer based electrochemical nucleic acid sensor for Vibrio cholerate detection. J. Phys. Conf. Ser. 358, 12009. doi:10.1088/1742-6596/358/1/012009

Pendry, J., Holden, A., Stewart, W., Youngs, I., 1996. Extremely low frequency plasmons in metallic mesostructures. Phys. Rev. Lett. 76, 4773–4776. doi:10.1103/PhysRevLett.76.4773

Pendry, J.B., Holden, A.J., Robbins, D.J., Stewart, W.J., 1999. Magnetism from conductors and enhanced nonlinear phenomena. IEEE Trans. Microw. Theory Tech. 47, 2075–2084.

Pendry, J.B., Holden, A.J., Robbins, D.J., Stewart, W.J., 1999. Low frequency plasmons in thin-wire structures. J. Phys. Condens. Matter 10, 4785–4809.

Puentes, M., 2014. Planar Metamaterial Based Microwave Sensor Arrays for Biomedical Analysis and Treatment.

Puentes, M., Schussler, M., Jakoby, R., 2011. 2D sensor array based on Split Ring

Resonators for monitoring of organic tissue. Sensors, 2011 IEEE 3–6.

Rabih, A., Begam, K., Ibrahim, T., Burhanudin, Z.A., 2014. Dielectric Properties of Properly Slaughtered and Non-properly Slaugheterd Chicken. J. Med. Res. Dev. 3, 107–120.

Ramakrishna, S.A., 2005. Physics of negative refractive index materials. Reports Prog. Phys. 68, 449–521. doi:10.1088/0034-4885/68/2/R06

Rissner, F., Egger, D. a, Romaner, L., Heimel, G., Zojer, E., 2010. The electronic structure of mixed self-assembled monolayers. ACS Nano 4, 6735–46. doi:10.1021/nn102360d

Saha, C., Siddiqui, J.Y., 2011. A comparative analyis for split ring resonators of different geometrical shapes. 2011 IEEE Appl. Electromagn. Conf. 1–4. doi:10.1109/AEMC.2011.6256871

Sauviac, B., Simovski, C.R., Tretyakov, S. a., 2004. Double Split-Ring Resonators: Analytical Modeling and Numerical Simulations. Electromagnetics 24, 317–338. doi:10.1080/02726340490457890

Sekar, V., Torke, W.J., Palermo, S., Entesari, K., 2012. A self-sustained microwave system for dielectric-constant measurement of lossy organic liquids, in: IEEE Transactions on Microwave Theory and Techniques. pp. 1444–1455. doi:10.1109/TMTT.2012.2187066

Shelby, R.A., Smith, D.R., Schultz, S., 2001. Experimental verification of a negative index of refraction. Science 292, 77–79. doi:10.1126/science.1058847

Shreiber, D., Gupta, M., Cravey, R., 2011. Comparative study of 1-D and 2-D metamaterial lens for microwave nondestructive evaluation of dielectric materials. Sensors Actuators, A Phys. 165, 256–260. doi:10.1016/j.sna.2010.12.004

Smith, D., Schultz, S., Markoš, P., Soukoulis, C., 2002. Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients. Phys. Rev. B 1–5.

Smith, D.R., Padilla, W.J., Vier, D.C., Nemat-Nasser, S.C., Schultz, S., 2000a. Composite Medium with Simultaneously Negative Permeability and Permittivity. Phys. Rev. Lett. 84, 4184–4187.

Smith, D.R., Vier, D.C., Kroll, N., Schultz, S., 2000b. Direct calculation of permeability and permittivity for a left-handed metamaterial. Appl. Phys. Lett. 77, 2246.

Solanki, P.R., Kaushik, A., Agrawal, V. V., Malhotra, B.D., 2011. Nanostructured metal oxide-based biosensors. NPG Asia Mater. 3, 17–24. doi:10.1038/asiamat.2010.137

Taxonomy, I., Linneas, C., 2014. Using DNA Barcodes to Identify and Classify Living Things. Ann. Bot. 1–28.

Tjong, V., Tang, L., Zauscher, S., Chilkoti, A., 2013. “Smart” DNA interfaces. Chem. Soc. Rev. doi:10.1039/c3cs60331h

Torun, H., Top, F., 2014. An antenna-coupled split-ring resonator for biosensing. J. Appl. … 116, 124701. doi:10.1063/1.4896261

Trabelsi, S., Nelson, S.O., Agricultural, R.B.R., 2003. Dielectric Methods for Multiparameter Microwave Sensor. Proceeding 5th ISEMA Conf. 56–63.

V.G. Veselago, 1968. The Electrodynamics of Substances With Simultaneously Negative Values of epsilon and miu. Sov Phys Uspekhi 10, 509–514.

Vahlberg, C., Yazdi, G.R., Jr, R.M.P., Syväjärvi, M., Uvdal, K., Spetz, A.L., Yakimova, R., 2005. Surface engineering of functional materials for biosensors. IEEE Sens. J. 504–507.

Verma, A.K., Omar, A.S., n.d. Microstrip resonator sensors for determination of complex permittivity of materials in sheet , liquid and paste forms 47–54. doi:10.1049/ip-map

Withayachumnankul, W., 2012. Metamaterial based microfluidic sensor for dielectric characterization. Sensors Actuators A. Phys. doi:10.1016/j.sna.2012.10.027

Withayachumnankul, W., Jaruwongrungsee, K., 2012. Metamaterial-inspired multichannel thin-film sensor. Sensors Journal, … 1–7.

Wiwatcharagoses, N., 2012. Metamaterial-inspired miniaturized microwave sensing probes. … (ECTC), 2012 IEEE 62nd 2, 2106–2111.

Wiwatcharagoses, N., Park, K., 2011. Microwave artificially structured periodic media microfluidic sensor. … (ECTC), 2011 IEEE ….

Woodley, J., Mojahedi, M., 2010. On the signs of the imaginary parts of the effective permittivity and permeability in metamaterials. J. Opt. Soc. Am. B 27, 1016. doi:10.1364/JOSAB.27.001016

Yang, J.J., Huang, M., Tang, H., Zeng, J., Dong, L., 2013. Metamaterial Sensors. Int. J. Antennas Propag. 2013, 1–16. doi:10.1155/2013/637270

Yue, X.H., Wang, W.J., Gui, T., 2010. Thin-film sensor based tip-shaped split ring resonator metamaterial for microwave application 1735–1739. doi:10.1007/s00542-010-1080-2

Zhang, F., Potet, S., Carbonell, J., Lheurette, E., Vanb??sien, O., Zhao, X., Lippens, D., 2008. Negative-zero-positive refractive index in a prism-like omega-type metamaterial. IEEE Trans. Microw. Theory Tech. 56, 2566–2573. doi:10.1109/TMTT.2008.2005891

Zheludev, N.I., 2010. The Road Ahead for Metamaterials. Science. 328, 582. doi:10.1126/science.1186756

Zhou, Y., Chiu, C.-W., Liang, H., 2012. Interfacial structures and properties of organic materials for biosensors: an overview. Sensors (Basel). 12, 15036–62. doi:10.3390/s121115036

Zhu, C., Ma, J.J., Chen, L., Liang, C.H., 2009. Negative index metamaterials composed of triangular open-loop resonator and wire structures. Microw. Opt. Technol. Lett. 51, 2022–2025. doi:10.1002/mop.24561