UNIVERSITI PUTRA MALAYSIA

INTEGRATED X-BAND MINIATURIZED STACK BANDPASS FILTENNA WITH METAMATERIAL SUPERSTRATE

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Doctor of Philosophy

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INTEGRATED X-BAND MINIATURIZED STACK BANDPASS FILTENNA WITH METAMATERIAL SUPERSTRATE

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Miniaturization and reliability of the communication front end remains as research interests in most high frequency system. One of the most assuring devices in order to achieve miniturization is Substrate Integrated Waveguide (SIW) technology. The first part of this thesis is focusing on the design and characterisation of a three-pole Chebyshev bandpass filter as a reference filter. The filter consist of three layers with 1.575 mm thick of RT/Duroid 5880 substrates. The concept of substrate integrated waveguide is used where the sidewalls of the resonators are formed by rows of copper vias. The diameter and the separation of the vias are 0.635 mm and 0.2 respectively. Compared to the wavelength at X-band, this separation is so small that the energy leakage through the sidewalls is negligible. The compact design of SIW bandpass filter able to produce the three pole bandpass filter responses.

To realize compact and efficient communication front end, radiating element is another most important devices that need to be considered. In the second parts of the thesis, a single bowtie antenna is firstly designed using Rogers Duroid 5880 with the thickness and copper thickness of 0.787 mm and 0.035 mm respectively. It is designed to have a center frequency of 10 GHz. It consist of two side identical patches and a strip. One end of the strip is connected to the SMA connector.

Conventionally, filters and antennas are integrated into a system by using standard 50Ω ports between them such as coxial connectors or transmission lines. However, bulkiness and difficulties in fabrication and incorporation with other electronic circuits are its major drawbacks. By integrating the filter and antenna into un-separated unit, the 50 Ω transition between both structures are

removed which contributes to a more compact and efficient system. In the third parts of the thesis, the integration of the filter and antenna producing a filtenna is realized which consist of two resonators and the antenna that also acts as a resonator. The filtenna is able to produce comparable filtering performance with currently reported filter.

In the fourth parts of this thesis, a novel negative index superstrate using Double H-shape Ring (DHSR) unit cell is designed for gain enhancement of filtenna. The pre-designed DHSR unit cell structure is used to develop a periodic structure with lateral dimension equal to the lateral dimension of the filtenna with 16 mm x 20 mm, for the miniaturization purposes. An array of 11 x 9 unit cells is constructed in a single layer of metamaterial (MTM) superstrate. A layer by layer NIM superstrate were incorporated with the designed filtenna to enhance the antenna gain of the broadside without effecting the filtering response. The distance between the filtenna and the first superstrate layer and between the superstrates have been optimized to obtain the optimum filtenna response. The distance from the filtenna to the bottom copper of the first layer superstrate is g_1= 15 mm at λo/2, where the λo is the free space wavelength at the resonance frequency of the filtenna. Different superstrate layers are saparated with air gaps of g_2= 3 mm. In addition, the effect of the MTM superstrate layers on the filtenna parameters have been studied. The results show more significant anticipated improvement in gain compared to the filtenna without superstrate.

In this thesis, the approach is to design a miniaturize communication front end that utilize metamaterial structures loaded filtenna for X-band application. The miniaturization is achieved by using smaller overall lateral dimension of superstrate structures, SIW bandpass filter, patch antenna and unseparated filter/antenna. The proposed superstrates and the filtenna have an overall dimension of 0.67λo x 0.54λo x 1.19λo at 10.16 GHz with 10.6 dB total broadside gain in simulation and 9.8 dB in measurement. This miniaturize communication front end which consist of filter, antenna and gain enhancer affords smaller size with the overall volume of $0.43\lambda o^3$ in the context of using metamaterial superstrate for gain enhancement reported in the earlier literatures.

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

INTEGRASI MINIATUR PENAPIS/ANTENA BERSUSUNAN MENEGAK DENGAN METAMATERIAL SUPERSTRAT BERINDEK NEGATIVE PADA JALUR-X

Oleh

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Miniatur and berkeboleharapan penghujung sistem komunikasi tetap menjadi minat didalam bidang penyelidikan dikebanyakan sistem yang berfrekuensi tinggi. Alatan pemancar dan penapis gelombang mikro adalah antara peranti-peranti penting di kebanyakan sistem komunikasi dan radar. *Substrate Integrated Waveguide* (SIW) adalah calon yang amat sesuai digunakan dalam penghasilan sistem yang miniatur. Bahagian pertama thesis ini memberi fokus kepada penghasilan penapis yang compak dengan mengaplikasikan penggunaan SIW. Penapis yang direka ini menggunakan bahan RT/Duroid 5880 dengan ketebalan sebanyak 1.575 mm. Konsep yang digunakan didalam SIW adalah dimana bahagian tepi dinding terdiri daripada tiang-tiang logam yang ditanam didalam bahan tersebut. Dimana diameter bagi setiap tiang berukuran 0.635 mm dan dijarakkan diantara satu sama lain sebanyak 0.2 mm. Jarak ini jauh lebih kecil jika dibandingkan dengan panjang gelombang pada jalur-X dimana kehilangan kuasa gelombang yang amat sedikit boleh diabaikan. Penapis yang menggunakan SIW ini terbukti mampu menghasilkan respon frekuensi seperti yang telah dijangkakan.

Untuk terus merealisasikan penghasilan penghujung sistem komunikasi yang miniatur dan efisyen, alatan pemancar adalah peranti lain yang perlu diambil kira. Dalam bahagian kedua didalam thesis ini lebih memberi fokus kepada penghasilan alatan pemancar secara berasingan. Ianya diperbuat daripada Roger Duroid 5880 dengan ketebalalan keseluruhan 0.787 mm dan dimana ketebalan logamnya adalah 0.035 mm yang direka pada frekuensi tengah 10 GHz. Alatan pemancar ini terdiri daripada dua sayap

logam yang sama dan satu jalur logam, dimana satu sisi jalur tersebut bersambung kepada penyambung SMA.

Pada tradisinya, penapis dan alatan pemancar dipisahkan oleh jalur transmisi yang bernilai 50Ω. Walaubagaimanapun, dengan pendekatan ini akan menjadikan penghujung sistem komunikasi sesuatu sistem yang bersaiz besar dan menghadapi permasaalahan dalam integrasi dengan peranti komunikasi/elektronik yang lain. Untuk mengatasi permasalahan ini penapis dan alatan pemancar tidak diasingkan, ianya dilakukan dengan membuang jalur transmisi diantara dua peranti ini yang menjadikan ianya lebih kompak dan efisyen. Bahagian ketiga daripada thesis ini merangkumi proses integrasi penapis dengan antena yang menghasilkan modul penapis/antena yang mana direalisasikan dengan dua lapisan alatan resonan yang dan satu lapis lagi adalah antena yang juga bertindak sebagai satu lagi alatan resonan. Modul penapis/antena tersebut berkebolehan mengeluarkan respon penapis yang sama seperti respon pada penapis panduan yang dihasilkan pada awalnya.

Bahagian keempat yang penting adalah penghasilan unit sel untuk gandaan dua cincin berbentuk-H (DHSR) untuk tujuan meningkatkan gandaan kepada prestasi antena yang telah dihasilkan. Penghasilan unit sel DHSR pada permulaan adalah untuk menghasilkan satu struktur periodik yang mempunya dimensi sisi yang sama dengan dimensi sisi penapis/antena yang berukuran 16 mm x 20 mm, bagi tujuan miniatur. Satu lapis lapisan MTM supersrat tersebut menggunakan susunan unit sel DHSR sebanyak 11 x 9 unit sel.

Satu demi satu lapisan MTM superstrat ini digabungkan dengan penapis/antena yang telah reka, yang mana bertujuan untuk mendapat gandaan gelombang antena dengan tidak memberi kesan buruk kepada response penapisan. Jarak diantara penapis/antena dengan supestrat yang pertama dan jarak diantara setiap superstrat telah dioptimakan setelah respon optima untuk penapis/antenna diperolehi. Jarak dari penapis/antena ke bahagian logam pada lapisan superstrat pertama adalah g_1 =15 mm pada $\lambda_o/2$ dimana λo adalah jarak gelombang diruang kosong pada frekuensi resonan untuk penapis/antena. Jarak diantara setiap superstrat adalah g_2 = 3 mm. Kesan setiap laipan MTM superstrat terhadap penapis/antena juga dikenalpasti, keputusan memaparkan adanya peningkatan pada gandaan gelombang jika dibezakan dengan penapis/antena tanpa superstrat.

Didalam thesis ini, pendekatan kami adalah untuk mencipta modul depan komunikasi yang kecil. Pengecilan modul tersebut berjaya dihasilkan dengan menggunakan keseluruhan dimensi litral superstrat yang lebih kecil. Selain menggunakan penapis dan antena yg tidak berasingan, penggunaan penapis SIW dipilih kerana strukturnya yang kompak berbanding penapis biasa. Superstrat dan penapis/antena yang dihasilkan mempunyai dimensi 0.67λo x 0.54λo x 1.19λo pada frekuensi 10.16 GHz dimana naikkan keseluruhan adalah 10.6 dB dalam simulasi dan 9.8 dB dalam pengukuran sebenar. Pengecilan modul depan komunikasi yang terdiri daripada penapis, antena dan penganda naikkan yang mempunyai keseluruhan isipadu sebanyak 0.43λo yang lebih kecil dihasilkan berbanding penyelidikan sebelumnya.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

RF	Radio Frequency
SIW	Substrate Integrated Waveguide
PCB	Printed Circuit Board
NIM	Negative Index Metamaterial
DHSR	Double H Shape Ring
SMA	Sub-Miniature version A
ATC	Air Traffic Control
CAD	Computer Aided Design
FSS	Frequency Selective Surface
ZIM	Zero Index Metamaterial
CST	Computer Simulation Technology
HFSS	High Frequency Structure Simulator
COCO	Coaxial Collinear
MTM	Metamaterial
LTCC	Low Temperature Co-fired Ceramic
LHM	Left-Handed Metamaterial
DHM	Double Negative Metamaterial
BWM	Backward Wave Material
NRI	Negative Refractive Index
ENG	Epsilon Negative
DPS	Double Positive
MNG	Mu-Negative

EBG	Electromagnetic Band-gap
SRR	Split Ring Resonator
HPBW	Half Power Beamwidth

CHAPTER 1

INTRODUCTION

1.1 Background

In the past few years, the research for efficient and reliable communication front end devices are rapidly implemented. Radiating elements and filters are very important components in many communications and radar systems. These type of communication front end devices are also extremely needed for military applications.

In these systems, filters are used to reject out-of-band noise and interference while conveying in-band signals. Resonator filter with low insertion loss structures can enhance the efficiency of the overall system. Waveguide (Guo, Shang, Lancaster, Member, & Xu, 2015; Sun, Member, & Xu, 2016) is an excellent choice for the implementation of filters with low loss, high Q and high power handling.

Substrate Integrated Waveguide (SIW) Technology is an artificial waveguide and as another alternative that offers more compact stucture. By utilizing rows of metallic vias built into a dielectric substrate that electrically connect two parallel metal plates, the SIW is realized which is similar to waveguide structure (Deslandes , D., Wu, 2003). The embedded laminated waveguide was the first generation of SIW structure fabricated using conventional Printed Circuit Board (PCB) (H.Uchimura, 1998). Since the invention, a variety of filters with different topology have been develope based upon SIWs (R. Sen Chen, Wong, & Zhu, 2015; Jia, Feng, Member, Xiang, & Wu, 2016; P. Li, Chu, Zhao, Chen, & Member, 2017).

Radiating element is another most important devices that need to be considered in having an efficient and reliable communication front end. Antenna with low profile and small sizes are highly need for installation especially in military applications. Microstrip antenna are highly utilizes in this application, as they can operate within the close proximity of a ground plane with efficient broadband radiation. In addition, microstrip antenna have other attractive properties such as low cost, light weight and ease of fabrication (H. W. Liu, Lei, Zhan, Qin, & Li, 2014; Samsuzzaman & Islam, 2014; Valavan, Tran, Yarovoy, & Roederer, 2014). Conventionally antenna and filter are connected by using 50Ω transmission line. This type of integration renders to bulky size, detuned filter response and more losses (Zheng, Wong, Zhu, & He, 2018). By integrating the filter and antenna into un-separated unit, the 50 Ω transition between both structures are removed which contributes to a more compact and efficient system (Cheng, Yusuf, & Gong, 2011; Yusuf, Gong, & Cheng, 2013)

1.2 Statement of Problem and Motivation

Recently, with the rapid growth and high demand of the communication system, researchers are also looking forward to the miniaturization and reliability of the communication front end as conventional devices such as filters and antennas are unable to response to the extended requirement of this system.

Miniaturization of this communication front end plays an important role in recent communication technology such as in fifth generation (5G) wireless communication system and their applications in military communication system. Miniaturized communication front end of microwave devices such as filter and antenna, make them suitable for phased array applications.

The objective of phased array application is to obtain an efficient beam steering characteristic especially used in 5G wireless communication system (Kioumars Pedram & Pouyanfar, 2018). In military communication system, phased array of communication frond-end module is also used as direction finders to estimate the location of an unauthorized, suspicious source of an electromagnetic signal.

Therefore, the study on miniaturization is an on going research to produce much smaller devices than fraction of wavelength, to support the next generation of wireless communication technology in specific purposes such as military.

Filters and radiating elements are most critical components in this communication system. Resonator filter based on substrate integrated waveguide (SIW) (R. Sen Chen et al., 2015; Jia et al., 2016) are prefered because of its compact in size, lower insertion loss, which is the key factor that helps improve the system reliability and efficiency.The traditional way to incorporate filters and antennas into a system is by using standard 50Ω ports such as coaxial connectors or transmission lines. The separate design for filters and antennas individually renders bulky size of the communication front end.

In addition, several studies had initiated investigation on the possibility of enhancing the performance of the patch antennas applications by incorporating superstrates structures. Some of them place on the top of the microstrip patch antenna (Arora, Pattnaik, & Baral, 2017; Chaker & Laamari, 2015; D. Li, Szabó, Qing, Li, & Chen, 2012) resulted in significant improvement of the directivity and gain of their antennas. At higher frequency,the bigger dimension superstrates are used to enhanced the gain of the antenna which are much smaller from the superstrates (Chaker & Laamari, 2015; Jin, Li, & Hong, 2012; Sahu, Tripathi, Singh, & Singh, 2014).Unfortunately, the design method inevitably had enlarged the size of the communication front end.

1.3 Research Aim and Objectives

The main goal of this study is an endeavour to develop miniaturize communication front end in improving the gain of its radiating elements by adding Negative Index Metamaterial (NIM) superstrates for X-band applications without distorting the filtering response. The lateral dimension of the bandpass filter and metamaterial superstrates are identical in order to achieve the main objectives.

It is broken down into three main objectives comprise of:

1. To design the miniturize communication front end with gain enhancement techniques.
2. To design a novel NIM structures that efficiently capable in producing materials with negative indices, investigates its properties and explore how the NIMs can be applied to filtenna design.
3. To design a novel approach of incorporating NIMs into filtenna for gain enhancement for communication front end for miniaturization purposes.
4. To design and analyze the vertically stacked substrate integrated waveguide (SIW) bandpass filtenna accordingly to match the incorporation techniques of the proposed NIMs superstrate and investigate its effect to the overall performances such as return loss, radiation pattern and gain.

1.4 Scope of Research

The scope of this thesis is to design the compact three poles bandpass filter by utilizing substrate integrated waveguide (SIW) incorporated with bowtie antenna with removed 50 Ω transmission line between them for X-band applications. The new Negative Index Metamaterial (NIM) superstrate is introduce to the design in a way to increase the gain of the overall system. The flow of this study is illustrated in Figure 1.1. The continous-lines represent the direction followed in this thesis to achieved the objectives, while the dashed-lines are reffering to other research areas that are out of the scope of this work.

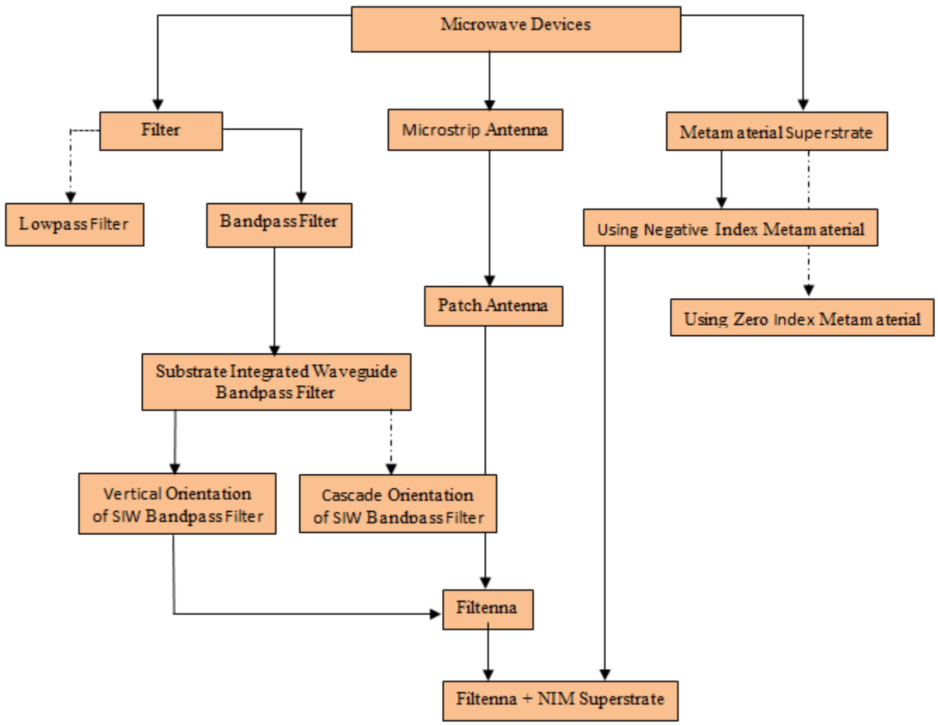

Figure 1.1: Scope of Research

1.5 Research Methodology

Firstly, to achieve the objectives of this study, extensive research on Substrate Integrated Waveguide (SIW) bandpass filtenna was carried out to understand its fundamentals and how to produce more compact design without affecting the expected results. The research on individual filter and radiating element also have been done as well as the technique to incorporate them together. Then, a 3D full-wave electromagnetic simulator (CST Microwave Studio, Version 2014) was used to simulate the structures. Next, an array of Negative Index Metamaterial (NIM) superstrate was used to enhance the gain of the overall system which located in distance on the top of filtenna. The unit cell of the metamaterial superstrate are designed for X-band applications also simulated using the same simulator. Finally, measurements have been done on each single device; bandpass filter, antenna and the three poles bandpass filtenna for with and without metamaterial superstrate to validate the design method. The developed methodology for designing three poles bandpass filtenna with metamaterial superstrate is ilustrated in flow chart shown in Figure 1.2.

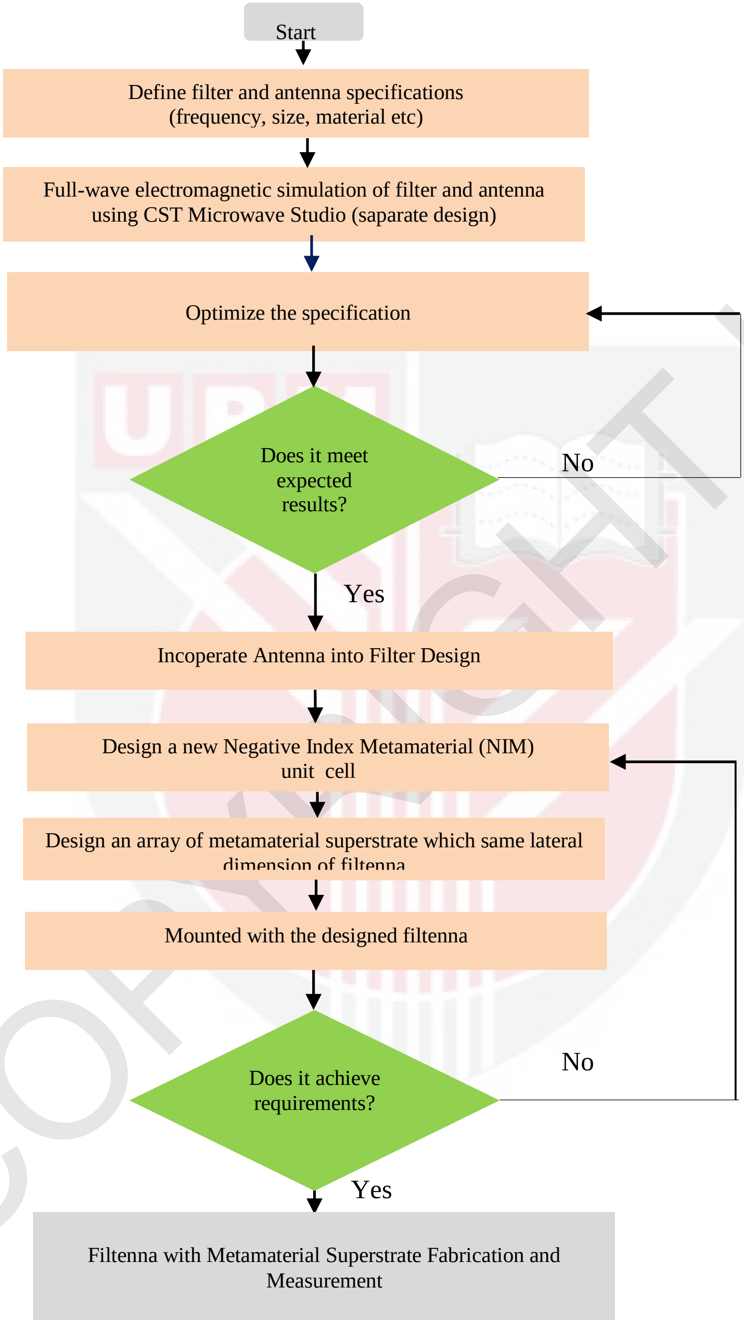

Figure 1.2: Flow chart of the overall structure design process

1.6 Organization of Thesis

This thesis basically consist of six chapters. Chapter 1 covers introduction of research study. In this chapter, the background of the research area, problem statement, research objectives, research scope and overview of research methodology have been discussed.

Chapter 2 starts with the theory of X-band and its application, followed by the theory of metamaterial as an artificial stuctures. This chapter also contains the literature review on the filtenna that currently reported can be used in communication front end. It provides the techniques in integrating filter and antenna into one module before detailing to another complex modules. This chapter also present the literature review on the application of metamaterial superstrate as a gain enhancer. Finally, a summary ends the chapter.

Chapter 3 contains the design of three poles bandpass filter as a reference filter utilizing an array of vias to realize the application of substrate integrated waveguide in the resonators. The vertically stacked Chebychev bandpass filter structures as well as their geometrical parameters also discusses. Section 3.2 focuses on the fomulations of design parameters required for microwave Chebychev bandpass filter. Section 3.3 present the method of extracting the coupling coefficients of Chebychev bandpass filter with the aid of a CAD simulator. Section 3.4 contains the actual process of extracting the quality factor and the coupling coefficients of the three-poles bandpass filter. Other sections provide the fabrication process and the result of the S-parameters. Content is reviewed at the end of the chapter.

Chapter 4 translates the experience of designing the single bowtie antenna. This section present the parametric analysis of the single bowtie antenna which discuss the parameter effect to the S-parameter of a single antenna.Then, at the end of the section, the process on how to incorporate the single bowtie antenna with the designed three poles bandpass filter is also discussed. Content is reviewed at the end of the chapter.

Chapter 5 describes the novel design of the Negative Index Metamaterial (NIM) superstrate for frequency band 8 -12 GHz. This section provides the geometrical parameters and discuss the constitutive parameters retrieved from the transmission and reflection coefficients of one unit cell to prove the negativeness of one unit cell. An array of 11 x 9 unit cells are designed on the integration of the metamaterial superstrate as a gain enhancer. The techniques of the incorporating an array of the metamaterial superstrate with the filtenna and the effect of the air gap to the overall performances were also discussed. Towards the end of the chapter, the discussion is more focuses on the overall performances and the conprehensive analyses throughout the chapter concerning theoretical and simulation validation as well as the design techniques adopted. At the end of the chapter, the comparison of the proposed method with the earlier reported work was also discussed and summarized.

In Chapter 6, the entire thesis is summarized and concluded, followed by disscussion of the major contributions of the work. Eventually, potential ideas for future work are suggested.
The summary of the thesis organisatition is shown in Figure 1.3 below;

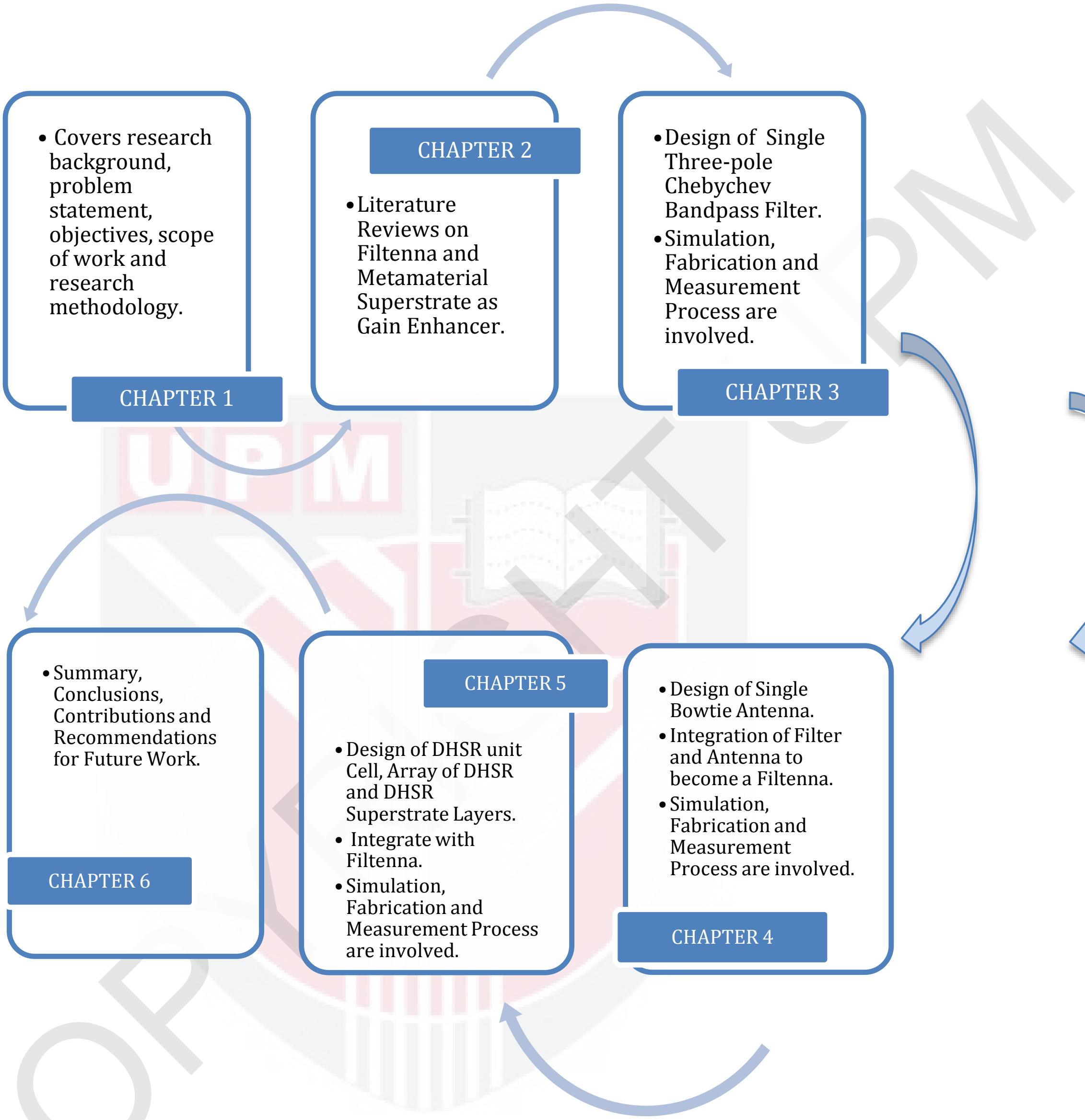

Figure 1.3: Summary of the thesis organization.

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LIST OF PUBLICATIONS

Journal Articles

A.Ramli, A.Ismail, A.R.H. Hawari and M.A. Mahdi, “The Effect of the Metamaterial Superstrate to the Vertically Stacked Bandpass Filter Antenna Performances,” *ARPN Journal and Applied Sciences,* Vol.11, No.5, pp.3147-3149, 2016.

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A.Ramli, A.Ismail, A.R.H. Hawari and M. A. Mahdi, “Metamaterial Superstrate Effects to the Stacked Bandpass Filter Antenna Performances,” *IEEE Proceedings*, *International Conference of the Radar, Antenna, Microwave, Electronics and Telecommunications Conference,* (ICRAMET 2015), pp: 32-35, 2015, 5-7th October 2015,Bandung Indonesia.

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