DESIGN OF SINGLE AND MULTILAYER INTERDIGITAL BAND PASS FILTER

MOHD FAIRUS BIN MOHD YUSOFF

A thesis submitted in fulfilment of the requirements for the award of the degree of
Master of Engineering (Electrical - Electronic and Telecommunication)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

OCTOBER 2004

DEDICATION

Specially…

To my beloved parents

To my kind brothers and sisters

And not forgeting to all friends

For their

Love, Sacrifice, Encouragements, and Best Wishes

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to my thesis supervisor, Associate Professor Dr. Mazlina Esa, for her encouragement, guidance, critics and friendship during the course of studies.

Not forgetting all my fellow postgraduate students and friends especially Ikhwan Peranggi , Abdul Shukur, Tee , Lim, Jaya Seelan, Asrul Izam and others for their moral support and helping me during th entire Masters programme. Without their continued support and interest, this thesis would not have been realized.

Last but not least, my gratitude also goes to all technicians especially Cik Rosmawati Othman for their co-operation throughout the critical period of completing this project. Thank you all.

ABSTRACT

Nowadays, there are many new telecommunication technologies developed such as *wireless LAN* and *Bluetooth* technology. Filters are essential to the operation of this technology. Interdigital filter is one of the available compact configurations. This thesis focuses on the design of two sets of interdigital band pass filter on single and multilayer structures at 2.45 GHz. Two designs have been proposed; asymmetrical and symmetrical interdigital band pass filters. They were designed using *Mathcad* mathematical software and electromagnetic simulations were done using Sonnet V9.52 simulator. The results showed that each filter operates well at the frequency of operation. Asymmetrical filters have excellent return losses of over -20 dB at the center frequency and minimized ripple from 0 to 2.79 dB. In contrast, symmetrical interdigital band pass filters have narrower bandwidth from 5.71% to 14.69% and very sharp roll off factor that can go up to 192.53 dB/GHz. Finally, the multilayer configuration showed that with the addition of dielectric substrates, the center frequency is shifted to 2 GHz and the bandwidth is broaden up to 50.6%.

ABSTRAK

Kini, pelbagai teknologi baru telah diperkenalkan dalam bidang telekomunikasi seperti *LAN* tanpa wayar dan *Teknologi Bluetooth*. Penapis merupakan satu komponen penting dalam teknologi ini. Penapis interdigital mempunyai konfigurasi struktur yang padat dan menarik. Tesis ini membincangkan dua jenis penapis interdigital dengan struktur satu dan pelbagai lapisan pada frekuensi kendalian 2.45 GHz. Dua kaedah rekabentuk dibentangkan iaitu penapis interdigital lulus jalur semetri dan tidak simetri. Rekabentuk dilakukan menggunakan perisian matematik *Mathcad*, manakala simulasi elektromagnet dijalankan menggunakan perisian *Sonnet* V9.52. Keputusan simulasi menunjukkan bahawa penapis beroperasi dengan baik pada frekuensi kendalian. Tambahan pula, penapis interdigital lulus jalur tidak semetri menunjukkan sambutan kehilangan kembali yang baik iaitu melebihi -20 dB pada frekuensi pertengahan serta mempunyai riak yang lebih kecil iaitu antara 0 hingga 2.79dB. Sementara itu, penapis interdigital lulus jalur simetri pula mempunyai lebar jalur yang lebih sempit iaitu antara 5.71% hingga 14.69% dan kecerunan yang tajam sehingga 192.53 dB/GHz. Akhir sekali, penapis pelbagai lapisan menunjukkan bahawa pertambahan lapisan dielektrik menyebabkan anjakan frekuensi pertengahan kepada 2 GHz dan pertambahan lebar jalur sehingga 50.6%.

TABLE OF CONTENTS

TITLE	i
DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
ABSTRAK	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	x
LIST OF FIGURES	xii
LIST OF SYMBOLS	xvi
LIST OF ABBREVIATIONS	xviii
LIST OF APPENDICES	xix

CHAPTER I INTRODUCTION

1.1	Introduction	1
1.2	Project Objective	1
1.3	Problem Statements	3
1.4	Research Contribution	3
1.5	Project Scope	4
1.6	Thesis Organization	7

CHAPTER II MICROWAVE FILTERS

2.1	Introduction		8
2.2	Filter Theory		8
2.3	Type of Filters		10
2.4	Scattering Parameter		13
2.5	Microstrip Transmission Lines		15
	2.5.1	Quasi – TEM Approximation	16
	2.5.2	Effective Dielectric Constant and Characteristic Impedances	17

CHAPTER III INTERDIGITAL BAND PASS FILTER

3.1	Band Pass Filter		19
3.2	Filter Synthesis		20
	3.2.1	Chebyshev Response	21
3.3	Interdigital Band Pass Filter		23
	3.3.1	Parallel Coupled Lines	25
	3.3.2	Even and Odd Mode Capacitance	27
	3.3.3	Even and Mode Characteristic Impedances and Effective Dielectric Constant	28
	3.3.4	Interdigital Band Pass Filter Design	31
3.4	Asymmetrical Interdigital Band Pass Filter		34
3.5	Symmetrical Interdigital Band Pass Filter		35
3.6	Multilayer Interdigital Band Pass Filter		36

CHAPTER IV SOFTWARE

4.1	Mathcad 2000		37
	4.1.1	Mathcad 2000 Resource Center	37
4.2	Sonnet V.9.52		39
	4.2.1	Software Tools	40

CHAPTER V RESULT AND DISCUSSION

5.1 Asymmetrical Interdigital Band Pass filter Designed Using Mathcad 43
5.1.1 Results For Asymmetrical Interdigital Band Pass Filter With Third Order (SAI-3) 44
5.1.2 Results For Asymmetrical Interdigital Band Pass Filter With Fifth Order (SAI-5) 45
5.1.3 Results For asymmetrical Interdigital Band Pass Filter With Seven Order (SAI-7) 46
5.2 Symmetrical Interdigital Band Pass Filter Designed Using Mathcad 47
5.2.1 Result for Symmetrical Interdigital Band Pass Filter with Third Order (SSI-3) 48
5.2.2 Result for Symmetrical Interdigital Band Pass Filter with Fifth Order (SSI-5) 49
5.2.3 Result for Symmetrical Interdigital Band Pass Filter with Seven Order (SSI-7) 50
5.3 Simulation Results of Asymmetrical Interdigital Band Pass Filters 51
5.4 Discussion of SAI Filters 59
5.5 Simulation Results of Symmetrical Interdigital Band Pass Filters 60
5.6 Discussion of SAI and SSI Filters 68
5.7 Multilayer Simulation Result 69
5.8 Discussion of MAI and MSI Filters 88

CHAPTER VI CONCLUSION AND FURTHER WORK

6.1 Conclusion 89
6.2 Suggestion for Further Works 90

REFERANCES 91

APPENDIX 94

LIST OF TABLE

TABLE NO	TITLE	PAGE
5.1	Even and odd mode characteristic impedances from *Mathcad* calculation	44
5.2	SAI-3 filter design parameter.	44
5.3	Even and odd mode characteristic impedances from *Mathcad* calculation	45
5.4	SAI-5 filter design parameter.	45
5.5	Even and odd mode characteristic impedances from *Mathcad* calculation	46
5.6	SAI-7 filter design parameter	46
5.7	Coupling coefficent from *Mathcad* calculation	48
5.8	SSI-3 filter design parameter	48
5.9	Coupling coefficent from *Mathcad* calculation	49
5.10	SSI-5 filter design parameter	49
5.11	Coupling coefficent from *Mathcad* calculation	50
5.12	SSI-7 filter design parameters	51
5.13	SAI filter simulation response	60
5.14	SSI filter simulation response	69

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Geometry of interdigital	
	(a) Asymmetrical	2
	(b) symmetrical	2
1.2	Project Flow Chart	6
2.1	Basic filter diagram	9
2.2	Low-Pass Filter Amplitude Response Curves	11
	(a) ideal	
	(b) sharp slope	
	(c) flat slope	
	(d) butterwoth response	
	(e) Chebychev respose	
	(f) elleptic response	
2.3	High-Pass Filter Amplitude Response Curves	11
	(a) ideal	
	(b) sharp slope	
	(c) flat slope	
	(d) butterwoth response	
	(e) Chebychev respose	
	(f) elleptic response	
2.4	Band pass Filter Amplitude Response	12
	(a) ideal	
	(b) sharp slope	
	(c) flat slope	

(d) butterwoth response
(e) Chebychev respose
(f) elleptic response
2.5 Frequency response for band stop filter. 13
(a) ideal
(b) sharp slope
(c) flat slope
(d) butterwoth response
(e) Chebychev respose
(f) elleptic response
2.6 Two Port Network Model 13
2.7 Microstrip transmission line structure. 15
2.8 Electric fields in microstrip. 16
2.9 Effective dielectric, ε_{re}. 18
3.1 Band pass filter consisting of low pass and high pass filters 19
3.2 Chebyshev response 23
3.3 Interdigital band pass filter structure 24
3.4 even mode of Quasi TEM modes pair of coupled microstrip lines 26
3.5 odd mode of Quasi TEM modes pair of coupled microstrip lines 26
3.6 Graf Coupling Coefficient versus S/H 29
3.7 Graf Single Quality Factor versus *l/L* 30
3.8 Asymmetrical interdigital band pass filter 34
3.9 Symmetrical interdigital band pass filter. 35
3.10 Cross sectional view of two-layer filter configuration 36
3.11 Cross sectional view of three-layer filter configuration. 36
4.1 Resource Center in *Mathcad* 2000 38
4.2 Three - dimensional view of the circuit in the six-sided metal box modeled in the project editor. 41
4.3 Example window for Xgeom module. 41
4.4 Simulation result from *Em control* 42

4.5	Return Loss response in *Emgraph*	42
5.1	SAI -3 filter layout	44
5.2	SAI -5 filter layout	45
5.3	SAI -7 filter layout	47
5.4	SSI -3 filter layout	49
5.5	SSI -5 filter layout	50
5.6	Simulation result for SSI-7	51
5.7	Sonnet structure for SAI-3 filter	52
5.8	Return Loss and Insertion Loss for SAI-3 filter	53
5.9	Simulated VSWR for SAI-3 filter	53
5.10	Simulated input impedance for SAI-3 filter	54
5.11	Simulated current distribution of SAI-3 filter	54
5.12	Sonnet structure for SAI-5 filter	55
5.13	Return Loss and Insertion Loss for SAI-5 filter	55
5.14	Simulated VSWR for SAI-5 filter	56
5.15	Simulated input impedance for SAI-5 filter	56
5.16	Simulated current distribution of SAI-5 filter	57
5.17	Sonnet structure for SAI-7 filter	57
5.18	Return Loss and Insertion Loss for SAI-7 filter	58
5.19	Simulated VSWR for SAI-7 filter	58
5.20	Simulated input impedance for SAI-7 filter	59
5.21	Simulated current distribution of SAI-7 filter	59
5.22	Sonnet structure for SSI-3 filter	61
5.23	Return Loss and Insertion Loss for SSI-3 filter	62
5.24	Simulated VSWR for SSI-3 filter	62
5.25	Simulated input impedance for SSI-3 filter	63
5.26	Simulated current distribution of SSI-3 filter	63
5.27	Sonnet structure for SSI-5 filter	64
5.28	Return Loss and Insertion Loss for SSI-5 filter	64
5.29	Simulated VSWR for SSI-5 filter	65

5.30	Simulated input impedance for SSI-5 filter	65
5.31	Simulated current distribution of SSI-5 filter	66
5.32	Sonnet structure for SSI-7 filter	66
5.33	Return Loss and Insertion Loss for SSI-7 filter	67
5.34	Simulated VSWR for SSI-7 filter	67
5.35	Simulated input impedance for SSI-7 filter	68
5.36	Simulated current distribution of SSI-7 filter	68
5.37	Sonnet structure two layer MAI filter	
	(a) First layer	70
	(b) Second layer	71
5.38	Return Loss and Insertion Loss for two layer MAI filter	72
5.39	Simulated VSWR for two layer MAI filter	72
5.40	Simulated input impedance for two layer MAI filter.	73
5.41	Simulated current distribution for two layer MAI filter	
	(a) First layer	73
	(b) Second Layer	74
5.42	Sonnet structure three layer MAI filter	
	(a) First layer	75
	(b) Second layer	75
	(c) Third layer	76
5.43	Return Loss and Insertion Loss for three layer MAI filter	76
5.44	Simulated VSWR for three layer MAI filter	77
5.45	Simulated input impedance for three layer MAI filter	77
5.46	Simulated current distribution for three layer MAI filter	
	(a) First layer	78
	(b) Second layer	78
	(c) Third layer	79
5.47	Sonnet structure two layer MSI filter	
	(a) First layer	80
	(b) Second layer	80

5.48	Return Loss and Insertion Loss for two layer MSI filter	81
5.49	Simulated VSWR for two layer MSI filter	81
5.50	Simulated input impedance for two layer MSI filter	82
5.51	Simulated current distribution for two layer MSI filter	
	(a) First layer	82
	(b) Second Layer	83
5.52	Sonnet structure three layer MSI filter	
	(a) First layer	84
	(b) Second layer	84
	(c) Third layer	85
5.53	Return Loss and Insertion Loss for three layer MSI filter	85
5.54	Simulated VSWR for three layer MSI filter	86
5.55	Simulated input impedance for three layer MSI filter	86
5.56	Simulated current distribution for three layer MSI filter	
	(a) First layer	87
	(b) Second Layer	87
	(c) Third Layer	88

LIST OF SYMBOLS

f_0	-	center frequency
ε_r	-	dielectric constant
h	-	substrate thickness
P_i	-	incident power
P_r	-	reflected power
P_L	-	power pass to load
IL	-	insertion loss
RL	-	return loss
W	-	width of substrate
t	-	thickness of conducting strip
ε	-	permittivity
μ	-	permeability
ε_{re}	-	effective dielectric constant
Z_c	-	characteristic impedances
C_d	-	capacitance per unit length with the dielectric substrate present
C_a	-	capacitance per unit length when the dielectric substrate is air
η	-	wave impedance in free space
λ_g	-	guided wavelenght
λ_o	-	free space wavelength
β	-	propogation constant
v_p	-	phase velocity
θ	-	electrical length
f_h	-	high cut off frequency high

f_l	-	low cut off frequency
Y_0	-	load characteristic admittance
C_p	-	parallel plate capacitance
C_f	-	fringe capacitance
J	-	Inverter admittance
Q_L	-	quality factor
k	-	normalized coupling coefficient
c	-	halaju cahaya
E	-	medan elektrik
L	-	resonator lenght
L_t	-	physical length measured from the input or output resonator to tap point
s	-	spacing between resonator

TABLE OF ABBREVIATIONS

SAI	Single layer asymmetrical interdigital filter
SSI	Single layer symmetrical interdigital filter
MAI	Multilayer asymmetrical interdigital filter
MSI	Multilayer symmetrical interdigital filter
FBW	Fractional Bandwidth
LTCC	Low Temperature Co- fired Ceramic
RF	Radio frequency
MICs	Microwave integrated circuit
TEM	Tranverse Electromagnetic Mode
VSWR	Voltage Wave Standing Ratio
dB	Decibel

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Mathcad File for designed Single Layer Asymmetrical Interdigital Band Pass Filter with order 5	95
B	Mathcad File for designed Single Layer Symmetrical Interdigital Band Pass Filter with order 5	104

CHAPTER I

INTRODUCTION

1.1 Introduction

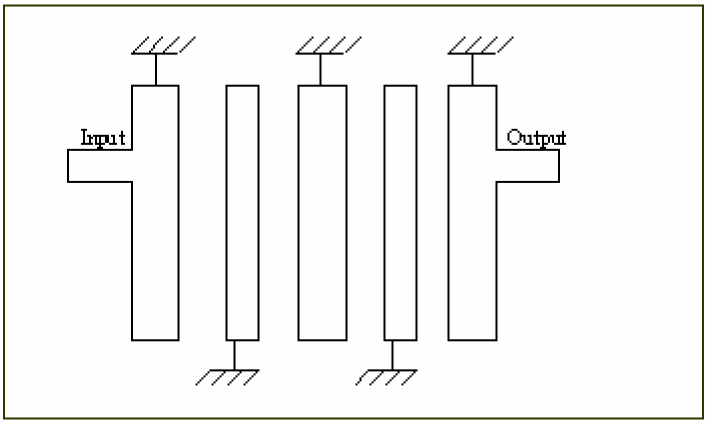
This chapter presents the objective, problem statement, research contribution, project scope and thesis organization.

1.2 Project Objective

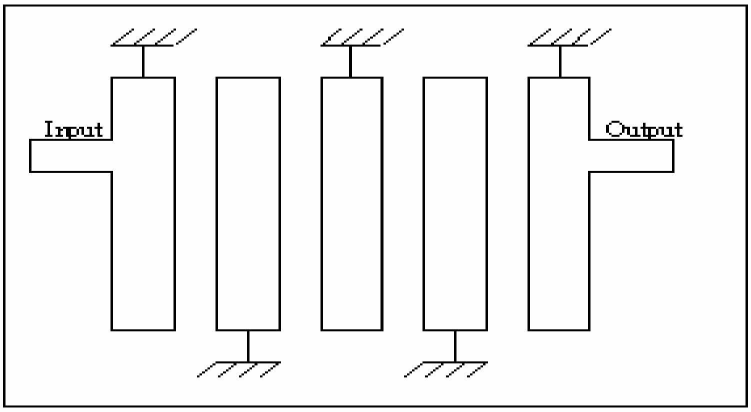
The objective of this project is to design asymmetrical and symmetrical chebyshev interdigital band pass filters at 2.45 GHz using *Mathcad* and *Sonnet* software's. These designed filters are of two configurations:

(i) Single layer configuration
(ii) Multilayer configuration.

The geometry of the filters is as shown in Figure 1.1.



(a)



(b)

Figure 1.1: Geometry of interdigital

(a) asymmetrical

(b) symmetrical

1.3 Problem Statements

Nowadays, many new technologies have been developed in electronics communication such as *Wireless Local Area Network (LAN)* and *Bluetooth* technology. Filters are essential in the system for excellent operation of this technology. Compact filter structures are available in demand for space-limited operations. Interdigital filter is one of the available compact configurations. There are many advantages using this structure. This project focuses on the performances of asymmetrical and symmetrical interdigital filter configuration on single layer and multilayer structures.

1.4 Research Contribution

The microstrip structure is chosen as the realization structure. This is because it has very simple geometry structures and widely used in practical. The mode of propagation in a microstrip is almost transverse electro magnetic (TEM). This allows an easy approximation analysis and yields wide band circuit. Furthermore, simple transition to coaxial circuit is feasible.

Some of the research contribution are state belows:

i. Development of *Mathcad* file of the design of interdigital asymmetrical and symmetrical interdigital band pass filters.
ii. Single layer and multilayer interdigital band pass filter configurations.

1.5 Project Scope

The project scope are as following:

- Literature review of interdigital band pass filter design and software's available.
- Design single layer asymmetrical and symmetrical interdigital band pass filters using *Mathcad* mathematical software.
- Simulation of the filters using *Sonnet* electromagnetic software.
- Analyze the performance of the designed filters and determine the optimum structures.
- Convert the optimum designed filter into respective multilayer configurations, simulate and analyze the performances.
- Thesis writing.

The specifications of the filters are as follows:

This project is to design a single and multilayer interdigital band pass filter at 2.45 GHz. The specification of the filter are shown below

- Center Frequency = 2.45 GHz
- Filter Response = Chebyshev response
- Band width = 0.3 GHz
- Pass band ripple = 0.2 dB
- Stop band attenuation = 30 dB

The board parameters are as follows:

- Dielectric constant = 9.6
- Substrates thickness = 1.27 mm
- Metal thickness = 35 um

Furthermore, the desired specifications are suitable with Bluetooth application [1] that is

i. Pass band in the frequency range of 2.45 GHz to 2.483 GHz.

ii. Lower stop band frequency of 1.96 GHz and 2.1 GHz are highly attenuated, which can reduce the crosstalk from local image signal and local-oscillator signal.

iii. Harmonic frequency in the range 4.8 GHz to 5 GHz, need to be reduced.

Chebyshev response is chosen because of its very sharp slope response and moderate complex mathematical formulations design.

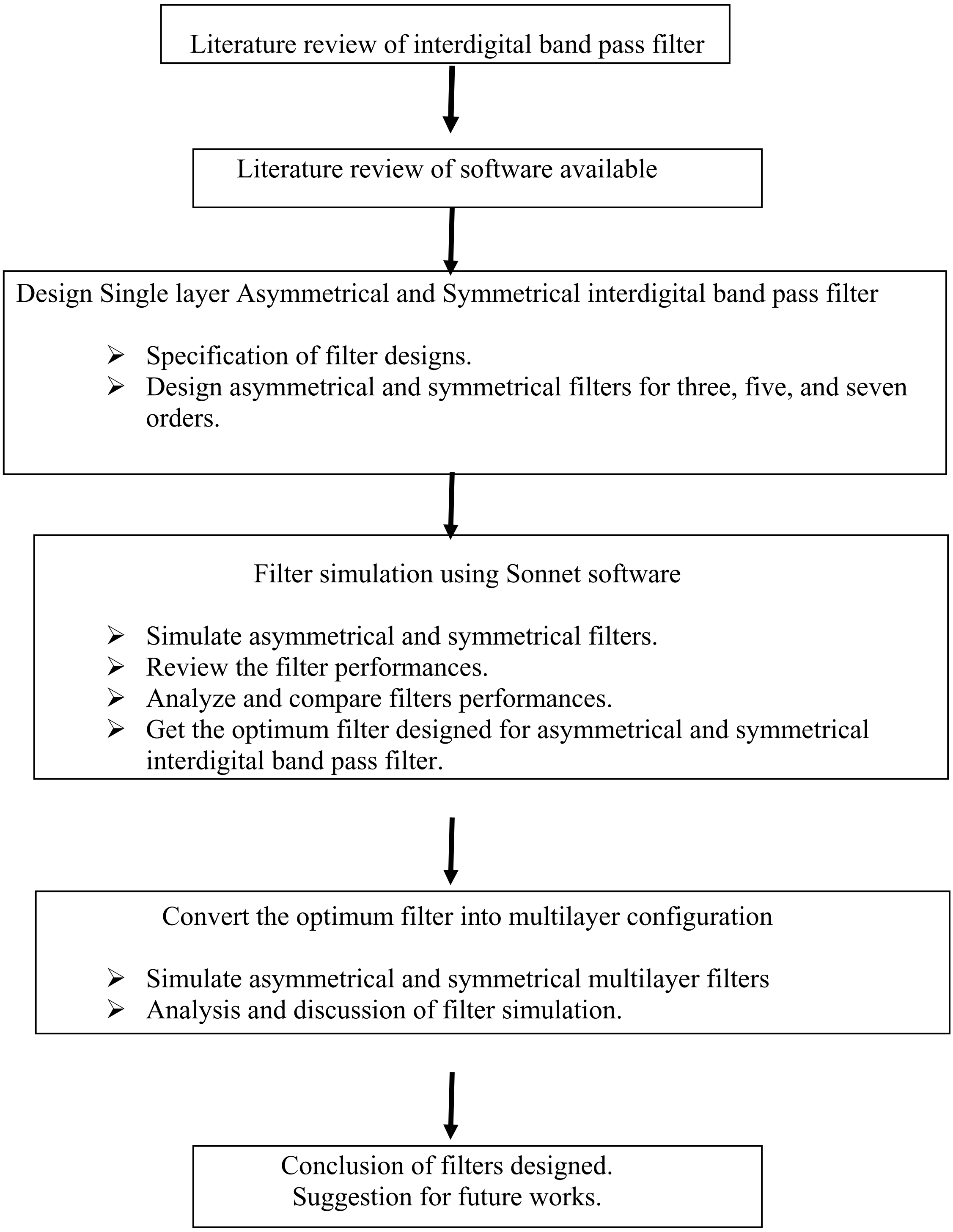


Figure 1.2 : Project Flow Chart

1.6 Thesis Organization

This thesis consist of six chapters. Chapter I present the objective, problem statements , research contribution, scopes of work, and thesis organisation.

Chapter II discusses the basic theory of interdigital band pass filters. This includes types of the filter, scattering paramaters and microstrip transmission line.

Chapter III presents the mathematical design procedure of interdigital band pass filters. This includes explanation of chebyshev response, parallel coupled design and formulations for the design. The optimum order of filter can be determined mathematically.

Chapter IV presents brief discussion of the software's used, i.e. *Mathcad* 2000 to solve mathematical equations while *Sonnet* V9.52 for electromagnetic simulation of the filters.

Chapter V presents all the theoretical and results of the filters. Discussions and comparations of the filter performances are made, for the single and multilayer configurations.

Finally, chapter VI is concluse the thesis. Suggestion for further work are also given.

REFERENCES

[1] Ching Wen Tang, “Harmonic- Suppression LTCC Filters With the Step-Impedance Quarter- Wavelength Open Stub,” IEEE Transaction on Microwave Theory and Techniques , Vol 52, No2 , February 2004 Page(s): 617-624

[2] Annapurna Das, Sisir K das, “Microwave Engineering”, Mc Graw Hill, 2001

[3] David M Pozar, “Microwave Engineering,” New York: Addison-Wesley, 2000

[4] Arthur B. Williams, Fred J Taylor, “Electronic Filter Design Handbook,” Second Edition, McGraw-Hill, 1988

[5] Jia-Shen G. Hong, M. J. Lancaster, “ Microstrip Filters for RF/ Microwave Apllications,” John Wiley & Sons, Inc, 2001

[6] K.C. Gupta, Ramesh Garg, Inder Bahl, Prakash Bhartia, “Microstrip Lines and Slotlines,” Artech House, 1996Volume: 34, No: 13, Page(s): 1278-1279.

[7] G.L Matthaei, L. Young, and E.M.T Jones, “Microwave Filters, Impedance Matching Networks and Related Structures,” New York: McGraw- Hill, 1964.

[8] Thomas A Milligan, “Dimension of Microstrip Coupled Lines and Interdigital Structures,” IEEE Transaction on Microwave Theory and Techniques, May 1977 Page(s): 405 –410

[9] Rashhid Ahmad Bhatti, Jahangir Khan Kayani, “Design and Analysis of a Parallel Coupled Microstrip Band Pass Filter,” 2nd International Bhurban Conference on Applied Science and Technology, June 2003, Page(s): 168 – 176

[10] Edward G. Cristal, “Tapped- Line Coupled transmission lines with Applications to Interdigital and Combline Filters,” IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-23, No12 , December 1975. Page(s): 1007 –1011

[11] Joseph S. Wong, " Microstrip Tapped –Line Filter Designed," IEEE Transaction on Microwave Theory and Techniques , Vol. MTT-27, No1 , January 1979, Page(s): 44 –50

[12] Choo Sik Cho, K. C. Gupta, "Design Methodology for Multilayer Coupled Line Filters," IEEE MTT-S Digest, 1997. Page(s): 785 –788

[13] "Mathcad User's Guide Student Version 2001," MathSoft Engineering & Education Inc, 2001

[14] Sonnet Tutorial Guide, Sonnet Software Inc. 2000

[15] Scrantom, C.Q, Lawson, J.C, " LTCC technology: W here We are and Where we are going to-ii, "Technologies for Wireless Applications, 1999. Digest. 1999 IEEE MTT-S Symposium, 21-24 Feb 1999, Page(s): 193 –200

[16] ThomasG Bryant, Jerald A. Weiss, "Parameters of Microstrip Transmission Lines and odd Coupled Pairs of Microstrip Lines", IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-16, No12 , December 1968 Page(s): 1021 –1027

[17] Arne Brejning Dalby, " Interdigital Microstrip Circuit Parameters Using Empirical Formulas and Simplified Model," IEEE Transaction on Microwave Theory and Techniques , Vol. MTT-27, No8 , August 1979, Page(s): 744 –752

[18] Sina Ahktazad, Thomas R Rowbotham, Peter B Johns, " The designed of coupled Microstrip Lines," IEEE Transaction on Microwave Theory and Techniques , Vol. MTT-23, No 6 , June 1975, Page(s): 486 –492

[19] G.L Mattaei, " Interdigital Band Pass Filters," IRE Transactions on Microwave Theory and Techniques, November 1962, Page(s): 479 –491

[20] R. J. Wenzel, "Exact Theory of Interdigital Related Coupled Band-Pass Structures," IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-13, No5, December 1965. Page(s): 559 –575

[21] Gardiol, Fred E, "Microstrip circuits," New York: John Wiley & Sons, 1994

[22] Young. Leo, "Microwave filters using parallel coupled lines," Artech House, 1972

[23] Inder Bahl and Prakash Bhartia, "Microwave Solid State Circuit Design," Second Edition, John Wiley & Sons, 2003

[24] J.S Hong, M. J. Lancester, " Development of New Microstrip Pseudo-Interdigital Bandpass Filter," IEEE Microwave and Guided Wave Letters , Vol 5, No 8, August 1995. Page(s): 261 –263

[25] S.W Ting, K.W.Tam, R.P. Martins, "Novel Interdigital Microstrip Bandpass Filter With Improved Spurious Response," IEEE, ISCAS 2004, Page(s): I 984 - I 987.

[26] S. V. Judd, Ian Whiteley, R. J. Clowes, D. C. Rickard, "An Analytical Method for Calculating Microstrip Transmission Line Parameters" IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-18, No, February 1970. Page(s): 78 –87

[27] Ravindranath T. kollipara, Ahmed S Mohammed, Thomas K Plant, Vijai J Tripathi, " Modeling and Design of Interdigital Structure," IEEE Transaction on Electron Devices, Vol 38, No. 11, November 1991, Page(s): 2575 –2577

[28] T.C . Chen, " Towards Optimum Multilayer Filter Design," IEE Proceedings-J, Vol 138, No 4, August 1991, Page(s): 241 –248

[29] Kiyotoshi Yasumuto, " Coupled Mode Formulation of Multilayered or Multiconductor Transmission Lines," " IEEE Transaction on Microwave Theory and Techniques, Vol. 44, No 4, April 1996. Page(s): 585 –590

[30] Caspi, Shimon and J. Adelman, *"Design Of Combline And Interdigital Filters With Tapped-Line Input",* IEEE Transactions on Microwave and Theory, MTT-36, no. 4, April 1988, pp. 759-763

[31] Sato, Risaburo and Edward G. Cristal,*"Simplified Analysis Of Coupled Transmission-Line Networks",* IEEE Transactions on Microwave and Theory, MTT-18, no. 3, March 1970, pp. 122-131

[32] Scanlan, John O., "Theory Of Microwave Coupled-Line Networks", Proceedings of the IEEE, Vol. 68, No. 2, February 1980, pp. 209-231

[33] M. Dishal, "A simple design procedure for small percentage bandwidth round-rod interdigital filters," IEEE Trans. Microwave Themy Tech. (Corresp.), vol. MTT-13, , Sept. 1965. pp. 696-698

[34] H. A. Wheeler, "Transmission-line properties of parallel strips separated by dielectric sheet:' IEEE Trans. Microwave Theory and Techniques, vol. MIT-1 3, March 1965. pp. 172-185