COMPACT MICROWAVE HAIRPIN LINE BAND PASS FILTER USING FOLDED QUARTER-WAVE RESONATOR

SAMSUL HAIMI BIN DAHLAN

A project report submitted in partial fulfillment
of the requirement for the award of the degree of
Masters of Electrical Engineering
(Electronics & Telecommunications)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

March, 2005

For my Mom, Wife, beloved son Akmal Safiy, my little angels Nina, Harith, Irsya, Amirul, Ilham and Sara. To Ajan, Kak Jie, Aca, Kak Nim and Ayu…

I am wealthy beyond measure because I have you all around

ACKNOWLEDGEMENT

Praise be to Allah s.w.t to Whom we seek help and guidance and under His benevolence we exist and without His help this project could not have been accomplished. I would like to express my sincere thanks and appreciation to Associate Professor Dr. Mazlina bte Esa, my project supervisor, for all the help, guidance and generous time given throughout the course of completing this project. My sincere appreciation also extends to all my friends, Teddy Purnamirza, Lester Chung, Keseven, Abdul Hafidz, Abd. Shukor, Ikhwan and Lai Mun. Thanks for your support, assistance and guidance. To my wife NurFiza Yanti, thanks for your love, your patience and inspirations. You always open my heart and rekindle my spirit.

ABSTRACT

Compact microwave hairpin band pass filter using half-wavelength folded resonator as a method to miniaturize resonator structure has been thoroughly studied in this thesis. Design were done by using the mathematic formulas and verified by using *SONNET LITEPlus* 8.0 software. Synthesis of the filter is using the insertion loss method. The initial design of a miniature hairpin filter was achieved by carefully selecting the resonator shape and the initial frequency. The shape was then fine tuned, and the response for the changes was plotted. This would indirectly represent the behavior of the circuit when parameter variation occurs. The step by step procedure to design the filter is presented. The design performance and characteristics in terms of electrical and physical parameters were compared with the conventional hairpin filter. The final design of the miniaturized hairpin filter has an overall size of 46% smaller compared to the conventional hairpin size. Better return loss properties were also observed from the miniaturized version. The first spurious frequency occurs at a higher frequency compared to that of the conventional hairpin filter. It is tunable depending on the value of the even-mode impedance that was chosen at the early stage of the design process. The bandwidth, however, was slightly narrower, which is 80% of the desired100 MHz. In terms of the response, miniaturized hairpin filter is having steeper skirting. However, it is comparable to that of the conventional hairpin filter.

ABSTRAK

Rekabentuk akhir penapis pin rambut model kecil mempunyai saiz keseluruhan yang 46% lebih kecil berbanding saiz pin rambut konvensional. Ciri kehilangan kembali yang lebih baik diperolehi. Frekuensi spurious pertama wujud pada nilai yang lebih tinggi. Ini pula boleh dilaraskan bergantung kepada nilai galangan mod genap yang telah dipilih pada peringkat awal proses rekabentuk. Walaubagaimanapun, lebar jalur adalah sempit sedikit iaitu 80% daripada lebarjalur yang dikehendaki iaitu 100 Mhz. Cerun sambutan pula lebih curam.Namun, ini sebanding dengan penapis pin rambut konvensional.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

BW	-	Bandwidth
C	-	Capacitance
F	-	Fractional bandwidth
f_i	-	Initial frequency
f_o	-	Centre frequency
g	-	Prototype element
h	-	Substrate thickness
IL	-	Insertion loss
I_e	-	Even mode current
I_o	-	Odd mode current
J	-	Admittance inverter
K	-	Coupling coefficient
L_{AR}	-	Ripple factor
n	-	Number of element
P	-	Net power
P_{in}	-	Input power
P_{LR}	-	Power loss ratio
P_r	-	Reflected power
Q	-	Q-value
S	-	Gap size
S_{11}	-	Return loss at port 1
S_{12}	-	Insertion loss from port 2 to 1
S_{22}	-	Return loss at port 2
S_{21}	-	Insertion loss from port 1 to 2

V_e	-	Even mode voltage
V_o	-	Odd mode voltage
W	-	Width
Z_o	-	Characteristic impedance
Z_{oe}	-	Even mode characteristic impedance
Z_{oo}	-	Odd mode characteristic impedance
Z_t	-	Transmission line impedance
ε_r	-	Dielectric Constant
ε_{eff}	-	Effective dielectric Constant
θ_e	-	Coupled line length of even mode
θ_o	-	Coupled line length of odd mode
θ_t	-	Coupled line length of transmission line
λ	-	Wavelength
λ_g	-	Effective Wavelength

LIST OF APPENDICES

CHAPTER I

INTRODUCTION

Band pass filter is widely used in telecommunication system, be it in receiving or transmitting devices, to filter out unwanted frequency. Smaller size and high performance filters are always desired to enhance system performance and to reduce the system cost. There are various ways of designing a filter. The most attractive configuration is planar structure due to its compactness and fairly easy to be manufactured [1]. There has been much research on planar resonators, which is the main component of a planar filter. Examples are parallel-coupled resonator, hairpin resonator, stepped-impedance resonator and miniaturized hairpin resonator. The main purpose of all these studies is to make the filters more compact.

The resonator is the main and basic component of a planar filter, hence it is necessary to properly select the resonator type to ensure the compact size of a filter is maximized. Conventional parallel-coupled filter is too space consuming. Hairpin-line resonator was then introduced to reduce the resonator size and shape [2]. The concepts of miniaturize hairpin resonator was introduced by Sagawa *et al* in 1989 [3]. The brilliant concept integrates lumped element capacitor and the planar resonator to reduce the size further. Therefore, this type of resonator posses smaller size compared to conventional hairpin. This type of resonator is actually a variation of stepped-impedance resonator. Thus, combining stepped-impedance resonator in conventional hairpin structure has eliminated the need of the lumped-element capacitor and hence enhanced the whole structure. Consequently, this made it more stable in terms of frequency variations.

This thesis presents the concept pioneered by Sagawa *et al* and improved by CM Tsai in developing a miniaturize hairpin resonator that operates at 2.45 GHz, the common frequency for ISM band application. A method to select proper resonator design is presented. Besides resonator design, filter topology is also taken into consideration. For microwave circuits, parallel-coupled-line and hairpin filters are widely used. These topologies can only be realized by using Chebyshev and Butterworth response. Since miniature hairpin resonator is a modified version of conventional hairpin resonator, the selection of the initial frequency has to be carefully considered. The study of filter parameters and the effect to filter response are also presented. These information is important especially for circuit optimizations.

Finally, SonnetLite Plus [4] software is then used to optimize and simulate the circuits with the aid of MathCAD [5] software for computation of design formulations.

1.1 Project objective

The objective of this project is to design a compact version of hairpin-line resonator configuration operating at 2.45 GHz.

1.2 Project scope

The scopes of the project are:

i) To modify the conventional hairpin resonator structure into more compact design configuration.
ii) To simulate the response and compare the results with the conventional hairpin filter in terms of performance and physical size.
iii) To study circuit behavior in terms of resonator element and in terms of filter configuration.

1.3 Project motivation

The trend of today's telecommunication device is to have high performance but small and handy devices. As people gets busier, electronic devices that allow users to be mobile, has become a necessity. The smaller the size, the easier for them to be carried around. The better the performance, the higher is the reliability. The factor that determines the overall size is the size of the components itself. Hence, if there are ways to reduce component size, this will indirectly compact the overall device appearance. The challenge is to built smaller circuit component but with same material and with minor changes in the manufacturing process and also able to maintain attractive features of the original circuit. One such component is the band pass filter. It is widely used in telecommunications system especially at the receiver and transmitter. Most of electronics components nowadays are made of VLSI technology that make them smaller relative to the band pass filter size that uses microstrip technology. Hence, in order to enhance the overall circuit compactness and integrate them together, compact filter structures have to be designed and developed.

1.4 Layout of thesis

The report consists of five chapters. The first chapter describes the objective, the project scope and project motivation. Chapter two covers theories on filters relevant to this project. This includes S-parameters application in microwave circuits, a brief discussion on the subject and equations concerning the theory were presented. Filter synthesis technique method were described together with discussion on filter response. This chapter also covers theories of resonator miniaturization, hairpin filter realization and characteristics of internal coupled resonator. Design methodology, specification and the discussion on the tools involved for circuit simulation was covered in chapter three. Chapter four discussed the result and analysis of the findings. These include the study of resonator behavior and all parameter variations that affect filter performance. Finally, chapter five covers the project conclusion and discuss in detail on recommendation and possible future work that can be done to enhance the application of miniaturize resonator and improve the performance.

CHAPTER II

BANDPASS FILTER THEORIES

This chapter describes briefly the history, requirements and considerations taken related to the development of a conventional hairpin band pass filter and miniaturized hairpin band pass filter. This includes all the related mathematical formulae and calculations of the responses. The concept of miniaturization is also presented to give clearer idea on how the process is being done.

2.1 Scattering Parameter (S-Parameter)

To characterize a microwave circuit, incident and reflected amplitudes of microwave at any port are referred [6],[10]. The incident and reflected wave amplitudes are normalized so that the square of these variables gives the average power in that wave in the following manner:

Input power at the nth port, $$P_{in} = \frac{|a_n|^2}{2} \tag{2.1}$$

Reflected power at the nth port, $$P_r = \frac{|b_n|^2}{2} \tag{2.2}$$

Where a_n and b_n represent the normalized incident and reflected wave amplitude at nth port. Supposed, a two port network is considered. The net power flows into any port is given by:

Net power, P is:

$$P = P_{in} - P_r$$

$$P = \frac{|a_n|^2 - |b_n|^2}{2} \qquad (2.3)$$

The relation between incient wave and reflected wave are expressed in term of scattering parameter S_{ij}'s, so:

$$b_1 = S_{11}\,a_1 + S_{12}\,a_2$$
$$b_2 = S_{21}\,a_1 + S_{22}\,a_2 \qquad (2.4)$$

The physical significance of the S-parameters is described as:

$$S_{11} = \frac{b_1}{a_1} \quad \text{, when } a_2 = 0$$

This is the reflection coefficient at port 1 when port 2 in terminated with matched load ($a_2 = 0$)

$$S_{22} = \frac{b_2}{a_2} \quad \text{, when } a_1 = 0$$

This is the reflection coefficient at port 2 when port 1 in terminated with a matched load ($a_1 = 0$)

$$S_{12} = \frac{b_1}{a_2} \qquad \text{, when } a_1 = 0$$

Attenuation of wave traveling from port 2 to port 1.

$$S_{21} = \frac{b_2}{a_1} \qquad \text{, when } a_2 = 0$$

Attenuation of wave traveling from port 1 to port 2.

When considering microwave circuits it is important to express several losses in term of S-Parameter (when the ports are matched terminated). For two ports network, if power fed at port 1 is P_{in}, power reflected at same port is P_r and power out put at port 2 is P_o, the following losses are defined in term of S-Parameter.

$$\text{Insertion loss (dB)} \quad = \quad 10\log\frac{P_{in}}{P_o} = 10\log\frac{|a_1|^2}{|b_2|^2}$$

$$= 20\log\frac{1}{|S_{21}|}$$

$$= 20\log\frac{1}{|S_{12}|} \qquad (2.5)$$

Transmission loss or Attenuation (dB)

$$= \quad 10\log\frac{P_{in} - P_r}{P_o}$$

$$= \quad 10\log\frac{1-|S_{11}|^2}{|S_{12}|^2} \qquad (2.6)$$

$$\text{Reflection loss (dB)} = 10\log\frac{P_{in}}{P_{in} - \mathrm{P_r}}$$

$$= 10\log\frac{1}{1-|S_{11}|^2} \tag{2.7}$$

$$\text{Return loss (dB)} = 10\log\frac{P_{in}}{\mathrm{P_r}}$$

$$= 20\log\frac{1}{|S_{11}|} \tag{2.8}$$

2.2 Synthesis technique

Two most popular techniques of filter synthesizing are *image parameter method* and *insertion loss method* [6]. The insertion loss method gives complete specification of a physically realizable frequency characteristic over entire stop and pass bands. It is the most preferred method for microwave filter design.

The basic design of microwave filters are made from a prototype low pass design. In the insertion loss method, a physically realizable network is synthesized that will give the desired insertion loss versus frequency characteristic. This method consists of the steps below:

(i) Design of a prototype low pass filter with the desired pass band characteristic.

(ii) Transformation of this prototype network to the required type filters with the specified center and band-edge frequency.

(iii) Realization of the network in microwave form using sections of microwave transmission lines whose reactance correspond to those of distributed circuit element.

2.3 Filter Responses

Filter response is defined by its insertion loss or power loss ratio, P_{LR}

$$P_{LR} = \frac{Power\ available\ from\ source}{Power\ delivered\ to\ load}$$

This quantity is the reciprocal of $|S_{12}|^2$ if both load and source are matched.
There are three main filter responses approximation, they are:

(a) Buterworth Response

Butterworth response is also known as Maximally flat response. The response is optimum in providing the flattest possible pass-band response for a given order. The insertion loss characteristic can be represented with formula :

$$IL = 1 + a_m{}^2 \omega \varpi^{2n}; \quad where\ \varpi = \frac{\omega}{\omega_c} \tag{2.9}$$

The Butterworth approximation exhibits a flat response in the pass-band and an increased of attenuation (monotonically) in the stop band. The rate of increase of the insertion loss for $\omega > \omega_c$ depends on the exponent $2n$, which is related to the number of filter order used in the filter network. The response is illustrated in Figure 2.1

(b) Chebyshev Response

The second approximation is Chebyshev response or well known as equal ripple response. As the name specified, Chebyshev response has ripple in the pass-band and stop-band. Compared to Butterworth, the insertion loss exhibits a much faster increment rate beyond cut off frequency, ω_c. Hence, this response is expected to have steeper skirting properties if compared to Butterworth. The ripple size of Chebyshev response is however controllable. It depends to the application requirement and a designer can specify the desired magnitude of the ripple. It is however related to the number of filter order in the filter system. Approximation of low-pass Chebyshev insertion loss response can be expressed as:

$$IL = 1 + a_m^2 \, T_n^2 \, (\omega') \tag{2.10}$$

where $\omega' = \omega / \omega_c$ and $T_n^2 = \cos(n \cos^{-1}x)$ for $x \leq 1$ or $\cos(n \cosh^{-1}x)$ for $x > 1$. The notation 'n' denotes the number of reactive element. Comparison of both responses is illustrated in Figure 2.1.

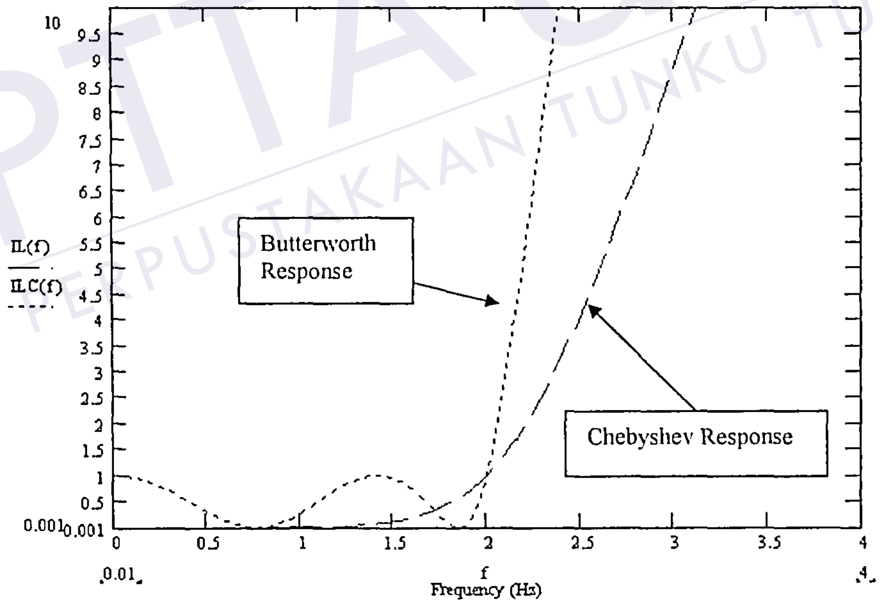

Figure 2.1: Low Pass profile of Chebyshev and Butterworth responses computed from MathCAD.

References:

1. Sheng Yuan Lee and Chih Ming Tsai " *New Cross-Coupled Filter Design Using Improved Hairpin Resonator*", IEEE, vol. 48, NO. 12, pp.2482-2490, Dec 2000.
2. E.G Cristal and S. Frankel, *"Hairpin-line and hybrid hairpin-line half-wave parallel-coupled-line filters,"* IEEE Trans. Microwave Theory Tech., vol. MTT-20, pp. 719-728, Nov. 1972.
3. Morikazu Sagawa, Kenichi Takahashi and Mitsuo Makimoto, *"Miniaturized Hairpin Resonator Filters and Their Application to Receiver Front-End MIC's"*, IEEE vol 37, No 12, pp.1991-1997, Dec. 1989.
4. Sonnet 8.51-Lite User's Guide (1986-2002). Sonnet Software Inc. USA.
5. MathCAD 2000 User's Guide. (1999). MathSoft Inc. USA.
6. Annapurna Das and Sisir Das *"Microwave Engineering"*, McGrawHill 2001, Singapore.
7. Mitsuo Makimoto and S.Yamashita *"Microwave Resonators and Filters for Wireless Communication Theory, Design and Application"*, Springer 2000, New York.
8. David M. Pozar " Microwave Engineering", John Wiley & Son 1989, Inc USA.
9. Chi-Yang Chang and Cheng Chun Chen *" A Novel Coupling Structure Suitable for Cross-Coupled Filters With Cross-Coupled Filters With Folded Quarter-Wave Resonators"*, IEEE VOL.13,NO.12, pp. 517-519, DEC 2003.
10. Cheng Chung Chen, Yi-Ru Chen and Chi Yang Chang*" Miniaturized Microstrip Cross-Coupled Filters Using Quarter-wave or Quasi-Quarter-Wave Resonators"*, IEEE VOL.51, NO. 1, pp. 120-131, JAN 2003.
11. Jun Sik Yuk, Jun Seok Park, Dal Ahn, Kwan Sun Choi and Juno Kim *" A Novel Accurate Design Method For The Hairpin Type Coupled Line Bandpass Filter"*, pp. 2171- 2174, 2001 IEEE MTF-S Digest
12. Sheng Yuan Lee and Chih Ming Tsai *" A New Network Model For Miniaturized Hairpin Resonators And Its Applications"*, pp. 1161-1164, IEEE MTT-S Digest 2000.

13. Shigetoshi Ohshima, Takafumi Tomiyama,Tomoyuki Kimpara and Tetsuya Sato *"Design and Fabrication of Superconducting Compact Filters"*, pp 821-824, IEEE 1999
14. Jia Sheng Hong and Michael J Lancaster *"Cross-Coupled Microstrip Hairpin-Resonator Filters"*, IEEE VOL.46, NO.1, pp. 118-122, January 1998.
15. George L. Matthaei, Neal O. Fenzi, Roger J. Forse and Stephen M.Rohlfing *"Hairpin-Comb Filters for HTS and Other Narrow-Band Applications"*, IEEE VOL. 45, NO.8, pp. 1226-1231, AUG 1997.
16. Calestino A. Corral, Claude S. Lindquist *" On The Band-Edge Selectivity Of Elliptic Filter"*, pp. 177-180, IEEE 1991.
17. B.Rawat and Rex Miller *" Band pass Filter for Mobile Communications"*, Microwave Journal, Vol. 27, NO. 10, pp. 146-150, Sept 1984.
18. Matthaei, Young and MT Jones *"Microwave Filters, Impedance-Matching Networks, And Coupling Structure"*, Artech House 1980, Inc. USA.
19. J.S Wong, *"Microstrip tapped-line filter design,"* IEEE Trans. Microwave Theory Tech., vol. MTT-27, pp. 44-50, Jan. 1979.
20. R.Levy *"Filters with Single Transmission Zeros at Real or Imaginary Frequencies"*, IEEE, VOL MTT-24, No.4 , pp. 172-181, April 1976.
21. Ralph Levy and John David Rhodes *" A Comb-Line Elliptic Filter"*, IEEE VOL. MTT-19, NO. 1, pp. 26-29, JAN 1971.