Study of slotline ring resonator based microwave filters

Jiang, Bo

2015

Jiang, B. (2015). Study of slotline ring resonator based microwave filters. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/62938>

<https://doi.org/10.32657/10356/62938>

**Study of Slotline Ring
Resonator Based Microwave Filters**

JIANG BO

SCHOOL OF ELECTRICAL&ELECTRONIC ENGINEERING

2015

Study of Slotline Ring Resonator Based Microwave Filters

JIANG BO

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirements for the degree of
Master of Engineering

2015

left blank

ACKNOWLEDGEMENT

First and foremost, I wish to express gratitude to my supervisor, Prof. Shen Zhongxiang, for his careful guidance, stimulating suggestion and profound knowledge in supervising my research project. Without his professional instruction during my research, I could not come this far for my graduate study.

I also appreciate help and precise instruction from Professor Zhu Lei, my former supervisor, and Professor Alphones for their patient explanation of problem inquiry.

Thanks are also given to Dr. Chen Dong, visiting scholar, Huang Xiaoguo, visiting student from China, Dr. Zhang Songbai, Dr. Zhang Runqi and Zhao Chen, PhD students in NTU, and Mr. Steve Lim and Mr. Ng Teng Kwee, Communication Research Lab technicians in NTU, for their help in enriching my understanding of microwave theory, using commercial software and problems solving during the completion of my thesis.

Especially, I am very grateful for the love and support of my parents.

Finally, I should express my thanks to any individual who ever helps me during my postgraduate studies.

left blank

TABLE OF CONTENTS

ACKNOWLEDGEMENT.....	i
SUMMARY	v
LIST OF FIGURES	vi
LIST OF TABLES	ix
Chapter 1 Introduction.....	1
1.1 Motivaion.....	1
1.2 Objectives	2
1.3 Main Contributions	3
1.4 Organisation.....	4
Chapter 2 Fundamentals and Literature Review	7
2.1 Fundamental Knowledge	7
2.1.1 Transmission Line	7
2.2.1.1 Microstrip Line	8
2.2.1.2 Slotline	9
2.2.1.3 Hybrid Microstrip-Slotline Structure.....	10
2.1.2 Multi-Mode Resonator	11
2.2 Literature Review of Ring Resonator Filters	12
2.2.1 Background	12
2.2.2 Methods of Splitting Degenerate Modes and Coupling.....	13
2.2.3 Design of Microstrip Ring Bandpass Filters	16
2.2.3.1 Dual-Mode Single and Multi-Band Planar Filters	17
2.2.3.2 Single Wideband Filter.....	22

Chapter 3	Bandpass Filter with Two Stubs.....	26
3.1	Bandpass Filter with Slotline Stubs in the Symmetrical Plane.....	29
3.2	Bandpass Filter with Stubs perpendicular to the Symmetrical Plane ..	34
3.3	Conclusion and Discusssion	42
Chapter 4	Bandpass Filter with Six Stubs.....	43
4.1	Design Principle.....	44
4.2	Experimental Results and Discussion.....	49
4.3	Conclusion	52
Chapter 5	Dual-Band Bandpass Filter with Adjustable Bandwidth.....	54
5.1	Design Principle.....	55
5.2	Experimental Results and Discussions	60
5.3	Conclusion	62
Chapter 6	Conclusions and Recommendation	63
6.1	Conclusions of Work Conducted	63
6.2	Recommendations of Futher Work.....	65
Author's Publications		66
References		67

SUMMARY

In this thesis, slotline-based ring filters are studied and investigated to design and implement several single-wideband and dual-band bandpass filters to overcome the shortcomings of microstrip ring resonator, such as narrow bandwidth, low fabrication tolerance and deformation of modes.

Three wideband bandpass filters using triple-mode slotline ring resonator are designed and fabricated. Two triple-mode wideband bandpass filters with 3dB fractional bandwidth of 66% and 63%, respectively, are initially designed by attaching two stubs at or perpendicular to the symmetrical plane of the ring resonator. These two circuits verify that the analysis of ring resonator can be carried out without considering the influence of coupling from microstrip feed-lines. Based on the concept of multi-mode resonator, another wideband bandpass filter with 3dB fractional bandwidth as high as 100.7% is then proposed and fabricated using a slotline resonator with 6 stubs. Finally, a dual-band bandpass filter with adjustable bandwidth is designed. All measured results agree with our designed ones, which verifies our design principle.

LIST OF FIGURES

Fig. 2.1 A two-wire transmission line. (a) without load, (b) with load.	7
Fig. 2.2 A microstrip-slotline T-junction (a) Schematic, (b) Equivalent circuit.	10
Fig. 2.3 Three types of microstrip ring resonator (a) Annular, (b) Square, (c) Triangular [4].	14
Fig. 2.4 Split mode (a) Coupled, (b) Local resonant, (c) Notch perturbation, (d) Patch perturbation [4].	15
Fig. 2.5 Coupling approaches (a) Loose, (b) Annular, (c) Interdigital [4].	16
Fig. 2.6 Dual-mode bandpass filter [5].	17
Fig. 2.7 Dual-mode filter using an impedance step as perturbation [14].	18
Fig. 2.8 Ring resonator filter with capacitors [34].	18
Fig. 2.9 Dual-band BPF with eight stubs [22].	20
Fig. 2.10 Dual-band bandpass filter with two stubs [24].	20
Fig. 2.11 Tri-band filter with four stubs[25].	21
Fig. 2.12. Dual-band transversal filtering section [9].	22
Fig. 2.13 Schematic of wideband bandpass filter with two stubs [28].	23
Fig. 2.14 UWB ring resonator [32].	24
Fig. 3.1 Proposed triple-mode slotline ring resonator with two loaded stubs (a) Schematic, (b) Equivalent transmission-line model.	28
Fig. 3.2 (a) Equivalent odd- and even-mode one-port bisection, (b) Normalized resonant frequencies versus electrical overall stub length.	29
Fig. 3.3 S-parameter versus electrical lengths of two slotline stubs at frequency 3.0 GHz under the fixed sum length of two slot stubs, $\theta_1 + \theta_2$. (a) $\theta_1 = \theta_2$, (b) $\theta_1 \neq \theta_2$	30

Fig. 3.4 (a) Layout of the designed wideband filter with two internally loaded slotline stubs (unit: mm), (b) Simulated and measured results.....	32
Fig. 3.5 Proposed triple-mode slotline ring resonator with two loaded stubs (a) Schematic, (b) Equivalent transmission-line model.	34
Fig. 3.6 Equivalent circuits of the triple-mode slotline ring resonator without stub in the symmetrical plane (a) Even-mode, (b) Odd-mode.....	36
Fig. 3.7 (a) Even-mode bisection, (b) Odd-mode bisection of the equivalent circuit of slotline ring resonator.	36
Fig. 3.8 (a) Normalized resonant frequencies f_i/f_{o1} , where f_i are $f_{e1}, f_{e2}, f_{e3}, f_{o1}, f_{o2}, f_{z1}, f_{z2}, f_{z3}$, versus electrical normalized arm length $t = \theta_l / \theta_r$, (b) Frequency response of the resonator under weak coupling.	38
Fig. 3.9 Fabricated filter (a) Physic layout (unit: mm), (b) Microstrip line layer, (c) Slotline layer.....	40
Fig. 3.10 Simulated and measured results of the designed wideband filter.....	41
Fig. 4.1 Proposed triple-mode slotline ring resonator with six loaded stubs (a) Schematic, (b) Equivalent transmission-line model.	45
Fig. 4.2 Equivalent circuits of the triple-mode slotline ring resonator without stub in the symmetrical plane (a) Even mode, (b) Odd mode.	46
Fig. 4.3 Normalized resonant frequencies versus electrical overall stub length, where f_i are $f_{o1}, f_{e2}, f_{o3}, f_z$, respectively. (a) $f_i/f_0, f_0 = 3\text{GHz}$, (b) f_i/f_z	48
Fig. 4.4 Frequency response of the resonator under weak coupling (a) $\theta_2 = 0$, (b) $\theta_2 = 30^\circ$	49
Fig. 4.5 Fabricated filter (a) Physic layout (unit: mm), (b) Microstrip line layer, (c) Slotline layer.....	50
Fig. 4.6 Simulated and measured results of the designed wideband filter with six slotline stubs (a) S-parameter of frequency response, (b) Group delay.	51

Table 4-1 Comparison our filter with previous designs.....	52
Fig. 5.1 Proposed dual-band slotline ring resonator with two loaded stubs. (a) Schematic. (b) Equivalent transmission-line model.	56
Fig. 5.2 S-parameter versus electrical lengths of two slotline stubs and the angle between them under weak coupling at frequency 3.0 GHz (a) $2\theta_s=90^\circ$, $\theta_2=0^\circ$, 45° and 90° , (b) $\theta_2=90^\circ$, $\theta_s=38^\circ$, 45° and 50°	57
Fig. 5.3 Equivalent circuit (a) even mode, (b) odd mode	59
Fig. 5.4 (a) Layout of the designed bandpass filter with two stubs. (unit: mm). Simulated and measured results (b) $\theta_2=90^\circ$, $\theta_s=38^\circ$. (c) $\theta_2=90^\circ$, $\theta_s=45^\circ$. (d) $\theta_2=90^\circ$, $\theta_s=50^\circ$	60

LIST OF TABLES

Table 4-1	Comparison our filter with previous designs.....	52
-----------	--	----

Chapter 1 Introduction

1.1 Motivation

Numerous bandpass filters have been investigated and designed using microstrip ring resonator because of their attractive features of compact size, high Q factor and multi-band. However, sufficient coupling between the microstrip feed-lines and the resonator is usually hard to achieve using a single-layer microstrip-line structure.

By using different coupling approaches, such as interdigital feed-line, the coupling can be enhanced but requiring extremely low fabrication tolerance for its small gap width. Furthermore, these existing approaches lead to deforming the resonant modes of the original ring resonator and causing the mode analysis of ring resonator more complex because the coupling between feed-lines and ring resonator has destroyed the symmetry of the ring. Meanwhile, the weak coupling between the feed lines and ring resonator also makes the microstrip line based filters hard to achieve wide bandwidth. Dual-band bandpass filters were studied, but without adjustable bandwidth. In this thesis, coupling between the microstrip feed-line and slotline ring resonator can be easily achieved to a high extent as

required using the microstrip-to-slotline cross junction, without noticeable influence of the resonant modes in a ring resonator. Meanwhile, wider bandwidth can be easily achieved without involving complex fabrication techniques. Three wideband bandpass filters are studied to analyze the influence of both stubs and position of the microstrip feed lines on the modes of ring resonator. A dual-band bandpass filter with adjustable bandwidth is also studied to improve the performance of existing dual-band ring filters.

1.2 Objectives

As mentioned in the previous section, the advantages of ring resonator are greatly suppressed due to the coupling problem. The objective is to overcome the coupling problem by introducing slotline based ring resonator thus controlling the resonant modes and coupling separately and then realize a much wider bandwidth than existing designs. Meanwhile, by proposing different types of structure, the influence of both positions of stubs and microstrip feed lines on the modes of the ring resonator will be investigated with even- and odd-mode analysis to realize single wideband bandpass filters. Besides wide bandwidth, because little research has been conducted

on the bandwidth adjustable dual-band ring filters, this thesis will present a new design using slotline ring resonator.

1.3 Main Contributions

Two main contributions in research are described below.

Three triple-mode wideband bandpass filters are designed and fabricated with a slotline ring resonator. In these designs, modes adjustment of the resonator can be made separately from the coupling part thus effectively reducing the design complexity. These principles are verified in Chapter 3 by adjusting the location and length of two stubs to construct two triple-mode wideband bandpass filters.

With these principles and based on the concept of multi-mode resonator, a triple-mode bandpass filter with a fractional bandwidth of 100.7% shows that the higher coupling degree between microstrip feed lines and slotline ring resonator can help to achieve a very wide bandwidth. By analyzing the influence of length and position of stubs, a novel bandwidth adjustable dual-mode dual-band bandpass filter is proposed to improve existing dual-band ring filters.

By using different number of stubs and placing them and microstrip feed-lines at different positions, the degenerate modes of a

ring resonator are effectively split to design different kinds of single wideband and dual-band bandpass filters. The mode shifting and suppression of these filters are investigated using even- and odd-mode analysis, thus leading to better understanding of the design principle and these methods can be effectively used in designing other microwave components.

1.4 Organisation

This thesis is divided into six chapters as follows.

Chapter 1 includes the motivation, the objective and the organization of this thesis. The application background of the RF/microwave filters is also briefly introduced.

Chapter 2 covers three parts. The first part introduces the fundamental knowledge needed for the design of planar filters. The second part introduces the background of microstrip ring resonator and focuses on the ring resonator itself and methods of coupling realization. The existing approaches of splitting the degenerate modes of the ring resonator and methods of achieving coupling between the feed-line and microstrip ring resonator are described in detail. The final part is to introduce design examples on the planar microstrip

dual-mode single- and multi-band bandpass filters. To design wide-band bandpass filters, approaches of splitting degenerate modes to form desired dual mode dual- or triple- band and methods of coupling mentioned in the second part are put into practice.

Chapter 3 introduces two novel wideband bandpass filters using a triple-mode slotline resonator. Two stubs are placed at or perpendicular to the symmetrical plane of the ring resonator to split the degenerate modes. They use the first-order pair of splitting degenerate modes and a higher order mode to construct a triple-mode wideband BPF. These two designs verify the principle that the coupling of microstrip feed-lines does not influence the modes thus simplifying the filter design.

Chapter 4 introduces a wideband bandpass filter with a fractional bandwidth of 100.7% using a six-stub slotline resonator. In order to increase the bandwidth, the microstrip feed lines with 180° - separation are used to suppress three different-order modes and then four slotline stubs are placed with a separation of 60° with respect to the symmetrical plane to adjust the remaining three different-order modes to obtain a very wide triple-mode passband response.

Chapter 5 presents a novel dual-band filter with adjustable bandwidth based on a slotline ring resonator. In principle, the three pairs of degenerate modes are excited and split by etching two slotline stubs with an angle along the ring resonator. By varying the angle between the stubs while fixing the stub lengths, controllable bandwidth in each band is realized and designed.

Chapter 6 provides a summary of the work conducted on triple-mode wideband bandpass filters and bandwidth-adjustable dual-band bandpass filter. Recommendations for future work are suggested as well.

Chapter 2 Fundamentals and Literature Review

In this chapter, fundamental knowledge of microstrip line and slotline, concept of multi-mode resonators will be reviewed. Then the concept of ring resonator and its applications in single wideband and dual-mode multi-band bandpass filters will be introduced in the literature review part.

2.1 Fundamental Knowledge

2.1.1 Transmission Line

As a basic element in microwave circuit design, transmission line acts a bridge between field analysis and circuit theory. A transmission line is a distributed-parameter network and often represented as a two-wire line as shown in Fig. 2.1 [1], where θ , Z_0 and Z_L are the transmission phase, characteristic impedance of the transmission line, and load impedance, respectively.

Fig. 2.1 A two-wire transmission line. (a) without load, (b) with load.

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \theta}{Z_0 + jZ_L \tan \theta} \quad (2.1)$$

When load impedance Z_L is equal to characteristic impedance Z_0 , the calculated input impedance Z_{in} is always equal to Z_0 , and the reflection coefficient is zero. When load is set to open- or short-circuit, the signal is completely reflected. The input impedances for open and short circuits are solved, respectively.

$$Z_{in} = -jZ_0 \cot \theta \quad (2.2)$$

$$Z_{in} = jZ_0 \tan \theta \quad (2.3)$$

2.2.1.1 Microstrip Line

Coaxial lines and waveguides are used as transmission lines in early days for their high power and wider bandwidth features. Then the planar transmission lines, such as stripline, microstrip and slotline etc, are chosen for their attractive features of compact size, low cost and especially its advantage of capable of integrating with active devices to construct Microwave Integrated Circuit(MIC) easily. A microstrip line is formed of a conductor, one substrate layer with relative thick dielectric and one ground plane. Comparing with strip line, it can concentrate most of the EM wave between the conductor and the ground plane and accentuate the frequency dispersion of the line [1].

The effective dielectric constant and characteristic impedance of a microstrip line is essential for designing microstrip line related microwave circuits. Different from the dielectric constant ϵ_r of the substrate, the effective

dielectric constant for the microstrip line is related to the thickness of the substrate and width of the conductor W because EM wave concentrates mostly between the conductor and the ground plane with relative small amount leaking into air above the substrate. The appropriate equation for the effective dielectric constant ϵ_e is given below [1],

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12d/W}} \quad (2.4)$$

The transmission phase θ along a microstrip line with length l is

$$\theta = \beta l \quad (2.5)$$

where β is proportional to the square root of ϵ_e . In this way, by adjusting the height and dielectric constant of the substrate and width of the conductor, we can change the phase of signal traveling along the microstrip line.

2.2.1.2 Slotline

Different from microstrip, slotline is formed by etching out a slot in the conducting plane, which is the ground plane in microstrip without metal at the other side of the substrate. Majority of the electrical field concentrates across the slot in the metal plate when the wave propagates along the side of the slot. The EM field also distributes inside the substrate layer and into the air. Therefore, the effective dielectric constant of slotline is far less than microstrip line when the dielectric constant, height of the substrate and the width of them are the same.

2.2.1.3 Hybrid Microstrip-Slotline Structure

It is easy to realize open stub and shunt stub with microstrip line while slotline can be used as short stub and serial stub. To combine these characteristics into circuit, slots are etched out on the ground plane of the microstrip circuits or microstrip line is placed at the other side of the substrate of slot circuits.

Fig. 2.2 A microstrip-slotline T-junction (a) Schematic, (b) Equivalent circuit.

Generally, T-junctions [2] are applied in these microstrip-slotline circuits, as shown in Fig. 2.2(a). The equivalent circuit for hybrid microstrip-slotline T-junction is obtained in Fig. 2.2(b), which acts like a power divider with ratio of $n:1$.

2.1.2 Multi-Mode Resonator

A boundary-confined 3D cavity or planar line can store energy of EM wave of particular frequencies and can act as a microwave resonator. The modes of the resonator is mainly determined by the physical dimension and effective dielectric constant inside and around that structure. Planar transmission line like microstrip and slotline based resonator obeys to these rules. For a uniform planar transmission line with physical length l , the wavelength λ_g of resonant modes can be calculated as

$$n\lambda_g = l \quad (2.6)$$

However, it is not convenient to calculate the resonant frequencies using this method when the transmission line becomes non-uniform. In order to solve it, the energy storing principle has been adopted. For the resonant modes, the energy is stored and consumes no power thus making the impedance looking inside the resonator to be zero at any point. By setting the sum of impedance or admittance of up side (Z_+ , Y_+) and down side (Z_- , Y_-) of the resonator to be

zero, we can get the equation to calculate the resonant modes below

$$Z_- + Z_+ = 0 \quad \text{or} \quad Y_- + Y_+ = 0 \quad (2.7)$$

These resonant modes cannot produce good passband if spacings between these frequencies are too big so that the coupling from feed lines is not strong enough to excite all of them. The multi-mode resonator concept is that the passband is mainly determined by the starting and ending modes, and more modes generated inside the desirable passband can get better insertion loss. Methods of calculating the resonant frequencies and forming multi-mode resonator will be discussed in the following chapters.

2.2 Literature Review of Ring Resonator Filters

2.2.1 Background

A lot of research has been conducted on ring resonator to construct different kinds of microwave devices since the degenerate modes are firstly split to form a dual-mode resonator by introducing a perturbation [3]. The ring resonator has low radiation loss and high-Q factor comparing to the patch resonator [4]. As most research utilizes the degenerate modes to form dual- or triple-mode single/multi-band bandpass filters, methods of splitting the degenerate modes are explored extensively. Firstly, different shapes of ring resonator, such as annular ring [4], square ring [5]-[6], triangular ring [7]-[8]

have been introduced. Asymmetrical coupling and perturbation are introduced in these designs to deform the degenerate modes. By introducing the perturbation, such as a small shape variation to the ring, the degenerate modes can be split. General approaches for perturbation are to add one or several small patches or notches along the ring resonator [10]-[17].

Besides small perturbation, other elements like stubs are brought in to split the degenerate modes as the length of the stub is sensitive in dual-mode filter design [18]. One or more stubs are placed at the exact or the two sides of the symmetrical plane with respect to the excited ports. The positions and ratios of the degenerate modes are generally controlled by the stub position and the ratio of the lengths or characteristic impedances between stubs and ring [19]-[33]. However, stub could be replaced by other elements like capacitor etc [34] to realize the function of splitting degenerate modes. Some other forms of perturbation are also possible, the ring loop could be replaced by capacitor [35]-[36] or inductor [37] and the ring could also be curved so that inner coupling is brought in to split the modes [38]- [40].

2.2.2 Methods of Splitting Degenerate Modes and Coupling

Many microstrip ring resonator with different shapes like annular ring, square ring and triangular ring have been proposed as shown in Fig. 2.3. In fact,

changing the shapes of the ring resonator but keeping the characteristic impedance of the ring resonator uniform will not be able to split the degenerate modes.

Fig. 2.3 Three types of microstrip ring resonator (a) Annular, (b) Square, (c) Triangular [4].

The degenerate mode are not split when the input and output feed-lines are applied to the ring resonator symmetrically. That is to say, degenerate modes refrain without asymmetrical coupling and perturbation. The resonant wavelength of the degenerate mode is given by the equation below:

$$2\pi r = n\lambda_g \quad (2.8)$$

The degenerate modes are excited and split when certain boundary conditions are implemented on the microstrip ring resonator [4].

The most often used approaches of splitting the degenerate modes of the

ring resonator are split modes. This approach was first reported by Wolff in [3], in which he used asymmetrical coupling feed-lines and notch perturbation to split the degenerate modes. Four types of mode-split approaches are classified in [4]. Figs. 2.4 (a) to (d) illustrate the basic circuit structures of these four types

Fig. 2.4 Split mode (a) Coupled, (b) Local resonant, (c) Notch perturbation, (d) Patch perturbation [4].

of split-mode approaches. These methods are proposed to deform the symmetry of the ring to separate the degenerate modes. After successfully splitting the modes, coupling to raise these modes have to be introduced to form passband.

Three types of coupling ever used are illustrated in Fig. 2.5 for the microstrip ring. The loose coupling and annular coupling are not strong and are

only able to realize narrow passband in related dual-mode single- and multi-band filters. Interdigital feed-lines have the ability to achieve wider bandpass but with problems such as deforming the original modes of the ring

Fig. 2.5 Coupling approaches (a) Loose, (b) Annular, (c) Interdigital [4].

and make the process of modes analyzing complex. Also, the small gap required for the interdigital feed-line has lower fabrication tolerance. Using the above theory of modes splitting and coupling feeding, many categories of single-band and multi-band microstrip ring circuits have been proposed.

2.2.3 Design of Microstrip Ring Bandpass Filters

Generally, the development of microstrip ring resonator has been divided into two categories: one is the dual-mode passband filters and the other is

single-band wideband bandpass filter with three or more modes.

Fig. 2.6 Dual-mode bandpass filter [5].

2.2.3.1 Dual-Mode Single and Multi-Band Planar Filters

At the first stage, only single narrow-band filter can be achieved for their small perturbation. One dual-mode selective bandpass filter in Fig. 2.6 using a meander microstrip loop resonator with 2.5% bandwidth at 1.58 GHz was proposed in [5]. A patch perturbation is placed at the symmetrical plane to split the first two degenerate modes to form a dual-mode passband. In that paper, it shows that mode splitting increases with the size of the patch and degenerate modes are not split without perturbation. Other forms of perturbation are then being proposed, a bandpass filter illustrated in Fig. 2.7 was investigated in [10] with a stepped-impedance segment placed at the symmetrical plane as perturbation element. By adjusting the angle of the stepped impedance element and the impedance ratio between the step element and annular ring, two

orthogonal degenerate modes is separated and controlled.

Fig. 2.7 Dual-mode filter using an impedance step as perturbation [10].

Besides introducing small perturbation in the form of patch and stepped impedance of transmission line, lumped circuit element is also being taken into consideration and application in splitting the degenerate modes. As shown in Fig. 2.8, two pairs of shunt capacitors are used as the perturbation to split the even- and odd-mode resonant modes [34]. The pair of shunt capacitors in the

Fig. 2.8 Ring resonator filter with capacitors [34].

symmetrical plane can be used to control the even mode, while the other pairs of capacitors could be used to control the odd mode based on even- and odd-mode circuit model analysis. Thus, the overall ring length can be reduced to less than a full wavelength at the designed frequency by increasing the capacitance. In [36], two pairs of capacitors are placed in the ring to connect the transmission line ring segment to construct a dual-mode bandpass filter with 4% bandwidth at 1.9 GHz. The capacitors could be used to control the odd- and even-mode frequencies independently.

As the research of the perturbation's influence on the modes distribution of microstrip ring resonator progresses, it becomes clearer that more significant perturbation can lead to wider passband. Then more ring resonators using more number of stubs with longer length are proposed.

Due to the small perturbation used, only single-band dual-mode bandpass filters were designed for a long time, and then a dual-mode dual-band bandpass filter is firstly proposed using a single ring resonator with eight stubs in Fig. 2.9 [22]. The degenerate modes of the first and second orders are excited and weakly split when parallel-coupled lines to input/output feed-lines are placed with 135° - separation without perturbation. Through even mode and odd mode analysis, the two pairs of modes in both bands move closely when coupling degree is reduced. Then eight stubs are brought in so that the fifth mode

Fig. 2.9 Dual-band BPF with eight stubs [22].

emerges while the 2nd order degenerate modes merge. Then the two first-order modes form the first passband and the fifth mode forms the second passband with the merged two second-order modes. Later the same author Luo in [23] utilized four stubs instead of eight to realize a dual-mode dual-band bandpass filter.

A ring-resonator attached with two open stubs is proposed for a

Fig. 2.10 Dual-band bandpass filter with two stubs [24].

dual-mode dual-band filter illustrated in Fig. 2.10 [24]. These stubs bring down the two first-order degenerate modes, which form the first passband. Meanwhile, one of the third-order degenerate modes shift downward. Together with a second-order degenerate mode, these two modes form the second passband. Three transmission zeros are properly distributed among the two passbands and upper stopband to realize good rejection.

After having successfully designed dual-band microstrip filters, a ring filter with more bands was proposed. The triple-band bandpass filter with two modes in each band is realized by placing four stubs in Fig. 2.11 with each two

Fig. 2.11 Tri-band filter with four stubs [25].

at and perpendicular to the symmetrical plane in [25]. With no stub perturbation, three pairs of degenerate modes can be excited and split by controlling the angle between the input/output ports and the coupling capacitor. Initially, the first and third pairs of degenerate modes are produced and split when the

input/output ports are placed with 45° or 135° angle along the ring resonator. Meanwhile, the second pairs of degenerate modes are suppressed by signal cancellation between the lower and upper ring paths. Then four stubs are introduced along the vertical and horizontal planes to split the second degenerate modes to form the second passband.

Besides multi-band filters with narrow passband, some research is reported to construct wideband bandpass filters by increasing further the stub electrical length, comparing to the dual-mode filters.

2.2.3.2 Single Wideband Filter

A wideband planar filter at 5GHz with sharp-rejection and low insertion-loss was proposed in [9]. The filter in Fig. 2.12 utilizes the transversal signal- interference between two parallel connected transmission-line segments to construct in-band signal combinations and out-of-band

Fig. 2.12. Dual-band transversal filtering section [9].

transmission zeros. Then using transversal techniques, a compact

bandpass filter with asymmetrical interdigital coupled lines was proposed in [30]. Two transmission zeros at two sides of the expected passband are obtained with transversal signal-interference techniques and five more zeros emerge by using two asymmetrical interdigital coupled lines thus forming a wide passband with excellent dc-choked property and out-of-band rejections.

Beside the theory of transversal signal-interference techniques, principle of multi-mode resonator is also applied in the designing of wideband passband ring filter. An ultra-wideband (UWB) bandpass filter using MMR has been proposed and experimentally verified [31]. The filter utilizes a dual-mode ring resonator to allocate its first two resonant frequencies in the passband, and the third resonant mode near 17.2 GHz contributes to the lowest passband to form a UWB passband with the first two modes.

Fig. 2.13 Schematic of wideband bandpass filter with two stubs [28].

Another wideband microstrip bandpass filters under multi-mode

resonance of an asymmetrical resonator was proposed in [28]. The first- and second-order even modes are shifted downward to be at each side of the first-order odd mode with almost equal space when increasing the lengths of the two stubs to one-eighth of the wavelength to form a triple mode wide passband in Fig. 2.13. Then two more modes can be introduced into the passband as the interdigital feed-lines are coupled to the resonator. An ultra-wideband bandpass filter was proposed in [32]. A ring resonator with two stepped-impedance stubs in Fig. 2.14 is used to form the passband while interdigital feed-lines with asymmetrical structure are developed to avoid signal transmission in the 5-GHz band.

Fig. 2.14 UWB ring resonator [32].

Fundamentals knowledge and development history of microstrip ring resonator have been introduced in this chapter. Multi-mode wideband and dual-mode multi-band narrowband filters based on ring resonator with different kinds of perturbations have been realized. However, few works have been

reported using slotline ring resonator. In the following three chapters, a class of filters based on slotline ring resonator will be presented.

Chapter 3 Bandpass Filter with Two Stubs

Microstrip line ring filters have been extensively studied because of their attractive features of compact size and relatively high Q factor [4]. Since Wolff [3] proposed a design of bandpass filter by splitting the degenerate modes on a ring resonator through the approach of deforming the symmetry of the ring, a variety of different forms of disturbance, especially adding stubs along or besides the symmetrical plane with respect to two external ports, are used to design narrow and wideband bandpass filters based on the concept of multi-mode resonator. In the first stage, single-band, dual-band and triple-band bandpass filter with short stubs or stepped-impedance perturbation were proposed using capacitive coupling between curved feed-lines and the ring resonator to obtain relative narrow bandwidth.

Then in order to increase the bandwidth, coupling methods such as using lumped capacitor and interdigital feed-lines with long open stubs as disturbance are utilized to strengthen the coupling to reach higher fractional bandwidth. However, the interdigital coupled lines may deform the modes of ring and make the analysis of the multi-mode resonators complicated. Meanwhile, the gap between interdigital feed-lines is very small thus requiring relative low fabrication tolerance and high cost.

Based on the analysis above, in this chapter we aim to develop wideband bandpass filters based on slotline ring resonator without using interdigital feeding lines to avoid deformation of the original modes and reduce the fabrication cost. In this work, two stubs are located with angle of zero and 90° with respect to the symmetrical plane to control the degenerate modes and the microstrip feed lines are placed just above the layer of the ring resonator as coupling. It is easy to analyze the modes of the ring resonator using slotline because the microstrip feed-line just suppress some modes of the resonator and generate some additional transmission zeros without shifting the modes.

The modes shifting can be analyzed using even- and odd-mode equivalent circuit in the following designed wideband bandpass filters. Two slotline stubs are placed at the symmetrical plane of ring resonator in the first design so that the odd modes can be adjusted by the stubs while the even modes remain unchanged. The microstrip feed lines are used to suppress the second even mode. In this way, the first-order even and odd modes can form a triple-mode along with the second odd mode.

In the second design, both two slotline stubs and the microstrip feed lines are placed with angle of 90° with respect to the symmetrical plane. With this position, only odd-mode part of the even and odd modes can be adjusted by the stubs. The first-order even and odd modes form triple-mode with higher-

(a)

(b)

Fig. 3.1 Proposed triple-mode slotline ring resonator with two loaded stubs (a) Schematic, (b) Equivalent transmission-line model.

order mode. The shift of modes is only influenced by the electrical length of the stubs once the position of both the slotline stubs and microstrip feed lines are determined. In this way, we separate the modes analysis of resonator from the

influence of feed lines' coupling thus simplifying the design process. Meanwhile, the microstrip feed lines are placed at a different layer comparing to the ring resonator and require less fabrication accuracy.

3.1 Bandpass Filter with Slotline Stubs in the Symmetrical Plane

Fig. 3.1 (a) shows the schematic of the proposed slotline ring resonator with two slotline stubs located at the symmetrical plane of the ring, with Z_r and Z_s as characteristic impedances of the slotline ring and stubs. In order to verify our design principle, two identical slotline stubs are placed without coupling. Using even- and odd-mode analysis of the bisection of the slotline ring resonator without consideration of the feed lines, as illustrated in the equivalent transmission-line model of the BPF in Fig. 3.2 (a), it can be easily seen that the slotline stubs can only influence the odd modes of the degenerate

Fig. 3.2 (a) Equivalent odd- and even-mode one-port bisection, (b) Normalized resonant frequencies versus electrical overall stub length.

modes. The resonant wavelength should increase when the length of resonant cavity increases. Then the odd modes should shift downward when length of stubs increases, meanwhile the even modes are fixed, as shown in Fig. 3.2 (b).

Fig. 3-3 (a) illustrates the calculated frequency responses of $|S_{21}|$ using the equivalent model in Fig. 3.1(b) with two identical stubs. Only degenerate modes exist when the stub lengths are set to zero. As electrical length of the

(a)

(b)

Fig. 3.3 S-parameter versus electrical lengths of two slotline stubs at frequency 3.0 GHz under the fixed sum length of two slot stubs, $\theta_1 + \theta_2$. (a) $\theta_1 = \theta_2$, (b) $\theta_1 \neq \theta_2$.

stubs increases to 30° and 60° , the first and second odd-mode resonant modes both shift downward with different rates. Meanwhile, the first even mode remains unchanged, as we expect.

In this design, the location of the microstrip feed lines is at a quarter of half the ring to the symmetrical plane. In this way, the feed-line is placed at the short-circuit point for the second even mode in even-mode equivalent-mode bisection so that the second even mode cannot be excited. In this way, the first and second odd modes can form the passband along with the first even mode.

Due to different shift rates of different-order modes, the third odd mode shifts downward just outside the upper stopband as the electrical length of slot stubs increases to one sixth of the ring. As the location of the microstrip feed lines are fixed and the electrical length of the feed lines is set as a quarter wavelength at the chosen center frequency, so the unwanted third order mode can only be eliminated using the slotline stubs. The sum of the two stubs' electrical lengths of has to be fixed so that the three modes designed in passband remain unchanged. As the third odd mode has short-circuit point along the signal path, it can be suppressed by adjusting the two stubs unequal so that the position of the feed line falls just above the short-circuit point of the third-odd-mode signal path. This can also be explained as an out-of-phase phase

difference between the inside and outside paths of the ring resonator. As illustrated in Fig. 3.3 (b), the 3rd odd-mode peak can be fully eliminated as two stubs are set to two different electrical lengths.

Fig. 3.4 (a) Layout of the designed wideband filter with two internally loaded slotline stubs (unit: mm), (b) Simulated and measured results.

By setting the electrical length of the microstrip feed-line to a quarter wavelength at the chosen center frequency 3GHz, the designed three modes can be raised to form a triple-mode wideband bandpass filter, as illustrated in Fig. 3.4(b).

The triple-mode wideband BPF has been designed and implemented on the substrate, Rogers 6010, with dielectric constant of 10.8 and thickness of 1.27 mm. Fig. 3.4 (a) shows the layout of the designed circuit. Simulated results are obtained from the IE3D software and they are plotted together with the measured results. The measured central frequency of the core passband is 3.0 GHz with a fractional bandwidth of 66.0% and the return loss is bigger than 15 dB from 2GHz to 3.5GHz. Moreover, both simulated and measured results show a wide upper stopband in a range from 4.0 to 5.5 GHz. It is clear that the third odd mode is satisfactorily suppressed while the two transmission zeros, generated by the ring resonator and the feed lines, can form a wide upper stopband, as expected. Comparing with the wideband filter proposed in [28], this filter has nearly the same fractional bandwidth and insertion loss. However, without the requirement of interdigital feedlines, the tolerance requirement of fabrication is higher and the filter is easy to fabricate.

The measured result agrees well with the simulated one thus verifying our design principle. The process of designing modes becomes simple using slotline

ring resonator regardless of the influence from the coupling of the microstrip feed lines on the modes of the ring. Meanwhile, as the location and length of the slotline stubs and location of feed lines can have influence on the modes, another wideband bandpass filter also using two slotline stubs but with different position and lengths has been studied and implemented below.

3.2 Bandpass Filter with Stubs perpendicular to the Symmetrical Plane

Fig. 3.5 Proposed triple-mode slotline ring resonator with two loaded stubs (a) Schematic, (b) Equivalent transmission-line model.

As explained above, the electrical length and location of slotline stubs will shift the degenerate modes while the location of the microstrip feed lines is relevant to coupling, which can be used to suppress modes. Then two microstrip feed lines and slotline stubs are placed with angle of half the ring while feeding point sits just above the cross point of the ring and slotline stubs.

Fig. 3.5(a) depicts the schematic of the proposed stub-loaded slotline ring resonator, where Y_r and Y_1 are the characteristic admittance of the slotline ring and two stubs, respectively, while θ_r , θ_1 denote the effective electrical lengths of the ring resonator and slotline stubs, respectively.

In our design, both the microstrip feed lines and slot stubs are placed with 90° -separation with respect to the symmetrical plane. As can be seen from Fig. 3.7, both the feed-lines and stubs are at the symmetrical plane for the even- and odd-mode bisections. So when we conduct even- and odd-mode analysis for the existing even- and odd-mode bisections as shown in Fig. 3.8, we can see that the odd-mode parts for both the resonator's odd and even modes will shift downward when increasing the electrical length of the slotline stub. Meanwhile, the even-mode parts for both the even and odd modes will remain unchanged.

In this way, the feed lines can raise the even-mode parts easier and the odd-mode parts by properly selecting the length of the stub.

Fig. 3.6 Equivalent circuits of the triple-mode slotline ring resonator without stub in the symmetrical plane (a) Even-mode, (b) Odd-mode.

Fig. 3.7 (a) Even-mode bisection, (b) Odd-mode bisection of the equivalent circuit of slotline ring resonator.

By incrementing the length of the slotline stub to be a quarter of the ring, we make the first two odd-mode parts almost equally spaced at the two sides of the first even-mode part to form a triple-mode passband. Due to the phase cancelling of signals inside and outside the ring circle, two transmission zeros occur below and above the three modes to obtain a good frequency selectivity.

Equivalent transmission-line model of the BPF in Fig. 3.5(b) is given in Fig. 3.6. In Fig. 3.6, $Y_{+,-}^{e,o}$ represents the port admittance of the even- and odd-mode, looking into the up and down sides, respectively. Under the even- and odd-mode resonances, the sum of admittance looking up and down should be zero. That is, $Y_+^e + Y_-^e = 0$ and $Y_+^o + Y_-^o = 0$, all the resonant frequencies can be simply determined. The ratio of characteristic impedances between slot stub and ring resonator is set as R where $R = Y_1/Y_r$. Therefore, the admittance of the network under even-mode excitation should be

$$Y_+^e = jY_1 \tan \theta_r / (R - \tan \theta_1 \tan \theta_r) \quad (3.1)$$

$$Y_-^e = jY_r \tan \theta_r \quad (3.2)$$

Similarly, we obtain the admittance of the odd mode below,

$$Y_+^o = -jY_1 / (R \tan \theta_r + \tan \theta_1) \quad (3.3)$$

$$Y_-^o = -jY_r \cot \theta_r \quad (3.4)$$

By setting $Y_+^e + Y_-^e$ and $Y_+^o + Y_-^o$ to zero, we obtain the relations below,

$$\tan \theta_1 \tan \theta_r = R + 1 \quad (3.5)$$

$$2R \tan \theta_r + \tan \theta_1 = 0 \quad (3.6)$$

Fig. 3.8 (a) plots the normalized resonant frequencies, f_{e1}/f_{o1} , f_{o2}/f_{o1} , f_{e3}/f_{o1} and f_{z1}/f_{o1} , f_{z3}/f_{o1} versus the normalized arm length of $t = \theta_1/\theta_r$ when R equals one. As seen in Fig. 3.8 (a), every pair of degenerate modes split into two even

and odd modes. Both the even and odd modes can be divided into two parts: the odd-mode part and the even-mode part, as illustrated in Fig. 3.7. The modes of odd-mode part for the even and odd modes shift downward while the modes

(a)

(b)

Fig. 3.8 (a) Normalized resonant frequencies f_i/f_{01} , where f_i are $f_{e1}, f_{e2}, f_{e3}, f_{o1}, f_{o2}, f_{z1}, f_{z2}, f_{z3}$, versus electrical normalized arm length $t = \theta_1/\theta_r$, (b) Frequency response of the resonator under weak coupling.

of even-mode part remain unchanged when increasing the ratio of $t = \theta_1/\theta_s$.

The modes f_{e1} , f_{o2} and f_{e3} shift downward when increasing the ratio of t

because these three modes are the odd-mode part and they are short-circuit at the point of the slotline stubs when t equals to zero. Meanwhile, the even-mode part such as f_{o1} and f_{e2} remain unchanged as these modes are open-circuit at the cross point of the slotline stubs and ring. Without slotline stubs introduced, only even-mode parts such as f_{o1} and f_{e2} can be raised while the odd-mode parts will be suppressed. However, with the increment of the slotline stubs, the short-circuit point of the odd-mode parts shift to the end of the slotline stub so that the point of the stub for the slotline is no longer the short-circuit point.

Then the microstrip feed-lines are capable to of increasing the modes of odd-mode part when their voltage wave distributions are not short-circuited at the position of the stub.

As the downward shifting extent of higher order modes is bigger than the lower ones, the odd- mode part f_{o2} merges with the even-mode part f_{o1} when t equals to 1. Meanwhile, the odd-mode parts f_{e1} and f_{e3} shift downward at the two sides of the merged f_{o1} and f_{o2} to form a triple-mode passband. When t is approaching zero, as seen from Fig. 3.8(a), the two transmission zeros are almost merging with the modes. Then the transmission zeros split further away from the mode when we increase t generally from 0 to 1. So the three modes between the two transmission zeros can be utilized to form bandpass filter with a good frequency selectivity. The $|S_{21}|$ of the frequency response of the filter

under weak coupling is shown in Fig. 3.8(b) to verify the analysis.

The dimension of the fabricated circuit is given in Fig. 3-9(a).

The circuit is fabricated on the substrate Rogers 3010 as illustrated in

(a)

(b)

(c)

Fig. 3.9 Fabricated filter (a) Physic layout (unit: mm), (b) Microstrip line layer, (c) Slotline layer.

Fig. 3.9(b) and (c), with dielectric constant of 11.8 and thickness of 1.27 mm. Simulated S parameter from ADS and the measured results are plotted together in Fig. 3.10. It is clear that the measured result agrees well with the simulated one. The center frequency of the

passband is set as 6.0 GHz with a fractional bandwidth of 63% with minimum insertion loss approximate below 10dB. The filter has a good frequency selectivity and stop band performance. The harmonic response is suppressed below -15dB from 9 to 12GHz. Comparing with the filters proposed in Chapter 3 and in [28], this filter has approximately the same fractional bandwidth and worse insertion loss. However, the upper and lower stopband rejection performance is better with sharper 3dB rejection skirts. In order to improve the insertion loss, material with thinner dielectric height may be used and the impedance ratio of slot and ring can be further investigated.

Fig. 3.10 Simulated and measured results of the designed wideband filter.

Therefore, a triple-mode wideband bandpass filter is proposed using a slotline ring resonator by introducing in two slot stubs. By allocating the microstrip feed-lines and stubs with 180°-separation,

the pairs of degenerate modes all split and one shift downward while the other one remains unchanged. Three modes between the pair of transmission zeros are used to form a triple-mode bandpass filter with a fractional bandwidth of 63% after increasing stub length to a quarter of the ring. The filter has good frequency selectivity and band stop performance and the measured results match the simulated results well thus verifying well our design principle in experiment.

3.3 Conclusion and Discussion

In this chapter, two first-order modes and one higher-order mode are used to form up triple-mode passband approximately 60% with two-stubs-loaded slotline ring resonator. In the modes designing process, the coupling strength of microstrip is not taken into consideration. By placing the microstrip at particular location, unwanted modes can be suppressed, then increasing the electrical length to almost a quarter of desirable central frequency to raise the triple modes to form up a triple-mode passband filter. However, though high coupling degree is easy to obtain via microstrip-slotline transition, the bandwidth achieved here is not wide enough comparing to other microstrip ring filters. In order to achieve higher bandwidth, multi-mode resonator concept will be applied in next chapter.

Chapter 4 Bandpass Filter with Six Stubs

Wideband bandpass filters (BPFs) have been extensively developed in recent years because the wideband applications of communication system. In [28], the first three resonant modes of microstrip-line ring resonator with paired stubs were employed to design a wideband BPF achieving a fractional bandwidth 64%. A quadruple-mode wideband bandpass filter with 3 dB fractional bandwidth 57.9% using a stepped-impedance microstrip-line ring resonator was designed [33].

As discussed in chapter three, wideband bandpass filter with fractional bandwidth as high as 60% are designed using two slotline stubs to overcome the shortcoming of deforming the modes of the microstrip ring resonator. However, wider bandwidth should be achieved when high coupling degree is easy to achieve for slotline ring resonator comparing to microstrip ring resonator. After studying the bandwidth of the two wideband bandpass filters in chapter three, it is clear that the bandwidth is determined by the separation between the start and end modes. But these two bandpass filters utilize the first two modes belonging to the same first-order modes and reduce the potential to achieving wider passband.

In this chapter, we aim to develop a bandpass filter using slotline ring resonator to achieve a fractional bandwidth much higher than 60%. In order to

achieve that goal, three modes from different pairs of degenerate modes are used to form a triple-mode wideband bandpass filter. The microstrip feed-lines are placed with 180° -separation to suppress one mode in each pair of degenerate modes. Four identical stubs located with an angle of 60° with respect to the symmetrical plane are used to adjust the positions of the remaining three modes.

4.1 Design Principle

Fig. 4.1(a) depicts the schematic of the proposed stub-loaded slotline ring resonator, where the Z_r , Z_1 and Z_2 are the characteristic impedances of the slotline ring and stubs, respectively. And θ_r , θ_1 and θ_2 denote the effective electrical lengths of the ring resonator and two individual stubs, respectively.

The microstrip feed-line placed with 180° -separation and at the symmetrical plane of both the even- and odd-mode bisections. This structure can suppress the first and third even modes and the second odd mode simultaneously. In this way, three remaining modes from different degenerate modes can be utilized to form a triple-mode passband. Based on analysis above, a higher fractional bandwidth can be achieved when all modes come from different orders.

However, as coupling strength from the feed-lines are not enough

(a)

(b)

Fig. 4.1 Proposed triple-mode slotline ring resonator with six loaded stubs (a) Schematic, (b) Equivalent transmission-line model.

to raise the three modes from three different orders, six slotline stubs are introduced to adjust these three modes with closer separation. These six stubs are utilized to adjust the remaining two odd modes and one even mode to form the desired triple mode.

Equivalent transmission-line model of the BPF in Fig. 4.1(a) is given in Fig. 4.1(b). For simplicity, we illustrate the even- and odd-

mode bisections of the circuit without two stubs in the symmetrical plane and ignoring the microstrip feed-lines in Fig. 4.2.

Fig. 4.2 Equivalent circuits of the triple-mode slotline ring resonator without stub in the symmetrical plane (a) Even mode, (b) Odd mode.

In Fig. 4.2(a), $Y_{+,-}^{e,o}$ represent the port admittance of the even- and odd-mode, looking into the up and down side. Under the even- and odd-mode resonances, i.e., $Y_+^e + Y_-^e = 0$ and $Y_+^o + Y_-^o = 0$, all the resonant frequencies can be simply determined from these equations. As the even- and odd-mode equivalent-circuit bisections are also symmetrical for the microstrip feed-lines, we can conclude that $Y_+^{e,o}$ is equal to $Y_-^{e,o}$. Therefore, the resonance conditions are $Y_+^e = 0$ and $Y_+^o = 0$.

In analysis, the ratio of characteristic impedances between slot stubs and ring resonator is R , where $R = Z_1/Z_r$. For simplicity, we can set the electrical length of the stub θ_2 to zero, Y_+^e for the even mode is then:

$$Y_+^e = \frac{Z_r + (Z_r \cot \theta_s - Z_1 \tan \theta_1) \tan(\theta_s/2)}{Z_r \{-jZ_r \cot \theta_s + jZ_1 \tan \theta_1 + jZ_r \tan(\theta_s/2)\}} \quad (4.1)$$

Similarly, we obtain Y_+^o of the odd mode:

$$Y_+^o = \frac{Z_r - (Z_r \tan \theta_s + Z_1 \tan \theta_1) \tan(\theta_s/2)}{Z_r \{jZ_r \tan \theta_s + jZ_1 \tan \theta_1 + jZ_r \tan(\theta_s/2)\}} \quad (4.2)$$

By setting Y_+^o and Y_+^e to zero, we can obtain resonant conditions for even mode (4.3) and odd mode (4.4) below.

$$\tan \theta_s + \tan(\theta_s/2) = R \tan \theta_1 \tan \theta_s \tan(\theta_s/2) \quad (4.3)$$

$$(\tan \theta_s + R \tan \theta_1) \tan(\theta_s/2) = 1 \quad (4.4)$$

Fig. 4.3(a) plots the four normalized resonant frequencies, f_{o1}/f_0 , f_{e2}/f_0 , f_{o3}/f_0 and f_z/f_0 versus the normalized arm length of θ_1/θ_s when R equals one. As seen in Fig. 4.3(a), only three modes exist when increasing ratio of $t = \theta_1/\theta_s$ because the the first and third even modes and the second odd mode are suppressed by the feed-lines. When $t < 1$, the only transmission zero is always above the three modes. So the three modes below the transmission zero can be utilized to form a triple-mode passband. Different from the microstrip ring resonator, the transmission zero, at 6 GHz, is from the signal phase cancellation from the outer circle to the inner circle instead of the up and down paths as the resonator is completely symmetrical for up and down paths.

As the four stubs can simultaneously control these three modes, and in order to add one more degree of freedom, two stubs are placed at the

symmetrical plane to control the two odd modes. As seen in Fig. 4.3(b), the second even mode and the transmission zero does not shift downward when increasing the ratio $3\theta_2/2\theta_s$ and fixing θ_1 .

(a)

(b)

Fig. 4.3 Normalized resonant frequencies versus electrical overall stub length, f_i are f_{o1} , f_{e2} , f_{o3} , f_z , respectively. (a) f_i/f_0 , $f_0 = 3\text{GHz}$, (b) f_i/f_z .

The frequency response $|S_{21}|$ under weak coupling is illustrated in Fig. 4.4. It is clear that three modes exist below one transmission zero, and the six stubs can be used to tune these three modes.

(a)

(b)

Fig. 4.4 Frequency response of the resonator under weak coupling (a) $\theta_2 = 0$, (b) $\theta_2 = 30^\circ$.

4.2 Experimental Results and Discussion

In this section, based on the above analysis, a triple-mode wideband BPF prototype is designed and optimized using ADS2009. The final detailed dimensions of the circuit are given in Fig. 4-5(a) along with its fabrication photograph in Fig. 4-5(b) and (c). The circuit is fabricated on a Rogers 3010 substrate, with dielectric

(a)

(b)

(c)

Fig. 4.5 Fabricated filter (a) Physic layout (unit: mm), (b) Microstrip line layer, (c) Slotline layer.

constant of 11.8 and thickness of 1.27 mm. Simulated S-parameter from ADS and the measured results are plotted as one in Fig. 4-6(a). It is clear that the measured results agree well with the simulated ones for the three main modes. Five modes and two transmission zeros are observed: three modes from the ring resonator and two modes from the feed-lines. The additional transmission zero is introduced because the

(a)

(b)

Fig. 4.6 Simulated and measured results of the designed wideband filter with six slotline stubs (a) S-parameter of frequency response, (b) Group delay.

microstrip feed-line is open-circuit at that frequency. The dual-mode passband around 7GHz is from modes of higher order and they will be investigated and utilized for the design of dual-band filters.

The center frequency of the passband is set as 3.0 GHz and the measured one is at 2.98 GHz with a fractional bandwidth of 100.7%. The minimal insertion loss is 0.72 dB and the return loss is larger than 11.5dB. Comparing with the filters proposed in [28] and [33], we can

see that our proposed filter has a good performance of much wider bandwidth, as shown in Table I. On the other hand, the group delay is less than 2ns within the realized passband from 1.48 GHz to 4.48 GHz, as is illustrated in Fig. 4-6(b). Although the upper stopband is not as wide as the one in [41], our design has a simple feeding structure and does not use many stubs above the slotline.

Table 4-1 Comparison of our filter with previous designs.

Wideband bandpass filters	Ref. [28]	Ref. [33]	Chapter 3	This Chapter
Fractional bandwidth (3dB)	64%	57.9%	66.0%	100.7%
Center frequency(GHz)	4.25	1.45	3.0	2.98
In-band insertion loss(dB)	0.9 (minimal)	0.6 (minimal)	1.1 (minimal)	0.72 (minimal)
Return loss(dB)	>17.5	>18.8	>15	>11.5

4.3 Conclusion

In this chapter, a triple-mode wideband bandpass filter has been proposed based on a slotline ring resonator and using three different degenerate modes. By allocating the microstrip feed-lines with 180°-separation to suppress two even modes, one odd mode as well as using six stubs to control the remaining three transmission modes, a

wideband bandpass filter with good performance has been designed. These three modes are properly adjusted to form a passband with 3dB fractional bandwidth as high as 100.7% with minimal in-band insertion loss 0.72 dB. Good agreement between the measured and simulated results verifies the design concept of our wideband filter.

Chapter 5 Dual-Band Bandpass Filter with Adjustable Bandwidth

With the emergence of different kinds of wireless system nowadays, multi-band bandpass filters with adjustable bandwidth are in high demand. In [10]-[17], non-uniform ring resonator with adjustable angle or meander ring with patch perturbation was utilized to split the degenerate modes. However, only one narrow band could be obtained using the above two approaches and can hardly meet practical requirements. In [39], a dual-band bandpass filter was proposed but with only a mode in the second band. Later, a dual-mode dual-band bandpass filter with only one single resonator was proposed in [22], in which eight stubs are used. Later, the same authors Luo and Zhu proposed a dual-mode triple-band bandpass filter with four stubs in [25]. These two bandpass filters mainly use the strong coupling between the feed-line and ring resonator to split the degenerate modes while stubs are used for exciting higher-order mode. A dual-band bandpass filter with only two stubs are proposed in [24]. Though, multi-band bandpass filters are proposed, researches are still ongoing to study the control of the bandwidth in each band.

In this chapter, a novel dual-band BPF with adjustable bandwidth based on a single slotline ring resonator using two slotline stubs is proposed and it is fed by two microstrip feed-lines at the 90°-separation for simultaneous exciting

the first six resonant modes without needing to deform the ring resonator as required in [22].

Comparing with the work described in Chapter 3, two stubs with the same electrical length are introduced to control the modes but with different angles. The operating principle and design procedure are described with the circuit model of ADS. Finally, a prototype of the filter is fabricated and measured results verify the simulated frequency response.

5.1 Design Principle

Fig. 5.1(a) depicts the schematic of the designed stub-loaded slotline ring resonator, where Z_r and Z_2 are the characteristic impedances of the slotline ring and two stubs, while $8\theta_r$, θ_2 and $2\theta_s$ denote the effective electrical lengths of the ring resonator, stub and the angle between the two stubs, respectively. Equivalent transmission-line model of the BPF in Fig. 5.1(a) is given in Fig. 5.1(b).

Fig. 5.2(a) illustrates the calculated frequency responses of $|S_{21}|$ using the equivalent model in Fig. 5.1(b) under the condition of weak coupling. We can see how modes change in response to the increment of the stub length θ_2 when the angle $2\theta_s$ between the stubs is set to a quarter of the ring. It is well known that, the degenerate modes cannot be split without perturbation. As seen in Fig.

Fig. 5.1 Proposed dual-band slotline ring resonator with two loaded stubs. (a) Schematic. (b) Equivalent transmission-line model.

5.2(a), only frequencies of degenerate modes at 3 GHz and approximately 6 GHz exist when the stub lengths are zero. Then the first-order degenerate modes are split and shift downward when the stub electrical length increases from zero to 45° and 90° . Meanwhile, it is easy to figure out that, the second-order even mode remains unchanged while the second-order odd and another third-degenerate mode shift downward when the stub's electrical length

(a)

(b)

Fig. 5.2 S-parameter versus electrical lengths of two slotline stubs and the angle between them under weak coupling at frequency 3.0 GHz (a) $2\theta_s=90^\circ$, $\theta_2=0^\circ$, 45° and 90° , (b) $\theta_2=90^\circ$, $\theta_s=38^\circ$, 45° and 50°

varies from zero to 45° . Finally, the second- and third-order degenerate modes form the second passband while these two first-order degenerate modes form the first passband. The separations of two modes in these two passbands are almost the same when the angle and stub electrical length are both set to 90° .

When the electrical lengths of stubs are fixed at 90° , the relation between the angle of two stubs and the space variations of two modes in two bands could be observed obviously from Fig. 5.2(b). Comparing the angle less than 90° with the angle bigger than 90° , variation of bandwidth in each passband is in the opposite direction. As illustrated in Fig. 5.2(b), when the angle is set to two times of 38° , separation of two modes for the first passband becomes narrow while the separation in second passband becomes wider compared to the case of 90° angle. And the separation of modes for the first passband is larger while the second smaller if the angle is set to two times 50° .

Based on the analysis above, a dual-band bandpass filter with controllable bandwidth in each passband is designed in theory with proper coupling. The symmetrical plane in Fig. 5.1(b) becomes perfect magnetic wall (M. W.) under the even-mode excitation and electric wall (E. W.) with odd-mode excitation, respectively. In this case, half of the circuit model becomes a one-port network with open-circuit for even-mode and short-circuit for odd-mode at the symmetrical plane, respectively.

In Fig. 5.3, $Y_{+,-}^{e,o}$ represents the port admittance of the even- and odd-mode, looking into the up and down sides. It is easy to conclude that $Y_+^e + Y_-^e = 0$ and $Y_+^o + Y_-^o = 0$ when the ring resonates under the resonance condition.

Fig. 5.3 Equivalent circuit (a) even mode, (b) odd mode

For simplicity of analysis, electrical length of the stub θ_2 is set equal to $2\theta_r$, which is a quarter of the ring, and the ratio of characteristic impedances between slot stubs and ring resonator is $R = Z_2/Z_r$. Then we can obtain Y_+^e and Y_-^e for even mode below:

$$Y_+^e = \frac{Z_r + j(-jZ_r \cot \theta_s + jZ_2 \tan \theta_2) \tan(3\theta_r - \theta_s)}{Z_r \{-jZ_r \cot \theta_s + jZ_2 \tan \theta_2 + jZ_r \tan(3\theta_r - \theta_s)\}} \quad (5.1)$$

$$Y_-^e = j \tan \theta_r / Z_r \quad (5.2)$$

Similarly, we can obtain Y_+^o and Y_-^o for odd mode below:

$$Y_+^o = \frac{Z_r + j(jZ_r \tan \theta_s + jZ_2 \tan \theta_2) \tan(3\theta_r - \theta_s)}{Z_r \{jZ_r \tan \theta_s + jZ_2 \tan \theta_2 + jZ_r \tan(3\theta_r - \theta_s)\}} \quad (5.3)$$

$$Y_-^o = -j \cot \theta_r / Z_r \quad (5.4)$$

As θ_2 is set equal to $2\theta_r$, the resonant conditions can be determined for even mode and odd mode by setting $Y_+^e + Y_-^e = 0$ and $Y_+^o + Y_-^o = 0$.

Fig. 5.4 (a) Layout of the designed bandpass filter with two stubs. (unit: mm). Simulated and measured results (b) $\theta_2=90^\circ$, $\theta_s=38^\circ$. (c) $\theta_2=90^\circ$, $\theta_s=45^\circ$. (d) $\theta_2=90^\circ$, $\theta_s=50^\circ$.

5.2 Experimental Results and Discussions

In this section, a slotline ring resonator with two stubs is utilized to design a compact dual-band bandwidth-controllable bandpass filter prototype at 3.0 GHz. The filter has been fabricated on the substrate Rogers 6010, with the dielectric constant of 10.8 and thickness of 1.27 mm. The circumference of the ring is a wavelength at the frequency 3GHz, and electrical length of the stubs are set to be a quarter of the

wavelength at 3GHz. Fig. 5.4 (a) shows the layout of the designed filter for the case of the angle between the stubs is set to 90° .

Simulated results for different angles are obtained from IE3D and they are plotted together with the measured results from Fig. 5.4(b), Fig. 5.4(c) and Fig. 5.4(d). The fractional bandwidths for two passbands are 15.9% and 24.2%, 22.0% and 14.9%, 31.5% and 6.6% for Fig. 5.4 (b), (c) and (d), respectively. The fractional bandwidth for the first passband increases from 15.9% to 22% and then 31.5% while it decrease in the second passband from 24.2% to 6.6% when the angle increases. The process reverses when angle decrease. Meanwhile, as illustrated in Fig. 5.4(c), the absolute bandwidths of two passbands are approximately equal when the angle is set to be 90° .

Measured results have reasonable agreement with the simulated ones. Comparing with dual-band bandpass filters in [22, 23, 25], the filter proposed in this chapter has a higher fractional bandwidth with fewer slotline stubs. However, the insertion loss is not as good as these three filters because of radiation loss. In order to achieve better insertion loss, relation between insertion loss and the dielectric constant, height, impedance ratio of slot stubs should be studied.

5.3 Conclusion

In this chapter, a dual-band slotline ring resonator bandpass filter with stub-loaded structure has been presented. The working principle of the proposed bandpass filter is described via calculated S-parameter results and a filter prototype using a single slotline ring resonator with two identical stubs of fixed electrical length placed along the ring resonator are designed and fabricated. Measured results show that dual-band bandpass filter with controllable bandwidth in each band has been achieved thus verifying the design principle.

Chapter 6 Conclusions and Recommendation

6.1 Conclusions of Work Conducted

In this thesis, a brief review of bandpass filters using ring resonator is introduced, which includes the design of dual-mode multi-band filters and single wideband filters with multiple-modes. In early days, patch, notch and capacitors were commonly used to design a single-band filter with two transmission modes. However, with the increased demand in multi-band wireless systems, small perturbations are not enough to realize dual- or triple-band bandpass filters.

By adding stubs at the symmetrical plane or other parts of a ring resonator, higher order degenerate modes could be controlled to construct various multi-band bandpass filters. Since a strong coupling between the feed-line and the ring resonator is usually hard to achieve, these filters can achieve a narrow bandwidth. In order to obtain wider bandwidth, interdigital feed-lines are usually introduced. But, this approach may enlarge the entire filter size and damage the original property of the resonator filter. Considering these problems, it is attractive to use the slotline ring resonator to design such kinds of filters.

Based on above considerations, this thesis presents three wideband bandpass filters using novel triple-mode stub-loaded ring resonator on slotline

structure. In chapter 3, by attaching two stubs at or perpendicular to the symmetrical plane of the ring resonator, two triple-mode wideband bandpass filters with a fractional bandwidth 66% and 63% are designed. These two circuits verify that the resonant modes of ring resonator can be excited without considering the coupling from the microstrip line. The electrical length and position of stubs for slotline ring resonator can be used to tune the modes.

In order to achieve wider bandwidth, based on the concept of multi-mode resonator that the bandwidth is mainly determined by starting mode and ending mode, a triple-mode wideband bandpass filter with a fractional bandwidth as high as 100.7% has been designed using three modes from three different degenerate modes in chapter 4. Because adjusting the location of the microstrip feed-line can help to suppress unwanted modes, three modes have been suppressed simultaneously by setting feed-lines with separation of half the ring.

As little research has been conducted for dual-band pass filter with adjustable bandwidth, in chapter 5, a dual-band bandpass filter with adjustable bandwidth has been proposed by changing the location of two stubs unlike those two in chapter 3. By increasing the stub lengths while maintaining the angle between stubs to be a quarter of the ring, the first-order degenerate modes shift down to form the first passband, while the second-order odd mode and one third-order mode move down to form the second passband.

Then two passbands with approximately the same absolute bandwidth are obtained when the electrical length and angle of the two stubs are both set to a quarter of the wavelength. With stub length fixed to a quarter wavelength, the bandwidth in each band can be controlled by varying the angle, thus forming a dual-band bandpass filter with adjustable bandwidth. Measured results in these designs agree with simulated one and verify our design principle.

6.2 Recommendations of Further Work

The following topics are suggested for future investigation:

1. New topology of the slotline ring resonator will be studied further to construct various multi-band bandpass filters. Besides slotline stubs as form of perturbation, microstrip line stubs can be used as another form of perturbation for slotline ring resonator. Most research are conducted with one ring structure, multi-ring resonator structure may be considered in the future.
2. Interaction between slotline stubs will be analyzed and used in the form of degenerate modes splitting.
3. Besides slotline ring resonator based filters, other types of microwave devices like power divider can also be designed using slotline ring resonator.

Author's Publications

- [1] B. Jiang, L. Zhu, and D. Chen, "A novel wideband bandpass filter using triple-mode slotline ring resonator," *Progress In Electromagnetics Research Letters*, vol. 40, pp.163–170, 2013.

References

- [1] D. M. Pozar, *Microwave Engineering*, 3rd edition, Wiley, 2005.
- [2] K. Chang and L.H. Hsieh, *Microwave Ring Circuits and Related Structure*, Wiley, 2004.
- [3] I. Wolff, "Microstrip bandpass filter using degenerate modes of a microstrip ring resonator," *Electron. Lett.*, vol. 8, no. 12, pp.302-303, Jun. 1972.
- [4] J. S. Hong and S. Li, "Theory and experiment of dual-mode microstrip triangular patch resonators and filters," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 4, pp.1237-1243, Apr. 2004.
- [5] J. S. Hong and M. J. Lancaster, "Microstrip bandpass filter using degenerate modes of a novel meander loop resonator," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 371-372, Nov. 1995.
- [6] J. S. Hong and M. J. Lancaster, "Bandpass characteristics of new dual-mode microstrip square loop resonators," *Electron. Lett.*, vol. 31, no. 11, pp. 891-892, May 1995.
- [7] R.-B. Wu and S. Amari, "New triangular microstrip loop resonators for bandpass dual-mode filter applications," in *IEEE MTT-S Int. Dig.*, pp. 941-944, Jun. 2005.

- [8] C. Lugo and J. Papapolymerou, "Bandpass filter design using a microstrip triangular loop resonator with dual-mode operation," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 7, pp. 475 -477, July 2005.
- [9] R. Gómez-García and J. I. Alonso, "Design of sharp-rejection and low-loss wideband planar filters using signal-interference techniques," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 8, pp. 530–532, Aug. 2005.
- [10] M. Matsuo, H. Yabuki and M. Makimoto, "Dual-mode stepped-impedance ring resonator for bandpass filter applications," *IEEE Trans. Microwave. Theory Tech.*, vol. 49, no. 7, pp. 1235-1240, July 2001.
- [11] A. Gorur, "Description of coupling between degenerate modes of a dual-mode microstrip loop resonator using a novel perturbation arrangement and its dual-mode bandpass filter applications," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 2, pp. 671–677, Feb. 2004.
- [12] B. T. Tan, J. J. Yu, S. T. Chew, M. S. Leong, and B. L. Ooi, "A miniaturized dual-mode ring bandpass filter with a new perturbation," *IEEE Trans. Microwave. Theory Tech.*, vol. 53, no. 1, pp. 343-348, Jan. 2005.
- [13] R.-J. Mao and X.-H. Tang, "Novel dual-mode bandpass filter using hexagonal loop resonators," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 9, pp. 3526 -3533, Sep. 2006.

- [14]J.-X. Chen, T. Y. Yum, J.-L. Li and Q. Xue, "Dual-mode dual-band bandpass filter using stacked-loop structure," *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 9, pp. 502 -504, Sep. 2006.
- [15]J. T. Kuo and C. Y. Tsai, "Periodic stepped-impedance ring resonator (PSIRR) bandpass filter with a miniaturized area and desirable upper stopband characteristics," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 3, pp. 1107 -1112, Mar. 2006.
- [16]X. Y. Zhang and Q. Xue, "Novel dual-mode dual-band bandpass filters using coplanar-waveguide-fed ring resonators," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 10, pp. 2183 -2190, Oct. 2007.
- [17]T.-L. Lin, J.-T. Kuo and S.-J. Chung, "Dual-mode ring resonator bandpass filter with asymmetric inductive coupling and its miniaturization," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 9, pp. 2808-2814, Sep. 2012.
- [18]L. Zhu and K. Wu, "A joint field/circuit model of line-to-ring coupling structures and its application to the design of microstrip dual-mode filters and ring resonator circuits," *IEEE Trans. Microwave. Theory Tech.*, vol. 47, no. 10, pp. 1938-1948, Oct. 1999.
- [19]U. Karacaoglu, D. Sanchez-Hernandez, I.D. Robertson and M. Guglielmi, "Harmonic suppression in microstrip dual-mode ring-resonator bandpass filter," in *IEEE MTT-S Int. Dig.*, 1996, vol. 3, pp.1635-1638.

- [20]A. C. Kundu and I. Awai, "Control of attenuation mode frequency of a dual-mode microstrip ring resonator bandpass filter," *IEEE Trans. Microwave. Theory Tech.*, vol. 49, no. 6, pp. 1113-1117, June 2001.
- [21]X. D. Hung and C. H. Cheng, "A novel coplanar-waveguide bandpass filter using a dual-mode square-ring resonator", *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 1, pp.13 -15, Jan. 2006.
- [22]S. Luo and L. Zhu, "A novel dual-mode dual-band bandpass filter based on a single ring resonator," *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 8, pp. 497 -499, Aug. 2009.
- [23]S. Luo, L. Zhu, and S. Sun, "A dual-band ring-resonator bandpass filter based on two pairs of degenerate modes," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 12, pp.3427 -3432, Dec. 2010.
- [24]S. Sun, "A dual-band bandpass filter using a single dual-mode ring resonator," *IEEE Microw.Wireless Compon.Lett.*, vol. 21, no. 6, pp. 298-300, Jun. 2011.
- [25]S. Luo, L. Zhu, and S. Sun, "Compact dual-mode triple-band bandpass filters using three pairs of degenerate modes in a ring resonator," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 5, pp. 1222 - 1229, May. 2011.
- [26]S. Fu, B. Wu, J. Chen, S.-J. Sun and C.-H. Liang, "Novel second-order dual-mode dual-band filters using capacitance loaded square loop

- resonator,” *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 3, pp.477-483, Mar. 2012.
- [27]L. H. Hsieh and K. Chang, “Compact, low insertion-loss, sharp-rejection, and wide-band microstrip bandpass filters,” *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 4, pp. 1241-1246, Apr. 2003.
- [28]S. Sun, and L. Zhu, “Wideband microstrip ring resonator bandpass filters under multiple resonances,” *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 10, pp. 2176-2182, Oct. 2007.
- [29]H. Ishida and K. Araki, “Design and analysis of UWB bandpass filter with ring filter,” in *IEEE MTT-S Int. Dig.*, vol. 3, pp. 1307-1310, Jun. 2004.
- [30]S. Sun, L. Zhu and H.-H. Tan, “A compact wideband bandpass filter using transversal resonator and asymmetrical interdigital coupled lines,” *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 3, pp.173 -175, Mar. 2008.
- [31]K. Song and Y. Fan, “Compact ultra-wideband bandpass filter using dual-line coupling structure,” *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 1, pp. 30-32, Jan. 2009.
- [32]C. H. Kim and K. Chang, “Ultra-wideband (UWB) ring resonator bandpass filter with a notched band,” *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 4, pp. 206 -208, 2011.

- [33]J. Fan, D. Zhan, C. Jin, and J. Luo, "Wideband microstrip bandpass filter based on quadruple mode ring resonator," *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 7, pp. 348-350, Jul. 2012.
- [34]M.-F. Lei and H. Wang, "An analysis of miniaturized dual-mode bandpass filter structure using shunt-capacitance perturbation," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 3, pp. 861 -867, Mar. 2005.
- [35]D. K. Paul, P. Gardner, and K. P. Tan, "Suppression of even modes in microstrip ring resonator," *Electron. Lett.*, vol. 30, no. 21, pp. 1772-1774, Oct. 1994.
- [36]B. T. Tan, S. T. Chew, M. S. Leong, and B. L. Ooi, "A dual-mode bandpass filter with enhanced capacitive perturbation," *IEEE Trans. Microwave. Theory Tech.*, vol-51, no. 8, pp.1906-1910, Aug. 2003.
- [37]M. Chongcheawchamnan, R. Phromlounsri, M. Krairisk, and I. D. Robertson, "Microstrip ring resonator filter with inductively-compensated parallel-coupled feed and stepped-impedance design," *Electron. Lett.*, vol. 43, no. 23, Nov. 2007.
- [38]J. S. Hong and M. J. Lancaster, "Capacitively loaded microstrip loop resonator," *Electron Lett.*, vol. 30, no. 18, pp. 1494 -1495, Aug. 1994.
- [39]T. H. Huang, H. J. Chen, C. S. Chang, L. S. Chen, Y. H. Wang and M.-P. Houn, "A novel compact ring dual-mode filter with adjustable

- second-passband for dual-band applications,” *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 6, pp. 360 -362, Jun. 2006.
- [40] Y. C. Chiou, C. Y. Wu and J. T. Kuo, “New miniaturized dual-mode dual-band ring resonator bandpass filter with microwave C-sections,” *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 2, pp. 67 -69, Feb. 2010.
- [41] P. Mondal, M. K. Mandal, and A. Chakrabarty, “Compact ultra-wideband bandpass filter with improved upper stopband,” *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 9, pp. 643–645, Sep. 2007.