INVESTIGATIONS ON SOME PLANAR MICROWAVE FILTERS

A Thesis submitted in partial fulfillment of the Requirements for the degree of

Master of Technology
In
Electronics and Communication Engineering
Specialization: Communication and Networks

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27th May 2014

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Under the Guidance of
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Dedicated to My family

DEPT. OF ELECTRONICS AND COMMUNICATION ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
ROURKELA – 769008, ODISHA, INDIA

Certificate

This is to certify that the work in the thesis entitled **Investigations on Some Planar Microwave filters** by **Katta Saran Krishna** is a record of an original research work carried out by him during 2013 - 2014 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electronics and Communication Engineering (Communication and Networks), National Institute of Technology, Rourkela. Neither this thesis nor any part of it, to the best of my knowledge, has been submitted for any degree or diploma elsewhere.

Place: NIT Rourkela
Date: 27th May 2014

Dr. Santanu K. Behera
Associate Professor

DEPT. OF ELECTRONICS AND COMMUNICATION ENGINEERING

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I certify that

a) The work contained in the thesis is original and has been done by myself under the general supervision of my supervisor.

b) The work has not been submitted to any other Institute for any degree or diploma.

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Katta Saran Krishna

27th May 2014

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Abstract

Filters are substantial microwave components. RF/Microwave filters can be implemented using transmission lines. In this thesis microstrip bandpass filters had been designed for RF/microwave applications. Some novel techniques like implementing the open split koch loop resonators, open split square loop resonators, and star shaped multi-mode resonators are implemented in designing the microstrip bandpass filters. Microstrip filters are used in this report to design bandpass filters because of their compact sizes.

The goal of this thesis is to investigate on some planar microwave bandpass filters. In this thesis four novel compact bandpass filters has been designed and simulated, specifically three pole koch resonator, seven pole koch resonator, three pole square loop resonator and compact UWB bandpass filter using MMR. The design and simulation of each and every filter is given in detail with including all the required specifications. From the previous research studies it is evident that, to design a good bandpass filter there should be a smooth passband and good stopband with higher insertion loss in the stopband. The four designs which are explained in this thesis has these important factors, which makes these filters useful for the microwave applications.

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CHAPTER ONE

Introduction

In the previous years, wireless communication systems has developed tremendously, there was a prompt development in ultra-wideband systems, wireless internet like Wifi and Wimax, broadband personal communication systems and 3G (third generation), 4G (fourth generation) technologies. Due to this rapid development there was a need for more rigid microwave components. And now a days satellite systems changed their path from static telecommunications systems to mobile, remote sensing and navigation applications. Microwave components plays an important role in the satellite systems. Microwave components include microwave resonant components such as microwave filters, dielectric resonant antenna arrays (DRA), duplexers. Because of the rapid growth in the wireless communication area, it created more challenging requirements that enforce challenges on various novel designs, optimization and understanding of components. In microwave filters the challenges are to be faced in miniaturization, bandwidth, phase linearity, and selectivity of the filters.

1.1 Microwave Communication:

The electromagnetic waves are the waves whose frequency ranges from 300 MHz - 300 GHz, these range of frequencies are referred as microwaves. The wavelength of this waves in free space is about 1 m – 1 mm. The electromagnetic spectrum is shown in figure 1.1, it demonstrates schematically the electromagnetic spectrum. Further some selected frequency spectrums are allocated into many frequency bands as betokened in Table 1.1. Frequency boundaries between RF and microwave are almost arbitrary. The boundary rely on the specific technologies established for the utilization of that particular frequency range. The applications that use RF/microwave frequency ranges are communications, remote sensing and many more.

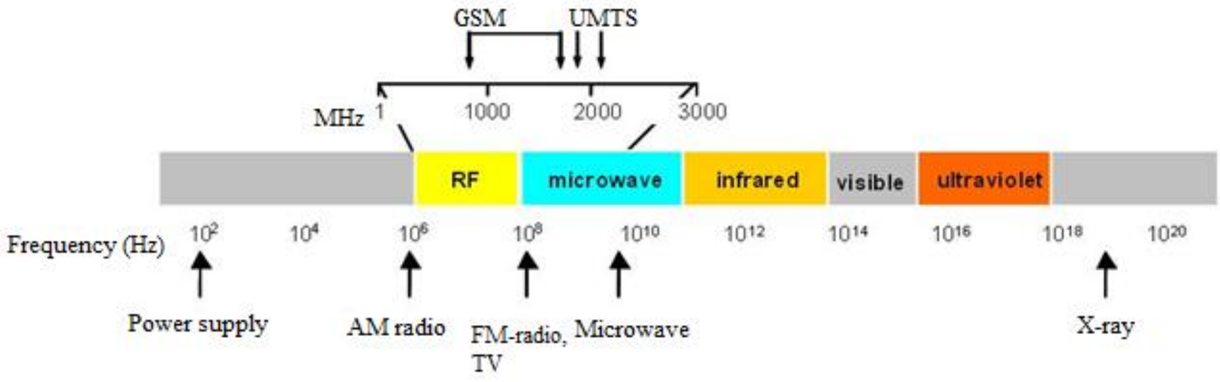


Figure 1. 1 Electromagnetic spectrum

Frequency range	Band designation
140-220 GHz	G-band
110-170 GHz	D-band
75-110 GHz	W-band
60-90 GHz	E-band
50-70 GHz	V-band
40-60 GHz	U-band

33-50 GHz	Q-band
26.5-40 GHz	Ka-band
18-26.5 GHz	K-band
12.4-18GHz	Ku-band
8-12.4 GHz	X-band
4-8 GHz	C-band
2-4 GHz	S-band
1-2 GHz	L-band
500-1000 MHz	UHF-band
50-500 MHz	VHF-band

Table 1.1 Frequency bands

1.2 Definition of a Filter

A filter is used to regulate the frequency response at a fixed point in the EM spectrum by providing low loss transmission at the preferred frequency band and high attenuation at remaining frequencies. Filters are extensively used in many applications like communications, remote sensing, radars etc. A filter is generally a two-port network.

1.3 Role of filters in microwave communication

Filters are essential in separating and sorting signals in communication systems. To cull or confine the RF/microwave signals within given spectral limits, filters are used. The role of filters in communication systems is to usually transmit and receive amplitude and/or phase modulated signals through a communication channel. To get rid of or suppress spurious frequencies from being transmitted or received in radio transmitters and receivers, filters are used. Evolving applications such as wireless communication remains to challenge RF/microwave filters with even more rigid requirements like smaller size, lighter weight and lower cost with better performance. Filters used in communication and radar applications, are implemented in different kinds of transmission lines comprising stripline, rectangular waveguide, and microstrip. Filters are also the integral part of multiplexers which are of major demand in the broadband wireless access communication systems.

1.4 Applications of filters

Microwave filters play an important role in almost every RF/microwave communications system. A microwave filter is basically a device that is used to discriminate between wanted and unwanted signals within a specified frequency band. The term microwave refers to the frequency range between 300 MHz and 30 GHz. As the communication systems evolve, higher frequencies are explored and new standards are set. Also, the filter requirements in terms of selectivity become more stringent due to the limited available frequency spectrum. Other filter specifications are generally dictated by the intended application. Examples of filter characteristics and applications will be presented in the next section.

1.5 Satellite filters

Satellite filters cover a large frequency range depending on the specific service offered by the satellite payload [1]. For example, navigation mobile satellite systems are naturally activated in the L and S bands (1-2 GHz, 2-4 GHz, respectively) and remote sensing applications will work mainly in the C band (4-8 GHz). For most viable communications, there is an outstanding high demand on the frequency spectrum, higher Ku band (12-18 GHz) and other upper frequency bands (20-30 GHz) are considered [2]. A communication satellite is basically a repeater that receives microwave signals, amplifies them and resends them to the receiving end. The bandwidth is divided into narrow band channels, since the practical considerations due to non linearities and effect of noise in power amplifiers. The partition and recombination of channels are done by means of input and output multiplexers individually. The input and output multiplexers are poised of many narrow bandpass filters (typical fractional bandwidths between 0.2% and 2%). Satellite microwave bandpass filters have been typically executed using waveguide technology due to high quality factors and high power handling capability. On the other hand, waveguide filters are bulky and heavy. There has been a significant amount of work done to reduce the size and weight of satellite filters. A fruitful solution involves using dual-mode cavities, i.e. cavities that support two degenerate resonances [5-7]. This reduces the amount of physical cavities by an aspect of two. Also, the usage of dual-mode cavities permits the implementation of topologies that are capable of producing transmission zeros at finite frequencies and hence improving filter selectivity.

1.6 Microwave filters in cellular communication

Microwave filters are very important components in cellular systems where stringent filter specifications are required both on the mobile station and base station levels. All modern full duplex personal communications systems require transmit and receive filters for each transceiver unit at least at the base station level. Transmit filters must be very selective to prevent out of band inter-modulation interference to satisfy regulatory requirements as well as prevent adjacent channel interference. Acceptable levels of adjacent channel interference in TDMA second generation mobiles are specified in GSM ETSI standards as C/A > -9dB. In practice a C/A of -6 dB is used in the network design. Also, the transmit filters must have low insertion loss to satisfy efficiency requirements. A typical transmit filter contains a return loss of 20dB and passband insertion loss of 0.8 dB. It is obvious that the technology used in filter realization in base stations is significantly different from that used in handsets. Although the filter specifications in handsets are less stringent due to lower power handling (33dBm maximum transmit power), size requirements remain a challenging task. One of the main difficulties is parasitic or unwanted coupling that is caused by the close proximity of the resonators.

Another application of filters is in cellular systems microwave links to connect base stations to BSC (base station controller) and then to the MSC (Mobile Switching Center). These are high-speed links with directive dish antennas. There are few licensed bands for transmission such as 8, 11, 18, 23, 24 and 38 GHz. The choice of the frequency band depends on spectrum availability, length of the hop and required link reliability. Filters for transmission systems are usually constructed using waveguide technology due to the high quality factors requirements and high power handling capabilities.

1.7 Literature review on Microwave filters

Despite the extensive literature in the field of microwave filters, several issues are still either not well understood or lack a systematic solution or accurate design procedure. For instance, one of the major difficulties with miniaturized and compact filters is parasitic coupling that can be in the order of the main coupling in compact filters. This makes it difficult to identify a sparse topology on which most of design and optimization methods are based. It is sometimes impossible to predict the behavior of the filter when using a conventional coupling topology based on the arrangement of physical resonators. Most importantly, the absence of a reliable circuit model that represents compact filters makes the optimization of this class of filters, within efficient and systematic techniques such as space mapping technique, impossible. The same argument holds for wideband filters that cannot be represented by the conventional low-pass prototypes that are based on a narrowband approximation.

One of the major difficulties with microwave filter design is the absence of a generic design technique to transform the low-pass prototype into physical dimensions except for few cases as in [5, 6]. A careful investigation of the available literature reveals that this is due to basing most of the design techniques unswervingly on the phenomenon of resonance. The dependence of the resonant frequencies of the resonators on the coupling strength (loading) is not systematically accounted for in the model. It is indeed shown that by using the phenomenon of propagation instead of resonance, it becomes straightforward to account for the piling of the resonances by the coupling components as in in-line direct-coupled resonator filters [3].

Despite the widespread use of dual-mode filters in satellite communications, the design and realization of this class of filters is not straightforward. The concept of dual-mode filters was anticipated by Atia and Williams in the 1970's [5-7]. In general, filters designed according to this theory require extensive optimization. Tuning elements are used as part of the CAD design as well as in compensating for inherent manufacturing errors. The resulting designs are very time-consuming, labor intensive, costly and at times extremely sensitive. A satisfactory solution to this problem is not known.

The main goal of this thesis is to find new techniques for the design of bandpass microstrip filters. Detailed investigation of the relevance of equivalent circuits used to represent the filter response to the field theory is carried out in detail. The new view is exploited to formulate new design and implementation methods for microwave filters.

1.8 Organization of Thesis

The organization of thesis is as follows:

Chapter one gives a brief overview about microwave communication, microwave filters and its applications, and literature review on microwave filters.

Chapter two is dedicated to the basic concepts of transmission lines, the discussion is strictly limited to the concepts which are helpful only in designing microstrip filters.

Chapter three gives a brief introduction to the types of microstrip filters and their applications.

In **Chapter four**, novel techniques which are used in designing the bandpass filters are presented. The novel designs includes OSKLRs and OSSLRs. The simulated designs and results are presented.

In Cha**pter five**, a new type of MMR is discussed, which is implemented in designing the UWB filter.

The simulated results of the UWB filter are presented in detail.

In **Chapter six,** general conclusion and suggestion for future work is presented.

CHAPTER TWO

Basic concepts of Transmission Lines

The essential theories and the equations which are helpful in designing the microstrip lines, discontinuities, components compatible for filter design, and coupled microstrip lines are concisely explained.

2.1 Microstrip Lines

2.1.1 Structure of the Microstrip

The common structure of a microstrip is demonstrated in Figure 2.1. A microstrip line of thickness t and width W sits on the top of a dielectric substrate. The dielectric substrate of thickness h has a relative dielectric constant ε_r, and there is a ground plane at the bottom of the structure.

2.1.2 Waves in Microstrip

The microstrip structure is inhomogeneous because the fields arising from the corners is exhibited into two media, “air above and dielectric below”. The microstrip will not be able to back a perfect TEM wave because of this inhomogeneous nature. This is due to that a perfect TEM wave has only transverse electric and magnetic field components whose propagation velocity is a function of the material parameters like permittivity ε and the permeability μ. However, the waves in a microstrip line does not possess longitudinal components of EM fields because of the presence of the dielectric substrate and the air which are called as two guided-wave media.

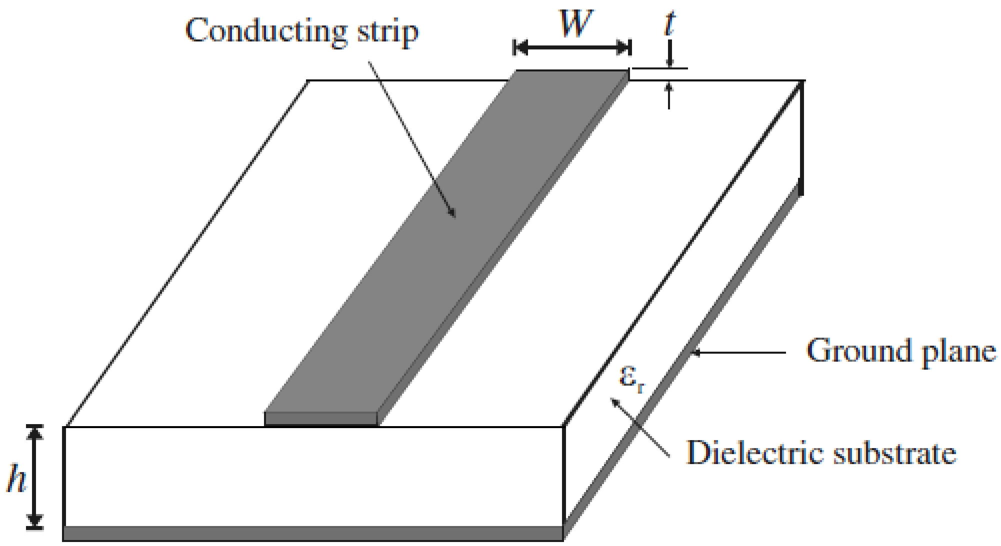


Figure 2. 1 Broad microstrip structure

2.1.3 Quasi-TEM Approximation

The longitudinal components may be neglected when the fields in the dominant mode of a microstrip line. These fields remain very much negligible than the transverse electric and magnetic components. In this instance, the dominant mode will be behaving like a TEM mode, therefore the transmission line theory for TEM mode can also be applicable for the microstrip line. This approximation is valid for most of the operating frequencies of the microstrip.

2.1.4 Guided Wavelength, Propagation Constant, Phase Velocity, and Electrical Length

The guided wavelength of the quasi-TEM mode is

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{re}}} \tag{2.1}$$

Here, λ_0 = free space wavelength. For the convenience, frequency is specified in gigahertz (GHz), and the guided wavelength in millimeters as monitors:

$$\lambda_g = \frac{300}{f(GHz)\sqrt{\varepsilon_{re}}}\, mm \tag{2.2}$$

The allied propagation constant β related to guided wavelength λ_g and phase velocity v_p can be given by:

$$\beta = \frac{2\pi}{\lambda_g} \tag{2.3}$$

$$v_p = \frac{\omega}{\beta} = \frac{c}{\sqrt{\varepsilon_{re}}} \tag{2.4}$$

where

$c \approx 3.0 \times 10^8$ m/s

The electrical length of the microstrip can be given by,

$$\theta = \beta l \tag{2.5}$$

Henceforth, $\theta = \pi/2$ when $l = \lambda_g/4$, and $\theta = \pi$ when $l = \lambda_g/2$. In designing the microstrip filters these two important parameters half-wavelength ($\lambda_g/2$) and quarter-wavelength ($\lambda_g/4$) microstrip lines are very essential.

2.1.5 Dispersion in Microstrip

In common the microstrip dispersions; viz., its phase velocity is not a constant factor but varies according to the operating frequency. The effective dielectric constant ε_{re} depends on the operating frequency. As the frequency of operation increases the value of effective dielectric constant reaches towards the actual value of dielectric constant. To consider the dispersion effect, the effective dielectric constant can be expressed as a function of frequency. Which can be given by the expression:

$$\varepsilon_{re}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{re}}{1+\left(\frac{f}{f_{50}}\right)^m} \qquad (2.6)$$

where

$$f_{50} = \frac{f_{TM_0}}{0.75+(0.75-0.332\varepsilon_r{}^{-1.73})W/h} \qquad (2.7)$$

$$f_{TM_0} = \frac{c}{2\pi h\sqrt{(\varepsilon_r - \varepsilon_{re})}} tan^{-1}\left(\varepsilon_r\sqrt{\frac{\varepsilon_{re}-1}{\varepsilon_r-\varepsilon_{re}}}\right) \qquad (2.8)$$

$$m = m_0 m_c \leq 2.32 \qquad (2.9)$$

$$m_0 = 1 + \frac{1}{1+\sqrt{(\frac{W}{h})}} + 0.32\left(\frac{1}{1+\sqrt{(\frac{W}{h})}}\right)^3 \qquad (2.10)$$

$$m_c = \{1 + \frac{1.4}{1+\frac{W}{h}}\left\{0.15 - 0.235exp\left(\frac{-0.45f}{f_{50}}\right)\right\} \quad For\,\frac{W}{h} \leq 0.7 \qquad (2.11)$$

$$and$$

$$1 \qquad\qquad For\,\frac{W}{h} \geq 0.7$$

The dispersion also effects the characteristic impedance, which is given by

$$Z_c = Z_c \frac{\varepsilon_{re}(f)-1}{\varepsilon_{re}-1} \sqrt{\frac{\varepsilon_{re}}{\varepsilon_{re}(f)}} \tag{2.12}$$

where

$Z_c -$ Quasistatic value of characteristic impedance

2.1.6 Losses in Microstrip

The radiation losses, conductors, and dielectrics, magnetic substrates (here the magnetic loss plays a role, like as ferrites) are the lossy components. The propagation constant is complex on the lossy transmission line; viz.,$\gamma = \alpha + j\beta$, where the attenuation constant is denoted by α which is the real part and the unit of α is nepers per unit length and is expressed in decibels dB/unit length, it is shown as

$$\alpha(dB/unit\ length\ ) = (20log_{10}e)\alpha(nepers/unit\ length)$$

$$\approx 8.686\alpha(nepers/unit\ length)$$

2.1.7 Enclosure Effect

Most of the microstrip circuits uses a metallic enclosure, for example filters. The metallic conducting walls effects the characteristic impedance and the ε_{re}. To overcome this enclosure effect, the height is taken eight times more than the height of the substrate and the distance from the walls is taken five times more than the height of the substrate.

2.1.8 Higher order modes and Surface Waves

By operating below the cutoff frequency of the dominant higher order mode, we can sidestep the excitation of the higher order modes. The cutoff frequency of the dominant higher order mode can be expressed as:

$$f_c = \frac{c}{\sqrt{\varepsilon_r}\,(2W+0.8h)} \tag{2.13}$$

Surface wave generates in the air dielectric interface on a metallic ground plane. The frequency related to surface wave mode can be given by:

$$f_s = \frac{c\,tan^{-1}\varepsilon_r}{\sqrt{2}\pi h\sqrt{\varepsilon_r - 1}} \tag{2.14}$$

2.2 Coupled microstrip lines

For implementing microstrip filters coupled microstrip lines are extensively used. A pair of coupled microstrip lines is described in Figure 2.2, they are in edge coupled configuration in which a pair of microstrip lines are of width *w* and separated by a distance *s*. This configuration generates two quasi -TEM modes, which are the even and odd modes shown in Figure 2.3.

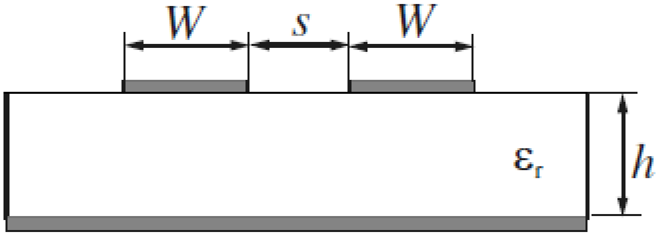
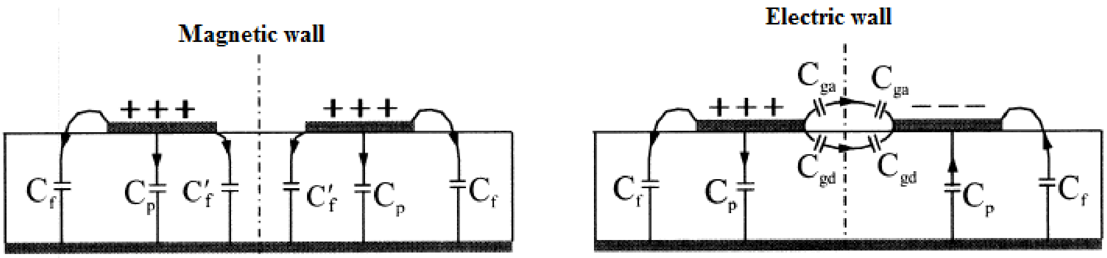


Figure 2. 2 Cross sectional view of the pair of coupled microstrip lines



(a) Even Mode (b) Odd mode

Figure 2. 3 Quasi-TEM modes of a coupled microstrip lines pair

Even mode:

In this mode, both microstrip lines carry the similar charges which are the positive ones or does have the same voltage potentials, due to this magnetic wall is formed at the symmetry plane, as illustrated in Figure 2.3(a).

Odd mode:

In this mode, both microstrip lines carry the charges with the opposite signs or does have the opposite voltage potentials, due to this electric wall is formed at the symmetry plane, as shown in Figure 4.3(*b*).

In the same time these two modes will be excited in common. As they are not pure TEM modes they have different phase velocities and different permittivities. Henceforth, these lines are categorized by the effective dielectric constants and the characteristic impedances for both the modes [23].

2.2.1 Design Equations

The characteristic impedances and the effective dielectric constants are given below. The expression for static approximation (dispersion is not considered) is expressed by:

$$\varepsilon^{e}{}_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{10}{v}\right)^{-a_e b_e} \qquad (2.15)$$

with

$$v = \frac{u(20+g^2)}{10+g^2} + g\exp(-g) \qquad (2.16)$$

$$a_e = 1 + \frac{1}{49} ln\left[\frac{v^4+(v/52)^2}{v^4+0.432}\right] + \frac{1}{18.7} ln\left[1+(\frac{v}{18.1})^3\right] \qquad (2.17)$$

$$b_e = 0.564\left(\frac{\varepsilon_r-0.9}{\varepsilon_r+3}\right)^{0.053} \qquad (2.18)$$

where $u = W/h$ and $g = s/h$. The error in $\varepsilon^{e}{}_{re}$ is within 0.7% over the ranges of $0.1 \le u \le 10, 0.1 \le g \le 10,$ and $1 \le \varepsilon_r \le 18.$

$$\varepsilon^{0}{}_{re} = \varepsilon_{re} + [0.5(\varepsilon_r+1) - \varepsilon_{re} + a_0]\exp(-c_0 g^{d0}) \qquad (2.19)$$

with

$$a_0 = 0.7287[\varepsilon_{re} - 0.5(\varepsilon_r+1)]\,[1-\exp(-0.17u)] \qquad (2.20)$$

$$b_0 = \frac{0.747\varepsilon_r}{0.15+\varepsilon_r} \qquad (2.21)$$

$$c_0 = b_0 - (b_0 - 0.207)\exp(-0.414u) \qquad (2.22)$$

$$d_0 = 0.593 + 0.694\exp(-0.562u) \qquad (2.23)$$

where

$\varepsilon_{re} -$ Static effective dielectric constant of single microstrip of width W

The error in $\varepsilon^{0}{}_{re}$ is of the order of 0.5%.

$$Z_{ce} = Z_c \frac{\sqrt{\varepsilon_{re}/\varepsilon^{e}{}_{re}}}{1-Q_4\sqrt{\varepsilon_{re}}\,.\,Z_c/377} \qquad (2.24)$$

where $Z_c -$ Characteristic impedance of single microstrip of width W

$$Q_1 = 0.8695u^{0.194} \tag{2.25}$$

$$Q_2 = 1 + 0.7519g + 0.189g^{2.31} \tag{2.26}$$

$$Q_3 = 0.1975 + \left[16.6 + (\frac{8.4}{g})^6\right]^{-0.387} + \frac{1}{241}\ln\left[\frac{g^{10}}{1+(\frac{g}{3.4})^{10}}\right] \tag{2.27}$$

$$Q_4 = \frac{2Q_1}{Q_2}\,\frac{1}{u^{Q_3}\exp(-g)+[2-\exp(-g)]u^{-Q_3}} \tag{2.28}$$

$$Z_{co} = Z_c\,\frac{\sqrt{\varepsilon_{re}/\varepsilon^0{}_{re}}}{1-Q_{10}\sqrt{\varepsilon_{re}}\,Z_c/377} \tag{2.29}$$

with

$$Q_5 = 1.794 + 1.14\,ln\left[1 + \frac{0.638}{g+0.517g^{2.43}}\right] \tag{2.30}$$

$$Q_6 = 0.2305 + \frac{1}{281.3}\ln\left[\frac{g^{10}}{1+(\frac{g}{5.8})^{10}}\right] + \frac{1}{5.1}\,\ln(1 + 0.598g^{1.154}) \tag{2.31}$$

$$Q_7 = \frac{10+190g^2}{1+82.3g^3} \tag{2.32}$$

$$Q_8 = exp\left[-6.5 - 0.95\ln(g) - (\frac{g}{0.15})^5\right] \tag{2.33}$$

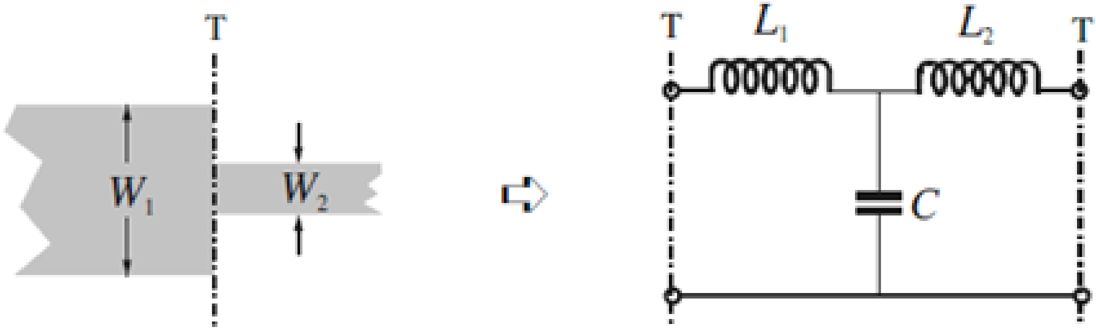
$$Q_9 = \ln(Q_7)\,(Q_8 + 1/16.5) \tag{2.44}$$

$$Q_{10} = Q_4 - \frac{Q_5}{Q_2}\,exp\left[\frac{Q_6\ln(u)}{u^{Q_9}}\right] \tag{2.45}$$

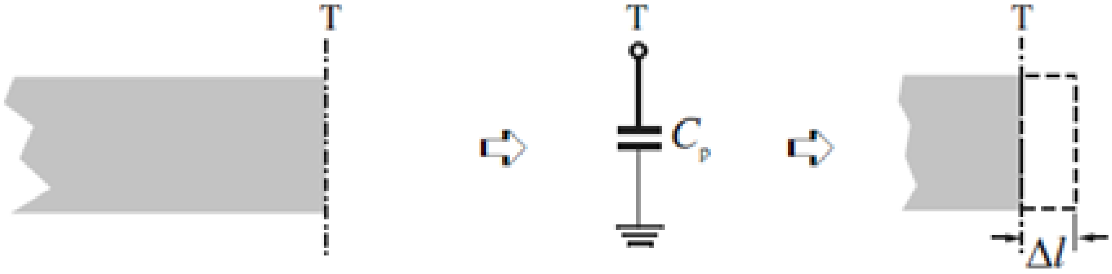
These closed-form expressions are also used to obtain precise values of capacitances for even and odd modes. The formulations of the effect of dispersion are found in above derived equations.

2.3 Discontinuities in Microstrip

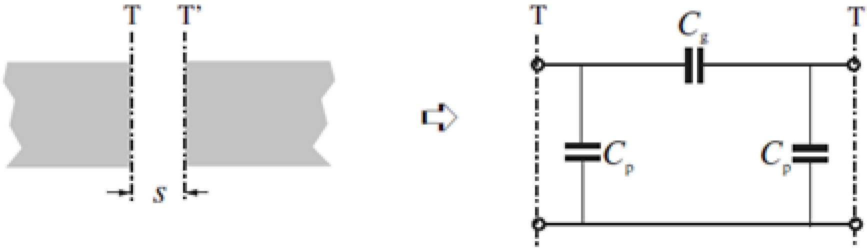
Discontinuities in microstrip would frequently come across in the practical filter structures which comprises open-ends, gaps, steps, junctions, and bends. Fig 2.4 shows certain distinctive layouts and layout equivalent circuits. Full wave EM simulations can be used to model the filter designs by considering the discontinuities.



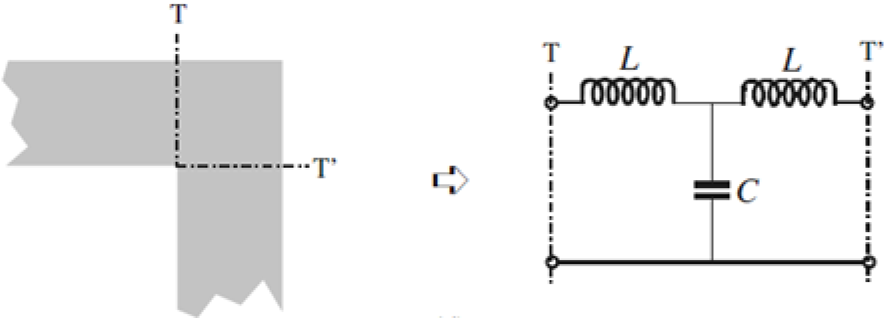
(a) Step



(b) Open-end



(c) Gap



(d) Bend

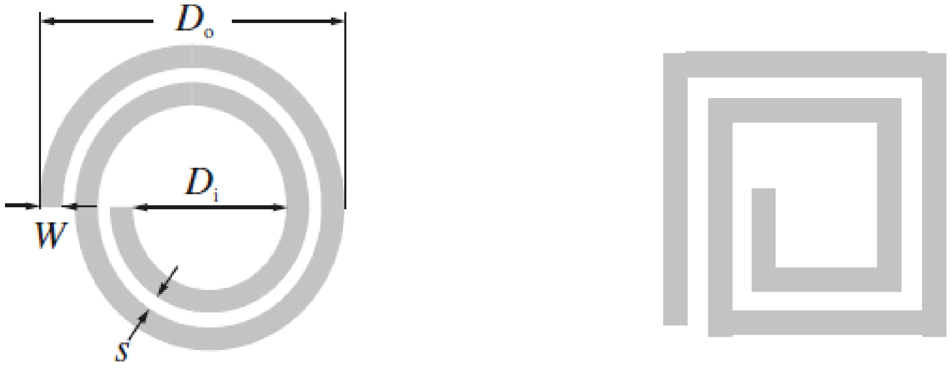
Figure 2. 4 Discontinuities in microstrip

2.4 Microstrip Components

Microstrip components are also taken into account to design the filters. They may have lumped and quasi lumped components, and resonators. These components are illustrated in Figures 2.5 and 2.6. The size of this components as compared to the free space wavelength are much smaller. Because this compact size they can easily manufacture by monolithic microwave integrated circuits.

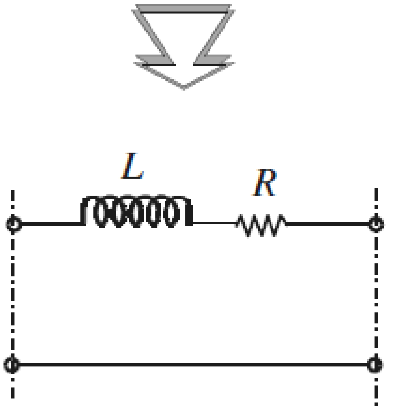
(a) high-impedance line

(b) meander line



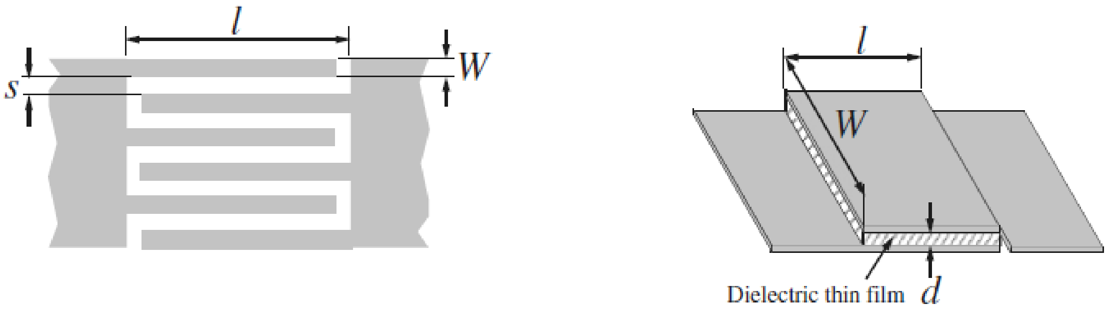
(c) circular spiral

(d) square spiral



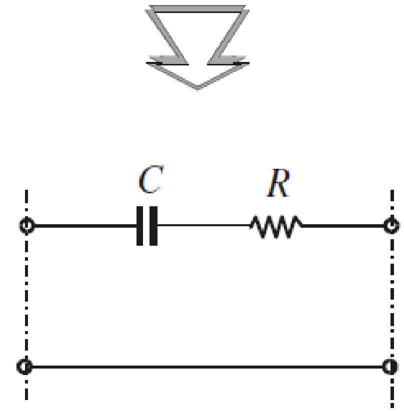
(e) ideal circuit representation

Figure 2. 5 Lumped-element inductors



(a) interdigital capacitor

(b) MIM capacitor



(c) ideal circuit representation

Figure 2. 6 Lumped-element capacitors

2.5 Resonators

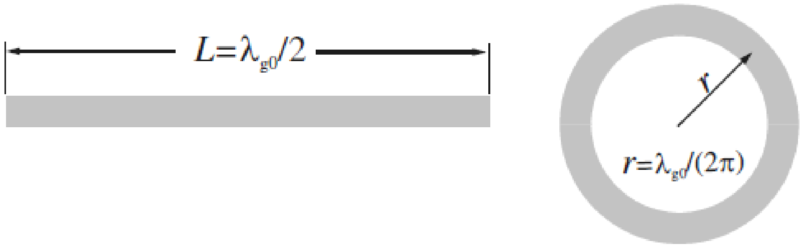
A structure which is able to enclose at least one oscillating electromagnetic field is called a Microstrip resonator. There are various forms of microstrip resonators. Microstrip resonators for filter designs may be classified as quasi lumped-element resonators or lumped-element and distributed line or patch resonators. Some classic configurations of these resonators are illustrated in Figure 2.7.

(a) lumped-element resonator

(b) quasilumped-element resonator

(c) $\lambda_{g0}/4$ line resonator (shunt-series-resonance)

(d) $\lambda_{g0}/4$ line resonator (shunt-parallel resonance)



(e) $\lambda_{g0}/2$ line resonator

(f) ring resonator

(g) circular patch resonator

(h) triangular patch resonator

Figure 2. 7 Some typical microstrip resonators

CHAPTER THREE

Types of Microstrip Filters and Their Applications

3.1 Lowpass and Bandpass Filters

Orthodox microstrip lowpass and bandpass filters such as pseudo-combline filters , stepped-impedance filters, semi-lumped element filters, open-stub filters, end- and parallel-coupled half-wavelength resonator filters, hairpin-line filters, interdigital and combline filters, and stub-line filters, are extensively used in various RF/microwave applications. Different types of lowpass and bandpass filters are listed below:

3.1.1 Lowpass Filters

There are two main steps in the design of microstrip lowpass filters. The initial one is to select a suitable lowpass model. The type of response, comprising and the number of reactive elements and passband ripple, will be determined by the required specifications. The lowpass filters are designed approximately in three types, they are:

- Stepped-impedance L-C ladder-type lowpass filters
- L-C ladder type of lowpass filters using Open-circuited stubs
- Semi-lumped lowpass filters having Finite-Frequency Attenuation Poles

3.1.2 Bandpass Filters

The Bandpass filters are designed approximately in seven types, they are:

- End-Coupled, Half-Wavelength Resonator Filters

- Parallel-Coupled, Half-Wavelength Resonator Filters
- Hairpin-Line Bandpass Filters
- Interdigital Bandpass Filters
- Combline Filters
- Pseudocombline Filters
- Stub Bandpass Filters
    - Filters with $\lambda g_0/4$ Short-circuited Stubs
    - Filters with $\lambda g_0/2$ Open-circuited Stubs

3.2 Highpass and Bandstop Filters

There are different types of microstrip Highpass and Bandstop filters are present including, narrow-band and wide-band bandstop filters, quasilumped element and optimum distributed highpass filters, as well as filters used for RF chokes. Different types of highpass and bandstop filters are listed below:

3.2.1 Highpass Filters

The Highpass filters are designed approximately in two ways, they are:

- Quasilumped Highpass Filters
- Optimum Distributed Highpass Filters

3.2.2 Bandstop Filters

The Bandstop filters are designed approximately in four ways, they are:

- Narrow-Band Bandstop Filters
- Bandstop Filters with Open-Circuited Stubs
- Optimum Bandstop Filters

- Bandstop Filters for RF Chokes

3.3 Coupled-Resonator Circuits

Coupled resonator circuit’s plays a vital role in the design of RF/microwave filters, mainly in the narrow-band bandpass filters which plays a key role in many microwave applications. Despite of any type of physical structure, there is a common technique which can be used for designing coupled resonator filters. The technique has been applied to the design of dielectric resonator filters, waveguide filters, microstrip filters, ceramic combline filters, micromachined filters, and superconducting filters. This design based on coupling coefficients of intercoupled resonators and the external quality factors of the input and output resonators. As this design is so useful and flexible, it can be used in designing many types of coupled resonator circuits.

3.4 Filter Miniaturization and Compact Filters

When compared to wave guide filters microstrip filters are very small in size. Nonetheless, there are some applications where the miniaturization is of primary importance, so smaller microstrip filters are required. If the size is reduced then it leads to increase in the dissipation losses in a given material and hence it tends to reduction in the performance. Even though this demerit doesn’t shows much effect on the miniaturization of the filters. Reduction of size in filters may be achieved by using high dielectric constant substrates or lumped elements, but very regularly for specified substrates, a change in the geometry of filters is required and as a result various new filter structures can be achieved. There are many new types of filters include ladder line filters, slow-wave resonator filters, compact open-loop and hairpin resonator filters, pseudointerdigital line filters, miniaturized dual-mode filters, multilayer filters, filters using high dielectric constant substrates and lumped-element filters.

3.5 Ultra-Wideband Filters

There are many emerging applications which are using ultra-wide band frequency range. For these emerging applications UWB or broad-band microwave filters are essential components. The applications include UWB wireless and radar systems also. Due to this rapid growth, it has stimulated the development of various types of UWB filters which includes short-circuit stubs, those using coupled single or multimode resonators, or quasilumped elements, those based on cascaded high-and-lowpass filters, and those with single or multiple notched bands.

3.6 Electronically Tunable and Reconfigurable Filters

Electronically tunable or reconfigurable filters are becoming more and more popular in the field of research developments, because of their growing significance in improving the capability of current and future wireless systems. Electronically reconfigurable microwave filters will be playing a vital role in the future cognitive radio and radar applications.

In common, to develop an electronically or reconfigurable filter, active switching or tuning elements such as semiconductor p-i-n and varactor diodes, RF MEMS, or other functional material based components including ferroelectric varactors need to be integrated within a passive filtering structure. Since microstrip filters can conveniently integrate this kind of small sizes, there has been significant development in the tunable or reconfigurable microstrip filters. These filters are classified into:

- Tunable combline bandpass filters
- RF MEMS tunable filters
- Piezoelectric transducer (PET) tunable filters
- Tunable high-temperature superconductor (HTS) filters

- Reconfigurable UWB filters
- Tunable dual-band filters
- Tunable Bandstop filters
- Reconfigurable/tunable dual-mode filters
- Reconfigurable bandpass filters based on switched delay-line approach
- Wideband bandpass filter with reconfigurable bandwidth

In general, bandwidth tuning or controlling is more difficult than frequency tuning and the design of an electronically tunable filter with a wider bandwidth is more difficult than a narrow bandwidth in terms of bandwidth control and tuning range.

3.7 Advanced RF/Microwave Filters

To meet the stringent requirements from RF/microwave systems (specifically from the wireless communication systems) there has been urging demand for advanced RF/microwave filters other than conventional chebyshev filters. The different types of advanced RF/microwave filters are listed below:

- Selective filters with a single pair of transmission zeroes
- Cascaded quadruplet (CQ) filters
- Trisection and cascaded trisection (CT) filters
- Transmission line inserted filters
- Linear-phase filters
- Extracted pole filters
- Canonical filters
- Multiband filters

3.8 High-Temperature Superconducting (HTS) filters

High-temperature superconductors are discovered in 1986, since the discovery high-temperature super conductivity has been at the pole position of advanced filter technologies and has changed the way of designing communication systems, namely medical instrumentation, electronic systems, military microwave systems, satellite communication systems, mobile communication systems, and radio astronomy and radars. Most of the superconducting filters are simply microstrip structures using HTS thin films. The development of HTS thin films and the fabrication of HTS microstrip filters are compatible with hybrid and monolithic microwave-integrated circuits. The most commercially available HTS materials are

1. Yttrium barium copper oxide (YBCO) - [$YBa_2Cu_3O7\text{-}x$, $T_c(k) \approx 92$]
2. Thallium barium calcium copper oxide (TBCCO) – [$Tl_2Ba_2Ca_1Cu_2Ox$, $T_c(k) \approx 105$]

Where $T_c(k)$ is the typical Transition temperature.

CHAPTER FOUR

Design of Bandpass filters Using Open split Resonators

Microstrip bandpass filters are used to cull or combine the RF/microwave signals within certain spectral boundaries within the electromagnetic spectrum. Dual mode resonator usage allows to realize the compact high quality of bandpass filter (BPF). There are two filters in this chapter which are designed using the fractal geometry and a filter which is designed on the base of square loop resonator, these filters are having a very low insertion loss which is less than -1db, reduced return loss and good pass band performance. This chapter is dedicated to the design of bandpass filters using novel open split resonators like Open split koch loop resonator's (OSKLR's) and open loop square resonators are designed. First a three pole compact Koch resonator is designed on a ptfe substrate and it is followed by the design of semi lumped bandpass filter using open split Koch resonator and a three pole element compact open loop square resonator.

4.1 Introduction

With the invention of new materials and innovative fabrication techniques, Microstrip filters are being extensively used in various microwave applications due to their high performance, small size and low cost. Microstrip band pass filters can be designed with the help of many topologies like end-coupled, half-wavelength resonator filters, parallel-coupled, half-wavelength resonator filters, hairpin-line bandpass Filters, interdigital bandpass filters, combline filters, pseudocombline filters, stub bandpass filters. Because of the relatively weak [9] coupling microstrip coupled line filters has been used to attain narrow bandwidth bandpass filters. This type of filters has many advantages like easy integration and low cost fabrication. The dual mode resonators helps in realizing compact high quality microwave bandpass filters [10].

Dual mode microstrip filters are generally in the form of a square, ring or a disk patch. Normally these square, ring or a disk patches are referred to as dual mode resonators. Due to the difficulty in the modes of coupling the two different rings make the circular ring resonators not practical for designing higher order filters [11]. The square ring resonator has the simple and strong coupling between two individual resonators. Nevertheless the degenerate modes are still coupled by a perturbation at more than one corners. Use of koch loop resonators doesn’t require this perturbations and modest coupling between all the modes is possible. The advantages of koch loop resonator is it has a smaller size than a normal koch patch [9] and resonant frequencies being controlled by changing the dimensions of the loop.

The backbone of fractal geometry is its recursive generating methodology which outlines with many complicated structures. Numerous fractal geometries like Koch curve, Hilbert curve, Sierpinski gasket, etc. have been studied extensively to improve numerous microwave devices [12], like microstrip bandpass filters, antennas etc.,. All these fractals have the advantage of miniaturization, multi-band, wide-band operation. The two basic properties of fractals are space filling ability and self-similarity. Here, space filling defines that a fractal shape can me filled in a finite region without increasing the whole area. Self-similarity defines that a part of the fractal geometry will always reflects the entire structure. The filters designed with fractal geometry are having reduced return loss and good passband performance.

4.2 Koch curve

The Koch curve is an example of fractal geometry. The features of Koch fractal geometry has been applied to various applications such as miniaturization of conventional antennas [13], ultra wide band filters [14], coupled -line bandpass filters [15], etc. To construct a Koch curve, a straight line should be divided into three parts which should be in equal size. Now, the section which is in the middle is replaced with an equilateral triangle by removing its base. The length is augmented by a factor of 4/3 after the first iteration. As these iterations will be repeated, the total length of the figure will become infinity and because of this the lengths of the new triangle moves to zero. Figure shows the fractal Koch curve structure. The one of the predominant features of the koch curve is, it can accommodate infinite length in a finite region.

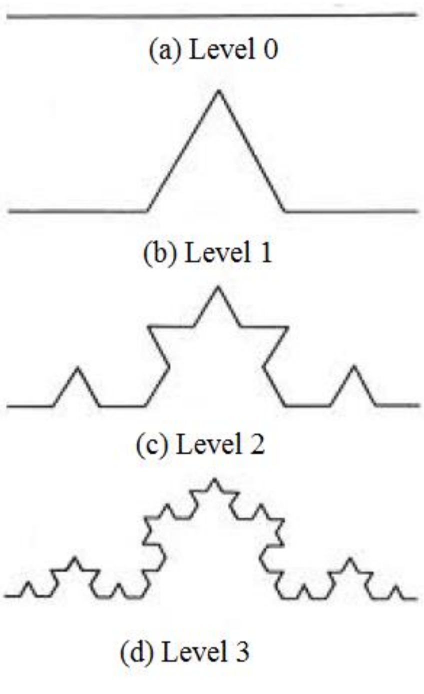


Figure 4. 1 Koch curve

4.3 Filter designs

4.3.1 A Three pole Open Split Koch Loop Resonator (OSKLR)

Open split koch loop resonators are used in these designs to design bandpass filters. These type of resonators works as lumped LC series elements because of their very small electrical size [16]. These can be used as building blocks of small size bandpass filters [17]. The capacitance and the inductance values can be regulated by altering the geometrical parameters of the coupled rings. This filter configuration has typically contains three OSKLRs, interconnected with a microstrip line. The patch sits on a Polytetrafluoroethylene (PTFE) substrate which is of thickness 0.49 mm and permittivity $\varepsilon_r = 2.43$. The filter has been modeled using the optimization code used in [18]. Here, the filter bandwidth can be regulated by altering the length of the unit cell, d, and the rejection band depth is based on the number of transmission poles, N, used for implementing the filter [25]. The structure of the filter is shown in the following figures 4.2, 4.3, and the s-parameter is shown in figure 4.4.

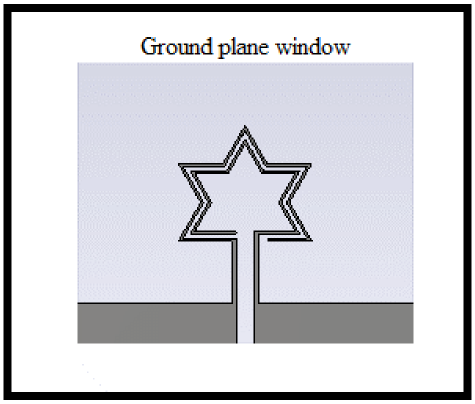
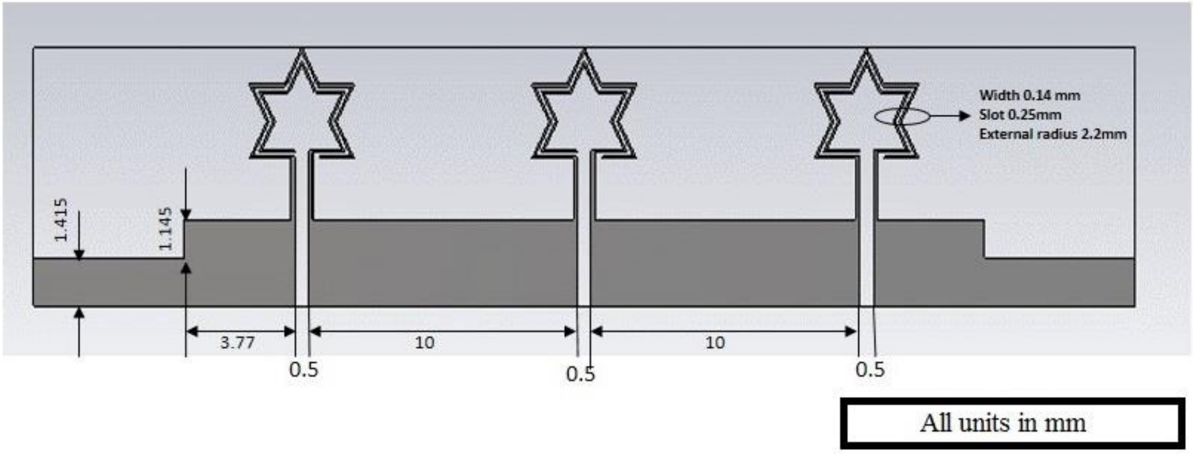
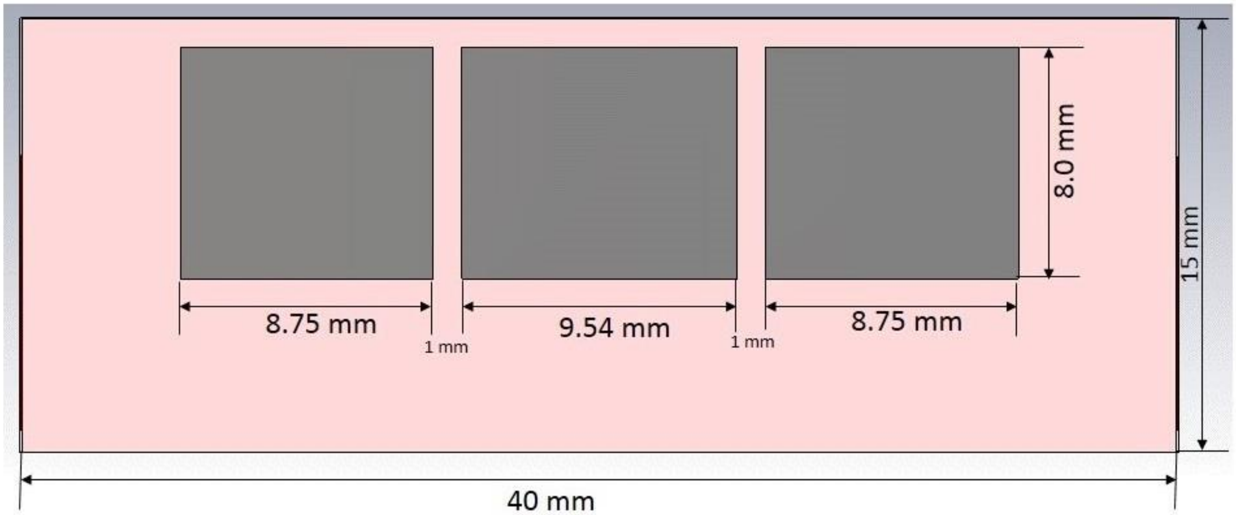


Figure 4. 2 Open Split Koch Loop Resonator



(a) Front view



(b) Ground plane view

Figure 4. 3 Design and dimensions of the simulated five pole OSKLR slow-wave filter

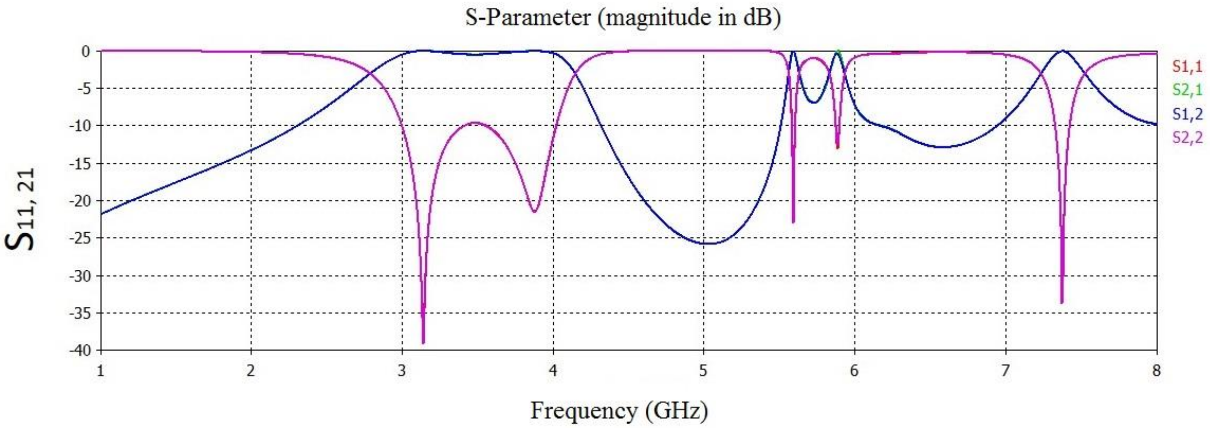


Figure 4. 4 S-Parameter of the designed filter

Dimensions of the filter

Parameters	Value
External koch radius	2.2 mm
Koch ring width	0.14 mm
Slot between the two koch rings	0.25 mm
Height of the PEC	0.05 mm
Length of the substrate	15 mm
Width of the substrate	40 mm
Height of the substrate	0.49 mm
Substrate material	PTFE, ε_r = 2.43

Table 4. 1 Dimensions of the three pole OSKLR

Simulated Results

The objective of the resonant frequency was about 3-4 GHz. The 50Ω length microstrip sections between OSKLRs produced a bandwidth of 28%. The design of the filter is shown in Figure 4.3. Here the filter is shortened by connecting the meander transmission lines to the OSKLRs. The S-Parameter result of the designed filter is shown in figure 4.4. The filter is simulated in a full-wave electromagnetic simulation in CST Microwave studio.

4.3.2 Seven pole Open Split Koch Loop Resonator (OSKLR)

This filter configuration has typically contains seven OSKLRs interconnected with a microstrip line. The patch sits on a RT/Duroid substrate which is of thickness 0.254 mm and permittivity $\varepsilon_r = 10.2$. The central frequency of this bandpass filter is $f_0 = 5\ GHz$. The structure of the filter is shown in the following figures 4.5, 4.6, and the s-parameter is shown in figure 4.7. A filter of order N = 7 is selected in order to attain good rejection band in outer band region. The geometry of the strip width and transmission line is taken from quasi-TEM code presented in [16].

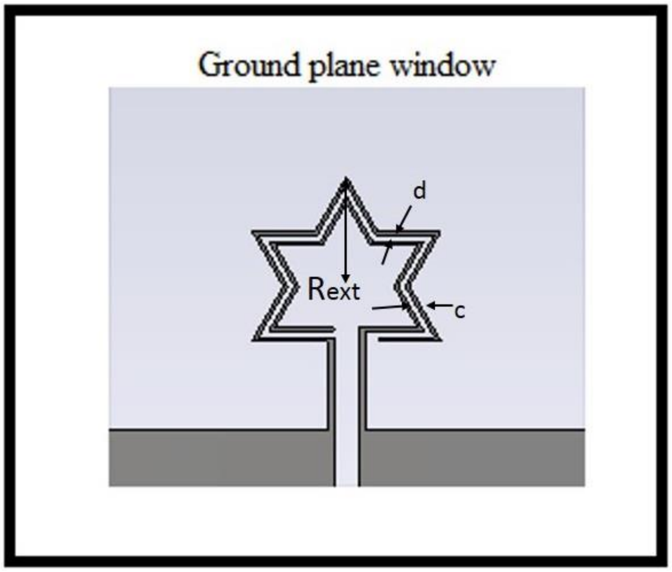
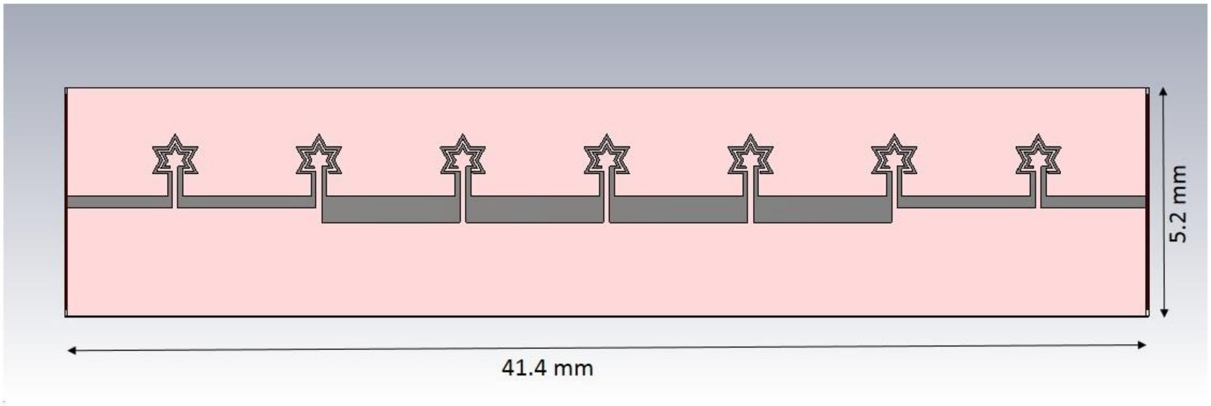
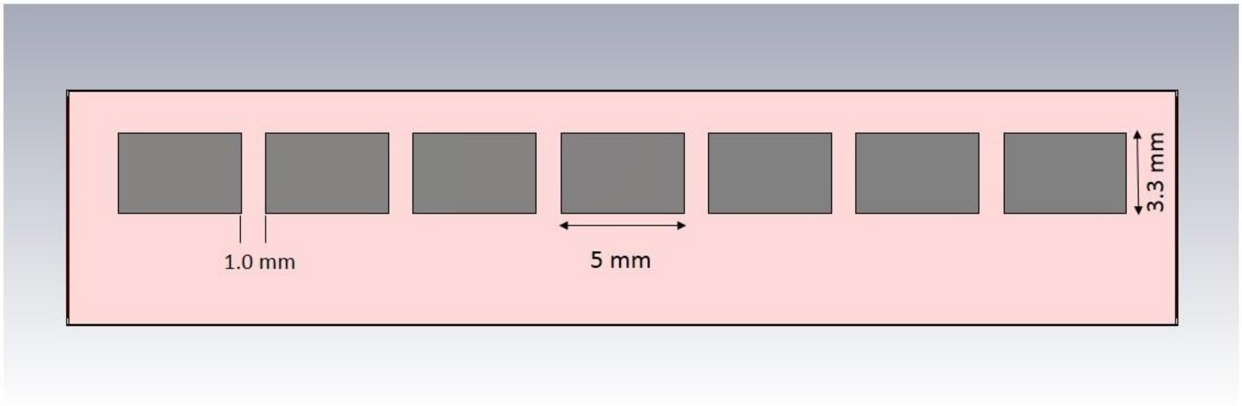


Figure 4. 5 *OSKLR*



(a) Front view



(a) Ground plane view

Figure 4. 6 Design and dimensions of the filter

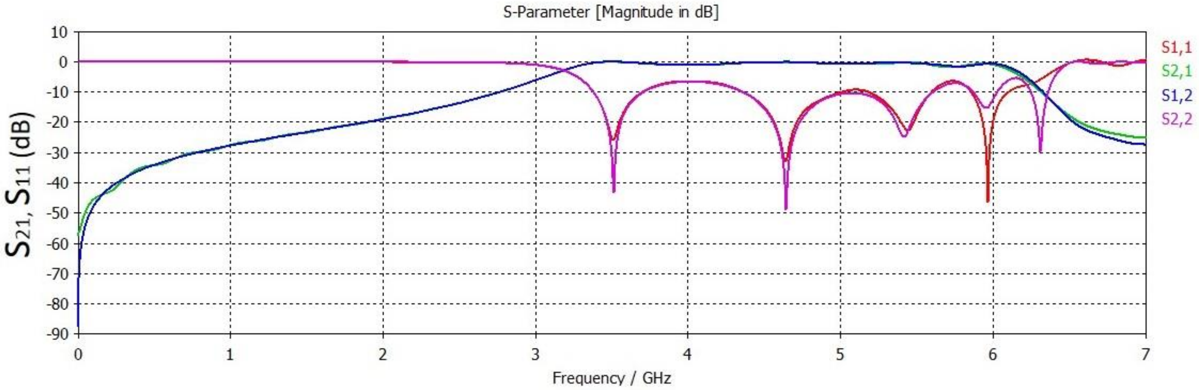


Figure 4. 7 S-Parameter of the designed filter

Dimensions of the filter

Parameters	Value
External koch radius (R_{ext})	1.101 mm
Koch ring width (c)	0.2 mm
Slot between the two koch rings (d)	0.2 mm
Height of the PEC	0.05 mm
Length of the substrate	41.4 mm
Width of the substrate	5.2 mm
Height of the substrate	0.254 mm
Substrate material	RT/Duroid, ε_r = 10.2

Table 4. 2 Dimensions of the seven pole OSKLR

Simulated Results

The final design and the results are shown in figures, comparing this results with measurements the central frequency of the filter (5 GHz) has been attained. This filter produced a bandwidth of 14%. The rejection curve at the both sides of the passband looks balanced. Here the filter is shortened by connecting the meander transmission lines to the OSKLRs. The S-Parameter result of the designed filter is shown in figure 4.7. The filter is simulated by a full-wave electromagnetic simulation in CST Microwave studio.

4.3.3 Three Pole Element Compact Open Loop Square Resonator

In this design a new type of open loop square resonator is implemented [20]. The proposed filter configuration has typically contains three OLSRs and a Polytetrafluoroethylene (PTFE) substrate is used which is of thickness 0.49 mm and permittivity $\varepsilon_r = 2.43$. The filter has been modeled using the optimization code used in [18]. The structure of the filter is shown in the following figures 4.2, 4.3, and the s-parameter is shown in figure 4.4.

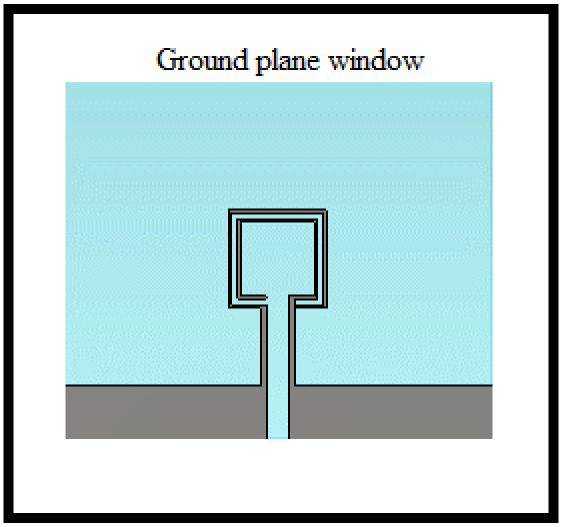
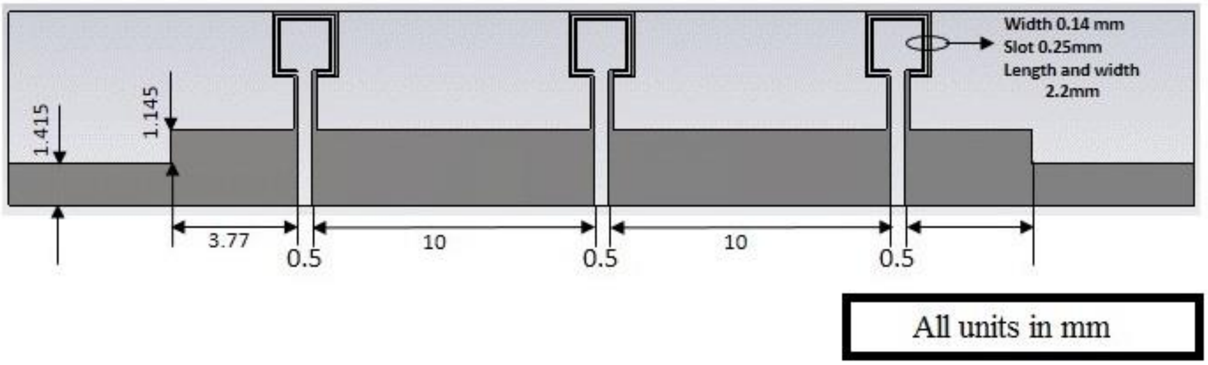
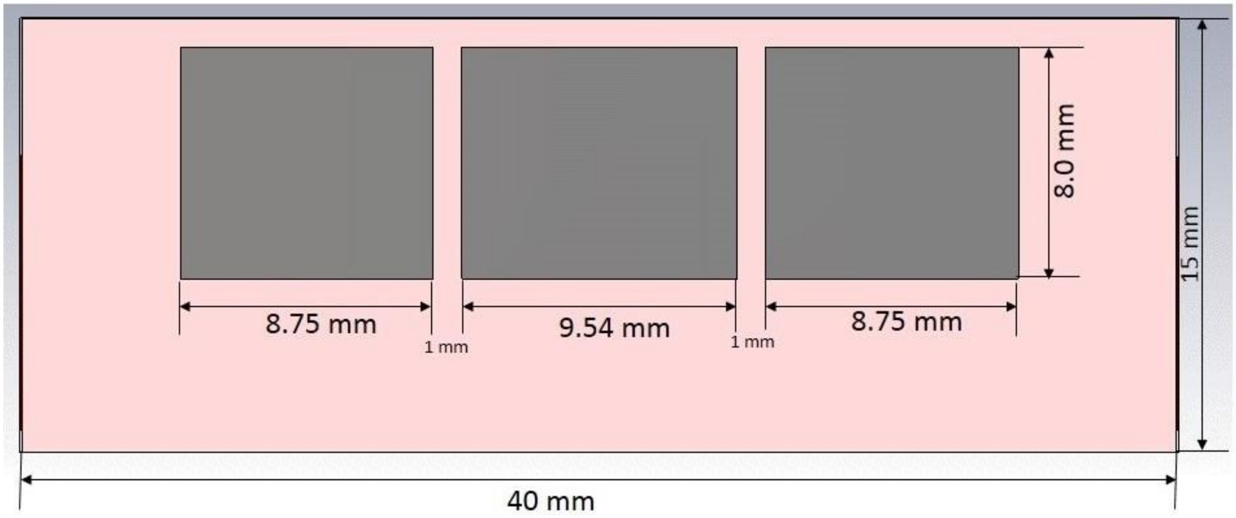


Figure 4. 8 Open Loop Square Resonator



(a) Front view



(a) Ground plane view

Figure 4. 9 Design and dimensions of the simulated three pole OLSR filter

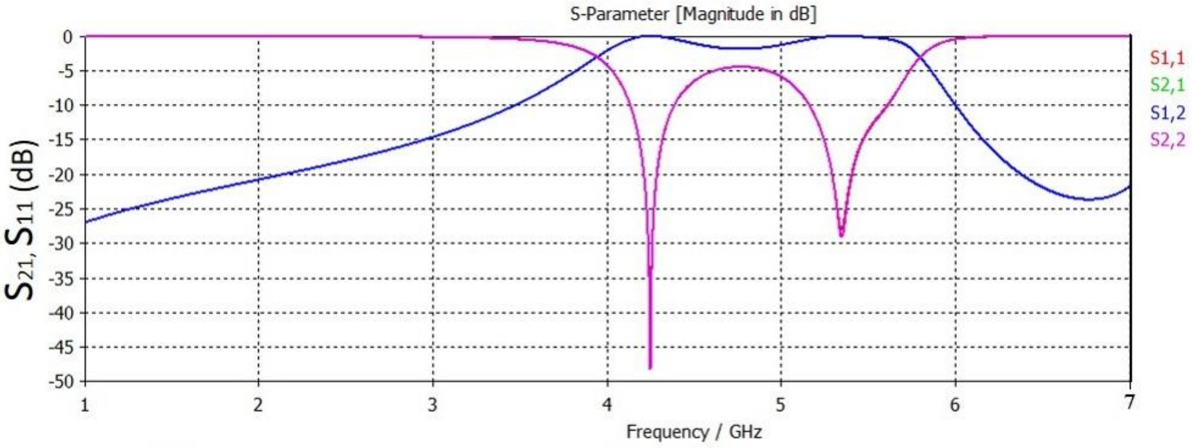


Figure 4. 10 S-Parameter of the designed filter

Dimensions of the filter

Parameters	Value
Length of the square	2.2 mm
Square loop width	0.14 mm
Slot between the two square loop	0.25 mm
Height of the PEC	0.05 mm
Length of the substrate	15 mm
Width of the substrate	40 mm
Height of the substrate	0.49 mm
Substrate material	PTFE, $\varepsilon_r = 2.43$

Table 4. 3 Dimensions of the three pole OLSR

Simulated Results

This filter has produced a bandwidth of 0.46%. The design of the filter is shown in Figure 4.9 and the s-parameter is shown in 4.10. Here the filter is shortened by connecting the meander transmission lines to the OLSRs. The S-Parameter result of the designed filter is shown in figure 4.4. The filter is simulated in a full-wave electromagnetic simulation in CST Microwave studio.

4.4 Conclusion

Design 1

A New Five Pole Open Split Koch Loop Resonator, has been designed and investigated. The desired bandwidth of 28% has been achieved. This resonator can be useful in the design of compact bandpass filters in microstrip technologies. The three pole bandpass filter has been designed on the basis of microstrip technology, the filter has been designed and simulated. Particularly simple circuit model is used in the design of this filter, where the circuit parameters are in quasi-analytical form. The bandwidth is tuned by the length of the line sections sandwiched between the OSKLRs. The results of the theoretical predictions and full-wave simulations are apparently matched and the results are upright at a comprehensive frequency range around the filter and passband.

Design 2

A bandpass filter has been designed and executed by using OSKLRs. In this design λ/4 inverters has been used with altered characteristic impedances joining the indistinguishable OSKLRs. The desired bandwidth of 14% has been achieved. The results of the theoretical predictions and full-wave simulations are apparently matched and the results are upright at a comprehensive frequency range around the filter and passband.

Design 3

A New Two pole Open Loop Square Resonator, has been designed and investigated. The desired bandwidth of 0.46% has been achieved. This resonator can be useful in the design of compact bandpass filters in microstrip technologies. The two pole bandpass filter has been designed on the basis of microstrip technology, the filter has been designed and simulated. Particularly simple circuit model is used in the design of this filter, where the circuit parameters are in quasi-analytical form. The position of first pole in this design tends to the OLSRs resonance frequency, and the bandwidth is tuned by the length of the line sections sandwiched between the OLSRs. The results of the theoretical predictions and full-wave simulations are apparently matched and the results are upright at a comprehensive frequency range around the filter and passband.

4.5 Comparison between the three filters

Filters	**Bandwidth**	**Dimensions**	**Substrate**
3 Pole Koch Resonator	28%	40 X 15 mm^2	PTFE
7 Pole Koch Resonator	14%	41.4 X 5.2 mm^2	RT/Duroid RO 3210
3 Pole Square Loop Resonator	0.46%	40 X 15 mm^2	PTFE

Table 4. 4 Comparison between the three filters

CHAPTER FIVE

Compact UWB Star Shaped Multiple-Mode Resonator for Bandpass Filter with Enhanced Upper-Stopband Performance

5.1 Introduction

In 2002 the U.S. Federal Communications Committee (FCC) released the unlicensed use of ultra-wideband (UWB) frequency spectrum for indoor and hand-held wireless communications. After that there has been a remarkable interest in investigation of variety of bandpass filters. In this chapter, an innovative ultra-wideband (UWB) bandpass filter with improved upper- stopband performance is designed. The filter is very compact in size. The filter is executed using multiple mode resonator (MMR). The three pairs of koch impedance-stepped stubs in shunt to a high impedance microstrip line forms the MMR. Two interdigital coupled lines are used in the input and output sides to improve the coupling degree. By altering the radius of the stars of the stubs, the MMR resonant modes can be allocated within the UWB range (3.1 – 10.6 GHz) by overpowering the counterfeit harmonics in the upper-stopband. The insertion loss is higher than 30.0 dB in the upper-stopband. The EM-simulated results are presented in this chapter.

5.2 Filter characterization

The proposed filter has a new topology of MMR which replaced the traditional MMR [13] [14]. The new topology of MMR is formed by attributing three pairs of star shaped impedance-stepped stubs in shunt to a simple microstrip line which has high impedance, as shown in Figure 5. 1. And the equivalent transmission line network is also shown in Figure 5. 2.

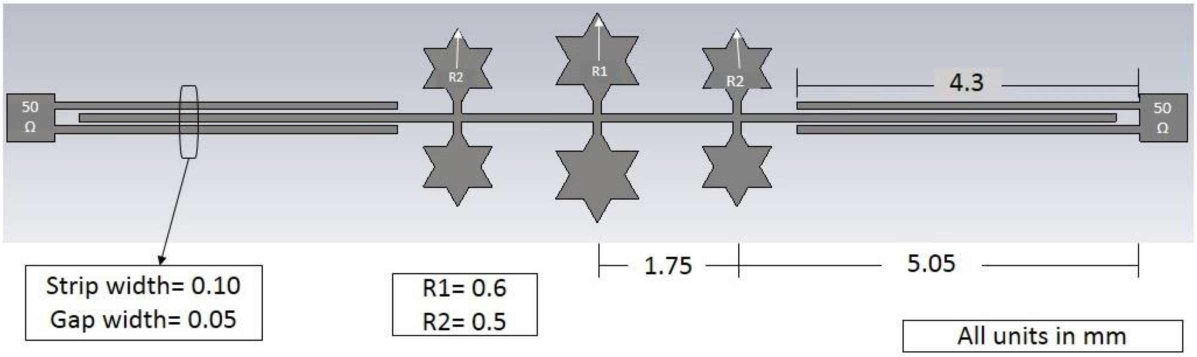


Figure 5. 1 Schematic of the UWB BPF

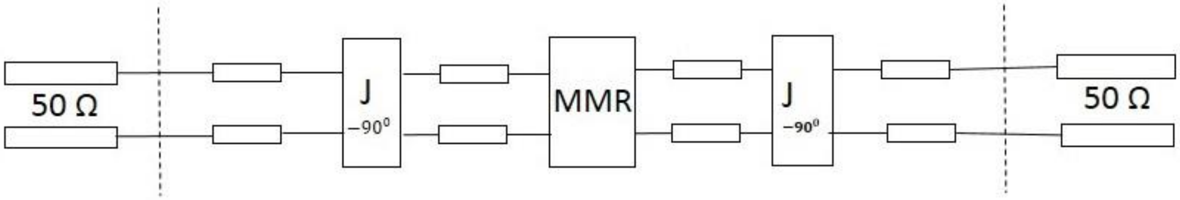


Figure 5. 2 Equivalent transmission line network for the proposed UWB BPF

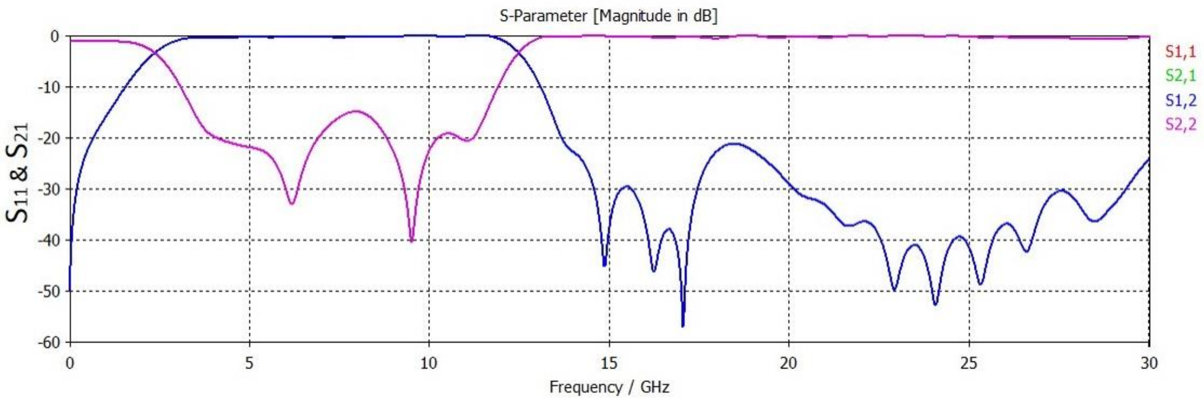


Figure 5. 3 Simulated frequency responses of the proposed BPF

5.3 Dimensions of the filter

Parameters	Value
R_1	0.6 mm
R_2	0.5 mm
Strip width	0.10 mm
Gap width	0.05 mm
Height of the PEC	0.05 mm
Length of the substrate	10 mm
Width of the substrate	14.8 mm
Height of the substrate	0.635 mm
Substrate permittivity	$\varepsilon_r = 10.8$

Table 5. 1 Dimensions of the compact UWB filter

5.4 Simulated Results

The proposed filter configuration has typically contains three pairs of MMR which sits on a substrate which is of thickness 0.635 mm and permittivity $\varepsilon_r = 10.8$. The structure of the filter is shown in the following figures 5.1, and the s-parameter is shown in figure 5.3. The simulated results shows that the filter has a passband at UWB frequency range and stopband over 12-30 GHz. The predicted responses on insertion and return losses are shown in the figure 5.3.

5.5 Conclusion

In this chapter, a compact UWB filter is designed and simulated. This filter has enhanced stopband performance. The filter is designed by using new multimode resonator method. The MMR is formed by joining the three star shaped pairs to a high impedance microstrip line. The design procedure is a bit complex when it is compared to rectangular MMRs [22] and circular MMRs [21], but this star shaped design gives improved upper stopband performance when compared to other MMRs.

It has a wide upper stopband with insertion loss more than 20 dB in the range of 14.5 to 30 GHz is realized. This filter is very compact as its dimensions are 10 X 14.8 mm^2.

CHAPTER SIX

Conclusion and Future work

5.1 Conclusion

The goal of this thesis is to investigate on some planar microwave bandpass filters. In this thesis four novel compact bandpass filters has been designed and simulated, specifically five pole koch resonators, two pole square loop resonator and compact UWB bandpass filter using MMR. The design and simulation of each and every filter is given in detail with including all the required specifications. From the previous research studies it is evident that, to design a good bandpass filter there should be a smooth passband and good stopband with higher insertion loss in the stopband. The four designs which are explained in this thesis has these important factors, which makes these filters useful for the microwave applications. The conclusions of the designs are:

- Koch fractal geometry is successfully applied in three designs, which gave the better results compared with using other structures.
- A new type of Open split koch loop resonator (OSKLR) has been developed and applied to the different filter structures. This OSKLR structure is the backbone for the two designs which are simulated successfully in this thesis.
- Successfully transformed the conventional square loop resonator into Open split square loop resonator. This open split square loop resonator successfully applied to the filter structure.

- Compact UWB bandpass filter has been designed effectively by using new type of MMRs. This filter gave us the better upper stopband performance when compared to other structures which containing different types of MMRs like circular MMR and square MMR.

6.2 Future Work

The prospects of the future work could be:

- The four designs can be fabricated and their results should be compared with the simulated results which are present in this thesis.
- Computational electromagnetic modelling techniques like FDTD/FEM can be implemented on the simulated designs.
- After fabricating all the four filters, they should be applied in microwave applications to check the performance of those filters in the real world.
- This thesis is dedicated in designing particularly planar microwave bandpass filters with the help of resonator circuits and MMRs. So, this work can be extended by designing other type of planar microwave filters like advance RF/microwave filters, superconducting filters, and tunable and reconfigurable filters.

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