Filters are essential components in any communication system. They are used to select or confine the RF microwave signals within assigned spectral limits so as to share the limited electromagnetic spectrum. Emerging applications in wireless communication demand RF microwave filter with even more stringent requirements: smaller size, lighter weight, lower cost along with better performance. Depending on the requirements and specification, RF microwave filters may be designed and realized in various transmission line structures, such as waveguide, coaxial line or microstrip line. Development of compact filters using resonators in microstrip configuration is discussed in this thesis.
1.1 Microwave Communication

Microwaves are electromagnetic radiation of frequencies from several hundred MHz to several hundred GHz. Microwave technology owes its origin to the development of radar, which started before World War II by necessity. Various investigators were trying to solve the problem of UHF/microwave bands with high power. At the heart of their investigation was the conventional vacuum tube, which at the time seemed to be the best approach. The high frequency shorting at these frequencies and longer transit time in the vacuum tube limited its operation in the lower frequencies. A solution to this problem was proposed in 1920 by German scientists H Barkhausen and K. Kurz through their Barkhausen-Kurz oscillator, a new type of vacuum tube that generated high frequency signals, but with a limited output power. The limitations of these devices paved way to the invention of new microwave device such as magnetron followed by klystron vacuum tube. With the production of these microwave devices, radar was finally a commercially, albeit a military, success at microwave frequencies. In the decades that followed, the use of microwaves was limited to telephone companies in the commercial sectors. By 1960’s, microwave communication has replaced 40% of the telephone circuits between the major cities. 1990’s have seen a continuous evolution of microwave developments, particularly in the consumer marketplace. Direct broadcast satellite services (DBS) to the home at high frequencies and power have occurred. Personal communicators, cellular phones and the like which are under the general category of personal communication systems (PCS), continue to be heavy growth areas. Microwaves have found applications in areas other than those in communications and in radar. They are also used in medicine, remote sensing, heating, industrial quality control, radio astronomy, in navigation via global positioning systems etc.
Chapter 1

1.1.1 Microwave frequency bands

The IEEE standard frequency allocation for various applications is illustrated in table 1.1.

<table>
<thead>
<tr>
<th>Band Designation</th>
<th>Frequency range</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLF</td>
<td>3-30KHz</td>
<td>Long distance telegraphy and navigation</td>
</tr>
<tr>
<td>LF</td>
<td>30-300 KHz</td>
<td>Aeronautical navigation services, Radio broadcasting, Long distance communication,</td>
</tr>
<tr>
<td>MF</td>
<td>300-3000</td>
<td>Regional broadcasting, AM radio</td>
</tr>
<tr>
<td>HF</td>
<td>3-30MHz</td>
<td>Communications, broadcasting, surveillance, CB radio</td>
</tr>
<tr>
<td>VHF</td>
<td>30-300 MHz</td>
<td>Surveillance, TV broadcasting, FM radio</td>
</tr>
<tr>
<td>UHF</td>
<td>300-1000MHz</td>
<td>Cellular communications</td>
</tr>
<tr>
<td>L</td>
<td>1-2 GHz</td>
<td>Long range surveillance, remote sensing</td>
</tr>
<tr>
<td>S</td>
<td>2-4 GHz</td>
<td>Weather detection, Long range tracking</td>
</tr>
<tr>
<td>C</td>
<td>4-8 GHz</td>
<td>Weather detection, long-range tracking</td>
</tr>
<tr>
<td>X</td>
<td>8-12 GHz</td>
<td>Satellite communications, missile guidance, mapping</td>
</tr>
<tr>
<td>Ku</td>
<td>12-18 GHz</td>
<td>Satellite communications, altimetry, high resolution mapping</td>
</tr>
<tr>
<td>K</td>
<td>18-27 GHz</td>
<td>Very high resolution mapping</td>
</tr>
<tr>
<td>Ka</td>
<td>27-40 GHz</td>
<td>Air port surveillance</td>
</tr>
</tbody>
</table>

Table 1.1 Frequency bands allocation for various applications

1.2 Filters

A filter is a two port network used to control the frequency response at a certain point in the electromagnetic spectrum by providing low loss transmission at frequencies for the desired band and high attenuation in the rest of the frequencies. Filters find applications virtually in any type of communication, radar or test and measurement systems.
1.2.1 Need for filters in microwave communication

Filters are essential in separating and sorting signals in communication systems. The electromagnetic spectrum is limited and has to be shared; filters are used to select or confine the RF/microwave signals within assigned spectral limits. They are used in a variety of communication systems which typically transmit and receive amplitude and/or phase modulated signals across a communication channel. Radio transmitters and receivers require filters to remove or suppress unwanted frequencies from being transmitted or received. Emerging applications such as wireless communication continue to challenge RF/microwave filters with even more stringent requirements 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 including rectangular waveguide, microstrip line and stripline. Filters are also the integral part of multiplexers which are of major demand in the broad band wireless access communication systems.

1.2.2 Evolution of filters

Filters in electric circuits have played an important role since the early stages of telecommunication and have progressed steadily in accordance with advancement of communication technology. The introduction of telephony which drastically reformed the technological landscape surrounding telecommunication system required the development of new technology to extract and detect signals contained within a specific frequency band. This technological advance further accelerated the research and development of filter technology.

The foundation of modern filter theory and practice took place during the period of World War II and the years immediately following, especially by such pioneers as P. L. Richards (1948). Work on microwave filters commenced prior to the war, a particularly significant paper being published by Mason and Sykes (1937). They used ABCD parameters, although not in matrix form, to derive the image impedance and image phase and attenuation functions of a rather large variety of
useful filter sections. Network theory was probably the most advanced topic in engineering at that time, Darlington having published his famous cascade synthesis theory as far back as 1939 (Darlington, 1939).

The direct-coupled cavity filter theory was one of the first great contributions from the group formed at Stanford Research Institute, among whose workers were Leo Young. The direct-coupled cavity filters have excessive length in coaxial or stripline form. This dimension was reduced by a factor of 2 with the introduction of parallel coupled lines (Ozaki et al., 1958; Cohn et al., 1958). Parallel coupling is much stronger than end coupling, so that realizable bandwidths could be much greater. The prime mover here was George Matthaei, who published the theory and practical realizations of interdigital filters (Matthaei, 1962) and the combline filter in the following year (Matthaei, 1962). Turning to other types of filters, waveguide bandstop filters were described by Fano and Lawson (1948). Low-pass filters in both waveguide and coaxial form are very important components in microwave systems, being used to reject unwanted harmonics in both high- and low-power systems. A very good account of the early development is given in the classic volume of Matthaei, Young, and Jones (1964). The previous reference leads naturally to the examination of the history of dielectric resonator filters.

Most of the early research was carried out in the early 1960's, as summarized in (Cohn, 1968). These filters consist of a number of coupled dielectric disks mounted in a waveguide beyond cut off. In order to give important size reduction, a high dielectric constant must be used, but originally such dielectrics possessed excessive temperature sensitivity. Now this drawback has been overcome with the development of high-Q ceramics with temperature coefficients of expansion comparable to those of invar. One of the first dielectrics having improved frequency stability was reported by workers at Raytheon (Masse and Pucel, 1972). Considerable improvements carried out at Bell Telephone Laboratories and Murata Manufacturing Company of Japan were reported at the Workshop on Filter Technology during the 1979 MTT-S International Microwave Symposium. Bell uses
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a barium titanate ceramic \((\text{Ba}_2\text{Ti}_{90}\text{Z}_0\text{O})\) having a relative permittivity of 40, and achieves resonator Q's between 5000 and 10000 in the 2-7-GHz frequency range (Plourde and Linn, 1977; Ren, 1978). Filters may be constructed in all the common transmission media ranging from waveguides to microstrip, and the technique is, therefore, quite versatile. Substantial size reductions have been made, particularly in the 3.7–4.2 GHz and 5.9–6.4GHz waveguide bands, and the filters are stated to have low cost.

Emerging applications such as wireless communications continue to challenge RF/microwave filters with ever more stringent requirements. The recent advances in novel materials and fabrication technologies, including high-temperature superconductors (HTS), low-temperature co-fired ceramics (LTCC), monolithic microwave integrated circuits (MMIC), micro-electromechanic system (MEMS), and micromachining technology, have stimulated the rapid development of new microstrip and other filters for RF/microwave applications. In the meantime, advances in computer-aided design (CAD) tools such as full-wave electromagnetic (EM) simulators have revolutionized filter design.

1.2.3 Filter classification

- **Classification of filters based on passband types**

  Filters are used in all frequency ranges and are categorized into four main groups:
  - Lowpass filter (LPF) that transmits all signals from DC to a cut-off value, \(\omega_c\), and attenuates all signals with frequencies above \(\omega_c\).
  - Highpass filter (HPF) that passes all signals with frequencies above the cutoff value \(\omega_c\) and rejects signal below \(\omega_c\).
  - Bandpass filter (BPF) that passes signal with frequencies in the range of \(\omega_1\) to \(\omega_2\) and rejects frequencies outside this range.
  - The complement to bandpass filter is the bandstop filter (BSF).
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Figure 1.1(a) to Fig.1.1(d) shows the characteristics of the four filter categories. Note that the characteristics shown are for passive filter.

![Attenuation, dB](image)

**Fig. 1.1** Frequency responses of (a) Lowpass filter (b) Highpass filter (c) Bandpass filter (d) Bandstop filter.

The characteristic of a passive filter can be described using the transfer function approach or the attenuation function approach. In low frequency circuit the transfer function \( H(\omega) \) description is used while at microwave frequencies the attenuation function description is preferred.

- **Classification of filters based on fractional bandwidth**

Fractional bandwidth or percentage bandwidth is a simple calculation, and gives a normalized measure of how much frequency variation a system or component can handle. If you know the center frequency and the bandwidth, the percentage bandwidth is:
Here "BW" is the *absolute* bandwidth and $f_c$ is the center frequency.

- **Narrow Band Filters**: below 5%
- **Moderate Band Width**: between 5% to 25%
- **Wide Band Filters**: greater than 25%

### Classification of filters by transmission media

The transmission media are characterized into two: Lumped elements and distributed elements. When the behavior of a resistor, capacitor, or inductor can be fully described by a simple linear equation, microwave engineers refer it to as a lumped element where operation is restricted to lower frequencies where they are physically much smaller than a quarter-wavelength.

At microwave frequencies, other factors must also be considered. To accurately calculate the behavior of the same 50-ohm resistor, you need to consider its length, width, and thickness of metal (due to the skin effect), and its proximity to the ground plane. This is when we must consider it as a distributed element. The transmission media at microwave frequencies include the following:

- Coaxial transmission lines
- Microstrip lines
- Strip lines
- Waveguides
Most transmission media that use two conductors, where one is considered ground include coaxial, microstrip and stripline. The transmission line that does not use a pair of conductors is waveguide.

1.2.4 Filter specifications

- Frequency specifications:
  - Center frequency and bandwidth ($f_0$ & BW) for BPF and BSF
  - Cut-off frequency ($f_c$) for LPF and HPF
  - Passband insertion loss
  - Return Loss and Flatness (ripple level)
  - Selectivity or skirt sharpness
  - Out of band rejection levels
  - Harmonic Rejection

- Power handling capability
  - Multipactor effects & voltage breakdown
  - Environmental specifications
  - Operational temperature limits
  - Pressure & humidity environments
  - Shock & vibration levels

- Mechanical specifications
  - Size, shape & weight
  - Type of input / output connectors
  - Mechanical mounting interfaces
• Lower frequency techniques limitations
  o Lumped element sizes (R,L,C) become comparable to wavelength
  o Radiation from elements causes undesirable effects and Increased losses
  o Wire connections between elements become part of circuit (parasitic)

1.2.5 Applications of filters

• Radar systems

World War II and the invention of radar led to significant developments in filters at various laboratories in the U.S. Work concentrated on narrow-band waveguide filters for radar systems. Advances on broad-band TEM filters for electronic support measures (ESM) systems and tunable narrow-band filters for search receivers were made. Most of this work is described in (Fano and Lawson, 1948).

Military applications required wide-band and tunable devices for electronic support measures receivers, which led to the development of highly selective wide-band waveguide filters, coaxial resonator and suspended-substrate multiplexers, and electronically tunable filters. One of the critical parts of any military system is the electronic counter measures (ECM) system and its associated ESM system. The ESM system detects and classifies incoming radar signals by amplitude, frequency, pulse width, etc., and the ECM system can then take appropriate countermeasures, such as jamming. One method of classifying signals by frequency is to split the complete microwave band of interest into smaller sub-bands. This can be done using a contiguous multiplexer, which consists of separate bandpass filters whose pass bands crossover at their 3-dB frequencies. The outputs of the individual channels can be detected, giving coarse frequency information while retaining unity probability of intercept (Tsui, 1992).
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- Communication systems:
  
  - Mobile and cellular systems

  Cellular communications base-stations demanded low-loss high power-handling selective filters with small physical size, capable of being manufactured in tens of thousands at a reasonable cost. These demands led to advances in coaxial resonator, dielectric resonator, and superconducting filters, and also methods of cost-reduction, including computer-aided alignment. Cellular radio handsets have required the manufacture of hundreds of millions of extremely small very low-cost filters, still with reasonably low loss and high selectivity. The filters used in cellular radio handsets have completely different requirements. The original analog handsets in the 1980s were large, bulky, and manufactured in relatively small volumes. However, these phones used an FDMA access scheme; thus, they were transmitting and receiving simultaneously. Handsets for second-generation TDMA systems, such as GSM, transmit and receive in different time slots.

  This has driven significant advances in integrated ceramic, surface, and bulk acoustic-wave active and passive filters using micromachined electromechanical systems (MEMS). Cellular radio has provided a significant driver for filter technology since the analog systems were launched in the early 1980s. This has resulted in various innovations in filter technology for both base-stations and handsets, which have depended upon the frequency planning of the various systems standards. In the U.S., the analog Advanced Mobile Phone Service (AMPS) used a frequency-division multiple-access (FDMA) scheme, and was allocated 869–894 MHz for base-station transmit (mobile receive) and 824–849 MHz for base-station receive (mobile transmit). The digital time-division multiple-access (TDMA) system (IS136) occupies the personal communications system (PCS) band from 1930 to 1990 MHz and 1850 to 1910 MHz and each 60-MHz band is sub-banded and allocated to operators in three 15-MHz and three 5-MHz segments. The American code-division multiple-access (CDMA) system (IS95) occupies both of the above
bands and is sub-banded into 5-, 10-, or 15-MHz segments. In Europe, the original analog total access communication system (TACS) occupied 890–905 and 935–950 MHz. This was extended (ETACS) to 872–905 and 917–950 MHz. The digital TDMA global system for mobile communications (GSM) (Glover, 1997) occupies 925–969 and 880–915 MHz and the bands from 1710 to 1785 and 1805 to 1880 MHz. These systems are not sub-banded. The third-generation universal mobile telecommunications system (UMTS) uses CDMA in the bands from 1920 to 1980 MHz and 2110 to 2170 MHz. The first analog systems required filters with percentage bandwidths in the region of 2% and with reasonable guard bands between channels. These specifications may be met with asymmetric generalized Chebyshev bandpass filters, typically with six resonators with a Q of 3000 and one or possibly two transmission zeros located on one side of the passband (Hunter, 2002).

Much smaller filters may be constructed using TEM transmission lines, which do not need a minimum cross sectional dimension to ensure propagation. The most significant developments were the parallel coupled-line filter (Cohn, 1958), which has found numerous applications in microstrip sub assemblies, the interdigital filter (Matthaei, 1962), and the combline filter (Matthaei, 1963).

The combline filter is of particular interest, as it has stood the test of time and variants of it are widely used in cellular radio base-stations. It consists of an array of equal-length parallel coupled conductors, each of which is short circuited to ground at the same end with capacitive loading on opposite ends. Here, we see that the capacitive loading will drive the resonant frequency of the resonators below that of the series couplings so that relatively strong inter-resonator couplings can occur. The combline filter has several advantages; firstly, it is compact, as the coupled conductors are typically one-eighth wavelength long. Secondly, the electrically short resonators will not re-resonate until typically six times the center frequency of the filter, giving a broad spurious-free stopband, which is not possible with wide-band interdigital filters. Thirdly, it is easier to manufacture than the interdigital filter, as
all the tuning screws required for electrical alignment can be on the same face of the filter. Finally, the center frequency of the combline filter may be tuned by an octave or more without causing significant distortion to its frequency response (Hunter and Rhodes, 1982). An accurate design method for wide-band combline filters is described in (Wenzel, 1971). The design of multiplexers using wide-band combline filters is reported in (Schumacher, 1976; La-Tourette, 1977; La-Tourette and J. L. Rohrds, 1978).

Recent advances in micromachined electromechanical systems (MEMS) have demonstrated that this technology may be suitable for handset filters. For example, micromechanical resonators with Q’s of 7450 at 100 MHz have been demonstrated (Nguyen, 2000). MEMS switches have also been used for tuning the values of lumped components within filters (Peroulis et al., 2001). The use of tunable filters may be useful in handsets for future systems operating at many different frequencies. An alternative technology for tuning of filter resonators is to use ferroelectric materials with tuning accomplished by an applied electric field (Lancaster et al., 1998; Vendik et al., 2000).

- **Satellite systems**

The satellite communications industry created demand for low-mass narrow-band low-loss filters with severe specifications on amplitude selectivity and phase linearity. These requirements resulted in the development of dual-mode waveguide and dielectric- resonator filters, and advances in the design of contiguous multiplexers. High performance waveguide filters were used to avoid problems caused by the devices used when channelized architecture was first implemented in Intelsat IV series launched in 1971. The first major electrical innovation was the use of dual-mode filters, where size reduction is obtained by exciting two orthogonal degenerate modes in the same physical cavity. This was first reported by Lin (1951). The first practical devices were developed by Comsat Laboratories, Canada (Atia and Williams, 1971; Atia et al., 1974). Dual-mode filters were first launched on
Intelsat IV A in 1976, after which they became the satellite industry standard. Indeed, new types of dual-mode filters are still being reported, (Guglielmi et al., 2001). Surface acoustic wave (SAW) filters also have applications in the satellite industry. Several satellites use dielectric resonators constructed from low-loss high-permittivity (20–100) temperature stable ceramics having high- $Q$ (up to 100,000) for filters to be realized in a fraction of the volume and weight of air-filled waveguide devices (Fiedziuszko et al., 2002). Probably the most significant development in this area was the dual-mode in-line device reported by Fiedziuszko (1982).

The sub-banded American systems require selective filters with percentage bandwidths as low as 0.25%. These filters require higher $Q$ resonators with much better temperature stability than achievable with coaxial resonator filters. Dielectric resonator filters have been proven useful in this respect. The most commonly used designs use a cylindrical puck of ceramic suspended on a support within a metallic housing. The fundamental mode of resonance is the $TE_{015}$ originally reported in (Cohn, 1968). The most commonly used material is calcium titanate–neodymium aluminate (Wersing, 1996), which has a relative permittivity of 45, a $Q$ of greater than 20,000 at 2 GHz, and a temperature coefficient of resonant frequency of less than 1 ppm/°C for the $TE_{015}$ mode.

Superconducting base-station filters are of interest because of their high $Q$ realizable in a very small physical size. For example, a microstrip realization of a fifth-degree Chebyshev bandpass filter with 890-MHz center frequency and 0.3% bandwidth, occupied a surface area of approximately 5 cm and exhibited 1-dB passband insertion loss (Zhang et al., 1995). A complete receiver front-end including 5-MHz bandwidth filters and integrated LNAs in the PCS band at 1.9 GHz is described in (Soares et al., 2001).

The transmit/receive diplexer can be replaced by a switch and a receive filter. The purpose of the receive filter is to protect the LNA and the mixer in the down-converter from being overdriven by extraneous signals.
Recent advances in SAW filter design have enabled them to compete in this market. Their main advantage is very small size (typically 3 x 3 x 1 mm) and low cost. Typically, they have 3-dB insertion loss and 2-W power handling. The most significant advance in SAW technology has been the replacement of the conventional transversal designs by SAW resonators, which are formed between acoustically reflective gratings on the surface of a SAW crystal (Tagami et al., 1997). Although these remarkable devices offer small size and low cost, their power handling and temperature stability is poor when compared with ceramic filters. Thus, they may not be suitable for third-generation systems where the transmitter and receiver operate simultaneously. However, recent developments in film bulk acoustic resonator (FBAR) devices show very impressive performance (Larson et al., 2000; Weigel et al., 2002).

All the miniature handset filter technologies thus far discussed use passive resonators. Alternatively, several workers are investigating the use of active filters. One design approach is to compensate for the losses in physically small resonators by cancelling them with negative resistance. The negative resistance can be achieved by two distinct methods. In the first method (Brucher et al., 1994), the negative resistance is achieved by connecting a series \( L/C \) resonator to the drain of a single common-source transistor, with a shunt \( L/C \) resonator connected to the source. Alternatively, two transistors may be connected in a feedback configuration (Fort, 1994). This method has been demonstrated in the 3.8-4.2 GHz band. A spiral monolithic microwave integrated circuit (MMIC) inductor is then cascaded with this negative impedance converter to obtain a high-Q inductor. This active inductance is then used to design bandpass filters. Although microwave filters are often described as a mature technology, it can be seen that this is not the case, and, hopefully, future applications will stimulate further advances in this exciting field.
1.3 Resonators for Microwave Communication

The main frequency bands assigned to the wireless communication are spread throughout a wide range, from several tens of MHz to several tens of GHz. A wide variety of resonators and filters can be applied to these frequency bands. A resonator is any structure that is able to contain at least one oscillating electromagnetic field. The resonating frequency of a resonator determines the frequency response of the corresponding filter. Resonators finding its use in microwave applications are further classified as follows.

1.3.1 Bulk wave, Surface Acoustic Wave and Helical resonator

For frequencies below 1 GHz, the most commonly used resonators are bulk wave, SAW and helical resonators. Bulk wave, SAW resonators/filters are used where there is strong demand for miniaturization and low loss characteristics; and helical resonators/filters are often utilized when a high level of power handling is necessary. In addition, bulk wave and SAW resonators show outstanding temperature characteristics, thus satisfying conditions for applications to narrow band filters.

1.3.2 Coaxial, dielectric, waveguide and stripline resonators

For a frequency range from RF to microwave, various kinds of resonators including the coaxial, dielectric, waveguide and stripline exist. Coaxial resonators have many attractive features including an electromagnetic shielding structure, low loss characteristics and small size but their minute physical dimensions for applications above 10GHz make it difficult to achieve manufacturing accuracy.

Dielectric resonators also possess a number of advantages such as low loss characteristics, acceptable temperature stability and small size. However, high cost and present-day processing technology restriction limits dielectric resonator utilization to applications below 50GHz.
Waveguide resonators have long been used in this frequency range, possessing two main advantages: low loss application and practical application feasibility up to 100GHz. However, the greatest drawback of the waveguide resonator is its size, which is significantly larger than other resonators available in the microwave region. The rectangular waveguide filter consists of a uniform section of rectangular guide with post (or other) discontinuities placed across the broad walls of the guide at approximately half-guide-wavelength intervals. Usually, the waveguide is operated in its fundamental mode (TE\textsubscript{10}) mode of operation.

Presently, the most common choice for RF and microwave circuits remains the planar resonator or stripline resonator. Due to practical features including small size, easy processing by photolithography, and good affinity with active circuit elements, many circuits utilize the stripline resonator. Another advantage of the planar resonator is a wide applicable frequency range which can be obtained by employing various kinds of substrate materials. However, the major drawback to the use of stripline resonators is a drastic increase in the insertion loss compared to other types of resonators, making it difficult to use them for narrow band filters. Still such resonators yield high expectations for application to ultra low loss superconducting filters, which are now under development and require fabrication methods using planar circuits such as stripline configuration.

1.3.3 Planar resonators

In microwave applications keeping filter structures to a minimum size and weight is very important. Hence, planar filter structures which can be fabricated using printed-circuit technologies would be preferred whenever they are available because of smaller size and lighter weight. As is known, microwave frequency-selective devices occupy a substantial volume in communications, radar, and radio-navigation facilities. As a rule, these devices, designed as systems of coupled resonators, often determine overall dimensions of individual modules and, sometimes, the entire setup. Moreover, the quality and the ultimate characteristics of
Introduction

Radio equipment depend directly on the frequency-selective properties of filtering devices. Hence, the search for new solutions for the design of miniature filters and studies aimed at miniaturization and improvement of frequency-selective properties of known designs are very topical and among the most important problems of modern radio engineering. It is well known that the most miniature "electromagnetic" filters are microstrip filters (MSFs), which are widely used in microwave devices because of the advantages of such electronic components. These filters have small dimensions and are reliable and easy-to-manufacture. The results of their high-speed quasi-static analysis of various and complex design versions agree well with experimental data. This fact allows the development of efficient program systems for the computer-aided design of MSFs. The overall dimensions of microstrip filters can be reduced using several well-known approaches, such as the use of folded strip line conductors in resonators, formation of smooth and stepwise irregularities in these conductors and application of substrates with a high value of permittivity. Evidently, the maximum effect can be attained by combining several methods for reduction of the MSF dimensions.

In order to improve frequency-selective properties of filters, the slopes of the amplitude-frequency response (AFR), should be more and the attenuation levels in the filter stopbands should be large. These characteristics depend on both the number of the filter resonators and many other design parameters of the device. Therefore, the study of selective properties of particular design versions with different numbers of resonators as functions of the frequency band, fractional bandwidth, permittivity of the substrate, and other design parameters is important. Such studies allow (1) determination of the limits of applicability of the chosen design and (2) creation of optimized MSFs that satisfy particular specifications and contain the minimum number of sections. Stripline resonators are further classified as stepped impedance resonators and transmission line resonators.
Chapter I

- **Stepped impedance resonators**

  Stripline resonators having non uniform impedance characteristics are generally classified under stepped impedance resonators. Despite its simple structure, the SIRs possess numerous features and possibilities for practical applications. SIRs finds its applications in filters, oscillators and mixers as a basic resonator in frequency band from RF to millimeter.

- **Transmission line resonators**

  The most typical transmission line resonators utilizing transverse electromagnetic modes (TEM) or quasi-TEM modes are coaxial and stripline resonators. These resonators possess a wide application frequency range from several 100 MHz range to several 100GHz and presently remain the most common choice for the filters in wireless communication. These resonators do not possess low loss properties. They do not have high Q values compared to waveguide or dielectric resonators. However, they do have valuable features as small size, simple structure and capability of wide application to various devices. Moreover, the most attractive feature of the microstrip line, stripline or coplanar line resonators is that they can be easily integrated with active circuits such as MMICs, because they are manufactured by photo lithography of metallic film on a thin dielectric substrate. There are numerous forms of microstrip resonators. In general, microstrip resonators for filter design may be classified as lumped element or quasi-lumped element resonators and distributed line or patch resonators.

  Microstrip-line resonators are the distributed elements such as quarter wavelength and half wavelength line resonators. The choice of individual components may depend mainly on the types of filters, the fabrication techniques, the acceptable losses or Q factors, the power handling and the operating frequency.

  Distributed line resonators shown in Fig.1.2 are termed as quarter wavelength resonators since they are $\lambda_{g0}/4$ long, where $\lambda_{g0}$ is the guided wavelength at the
fundamental resonant frequency $f_0$. They can also resonate at other higher frequencies when $f = (2n - 1)f_0$ for $n=2, 3…$

$$l = \frac{\lambda_{g0}}{4}$$

**Fig. 1.2** Some typical microstrip resonators (a) $\frac{\lambda_{g0}}{4}$ line resonator (Shunt series resonance) (b) $\frac{\lambda_{g0}}{4}$ line resonator (shunt parallel resonance)

Another typical distributed line resonator is the half wavelength resonator as shown in Fig. 1.3 which is $\frac{\lambda_{g0}}{2}$ long at its fundamental resonant frequency and can also resonate at $f = n f_0$ for $n=2, 3…$

$$l = \frac{\lambda_{g0}}{2}$$

**Fig. 1.3** $\frac{\lambda_{g0}}{2}$ line resonator

This type of line resonator can be shaped into many different configurations for filter implementations such as closed or open loop resonators. These are simpler to design and easier to fabricate. Closed ring resonator is merely a transmission line formed in a closed loop (Fig. 1.4). The circular ring will resonate at its fundamental
Chapter 1

frequency $f_0$ where its median circumference $2\pi r = \lambda_{g0}$, where $r$ is the mean radius of the ring. The higher resonant modes occur at $f = n f_0$ for $n=2, 3$...

![Fig. 1.4 Circular and square closed ring resonator](image)

Figure 1.4 shows the open loop resonators with a fundamental resonant frequency half that of the closed ring resonators. In the case of rectangular ring resonators the fundamental frequency is determined by the average perimeter.

![Fig. 1.5 Circular and square $\lambda_{g0}/2$ open loop resonators](image)

The ring resonators shown in Fig. 1.6 is another type of distributed line resonators called split ring resonators (SRR), formed by two coupled conducting open loop resonators printed on a dielectric slab.

![Fig. 1.6 Circular and square split ring resonator](image)
They are considered as electronically small resonators with very high Q and very useful structure in constructing filters requiring sharp notch or pass a certain frequency band. It is possible to construct this type of line resonator into different configurations such as folded and meander loop resonators to reduce the size.

The above portrayal has inspired the investigation of planar loop resonators and their behavioral flexibility in miniaturizing filter structures for present day applications

1.4 Outline of Present Work

Study of the characteristics of planar loop resonators and their use in the construction of filters at microwave frequencies are presented in this thesis. A detailed investigation of parameters affecting the strength of coupling and the resonant frequency are also carried out. Techniques for size reduction in band stop and bandpass filters are using planar loop resonators are developed. Different configurations of compact bandstop and bandpass filters using loop resonator are simulated and experimental results on optimal filter configuration are presented.

1.5 Organisation of the Thesis

Chapter 1 Introduction

This chapter starts with a brief outline regarding relevance of microwave filters, evolution and their uses in communication technology. A brief introduction of planar filters has also been presented.

Chapter 2 Review of Literature

This chapter presents a thorough review of literature on the development in the field of microwave filters giving special attention to planar bandstop and bandpass filters. Attempts have been made to cover all the important development in
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microstrip filter theory and experiment. Various types of loop resonator filters based on their specific geometries with their gradual development have been studied to arrive at the motivation of the present thesis.

Chapter 3 Methodology

In this chapter, the methodology adopted for characterizing the filter is described. It deals with the various techniques employed for the design, fabrication and measurement of filters. Simulation and parametric analysis using commercial EM simulation packages Ansoft-HFSS and IE3D are also outlined.

Chapter 4 Planar loop resonator filters

This chapter provides the details of the studies undertaken for the design and development of microstrip planar filters using novel coupling techniques on microstrip loop resonators and finding its utility in compact bandstop and bandpass filters. Parameters affecting the strength of coupling and the resonant frequency are investigated. Techniques for size reduction in bandstop and bandpass filters are developed and empirical formula for the resonant frequency for different types of resonators are deduced.

Chapter 5 SRR based microstrip bandstop filter

In this chapter the propagation characteristics of a microstrip line loaded with an array of SRR as superstrate is investigated. The response of different types of loop resonators is also portrayed.

Chapter 6 SRR based waveguide filter

This chapter presents the behavior of SRR in waveguide for the development of bandstop and bandpass filters. A detailed investigation of band rejection at the second resonance is carried out and exploited to develop a variable bandwidth bandstop filter. Also the frequency response of the waveguide below cut-off with
bandstop filter. Also the frequency response of the waveguide below cut-off with SRR insert is explored for the development of bandpass filter. This study leads to the phenomenon of waveguide miniaturization.

Chapter 7 Conclusions

This chapter serves the conclusions drawn from the study with directions for future work. It describes the important findings of the thesis and salient features of the proposed microstrip filters.

References


Chapter 1


Introduction


Chapter 1


