Chapter Two

REVIEW OF LITERATURE

This chapter serves to review the important developments in conventional and advanced resonators used for the design of planar bandstop and bandpass filters. Filter structures with different types of resonators for bandstop and bandpass characteristics are reviewed with illustrations. Recent findings in filter miniaturization are also presented.
2.1 Microwave Filters

Microwave communication links are an important practical application of microwave technology and are used to carry voice, data over distances ranging from intercity links to deep-space spacecraft. They find applications in virtually any type of microwave communication, radar, or test and measurement system. In some applications such as communication satellite and mobile communication devices, it is critical that filters be devised with small size, light weight, and lower cost along with stringent electrical characteristics. Planar filter geometries are well suited for meeting these requirements.

The recent advances in novel materials and fabrication technologies, including monolithic microwave integrated circuit (MMIC), microelectromechanic system (MEMS), micromachining, high-temperature superconductor (HTS), and low-temperature co-fired ceramics (LTCC) have stimulated the development of new types of filters.

2.2 Microstrip Bandstop Filters

Spurious passband rejection in microwave filters is key aspect in certain applications that require huge stopband extending above the first and even higher order harmonics of the target frequency. Lumped circuit elements like inductors and capacitors are commonly employed as resonant circuits at lower frequencies but at microwave frequencies, planar circuits are preferred as they are of low cost, light weight and can be easily fabricated using printed circuit technology. Band rejection in microstrip transmission line is the phenomenon which occurs when a main transmission line is electrically or magnetically coupled to half wavelength resonators spaced quarter wavelength apart. The resonators used may be open circuited stub, short circuited stub,
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hair-pin resonators (Hong and Lancaster, 2001), closed ring resonators, open loop resonators and split ring resonators (Garcia et al., 2004).

Bandstop filters particularly notch filters are an important noise reduction device commonly used in cable televisions, satellite location systems, mobile phones, and numerous other applications. Conventional notch filters suffer from various technical limitations, mostly related to the use of discrete inductors, including: large size, difficulty in integrating onto a single integrated circuit, high power consumption, and susceptibility to parasitic effects in the gigahertz range. A filter with an optimum frequency response curve and reduced size is very essential to a microwave system. Planar filters are popular and have low cost and light weight; particularly, such filters are easily fabricated using printed circuit technology. Since size reduction is always important, the planar filter frequently requires a change in geometry for circuit miniaturization (Gorur et al., 2001, Fig. 2.1; Matthaei et al., 1964; Nguyen and Chang, 1985; Bates, 1977).

![Fig. 2.1 Layout of the bandstop filter and its frequency response](image)

Various types of microstrip notch filters are common but modifications are still being reported, employing resonators of different shapes like triangular resonators (Chen et al., 2004), spurline (Nguyen and Chang, 1985), stubs or some combinations (Tu and Chang, 2005). The level of rejection depends on the coupling between feed line
and resonator. Harikrishna et al., (2007, Fig. 2.2) employed electromagnetic coupling between the transmission line and the resonator to achieve better rejection.

![Configuration of EM coupled square ring resonator notch filter and its frequency response.](image)

**Fig. 2.2** Configuration of EM coupled square ring resonator notch filter and its frequency response.

This method has the additional advantage of flexibility of easy coupling gap adjustment and resonator/circuit replacement or modifications. Added advantage of this type of flexible EM coupling is that resonating circuits can be replaced or additional notch resonators can be added easily without affecting the underlying feed line and port connections, thus giving multifrequency operation.

Traditional techniques based on half wavelength short circuit stubs, chip capacitors or cascaded rejection band filters, are either narrow band, have increased device area or include significant insertion loss. As an alternative, it has been recently demonstrated that electromagnetic band gap (EBG) can be efficiently used to achieve harmonic suppression in microwave circuits. Among several approaches, remarkable findings are unipalnar EBG structure proposed by Itoh et al., (1999) and the Wiggly line concept recently introduced by Lopetegi et al., (2004) to achieve multi-spurious rejection in coupled line bandpass filters. The main advantage of EBG over traditional technique is the possibility to introduce the rejecting structure within the active device
region, thus avoiding the need to cascade the additional stages. However in EBGs the frequency selectivity is based on their periodicity and several stages are required to obtain significant rejection levels. Since the EBG period scales with signal wavelength, the required dimension of the structure may be too big at moderate or low frequencies, or its efficiency very poor in certain applications where miniaturization is mandatory.

Recently, split-ring resonators (SRRs) (Pendry et al., 1999) and complementary split-ring resonators (CSRRs) (Falcone et al., 2004) have been used in planar circuit technology for the design of novel printed microwave components, in particular, bandpass and bandstop filters (Safwat et al., 2007 and Bengin et al., 2007). Pendry et al., (1999) demonstrated that an array of SRRs exhibits negative permeability near its resonant frequency and successfully applied to the fabrication of left-handed metamaterial (LHM). Marques et al., (2002) reported that SRRs should be excited with a time varying magnetic field with a significant component parallel to the ring axes. SRRs etched at the top metal level in the close proximity to the central strip guaranteed efficient magnetic coupling as reported by Garcia et al., (2004).

It has been shown that when loaded with SRRs, both microstrip lines (Garcia et al., 2005a; Burokur et al., 2005; Garcia et al., 2005b) and coplanar waveguides (Falcone et al 2004; Baena et al., 2005) behave as compact, high-Q, bandstop filters with deep stopbands in the vicinity of their resonant frequencies. This phenomenon is due to the presence of SRRs in close proximity to the transmission line generating an effective single-negative (SNG) medium with negative effective permeability, \( \mu_{\text{eff}} \), around their resonant frequencies, and previously propagating waves (in the absence of SRRs) become evanescent waves. As a result, the signal propagation is inhibited. Having a strongly anisotropic electromagnetic nature, the SRR is able to inhibit signal propagation in a narrow band in the vicinity of its resonant frequency, provided that it is illuminated by a time-varying magnetic field with an appreciable component in its axial
direction. If two arrays of SRRs exist closely at both sides of the host microstrip line, a significant portion of the magnetic fields induced by the line is expected to cross the SRRs with the desired polarization which constitute an effective SNG medium with negative \( \mu_{\text{eff}} \) consequently inhibiting the signal propagation. Based on this explanation, an SRR-based bandstop microstrip filter has been designed and fabricated by Oznazli and Erturk (2007 Fig. 2.3). A total of six square shaped SRRs replacing the conventional circular SRRs have been implemented to improve the coupling between the transmission line and the SRR array.

![Fig. 2.3 Fabricated SRR-based microstrip bandstop filter and its frequency response.](image)

A novel compact stopband filter consisting of a coplanar waveguide (CPW) with split ring resonators (SRRs) etched in the back side of the substrate has been presented by Martín et al., (2003). By aligning SRRs with the slots, a high inductive coupling between line and rings is achieved, resulting in a sharp and narrow rejection band in the vicinity of the resonant frequency of the rings. In order to widen the stopband of the filter, several ring pairs tuned at equally spaced frequencies within the desired gap are cascaded.

In a similar fashion, when loaded with CSRRs (which is the negative image of SRR), microstrip lines also behave as high-Q bandstop filters with deep stopbands
around their resonant frequencies (Falcone et al 2004; Ying and Alphones, 2005). Since CSRRs are dual counterparts of SRRs, etching CSRRs in the ground plane just beneath a microstrip line (simplest and most standard configuration) yields an effective SNG medium with negative $\varepsilon_{\text{eff}}$. It has been demonstrated that CSRR etched in the ground plane or in the conductor strip of planar transmission media (microstrip or CPW) provide a negative effective permittivity to the structure. Being the dual counterpart of the conventional SRR, the CSRR requires the excitation of a time-varying electric field having a strong component parallel to its axis so that it can resonate at some frequencies. A microstrip transmission line induces electric field lines that originate from the central strip and terminate perpendicularly on the ground plane. Owing to the presence of the dielectric substrate, field lines are concentrated just below the central conductor, and the electric flux density reaches its maximum value in the vicinity of this region. Hence, if an array of CSRRs is etched on the ground plane just aligned with the microstrip line, a strong electric coupling with the desired polarization is expected. As a result, a linear array of CSRRs constitutes an SNG medium with a negative $\varepsilon_{\text{eff}}$. Based on this explanation, CSRR-based bandstop microstrip filter was fabricated by Oznazli and Erturk (2007, Fig. 2.4).

![Fig. 2.4 CSRR-based microstrip bandstop filter and its frequency response.]

Since SRR /CSRR dimensions are much smaller than signal wavelength, the proposed filters are extremely compact and can be used to reject frequency parasitic in CPW structures by simply patterning properly tuned SRRs in the back side metal. Easy
fabrication and compatibility with MMIC or PCB technology are additional advantages. These resonators were also been used for the design of frequency selective structure in planar circuit technology (Marques et al., 2003). The relevant characteristic of all these resonators which are inspired on the canonical topology proposed by Pendry et al., (1999) is the electrical length. This can be made very small due to the edge capacitance between concentric rings. Hence these resonators can be considered as planar lumped elements which opened the door to new design strategies where design miniaturization is of major concern. The limitations of the EBG periodic structure could be overcome by SRRs properly coupled to the host transmission media, either in the active device region or in the input/output accessing ports. CSRR has been successfully applied to the narrow band filters and diplexer with compact dimensions (Bonache et al., 2005, 2006). Since propagating waves in the absence of etched CSRRs become evanescent waves, the signal propagation is again inhibited. Finally, as in the case of SRRs, these structures can be converted to bandpass filters with small modifications (Wu et al., 2006, 2007; Gil et al., 2006; Bengin et al., 2007).

The defected ground structure was first proposed by Park et al., (1999) based on the idea of photonic band-gap (PBG) structure, and had found its application in the design of planar circuits and low-pass filters (Yablonovitch et al., 1991; Park et al., 1999; Lim et al., 2002). Defected ground structure is realized by etching a defective pattern in the ground plane, which disturbs the shield current distribution in the ground plane. This disturbance can change the characteristics of a transmission line such as equivalent capacitance and inductance to obtain the slow-wave effect resulting bandstop property. A square split-ring resonator (SRR) defected ground structure (DGS) was studied by Wu et al., (2006, Fig. 2.5). This DGS structure has a flat low-pass characteristic and a sharp bandstop property compared to the conventional dumbbell DGS. In order to enhance the out-band suppression, an improved SRR DGS cell with open stubs loaded on the conductor line was proposed.
The frequency response measured in the fabricated prototype device exhibited pronounced slopes at either side of the stopband and near 0 dB insertion loss outside that band.

2.3 Microstrip Bandpass Filters

With the advent of advanced materials and new fabrication techniques, microstrip filters have become very attractive for microwave applications because of their small size, low cost and good performance. There are various topologies to implement microstrip bandpass filters such as end-coupled, parallel coupled, hairpin, interdigital and combline filters.

The microstrip parallel-coupled half-wavelength resonator filter, proposed by Cohn (1958) has been one of the most commonly used filters. A parallel-coupled microstrip bandpass filter structure consists of open circuited coupled microstrip lines. This parallel arrangement of resonators gives relatively large coupling and therefore this configuration is suitable for implementing printed-circuit microstrip filters for
bandwidths from 5% up to 35%. Fringing effects at the ends of the resonators are taken into account and therefore there is no need of additional tuning or adjustments. Filter length can be considerably reduced by using substrate with high dielectric constant. Insertion loss of the filter can be reduced by using low loss substrates. This type of filter has many advantages such as easy design procedures, a wide bandwidth range and a planar structure. They can be easily fabricated and it exhibits reasonably good performance compared to other planar circuit filters.

Recently Chang and Itoh introduced a modified parallel-coupled filter structure to improve the upper stopband rejection and the response symmetry (Chang and Itoh, 1991). Matthaei and Hey-Shipton proposed an aligned microstrip parallel-coupled resonator array filter for design of compact narrow-band filters (Matthaei and Hey-Shipton, 1994). Superconducting filters of this type have been developed by Zhang and his colleagues for cellular communication (Zhang et al., 1995). In order to reduce the size of half-wavelength resonator filters, Hong and Lancaster have proposed the so-called ladder microstrip line structures (Hong and Lancaster 1995a, Fig.2.6).

Fig.2.6 Conventional microstrip parallel coupled filter and its frequency response

There are several disadvantages of the traditional parallel coupled filters. One of the disadvantages is that the first spurious passband appears at twice the basic passband
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frequency. This is due to the inequality of the even- and odd-mode velocities of the coupled microstrip line. This phenomenon greatly limits the applications of the parallel coupled filters. Also, the filter shows a steeper roll-off on the lower frequency side than on the higher frequency side. The asymmetry in the frequency response is apparent when looking on to the passband group delay. The frequency response symmetry is also important in applications involving pulsed signals.

Several designs have been reported to overcome the inherent disadvantages of the parallel coupled resonators by modifying their structure. Riddle, (1988) showed that an over-coupled resonator extends the phase length for the odd mode to compensate difference in the phase velocities. In 1991, Chang and Itoh (1991) proposed a new filter modifying the traditional parallel coupled filter which fitted in a quite narrow channel resulting in an improvement in the upper stopband rejection by at least 15 dB with symmetric frequency response. The corrugated coupled microstrips were designed for equalization of modal phase velocities in parallel coupled filter for eliminating the spurious response at twice the passband frequencies (Kuo, 2002). Kuo and co-workers (2003) applied over-coupling to the end stages and thus increasing the image impedance of the filter. Coupled microstrip stage with higher image impedance is shown to have smaller difference in the even and the odd mode relative permittivities and parallel-coupled microstrip filters with higher image impedances also showed an improved rejection at double the resonant frequency.

The spurious frequency of the conventional planar filters with half-wavelength resonators is two or three times the fundamental frequency. For efficient harmonic suppression, several unique structures have been designed. Stepped-impedance resonators (SIR) have been found advantageous in designing microstrip bandpass filters (Makimoto and Yamashita, 1980; Lee and Tsai, 2000; Zhu and Wu, 2000; Denis et al., 1988; Makimoto and S. Yamashita, 2001) with good stop band performance. One of the
key features of an SIR is that its resonant frequencies can be tuned by adjusting its structural parameters, such as the impedance ratio of the high- and low- segments. As a result, the first spurious harmonic can be much higher than $2/f_0$. The design in (Zhu and Wu, 2000) completely suppresses the resonance with an inductive effect, and the first parasitic response is observed at frequencies close to $3/f_0$. A combination of different SIR structures can also be adopted for a bandpass filter with wide stopband (Denis et al., 1988; Makimoto and S. Yamashita, 2001). Nonconventional SIRs can be used to construct high-performance bandpass filters with the control of spurious responses outside of a selected bandwidth over a very large frequency range. A bandpass filter based on parallel coupled structure using SIR unit cells to control the higher harmonics is demonstrated by Kuo et al., (2003, Fig. 2.7) where he applied tapped couplings to both the first and last resonators to fully control the positions of the two extra zeros.

![Fig. 2.7 Photograph of the SIR based bandpass filter and its frequency response.](image)

This is a very useful feature for practical receivers in rejecting image frequencies and enhancing the rejection level in the stopband of a bandpass filter. Currently, filters with compact size which suppress spurious sidebands having wider upper stopbands are required for several wireless communication systems. However, most of the planar bandpass filters built on microstrip structures are large in size and their first spurious resonance frequencies appear at $2/f_0$ and $3/f_0$, which may be close to the desired frequencies. The half-wavelength resonators inherently have a spurious
passband at $2f_0$, while quarter-wavelength resonator filters have the first spurious passband at $3f_0$, but they require short-circuit connections with via holes, which are not quite compatible with planar fabrication techniques.

One of the typical folded-line resonator filters is a hairpin line filter, introduced by Cristal and Frankel (1972). Further miniaturised hairpin resonator filters were reported by Sagawa et al. (1989) for application to receiver front-end microwave-integrated circuits. Matthaei et al. (1996, Fig. 2.8) developed narrow-band hairpin-comb filters using hairpin resonators in such a way that their filtering properties are similar to those of comb-line filters.

![Fig. 2.8 Six-pole microstrip pseudo-interdigital bandpass filter and its frequency response.](image)

This type of filter may be conceptualised from the conventional interdigital bandpass filter whose resonator element is quarter-wavelength long at the midband frequency and is short-circuited at one end and open-circuited at the other end.

The microstrip ring resonator is finding wide use in many bandpass filters (Chang, 1996). In the microwave communication systems, efficient bandpass filters with compact size are required. Many conventional microstrip bandpass filters having high selectivity, use hairpin resonators or ring resonators (Hong and Lancaster, 1998; Yang and Chang, 1999; Yabuki, 1996). However, the conventional end-to-line coupling structure of the ring resonator suffers from high insertion loss (Gopalakrishnan and
Chang, 1994). The coupling gaps between the feed lines and resonator also affect the resonant frequencies of the resonator. To reduce the high insertion loss, filters using an enhanced coupling structure or lumped capacitors were proposed (Hsieh and Chang, 2000; Jung et al., 1999; Zhu and Wu, 1999; Matsuo et al., 2001; Hsieh and Chang, 2002). However, the filters using this enhanced coupling structure still have coupling gaps. In addition, the filters using lumped capacitors are not easy to fabricate. Ring resonators using a high temperature superconductor (HTS) to obtain a very low insertion loss have been reported (Hong et al., 1999). This approach has the advantage of very low conductor loss, but requires a complex fabrication process.

It has been proven that square ring filter elements edge coupled to tapped input/output lines provide narrow bandwidth in the passband and good rejection in the stopband (Yu and K. Chang, 1998). However the corresponding insertion losses are rather high. Increasing the coupling between the ring resonator and the input/output lines will promote a decrease in the insertion losses. Therefore rectangular ring resonator can provide better performance when compared with square ones as per the investigation of Peixeiro (2000).

Saveedra, (2001, Fig. 2.9) proposed a bandpass filter with a ring resonator that uses quarter-wave ($\lambda/4$) edge-coupled lines as the coupling mechanism. Special attention is devoted to the physical structure of the ring to eliminate dual modes, which manifest themselves as a double-resonance in the frequency response of the ring.

Fig. 2.9 Symmetric square ring resonator and its frequency response
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When the ring is loaded with coupled lines on all sides, the structure becomes essentially symmetric and the double-resonance disappears since the impedance is uniform throughout the structure.

Filtering at 3G operating frequencies is inherently a problem. Waveguide and, more generally, 3D approaches which are widely used in 2G base stations for their performance, are not affordable any further in nano- and pico-cellular networks. These applications need more compact solutions such as planar ones that are not commonly used in 2G systems because of their relatively high losses, tuning difficulties and low power handling. In this field of application, microstrip dual-mode filtering (Curtis and Fiedziuszko, 1991; Mansour, 1994) is an interesting technique. For dual-mode operation, a perturbation is introduced in the resonator in order to couple its two degenerate modes. Depending on the position and size of the perturbation, different filter responses can be obtained. Transmission zeros at finite frequencies can also be generated and controlled by the same mechanism.

The first demonstration of dual-mode operation in a microstrip ring has been presented by Wolf who used a circular ring (Wolf, 1972). The circular ring is, unfortunately, not practical for the design of higher order filters because of the difficulty in coupling the modes of two different rings. Only second order dual-mode filters based on a circular ring have been reported in the literature. Later work on this structure mainly focused on the control of the characteristics of the response of second order filters such as the generation and control of transmission zeros at finite frequencies (Karacaoglu et al., 1994; Kundu and Awai, 2001). A partial solution to the limitations of the circular ring is given by the square ring which allows simpler and stronger coupling between two different resonators. The investigation of a new dual-mode microstrip square loop resonator for the design of compact microwave bandpass filters was presented by Hong and Lancaster, (1995b). New filters were developed from the bandstop filter to achieve a wide passband and two sharp stopbands. Hsieh et al., (2003,
Fig. 2.10) developed a new compact, low insertion-loss, sharp-rejection, and wide-band microstrip bandpass filter from a bandstop filter using a ring resonator with direct-connected orthogonal feeders.

Fig. 2.10 Configuration of the cascaded dual-mode ring resonator and its transmission characteristics.

The new filters were designed for mitigating the interference in full duplex systems in satellite communications.

Microstrip bandpass filters using distributed element components are quite popular in modern communication systems. The design approach associated with coupled-resonator microstrip filters provided in (Hong and Lancaster, 1996) makes the filter simulation procedure simple and routine. Half-wavelength resonators (Cohn, 1958) and Open-loop coupled-resonators (Hong and Lancaster, 2001, Fig. 2.11) are widely used in designing filters. Since the lengths of these resonators are to be at least a half-wavelength, these filters are too large to be used in mobile communication systems where size is a significant parameter. Therefore, some novel open-loop resonators are required for filters’ miniaturizations, and the electromagnetic fullwave analysis tools are used to simulate the electromagnetic properties. Hong and Lancaster (1997), introduced a new class of microstrip bandpass filters based on coupled slow-wave open-loop resonators. They showed that the use of slow-wave open loop resonators enable various
filters including those of elliptic or quasi-elliptic function response to be designed, that are not only of compact size, but also have a wide upper stopband.

Fig. 2.11 Microstrip open-loop coupled-resonator bandpass filter and its frequency response.

Several designs have been developed in order to increase the filter selectivity. Hong and M. J. Lancaster, (2000a) reported a printed filter composed of square open-loop resonators. In this structure, the transmission zeros were obtained by classical cross-coupling interactions between nonadjacent resonators. This work is based on previous results by (Hong and Lancaster, 1996, Yu and Chang, 1998), in which elliptic transfer functions were implemented by using similar square open-loop resonators combined with cross couplings between nonadjacent resonators. Another example of a printed filter which uses side cross-coupling interactions can be found in Hong and M. J. Lancaster, (1998), where hair pin resonators were placed in a square matrix in order to achieve an elliptic-transfer function for a 2nd-order filter.

Asymmetric trisection bandpass filters with diagonal cross-coupling using open-loop resonators have also been proposed (Hong and Lancaster, 1999). Cross-coupled bandpass filters have attracted much attention because they have one or more transmission zeros in the stopband to reject possible interferences. A previous study by Prayoot and Jaruek (2006) presented a new class of microstrip slow-wave open-loop
resonator filters with reduced size and improved stopband characteristics. A comprehensive treatment of both ends loaded with either triangular or rectangular ends is described, leading to the invention of a microstrip slow-wave open-loop resonator. The filters are not only compact in size due to the slow wave effect, but also have a wider upper stopband resulting from a dispersion effect.

A low loss dual-band microstrip filters using folded open-loop ring resonators (OLRRs) is proposed by Chen and Cheng, (2006, Fig. 2.12).

![Frequency response of folded open loop resonator dual-band filter.](image)

**Fig. 2.12** Frequency response of folded open loop resonator dual-band filter.

The first and second passbands of the designed dual-band filter can be easily and accurately shifted to a desired frequency by adjusting the physical dimensions of OLRRs.

In order to suppress spurious response, a number of technologies have been investigated. Electromagnetic periodic structure (EPS) was first introduced to control light wave propagation in the optical frequency bands. It can provide stopband and slow-wave characteristics by etching cells in shapes such as rectangles and circles on the ground plane (Her et al., 2003; Radisic et al., 1998). For a properly designed EPS, the propagation of electromagnetic waves can be forbidden in some specific frequency bands. Most of the EPS concepts have been widely utilized in several microwave and millimeter-wave circuits, such as lowpass filters and patch antennas (Coccioli et al.,
1998; Kim et al., 2000), but few applications for bandpass filters have been developed. Her et al., (2004) proposed an EPS bandpass filter (EPS-BPF) unit cell realized by open-ended stub with EPS patterns on the ground plane. In order to improve the performance, four EPS-BPF unit cells were periodically loaded which not only improved the rolling skirt, but also increased the overall stopband rejection. Wu et al., (2006) constructed a PBG based bandpass filter with square perforations of different dimensions in the ground plane of a microstrip transmission line to achieve a double band stop PBG structure. Thus, the transmission ability of the microstrip line was blocked at different frequency ranges to create a bandpass filter.

DGS (defected ground structure) (Fu and Yuan, 2005; Alfano et al., 2005), complementary split ring resonators (CSRRs) (Burokur et al., 2005; Xu et al., 2006) are widely used in band pass filter design. The CSRR, which is the negative image of an SRR (Falcone et al., 2004), when etched in the ground plane or in the conductor strip of planar transmission media (microstrip or coplanar wave guide-CPW) provided a negative effective permittivity to the structure and signal propagation is inhibited (stopband behavior) in the vicinity of their resonant frequency. Bonache et al., (2006) focused on the application of CSSRs for the design of planar microwave filters in microstrip technology. A new design methodology to achieve the desired frequency responses based on the use of filter cells consisting of the combination of CSRRs with series gaps and shunt stubs was implemented. This is the first time that CSRRs were used for the design of practical planar filters at microwave frequencies. Using CSRR, a new technique is proposed by Mondal et al., (2006. Fig.2.13) to design a compact BPF having wide fractional bandwidth (FBW) variation. Bandpass filtering is obtained by cascading a LPF and a HPF section. The BPF has a number of advantages: compactness, sharp rejection, low insertion loss and low cost. A single section BPF provides skirt attenuation rate at least 50 dB/GHz on both sides of the passband.
A new concept “Substrate Integrated Waveguide (SIW)” has already attracted much interest in the design of microwave and millimeter-wave integrated circuits. Zhang et al. (2007) introduced a bandpass SIW filter based on CSRRs for the first time. The SIW was synthesized by placing two rows of metallic via-holes in a substrate. The field distribution in an SIW is similar to that in a conventional rectangular waveguide. Hence, it takes the advantages of low cost, high Q-factor and can easily be integrated into microwave and millimeter wave integrated circuits. The filter consisted of the input and output coupling line with the CSRRs loaded SIW. Using the high-pass characteristic of SIW and bandstop characteristic of CSSRs, a bandpass SIW filter was designed and fabricated.

For lower frequency bands of mobile communications systems such as for GSM 900 MHz band, the size reduction is a major requirement, and therefore filters with more compact resonators are needed. Banciu (2002) proposed new resonator which occupies less than 51% of the surface area of the square open loop resonator designed for 900 MHz. Advances in high temperature superconducting (HTS) circuits and microwave monolithic integrated circuits (MMIC) have additionally stimulated the development of various planar filters, especially narrow-band bandpass filters which play an important role in modern communication systems (Ma et al., 2005; Zhang et al., 2005; Tsuzuki et al., 2000; Hong et al., 2000a; Liang et al. 1995). A more compact open
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Loop dual mode filter is developed by Athukorala et al., (2009) but with a second spurious at $3f_0$. To overcome this problem, some approaches endeavor to achieve harmonic rejection without degrading the in-band performance. The harmonics can be removed by equalizing the odd- and even-mode phase velocities of the coupled lines. The phase velocities compensation can be performed by utilizing substrate suspension (Kuo et al., 2004). Another method is to employ stepped-impedance resonators (SIRs). A combination of different SIR structures with the same fundamental resonant frequency but various high-order frequencies can be adopted for spurious-free BPFs with wide stopband (Chen et al., 2005). The spurious responses can also be suppressed by introducing transmission zeros around the harmonic frequencies (Sun and Zhu, 2005; Tu and Chang, 2006). All the above methods try to reflect the harmonic signals at the filter ports. The second harmonics of coupled-line BPFs are rejected without requiring any extra circuit and degrading in-band performance (Zhang and Xue, 2009, Fig 2.14). It is based on discriminated coupling, that is, the coupling region blocks unwanted signals of certain frequencies and allows the transmission of signals of other frequencies.

Fig. 2.14 Layout of designed filter and simulated frequency response
The HTSC (high temperature superconductor) films have very low microwave surface resistance, which is 2-3 orders lower than that of normal conductor in the L and S bands, and they are widely used in microwave devices. The use of the HTSC films will drastically improve the system performance and hence, HTSC filters are widely used in mobile communications and satellite communications for their high-selectivity, low loss, small volume, light weight and the property to easily integrate with other microwave circuits. Liang et al., (2008) developed a sixth-order miniature HTSC wide-band filter with improved novel open-loop resonators on a 14.8×9.6 mm2 YBCO/ LaAlO3/YBCO substrate.

2.4 Waveguide Filter Using Planar Loop Resonator Insert

Rectangular waveguides have been a sustainable solution over the past few decades to design robust, low loss and high power circuits at microwave and millimeter-wave frequencies. Metal inserts placed in the E-plane of a rectangular waveguide along the waveguide axis offer the potential of realizing low cost, mass producible and low-loss millimeter-wave filters (Arndt et al., 1988; Gololobov and Yu., 1987). The classical rectangular waveguide theory is still usable to build various filter structures, which are viable to meet requirements of the modern technology (Postoyalko and Budimir, 1994). However, reduction of the physical size of such structures has become one of the primary goals. The concept of left-handed medium (LHM) have become the subject of extensive investigations owing to their capability to provide unconventional properties to different propagation media (Veselago, 1968; Pendry et. al., 1999; Smith et.al., 2000). This approach makes use of the left-handed medium created by novel type of resonance element, split ring resonator (SRR) in combination with thin metal wire line (Smith et.al., 2000). These are printed on the dielectric slab, which is then inserted into the plane of symmetry of the rectangular waveguide.
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The SRR-loaded waveguide bandstop filter is realized as a cascade of the resonator unit cells by Shelkovnikov et al., (2006, Fig. 2.15). The transmission line is loaded with the slab of a composite material, which conveniently facilitates both split ring resonators with the metal septa on the top plane, and a thin wire line stretched throughout the full length of the dielectric on its bottom plane.

![Fig 2.15 Configuration of an SRR-loaded waveguide bandstop filter and its frequency response](image)

Fig. 2.15 Configuration of an SRR-loaded waveguide bandstop filter and its frequency response

The left-handed properties imposed by double ring and SRRs is made use in rectangular waveguide filters in order to achieve miniaturization (Hrabar et al., 2005, Fig 2.16). The capability of rectangular CSRR elements to design waveguide bandpass filters and its miniaturization method have been demonstrated by Bahrami and Hakkak(2008).

![Fig 2.16 SRR based bandpass filter and its frequency response](image)

Fig 2.16 SRR based bandpass filter and its frequency response
These structures are able to alter the electromagnetic boundary conditions of the structure and inhibit propagation of signal in a certain frequency band. Thus, the traditional miniaturization techniques, which commonly employ dielectric-filled waveguides with standard dimensions bound to the wavelength ($\lambda$), may be enhanced to achieve more compact high performance waveguide components.

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