CHAPTER 1

Introduction and Scope of the Thesis

1.1 Introduction

Nowadays miniaturized components/systems with improved performance are in great demand for modern wireless communication and ultra-wideband (UWB) systems. An antenna and a bandpass filter (BPF) are most common and essential components employed at the front-ends of any wireless transceiver. The use of an antenna and a BPF at the front-end of the microwave transmitter and receiver is shown in Figure 1.1. In the transmitter shown in Figure 1.1(a), a BPF follows a power amplifier and is used to select in-band signal and reject out-of-band frequency components generated by non-linearities of the transmitter circuitry, before being sent to an antenna for transmitting the microwave signal. This prevents the transmitter from interfering with other frequency signals. In the receiver shown in Figure 1.1(b), the microwave signal picked up by the antenna is sent to BPF (pre-selector). The output of BPF in the receiver is fed to low noise amplifier (LNA). This arrangement of the antenna and filter reduces noise and interference in the receiver before microwave signal is converted to intermediate frequency (IF) signal through the use of mixer and oscillator [Pozar (2005)]. However, degradation of front-end performance is caused due to impedance mismatch between the antenna and the BPF. The impedance of the antenna should be matched to the input impedance of the filter in the receiver and input impedance of the antenna is to be matched with the output impedance of the filter in the transmitter, so that maximum power is transferred from the antenna to filter in the receiver and filter to the antenna in the transmitter. Hence, for efficient transfer of power, matching circuits are required for the front-ends of any wireless transceiver [Pozar (2005)]. Matching circuits can improve the system performance but this will increase the size of the antenna-filter combination. Also, it would increase the manufacturing cost of the combination of filter and antenna. In addition, the finite length of the transmission line connecting the antenna to filter will increase the system losses. Therefore, to design and develop compact and cost-effective system having reduced losses and improved signal-to-noise ratio (S/N) performance, one has to get rid of the matching network between the antenna and filter. This can be done by directly integrating the antenna with filter, and this combination is called filtering antenna. Therefore, the research is driven by the goal of achieving a successful and efficient integration of filter and antenna for various wireless communication systems.

1.2 Microwave Filters

1.2.1 Introduction

Filters play important role in many RF/microwave applications. They are used to separate or combine different frequencies. 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. Emerging applications, e.g. in wireless communication, continue to pose the challenges for RF/microwave filters with ever more stringent requirements —better performance, smaller size, less weight and lower cost.

Microwave filters are two port, reciprocal, passive, linear devices which attenuate heavily the unwanted signal frequencies while permitting transmission of wanted frequencies. The microwave filter is represented by a two-port network [Hong and Lancaster (2001)] as shown in Figure 1.2.

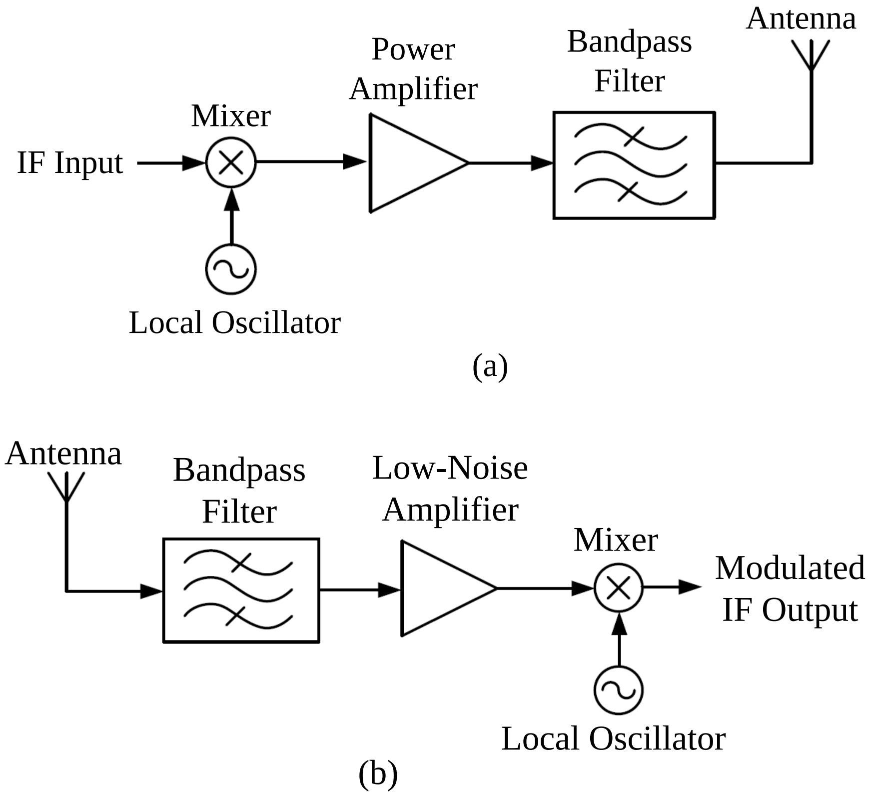

Figure 1.1: Block diagram of part of (a) a microwave transmitter, and (b) a microwave receiver [Pozar (2005)].

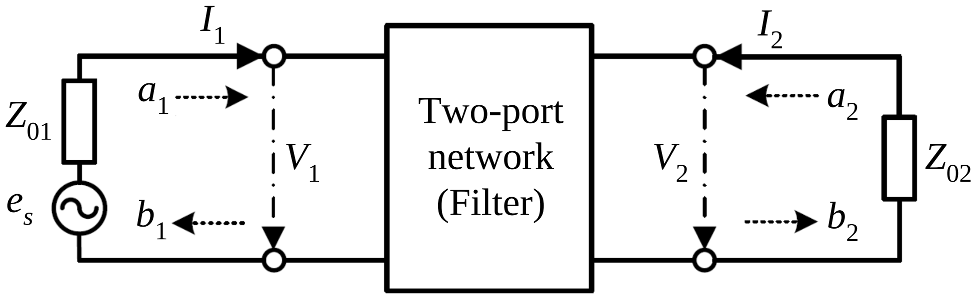

Figure 1.2: Two-port network representation of a microwave filter. V_1, I_1 are the voltage and current at the port 1 and V_2, I_2 are port 2 quantities, Z_{01} and Z_{02} are the terminal impedances at the port 1 and 2 respectively [Hong and Lancaster (2001)].

The input/output transmission and reflection coefficients for the two-port network in Figure 1.2 are represented by the incident waves (a) and the reflected waves (b). These variables are defined from the voltage (V) and current (I) variables, as computed by [Hong and Lancaster (2001)]

$$\begin{aligned} a_n &= \frac{1}{2}\left(\frac{V_n}{\sqrt{Z_{0n}}} + \sqrt{Z_{0n}}\, I_n\right) \\ b_n &= \frac{1}{2}\left(\frac{V_n}{\sqrt{Z_{0n}}} - \sqrt{Z_{0n}}\, I_n\right) \end{aligned} \quad n = 1 \text{ and } 2 \tag{1.1}$$

The performances of microwave filters are commonly described by *S*-parameters. The *S*-parameters for a two-port network are related to the incident waves (*a*) and the reflected waves (*b*). Reflected waves in terms of incident waves are presented in matrix form as follows:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} S_{12} \\ S_{21} S_{22} \end{bmatrix} . \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{1.2}$$

where $S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$ is the input reflection coefficient with output properly terminated,

$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$ is the forward transmission coefficient from port 1 to port 2,

$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$ is the output reflection coefficient with input properly terminated,

and

$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$ is the reverse transmission coefficient from port 2 to port 1.

The parameters S_{11} and S_{22} are also called the reflection coefficients, whereas S_{12} and S_{21} are the transmission coefficients. These are the parameters directly measurable at microwave frequencies. The *S* parameters are, in general, complex, and it is convenient to express them in terms of amplitudes and phases, that is, $S_{mn} = |S_{mn}| e^{j\varphi_{mn}}$ for *m*, *n* = 1, 2. Often their amplitudes are given in decibels (dB), which are defined as

$$20\log\left|S_{mn}\right| \text{ dB} \qquad m, n = 1, 2 \tag{1.3}$$

The basic parameters of a microwave filter viz. passband, stopband, insertion loss, return loss, phase delay, and group delay are defined in [Haykin (1994), Hong and Lancaster (2001)].

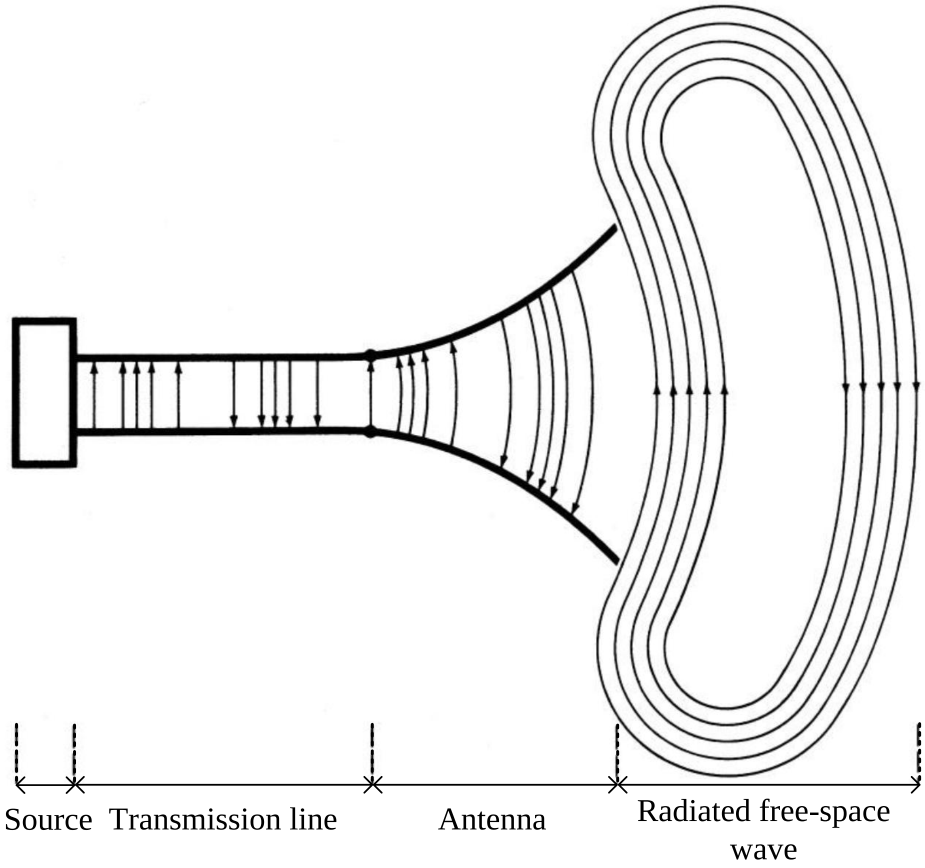

Figure 1.3: Antenna as a transition device [Balanis (2005)].

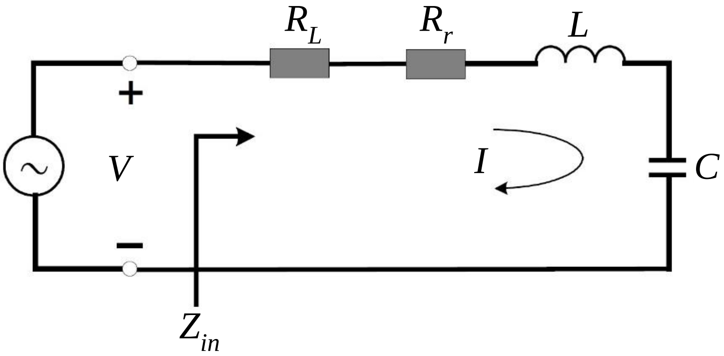

Figure 1.4: Equivalent circuit model of antenna [Balanis (2005)].

1.3 Antenna Theory

1.3.1 Introduction

The antenna is an important and an essential part of any wireless transceiver. According to the IEEE standards [IEEE Definition (2013)], an antenna is defined as “a part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic (EM) waves”. In other words, without antenna there would be no wireless communication. This definition signifies that there are two types of antennas: transmitting antennas and receiving antennas. Transmitting antennas are the antennas which take the signals from a transmission line, convert them into EM waves and then radiate them into free space. Whereas receiving antennas operate in reverse, i.e., they collect the EM waves from free space, convert them into signals and then put them back in the transmission line. An example of the antenna as a transition device is shown in Figure 1.3 [Balanis (2005)]. The equivalent circuit model of antenna consists of a voltage source, a current, an impedance and an *RLC* network. An illustration of the equivalent circuit model of antenna is provided in Figure 1.4 [Balanis (2005)].

In order to describe the performance of an antenna, various antenna parameters namely the return loss, frequency bandwidth, radiation pattern, gain and efficiency have been considered for the proposed research work. These parameters are defined in [Balanis (2005)] and [IEEE Standard (2013)].

1.3.2 Planar Monopole Antennas

The geometrical configuration of a simple quarter wavelength monopole antenna is shown in Figure 1.5(a). The quarter wavelength monopole antenna is derived from the half wavelength dipole antenna, by substituting the bottom arm of the dipole antenna with a large metallic ground plane perpendicular to the vertical arm. According to the image theory, reflections from the large conducting ground plane produce a "virtual monopole" below the ground, as shown by the dotted line in Figure 1.5(b). Therefore, the monopole antenna (MPA) can also be evaluated as the dipole antenna. The input impedance and radiation resistance of a monopole are exactly half the values of the corresponding dipole, whereas directivity twice of the dipole due to the radiation in the upper half only [Stutzman and Thiele (1981)].

The conventional vertical wire MPA is unable to provide wideband characteristics and is also not suitable for compact devices. Therefore, planar MPAs having radiating patch and/or slot of different shapes and the partial ground plane which yield wide impedance bandwidth and omnidirectional radiation pattern when properly excited are described in the literature [Allen *et al*. (2007)]. The full (complete) ground plane of planar MPA is the main limiting factor for obtaining wide impedance bandwidth. This limitation is nicely mitigated using truncated/partial ground plane. The geometries of the circular patch antenna with full and partial rectangular ground planes are shown in Figure 1.6.

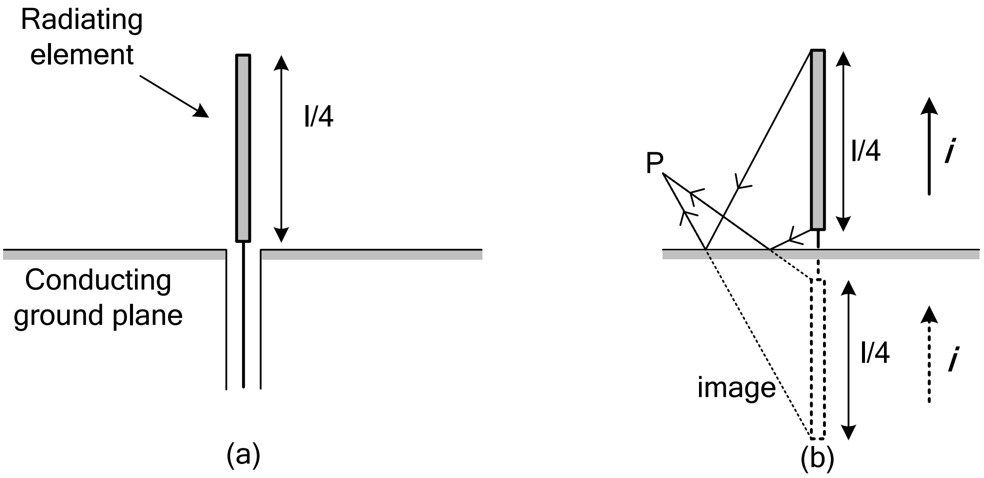

Figure 1.5: Geometrical configuration of (a) simple monopole antenna and (b) corresponding equivalent dipole with mirror image [Stutzman and Thiele (1981)].

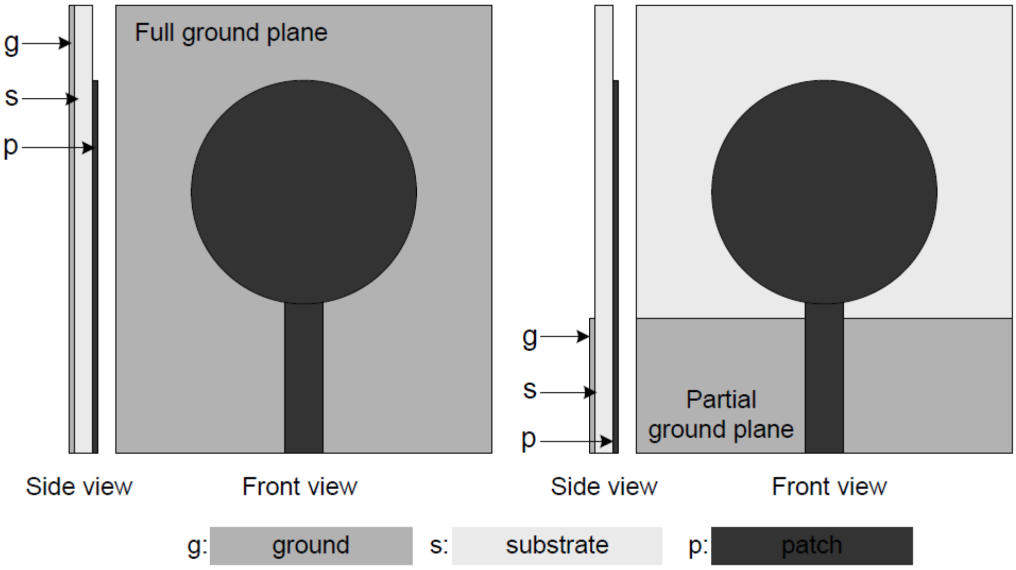

Figure 1.6: Circular patch antenna with full and partial ground planes.

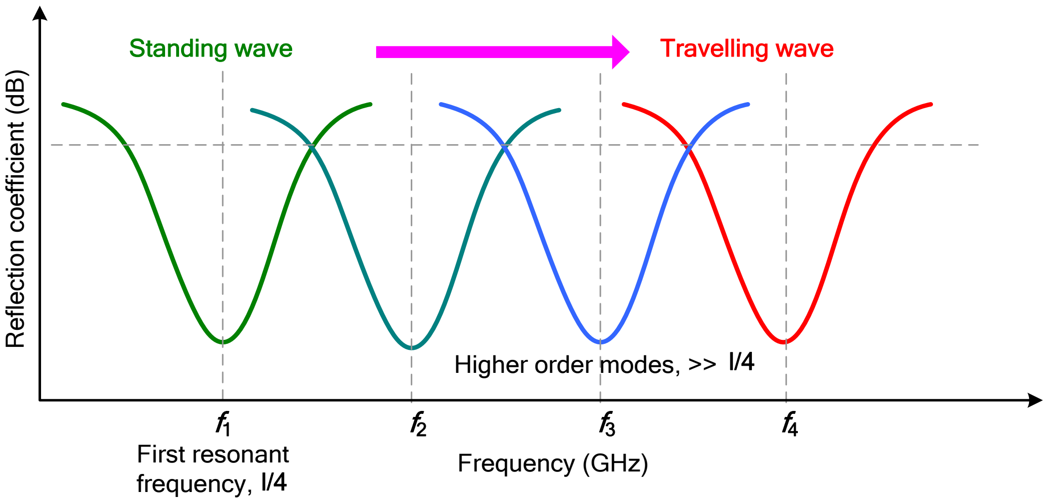

Figure 1.7: Operating principle of the planar monopole antenna with overlapping closely spaced modes [Allen *et al.* (2007)].

The wideband characteristic of the planar MPA originated from two facts. One is the reduction of the quality factor, due to the broad radiating patches in place of thin wire and the use of a substrate with low losses. Another is the monopole with a finite ground plane which can support multiple higher resonating modes along with the fundamental quarter wavelength mode. The overlapping of different modes with appropriate impedance matching is responsible for obtaining the wideband characteristic [Allen *et al.* (2007)] as shown in Figure 1.7.

Towards the lower frequency at the fundamental quarter wave mode, when the wavelength is greater than the antenna dimension, the EM wave can easily ‘couple’ into the antenna structure to operate in an oscillating mode known as standing wave. While with the increase of frequency, the antenna starts to operate in a hybrid mode composed of standing and travelling waves. At the higher frequency side, the antenna structure becomes larger in terms of wavelength and travelling wave becomes more critical to the antenna operation, since the EM wave needs to travel down the antenna structure.

1.4 Review of Some State-of-The-Art Research Studies on Microstrip Filters, Monopole Antennas, and Filtering Antennas

In this section, a brief review of the past research studies, which are relevant to the present research work is given. These will include wideband and ultra-wideband bandpass filters, monopole antennas, and filtering antennas.

1.4.1 Review on Microstrip Filters

Filters are of immeasurable importance to wireless equipment because they are always located between the input and output stages of the RF active circuits. Several types of microstrip filters viz. lowpass filter (LPF), highpass filter (HPF), bandpass filter (BPF), bandstop filter (BSF) and notch filter are used for various applications. Out of these filters, BPF is widely used for wireless applications. Various types of BPFs are reported in the literature. In the end-coupled microstrip BPF reported in the literature [Matthaei *et al*. (1980)], coupling between resonators is less and hence bandwidth is also poor. In parallel-coupled half-wavelength resonator filter [Matthaei *et al*. (1980)], adjacent resonators are parallel to each other which give relatively large coupling and wider bandwidth as compared to the end-coupled microstrip filter but at the cost of increased size. Hence, to achieve compact size filter, hairpin-line BPF is reported [Cristal and Frankel (1971)]. This filter is compact in size. In addition, more coupling occurs between resonators of this type of filter and it gives wider bandwidth as compared to parallel-coupled microstrip filter. But stopband performance of the hairpin-line BPF is poor. The description of another type of BPF called interdigital bandpass filter (IBPF) is available in the literature [Matthaei *et al.* (1964)]. It has certain attractive features such as its compact structure, wide bandwidth and low loss characteristic but requires the use of grounding microstrip resonators, which is usually accomplished using via-holes [Matthaei *et al.* (1964), Hong and Lancaster (2001)]. But in conventional IBPF, an unwanted frequency band at around three times the midband frequency is obtained [Hong and Lancaster (2001)], which is not desired for receiver circuitry of a wireless communication system, and hence, it should be suppressed for obtaining wide stopband.

In the literature [Liang and Chang (2009), Wang *et al.* (2009), Shaman (2012), Chen *et al.* (2013), Nie *et al.* (2014), Tanii and Wada (2014), Chen *et al.* (2015)], different designs methodologies of BPFs are proposed to obtain wide stopband, compact filter size and low insertion loss. But simultaneously achieving all the desired characteristics of a BPF is difficult. A compact bandpass filter (BPF) with a wide upper stopband using a short-circuited microstrip coupled-line hairpin resonator is presented by Nie et al. [Nie *et al.* (2014)]. In 2009, Liang et al. [Liang and Chang (2009)] reported interdigital stepped impedance resonator to achieve strong coupling between adjacent resonators for designing wideband BPF. A wideband microstrip BPF using a folded multiple-mode resonator is reported by Wang et al. [Wang *et al.* (2009)]. In 2012, Shaman et al. [Shaman (2012)] presented compact wideband BPF constructed using two sections of three coupled lines, which are quarter wavelength long at the midband frequency separated by non-uniform line resonator. In order to allow the filter to exhibit two new symmetric transmission zeros around the desired passband, one of the outer coupled lines of each section was shorted to ground. As a result, the two new transmission zeros around the passband are obtained which enhanced the selectivity of skirts of the desired passband significantly. In 2013, Chen et al. [Chen *et al.* (2013)] reported a compact dual-mode wideband BPF constructed by cascading the stub of patch resonator with the input/output defected microstrip structure (DMS) and overlapping partly with each other between the stub of resonator and middle conductor strip of input/output DMS. A dual-path resonator for a wideband BPF is proposed by Tanii et al. [Tanii and Wada (2014)] using a coupled-line and a transmission line with inductive elements. It realizes a dual-mode resonance by an open-circuited interdigital coupled-line and a transmission zero near the lower cut-off frequency due to the effect of the dual-path. In 2015, Chen et al. [Chen *et al.* (2015)] reported a compact high-selectivity microstrip BPF utilizing a quad-mode resonator, which is the combination of a short-circuited stub loaded open-ended resonator and a short-circuited stub loaded short-ended resonator.

Since Ultra-wideband (UWB) technology has great potential in the development of various modern transmission systems, for instance, through-wall imaging, medical imaging, vehicular radar, indoor and hand-held UWB systems. Additionally, UWB BPF is one of the key components in UWB systems. Hence, in February 2002, the U.S. Federal Communications Commission (FCC) authorized the unlicensed use of UWB devices for a variety of applications [FCC (2002), Aiello and Rogerson (2003), Yang and Giannakis (2004)]. For the indoor and hand-held UWB systems, the FCC recommended that the UWB bandwidth must be strictly contained between 3.1 and 10.6

GHz. To meet these requirements on emission level as defined in [FCC (2002)], the research effort in the academic and industrial spheres has recently been intensified in the design and development of UWB bandpass filters, covering whole UWB passband with the fractional bandwidth of 110% and centre frequency of 6.85 GHz. This is due to the fact that the UWB bandpass filter (BPF) is one of the key components in UWB systems. To satisfy the FCC's requirements as portrayed in [FCC (2002)], a preferred UWB BPF should have good selectivity, uniform group delay and low insertion loss over its passband. In addition to these characteristics, the filter should be very compact in size with good out-of-band rejection to meet the growing demand for modern UWB communication technology.

Various techniques developed for the design of UWB BPF have been reported in the literature [Ishida and Araki (2004), Wang *et al*. (2005), Zhu *et al*. (2005), Hu *et al*. (2006), Gomez-Garcia and Alonso (2006), Yang *et al*. (2007), Yao *et al*. (2009), Fallahzadeh and Tayarani (2010), Yang *et al*. (2011), Chu *et al*. (2011), Ghatak *et al*. (2011), Sarkar *et al*. (2012), Ahmed and Virdee (2013), Taibi *et al*. (2015), Li *et al*. (2015), Jhariya *et al*. (2015), Kumar *et al*. (2016), Zhang *et al*. (2016)]. UWB BPFs developed using ring resonators are reported in [Ishida and Araki (2004), Yang *et al*. (2011)]. The UWB BPFs designed with microstrip-to-coplanar waveguide (CPW) coupling structure are reported in [Wang *et al*. (2005), Hu *et al*. (2006)]. In [Zhu *et al*. (2005), Yao *et al*. (2009), Chu *et al*. (2011), Ahmed and Virdee (2013), Li *et al*. (2015), Jhariya *et al*. (2015), Kumar *et al*. (2016), Zhang *et al*. (2016)], concept of multimode resonator (MMR) is used for development of UWB BPFs. The UWB BPF reported in [Ahmed and Virdee (2013)] is compact in size but selectivity is marginal and upper stopband is narrow with attenuation level of 18 dB. In [Gomez-Garcia and Alonso (2006), Yang *et al*. (2007), Ghatak *et al*. (2011), Sarkar *et al*. (2012)], cascading of high-and low-pass filters is investigated to achieve the characteristics of UWB BPF. The UWB BPF using the cascaded connection of defected microstrip structures is described in [Fallahzadeh and Tayarani (2010)] and a uniform line loaded with stepped-impedance open-stub is investigated in [Taibi *et al*. (2015)]. The UWB BPFs reported in the literature need improvement in terms of size and out-of-band performance.

Various techniques have been discussed in the literature for suppressing unwanted harmonics in order to achieve improved out-of-band performance. For suppressing the unwanted spurious response, a slit configuration in the filter geometry called spurline is reported in the literature [Nguyen and Chang (1985), Tu and Chang (2005), Wang *et al*. (2010), Lingqin *et al*. (2012)]. In 1985, Nguyen and Chang [Nguyen and Chang (1985)] reported detailed analysis and design of spurline configuration, and spurline based BSF was also investigated. By applying the inherently compact characteristic of spurline, a BSF using the combination of open stubs and a spurline is reported by Tu et al. [Tu and Chang (2005)]. The reported BSF shows a much deeper rejection and wider stopband than the conventional open-stub BSF without increasing the circuit size. Wang et al. [Wang *et al*. (2010)] presented an asymmetrical spurline filter with dual-bandgap characteristics and applied it as the load network of the class-E power amplifier to improve the output power and efficiency. Lingqin et al. [Lingqin *et al*. (2012)] reported a BPF with wide stopband using quarter-wavelength SIR, dumbbell-shaped DGS and symmetrical spurline which can suppress the second and third harmonics effectively. Hence, spurline offers excellent band gap characteristics along with compactness but suffers from the limitation of narrow stopband.

Defected ground structure (DGS) realized by etching a defected pattern in the ground plane can provide bandgap characteristics from its resonance property [Kim *et al*. 2000]. DGSs can find potential application in microwave circuits to suppress spurious responses and reduce circuit size [Ahn *et al*. 2001]. Various shapes of DGSs viz. dumbbell-shape [Kim *et al*. (2000), Ahn *et al*. (2001), Lim *et al*. (2002), Liu *et al*. (2004), Mollah *et al*. (2005)], rectangular slot and metal-loaded slots [Zhang and Mansour (2004)], cross-shape [Chen *et al*. (2006)], complementary split-ring resonator shape [Weng *et al*. (2008)], H-shape [Mandal and Sanyal (2006)], elliptic-shape [Chen *et al*. (2009)], fork-shape [Yu *et al*. (2009)], modified Pi-shape [Mourya *et al* (2010)], interdigital-shape [Liu *et al*. (2015)], U-shape and V-shape [Woo *et al*. (2006), Ting *et al*. (2006)] are reported. A microstrip line with a dumbbell-shaped DGS which produces excellent bandgap effect at some frequencies was investigated [Kim *et al*. (2000), Ahn *et al*. (2001), Lim *et al*. (2002), Liu *et al*. (2004)]. Rectangular slot and metal-loaded slots have been used in the ground plane to observe the bandgap characteristics [Zhang and Mansour (2004)]. Chen et al. investigated a cross-shaped DGS, which is a combination of I- and H-shaped DGSs [Chen *et al*. (2006)], whereas a complementary split ring resonator DGS is reported by Weng et al. [Weng *et al*. (2008)]. Certain shapes of DGSs, such as H-headed dumbbell-shape [Mandal and Sanyal (2006)], elliptic-shape [Chen *et al*. (2009)], and fork-shape [Yu *et al*. (2009)] have less defected ground area and provide improved performance as compared with dumbbell-shape. Modified Pi-shaped DGS [Moyra *et al* (2010)] and interdigital-shaped DGS [Liu *et al*. (2015)] provide sharper transition response with good passband performance. Woo et al. analysed U-slot and V-slot DGSs which provide the band-rejection property with improved Q-factor [Woo *et al*. (2006)].

Further, in order to improve out-of-band performance for a compact size filter, several approaches are reported in the literature. In [Garcia-Garcia *et al*. (2006), Wong and Zhu (2007)], electromagnetic band-gap structures are studied, and open-circuited stubs embedded in the input and output feedlines are investigated in [Gong *et al*.

(2008)] to suppress the harmonic response. In [Gao *et al*. (2008), Wei *et al*. (2008), Yang *et al*. (2008), Song *et al*. (2014)], defected ground structures (DGSs) are used to suppress spurious response. For obtaining wide upper stopband, three pairs of tapered DGSs are studied in [Song *et al*. (2014)]. In the filter reported in [Song *et al*. (2014)], upper stopband is extended up to 30 GHz with attenuation level greater than or equal to 15 dB only and size of the filter is also large. Hence, scope still exists for further improvement in the performance of UWB BPFs reported in the literature.

1.4.2 Review on Monopole Antennas

The wireless communication system has been experiencing a revolutionary growth in the last few decades. This growth has been caused due to invention of many wireless products and services for global positioning system (GPS), satellite communication, mobile communication, amateur radio operations, and authorization of unlicensed use of UWB technology by the U.S. Federal Communications Commission (FCC) in 2002 for imaging, vehicular radar, indoor high data rate communications [FCC (2002), Aiello and Rogerson (2003), Yang and Giannakis (2004), Adamiuk *et al*. (2012)]. In these systems, the size of both antennas and filters designed using first principles is comparable to the wavelength of the signal. The components designed in this way would be of large physical size for the desired applications and hence need was felt to miniaturize the conventionally designed antennas. Keeping this aspect in view, various types of antennas [Lai and Luk (2008), Sharma *et al*. (2015), Joshi and Singhal (2018), Lee *et al*. (1999), Liang *et al*. (2005), Liu *et al*. (2011), Liu *et al*. (2013), Goswami and Karia (2017), Amini *et al*. (2015), Pandey and Meshram (2015), Sam and Zakaria (2017), Li *et al*. (2006), Azenui and Yang (2007), Sayidmarie and Fadhel (2012), Tang *et al*. (2016), Ranjan *et al*. (2017), Tripathi *et al*. (2014), Lin *et al*. (2012), Ahmed and

Sebak (2008), Hossain *et al*. (2016), Abed *et al*. (2013)] have been investigated. Among these antennas, planar monopole antennas of different shapes viz rectangular, circular, and elliptical have been of particular research interest because of their compact size, simple structure, ease of fabrication and providing wide frequency impedance bandwidth, and omnidirectional radiation patterns.

A compact wideband antenna composed of an asymmetric trapezoid ground plane and a modified rectangular monopole patch is reported by Liu et al. [Liu *et al*. (2013)]. The wideband/UWB monopole antennas using circular-shaped patch are reported in [Liang *et al*. (2005), Sam and Zakaria (2017), Li *et al*. (2006)] while elliptical-shaped patches have been used to obtain wideband/UWB monopole antenna in [Li *et al*. (2006), Azenui and Yang (2007), Liu *et al*. (2011), Sayidmarie and Fadhel (2012), Tang *et al*. (2016)]. The wideband/UWB monopole antenna using the flower-shaped patch [Ranjan *et al*. (2017)], and hexagonal-shaped patch with Koch fractal geometry [Tripathi *et al*. (2014)] are reported. Ahmed and Sebak reported a UWB antenna consisting of stepped-rectangular patch and half circular disc with the circular slot [Ahmed and Sebak (2008)] while Hossain et al. investigated UWB antenna using the ring-shaped patch with slot and upper cutting edge [Hossain *et al*. (2016)]. A UWB slot antenna is reported using the stepped-circular-shaped slot and stepped-circular stub [Abed *et al*. (2013)]. The reported antennas are large in size and hence need was felt to miniaturize these antennas. Also, these antennas have some other drawbacks, such as poor band-edge selectivity and the presence of unwanted harmonics. Due to these drawbacks, chances of unwanted frequency components being received by the antennas cannot be ruled out. This would affect the performance of systems using these antennas. Hence, the antenna is usually followed by a suitable BPF to improve the system performance over the frequency band of operation and to suppress unwanted harmonics.

1.4.3 Review on Filtering Antennas

This section presents a literature review of the integrated design of filter with antenna. Generally, filter-antenna combination is designed by cascading an antenna and a BPF, and incorporating a matching network between them. The design approaches using the matching network are presented in [Pues *et al*. (1989), An *et al*. (1992)]. In order to obtain compact integrated system and improved performance of a transceiver used for wireless communication as well as UWB systems, it is imperative to place BPF in close proximity with the antenna by reducing the length of the transmission line connecting the antenna to BPF. That provided the researchers with a purpose to integrate filter and antenna into a single compact component, known as filtering antenna that performs filtering and radiation functions simultaneously. A design approach of the antenna and filter integration without the matching network has been presented for the first time by Le et al. with the use of filter synthesis [Le *et al*. (1998)]. The filter has been implemented on the various structures for size reduction, which show a microstrip filter integrated with a patch antenna [Abbaspour-Tamijani *et al*. (2002), Queudet *et al*. (2002)], an E-plane waveguide filter integrated with a patch antenna [Goussetis *et al*. 2002]. An integrated design of antenna and filter is reported which share same ground plane to achieve compact co-design of filter-antenna sub-system [Zuo *et al*. (2009)]. The cascaded approach used to design antenna-filter systems is reported in [Mandal and Chen (2010), Wu *et al*. (2013), Cheng and Li (2017), Feng *et al*. (2017)]. In [Mansour *et al*. (2014)], a resonator of the filter structure is replaced by the radiating element to obtain a compact filtering antenna having both filtering and radiation characteristics. In 2016, a compact planar antenna integrated with the lowpass filter (LPF) for suppression of upper harmonic band is reported [Sun *et al*. (2016)].

Zayniyev and Budimir reported a design of a patch antenna integrated with the folded stepped-impedance resonator (SIR) filter to reject the unwanted harmonic response [Zayniyev and Budimir (2009)]. Multi-layer circuit technology has been used to implement a multi-layer antenna-filter structure [Jianhong *et al*. (2009)]. This approach [Jianhong *et al*. (2009)] has been used to design a hairpin filter positioned at the bottom layer combined with the patch antenna placed on the top layer of the component. This work exhibited a two-pole response and well-shaped radiation pattern. In [Zayniyev and Budimir (2010)], the design approach presented the dual-band filter integrated with the dual-band patch antenna. This component was designed for use in the modern wireless system, e.g. the wireless local area network system. The concept of filter design has again been utilised with the co-design of antenna and filter integration. The co-design approaches have been implemented on microstrip filter with an inverted-L antenna [Chuang *et al*. (2011)], the microstrip filter with Γ-shaped antenna [Wu *et al*. (2011)], and the substrate-integrated-waveguide (SIW) filter with patch antenna [Yusuf *et al*. (2013)].

Further, in order to fulfil the requirement of UWB systems, efforts have been made to integrate UWB BPF with UWB antenna to obtain UWB filtering antenna. A compact UWB BPF integrated with the arc-slot modified antenna has been investigated to enhance its radiation performance characteristics in the higher portion of the UWB frequency band [Tang *et al*. (2016)]. Circularly-slotted-flower-shaped UWB antenna is combined with flower-shaped UWB BPF to achieve UWB filtering antenna with improved performance [Ranjan *et al*. (2017)]. Chen and Zhou investigated a filter-antenna subsystem in which UWB filter is placed where the microstrip feed line was located [Chen and Zhou (2009)]. Djaiz et al. investigated the antenna-filter cascaded system composed of a rectangular slot antenna with an UWB interdigital hairpin resonator filter [Djaiz *et al*. (2011)]. The antenna-filter combination proposed by them does not require additional matching circuit. An UWB integrated filter-antenna subsystem is reported without any additional line for integration of antenna and filter [Sahoo *et al*. (2017)]. The UWB filtering antenna is reported with shorting pins to improve the in-band selectivity [Wong *et al*. (2013)]. The reported filtering antennas require improvement in terms of size and/or filtering and radiation performance.

1.5 Motivation and Problem Definition

- Literature review on wideband BPF indicates that different techniques are available for obtaining the desired characteristics i.e. wide passband and stopband, sharp roll-off, suppression of unwanted harmonics, and compact size filter. But available techniques do not simultaneously fulfill all the desired characteristics of a BPF.
- Literature survey on integrated design of BPF with antenna called filtering antenna presented earlier reveals that not much work has been done on wideband filtering antenna.
- The wideband filtering antennas reported in the literature require improvement in terms of size and/or filtering and radiation performance.
- Various techniques for the design of UWB BPF have been reported in the literature. The UWB BPFs reported in the literature need improvement in terms of size, out-of-band performance and selectivity.
- Similarly, after going through UWB filtering antennas reported in the literature, it can be said that reported filtering antennas need improvement in terms of size and filtering as well as radiation performance.

1.6 Objectives of the Proposed Research Work

The main objectives of the research work presented in this thesis are as follows:

- Design and development of the compact highly selective BPF with wide stopband having highly suppressed unwanted harmonics for L-band wireless applications
- Design and development of wideband monopole antenna and integration of the foregoing L-band BPF with the wideband monopole antenna for the purpose of obtaining sharp cut-off performance in the desired passband of the L-band filtering antenna with significant suppression of unwanted frequency bands
- Design and development of the compact UWB BPF having sharp roll-off, low insertion loss and improved upper stopband performance with highly suppressed out-of-band unwanted harmonics for applications in modern UWB communication system and in portable UWB systems
- Design and development of compact UWB monopole antenna and integration of the foregoing UWB BPF with the UWB monopole antenna in order to achieve compact UWB filtering antenna having good cut-off performance and wide stopband with highly suppressed unwanted harmonics

To achieve the aforesaid objectives, the proposed research work follows a list of steps which are given as follows:

- The design and simulation study of the compact wideband IBPF and its modification using spurlines and DGSs to obtain wide stopband for L-band wireless communication applications

- Fabrication of the prototype of the conventional IBPF and modified IBPF using printed circuit board (PCB) prototyping machine and soldering of SubMiniature version A (SMA) connectors for experimental study
- Experimental study of filter characteristics of both conventional IBPF and modified IBPF i.e. measurement of variations of S-parameters, group delay and phase response versus frequency
- The design and simulation study of a wideband monopole antenna, which covers at least L-band frequency range (1 – 2 GHz) for the purpose of its integration with the designed modified IBPF
- Experimental study on the prototype of wideband monopole antenna i.e. measurement of its input and radiation characteristics and comparison of experimental results with respective simulation results
- Integration of wideband monopole antenna with L-band modified IBPF and simulation study of the integrated L-band filtering antenna to obtain compact filtering antenna having both filtering and radiation characteristics with high band-edge selectivity within its passband and reasonably suppressed out-of-band unwanted harmonics
- Experimental study on the prototype of the L-band filtering antenna for its input characteristic, radiation patterns, and realized gain-frequency characteristic, and comparison of experimental results with respective simulation results
- (a) Design and simulation study of the compact modified multi-mode resonator (MMR)-based UWB BPF, (b) Design and simulation study of DGS-based LPF having wide stopband for its integration with the UWB BPF, (c) Proposing equivalent *RLC* circuit model of DGS-based LPF, (d) Design and simulation study

of modified MMR-based UWB BPF integrated with DGS-based LPF to achieve sharp band-edge selectivity within the proposed BPF passband and highly suppressed out-of-band unwanted harmonics.

- Experimental study on prototypes of the UWB BPF, the DGS-based LPF, and the integrated version of UWB BPF with DGS-based LPF i.e. measurement of variations of *S*-parameters and/or phase and group delay responses with frequency, and comparison of experimental results with respective simulation results
- The design and simulation study (for its input characteristic, radiation patterns, realized gain-frequency characteristic, total efficiency-frequency characteristic and pulse handling capability) of UWB monopole antenna for the purpose of its integration with the proposed UWB BPF
- Experimental study on the prototype of UWB monopole antenna i.e. measurement of antenna's input characteristic, radiation patterns and realized gain-frequency characteristic, and comparison of experimental results with respective simulation results
- Design and simulation study (for its input as well as radiation characteristics along with surface current distributions, and time domain analysis through computer simulation technology (CST) microwave studio (MWS) software to ascertain its pulse handling capability) of UWB antenna integrated with the optimized UWB BPF in order to obtain compact UWB filtering antenna having good band-edge selectivity within its passband and highly suppressed out-of-band unwanted harmonics
- Experimental study on the prototype of the optimized integrated design of UWB filtering antenna i.e. measurement of variations of the reflection coefficient,

radiation patterns, and realized gain with frequency and comparison of experimental results with respective simulation results

- All simulation studies were performed using finite element method (FEM) based Ansys high frequency structure simulator (HFSS) software.
- The use of circuit designer software and PCB prototyping machines for the PCB fabrication technology (employed for all proposed filters and antennas)
- The performance comparison of all the proposed bandpass filters, monopole antennas, and filtering antennas with the corresponding circuit components reported in the literature

1.7 Scope of the Thesis

In the present thesis, an effort is made to propose and investigate through simulation and measurement the miniaturized versions of some BPFs, monopole antennas, and filtering antennas with improved passband and stopband performance. Initially, a compact BPF having good band-edge selectivity with improved passband and stopband performance is investigated for L-band wireless communication applications. Further, a compact wideband monopole antenna is designed and integrated with L-band BPF to get compact L-band filtering antenna with sharp cut-off performance, good impedance matching within the desired passband and highly suppressed out-of-band (unwanted) harmonics. In addition, the study on a compact UWB BPF having good band-edge selectivity and improved passband and stopband performance is reported. A compact defected ground structure (DGS)-based lowpass filter (LPF) is integrated with the UWB BPF for improvement of stopband performance of the UWB BPF. Further, a new compact UWB monopole antenna is designed and integrated with UWB BPF to achieve compact UWB filtering antenna having good band-edge selectivity and highly suppressed unwanted harmonics. For demonstrating the superiority of the proposed filters, antennas, and filtering antennas, dimension and performance-based comparisons of these components with the respective components reported in the literature are done and the results for the comparisons depict the superiority of the proposed components. The research work carried out for the present thesis is described in six chapters as given below.

Chapter 1 is an introductory chapter, which is divided into seven sections. The first section introduces the main topic of the thesis, i. e. microstrip filters integrated with antenna, called filtering antenna. The second and third sections give the introduction along with some basic concepts concerning microstrip filters and planar monopole antennas. Review of some state-of-the-art research studies on different types of BPFs, monopole antennas, and filtering antenna is given in section fourth. Literature survey includes brief description of all simulation and experimental studies reported so far in this field. It also makes an attempt to track the stages of development in the area to bring out the state-of-the-art. The section fifth outlines the major outcomes resulting from the literature survey. It also includes motivation behind the thesis with problem definition. The sixth section lists the main objectives of the research work presented in this thesis.

Chapter 2 investigates the compact modified microstrip IBPF having low insertion loss in the passband, good passband selectivity and wide stopband with high out-of-band rejection capability for L-band applications. Starting from conventional IBPF and incorporating two subsequent design modifications, the final optimized design of the filter is proposed. The proposed filter consists of combination of two pairs of spurlines and a pair of DGSs containing SIRs with the conventional IBPF. The reduction in size and wide stopband characteristic of the filter result from band-notched characteristic of spurline, and harmonic suppression along with miniaturization characteristic of DGS. The spurious response suppression characteristics of spurlines and DGS are validated using the computed values of respective equivalent circuit parameters (R, L, and C). Details about different stages of the filter design using a pair/pairs of spurlines and a pair of SIR-shaped DGS are discussed and all the required simulation and measurement results are presented in this chapter. The proposed BPF has stopband attenuation better than 17 dB up to a frequency of approximately six times the centre frequency of the desired passband. For the validation of simulation results, the prototype of the proposed filter was fabricated and its characteristics, viz. variations of S–parameters, group delay and phase responses of the filter versus frequency were measured experimentally. The experimental results for the proposed BPF are nearly in agreement with the respective simulation results.

Chapter 3 reports an integrated design of compact filtering antenna having sharp cut-off performance and highly suppressed unwanted harmonics for various L-band wireless communication applications. The proposed filtering antenna is obtained by integrating a modified elliptic-shaped monopole antenna with a modified IBPF. The modified IBPF is responsible for obtaining improved cut-off performance in the desired frequency band with suppression of out-of-band (unwanted) harmonics. In the initial phase, a modified wideband elliptic-shaped monopole antenna was designed and analysed through numerical simulation and measurement. Further, the modified IBPF reported in **chapter 2** was integrated with the proposed wideband monopole antenna without any extra matching circuit to achieve the compact integrated system with good impedance matching within the desired passband and wide stopband with reasonably suppressed out-of-band (unwanted) harmonics. The proposed integrated system will henceforth be referred to as filtering antenna. The simulated -10 dB reflection coefficient bandwidth of the proposed filtering antenna covers the frequency range 1.01 – 1.96 GHz with improved band-edge selectivity and unwanted harmonic suppression up to 8 GHz (= 5.4 f_0, where f_0 is the centre frequency of passband). It has nearly stable omnidirectional radiation patterns over the whole passband. The proposed filtering antenna was fabricated and experimentally tested. The experimental results are nearly in agreement with corresponding numerical simulation results.

Chapter 4 presents the compact UWB BPF having good band-edge selectivity and wide stopband with high rejection capability. The proposed filter uses modified MMR, open- as well as short-circuited stubs at input and output ports, and DGS-based compact LPF. The modified MMR, which consists of meandered coupled-lines, stepped-impedance stubs, open-circuited stubs and coupled-line sections is responsible for compactness along with good impedance matching in the passband of the filter. Stepped-impedance stubs, which are used to nullify the effect of mutual coupling between meandered lines are analysed in detail. To obtain wide stopband for compact size filter, DGS-based LPF is used. The LPF is realized using four non-uniform-cascaded configurations of DGS units along with a 50 Ω microstrip line. Each DGS unit, which consists of a combination of three isosceles U-shaped DGSs is analyzed in terms of an equivalent *RLC* circuit model. Further, an equivalent *RLC* circuit model of the LPF is proposed to validate its results obtained through numerical simulation and experimental studies. The proposed compact filter formed by integrating modified MMR-based UWB BPF with the DGS-based LPF is numerically simulated and experimentally tested to obtain its characteristics: variations of scattering parameters, group delay and phase response versus frequency. The proposed filter has simulated passband (3-dB bandwidth) frequency range 3 – 11 GHz with wide stopband: attenuation better than 40 dB and 25 dB over the frequency ranges 11.7 – 20.5 GHz and

11.2 – 30 GHz respectively. The experimental results for the proposed filter are nearly in agreement with corresponding numerical simulation results.

Chapter 5 presents a new compact UWB filtering antenna having good passband cut-off performance and wide stopband with highly suppressed out-of-band (unwanted) harmonics. The proposed UWB filtering antenna is obtained by integrating UWB monopole antenna with the optimized version of UWB BPF. The UWB BPF is responsible for obtaining improved cut-off performance with suppression of unwanted harmonics of the proposed UWB filtering antenna. Initially, a compact UWB antenna is designed and investigated through numerical simulation and experimental studies. Further, the geometrical parameters of UWB BPF reported in **chapter 4** are optimized to obtain desired reflection and transmission characteristics using numerical simulation software for its integration with the UWB antenna to improve the passband band-edge selectivity and unwanted harmonic suppression capability of the proposed UWB filtering antenna. Furthermore, the optimized UWB BPF is integrated with the proposed UWB antenna without any extra matching circuit to achieve a compact integrated system with good impedance matching. The proposed integrated system is called the UWB filtering antenna. The proposed UWB filtering antenna is investigated through numerical simulation and experimental studies. The simulated -10 dB reflection coefficient bandwidth of the proposed UWB filtering antenna covers the frequency range 3.07 – 10.72 GHz with improved band-edge selectivity and unwanted harmonic suppression up to 30 GHz (= 4.35 f_0, where f_0 is the centre frequency of passband). It has nearly stable omnidirectional radiation patterns over whole UWB frequency band. The proposed filtering antenna was fabricated and experimentally tested for obtaining measured variations of its reflection coefficient, radiation pattern, and realized gain versus frequency. The experimental results for the filtering antenna are nearly in agreement with respective numerical simulation results. The proposed filtering antenna can be a suitable candidate for UWB applications.

In chapters 2, 3, 4, and 5, performance and dimension based comparisons of the proposed filters, antennas, and filtering antennas with the respective components reported in the literature are also provided.

Finally, **Chapter 6** summarizes and concludes the whole work. The scope for future work in the related area is presented at the end of this chapter.

At the end, the references are intended to include the significant source of reference material for different types of BPFs, monopole antennas, and filtering antennas related to present work for wireless communication and UWB applications.