1 Introduction

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Filters play an irreplaceable role in virtually any type of radio frequency (RF)/microwave system today. With the recent rapid development and widespread use of various wireless communication systems, ever-more stringent requirements are posed on RF/microwave filters – smaller size, higher performance, and lower cost are all simultaneously required today. Even more recently, multi-band operation is considered necessary to solve the challenges of insufficient capacity of the various wireless systems. To that end, high-performance and compact microwave filters that operate at two or more non-harmonically related frequencies are greatly needed, and several different approaches to their design are being investigated today.

While waveguide architecture has been traditionally used to design filters with high quality factors and capable of handling high power, their bulky construction proved to be a limiting factor for applications where miniaturization is a primary concern. To that end, various planar solutions were developed, based on transmission electron microscopy (TEM) or quasi-TEM transmission lines. Besides compact dimensions, the main advantages of planar filters are easier integration in the circuit or module environment, and well-developed and automated manufacture procedures that typically require no manual tuning.

In this book, we present the most recent results in the development of multi-band planar filters. We focus on the microstrip architecture, but note that most of the filters presented here could easily be redesigned in other architectures, such as coplanar waveguide, or stripline.

This edited book presents the results of the research efforts of four well-established research groups, all working in the field of multi-band filter design, performed within the FP7 project MultiWaveS funded by the European Commission under Framework Programme 7, grant no. PIRSES-GA-2009-247532. The book presents in detail six competing approaches and concepts which are used to solve a common problem: the design of compact microstrip multi-band filters with high performance. The approaches presented range from the conventional one, to the application of advanced multi-layer fabrication technologies, and to the development and application of several novel resonator geometries and filter concepts. The book consists of eight chapters, where each chapter starts with an introduction and ends with conclusions and a list of references.

Chapter 1, the Introduction, is followed in Chapter 2, by a comprehensive overview of the existing methods for the design of dual-band and tri-band filters, together with representative solutions from the literature for all types of filters. Specifically, Sections 2.1–2.4 provide a detailed discussion of the existing planar solutions, while Section 2.5 addresses other advanced multi-band filters, including tunable, non-planar (3-D), superconductive, multi-layer, and other solutions. The existing design methods for multi-band bandpass filters are divided into four groups, and the most representative from each group are presented and analyzed. Apart from dual-band and tri-band bandpass filters, this chapter also presents multi-band bandstop filters proposed in recent years.

Chapter 3 is specifically devoted to the theoretical foundations, where recent developments in algorithms for the construction of multi-band transfer functions are described. Two approaches developed by the authors are presented in detail: one an optimized approach, where poles and zeros of the filter function are systematically positioned and fine-tuned to achieve equi-ripple passbands and/or stopbands, and the other a rigorous approach where the reactance function of a passive liquid crystal (LC)-one-port is used as frequency mapping function. In both cases, the mathematical theory is discussed, examples are presented, and both techniques have proved to produce excellent results.

The remaining chapters are devoted to detailed presentation of specific solutions for the design of multi-band filters developed by the authors.

One of the most widely used approaches in the design of multi-band bandpass filters is to combine two single-band filters to obtain a dual-band response, and to combine a single-band and a dual-band filter to obtain a tri-band response. However, although it allows independent control of the passbands, this approach most often results in filters with increased size. On the other hand, filter miniaturization can be achieved using conventional quarter-wavelength resonators instead of their half-wavelength counterparts which are two times longer. The size of such single-band filters can further be reduced by using traditional techniques, such as folding the resonators of which a filter is composed. This approach has been used in Chapter 4, where dual-band and tri-band bandpass filters based on quarter-wavelength resonators and developed by the authors are presented. A detailed description of their design procedures is given and the filters are compared with other similar solutions. The proposed filters outperform all other recently published configurations since they exhibit high selectivity and compactness, excellent transmission and return-loss characteristics, and, at the same time, allow independent control of all passbands.

A number of multi-band filters have recently been published based on the use of various innovative geometric designs. Nevertheless, grounded patch resonators or mushroom structures are also known, and widely exploited in antenna design, but have not been extensively adopted for multi-band filter applications, despite a number of advantages over other commonly used planar resonators. Chapter 5 focuses on the design of compact dual-band filters using the grounded patch resonator (GPR) and its modifications. Since the square GPR is inherently a non-degenerate dual-mode resonator, it is shown how to independently control the two fundamental modes by changing the geometrical parameters of the resonator. Introduction of a slot perturbation in the rectangular GPR gives the perturbed grounded patch resonator (PGPR) and the behavior of such a structure is analyzed in detail. It is demonstrated that the inter-resonator couplings of the PGPR at two centre frequencies can be adjusted separately, which allows the design of dual-band filters with independent passband centre frequencies and respective bandwidths. Unlike many other approaches, this method allows passbands to be spaced further apart than is typically possible with narrow-band coupled-resonator methods.

Chapter 6 presents novel dual-band filters based on the use of fractal curves – space-filling curves that, theoretically, allow the design of infinite-length lines on a finite substrate area. Due to their space-filling ability, fractal curves have great potential for miniaturization of passive microwave circuits. Special attention has been given to the Hilbert fractal curve, which is very convenient for application in resonators and filters due to its configuration. In the first part of the chapter, two dual-band bandpass filters, based on the Hilbert fractal curve and proposed recently by the authors are shown, which exhibit small size and good performance in terms of insertion loss and selectivity, and are comparable to other recently published solutions. In addition, the proposed filters allow independent control of the passbands and their fabrication is very simple since the circuits are fully planar and do not require vias or multi-layer structures. In the second part of the chapter, the Hilbert fractal curve is also used to design a complex resonator that consists of two dual-mode resonators. The proposed resonator, which exhibits many degrees of design freedom, has been used to design one tri-band bandpass filter and one tri-band bandstop filter. Owing to a specific configuration and various couplings that exist in the structure, the proposed bandpass filter simultaneously exhibits very good performance and very compact dimensions. In comparison to other tri-band bandpass configurations, the proposed structure is the most compact one and it has significantly better selectivity, as well as the possibility to independently control the passbands. The proposed tri-band bandstop filter is also characterized by good performance and it represents the first tri-band bandstop filter operating at 2.4, 3.5, and 5.2 GHz.

All filters presented so far have followed one of the typical approaches to the design of multi-band filters, such as the superposition of single-band filters or the use of complex multi-mode resonators. Although allowing various degrees of design freedom in terms of the independent control of passbands, and exhibiting different relative weaknesses and strengths, all of these approaches have one thing in common: resonators which form filters are regarded as electronic components, and then suitably coupled to result in a desired filtering response. In Chapter 7, we propose an alternative view to the design of electrical circuits, multi-band filters in particular, where the resonator is not considered as a component, but rather as a piece of material tailored to exhibits specified filtering properties. Namely, we show how artificial electromagnetic materials, also called metamaterials, can be used to design multi-band filters with novel properties – small size, low losses, and reduced group delay. To achieve such behavior, we focus on a specific sub-class of metamaterials, called near-zero (NZ) metamaterials, which have recently been shown to support propagation of electromagnetic waves with the zero propagation constant, giving rise to various interesting phenomena. The chapter focuses on NZ propagation of quasi-TEM modes, needed for the design of NZ microstrip filters. It examines both the permittivity NZ and permeability NZ propagation of quasi-TEM waves and demonstrates how they can be used to design single-band NZ filters. Finally, this idea is extended to multi-band filters, and a dual-band microstrip NZ filter is presented and analyzed. Owning to its flat phase response, such filters are promising candidates for applications where flat group delay is required.

Chapter 8 presents recent advances in the field of multi-layer microwave filters, as multi-layer technologies provide three-dimensional flexible designs with the integration of microwave components, circuits, andsub-systems. They have been recognized as promising for the integration of multi-standard or multi-band functions in a single device, with the aim to reduce the complexity and size of the system. In this chapter, recent results of the authors are presented, including filters realized using low-temperature co-fired ceramics (LTCC), and liquid crystal polymer (LCP) technologies. The chapter demonstrates a novel approach to filter design which relies on non-traditional resonators based on a combination of right-handed and left-handed transmission line sections and capacitively loaded cavities. In this way, filter characteristics can be drastically improved and their functionalities enlarged. Among the presented devices are ultra-wideband (UWB) filters, dual-band filters, and tunable single-band and dual-band filters. In all cases, the use of multi-layer technology has resulted in miniature filters, highly demanded today by various wireless applications.

The chapters present a detailed overview of the competing approaches, as well as providing full insight into the design procedures of some of the best dual-band and tri-band microstrip filters today. Apart from simulation and measurement results, which are compared for each presented filter, real-world fabrication-related details are discussed, such as process and/or material tolerances.

This book, which comprises theoretical foundations, detailed design rules, comparisons of measured and simulated results, as well as discussion of the influence of fabrication tolerances, is aimed at a wide audience, ranging from students to the industry professionals in the field of microwave engineering.

2 Design methods of multi-band filters

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2.1 Introduction

Development of a number of wireless communication standards and devices imposed a requirement for components to simultaneously operate at two or more frequencies that correspond to the standards such as IEEE 806.16, IEEE 806.11, GSM, CDMA, etc.

Dual-band bandpass components were the first multi-band circuits to answer this requirement. The first dual-band filter was proposed almost two decades ago [1], and since then there has been a growing interest in dual-band filters.

In comparison to dual-band filters, design of bandpass configurations with three or more bands represents a greater challenge when it comes to filter performance and compactness, because good characteristics have to be achieved in three or more closely positioned passbands. In addition to possible signal crosstalk in closely positioned passbands, design of these filters is a demanding task since it requires a steep slope of transfer function. What is more, almost all bands that are commercially used are closely positioned – for instance WiFi, WiMAX, and GSM systems that operate at 0.9/1.8 GHz, 2.4/2.45 GHz, 3.5 GHz, and 5.2/5.25 GHz.

A number of multi-band bandpass filters and design methods can be found in the literature; in this chapter, an overview of those methods will be given and comparisons made. Although great attention has been paid to multi-band filter development in recent years, significantly fewer papers have been published on configurations with three or more bands in comparison to those devoted to dual-band structures.

Broadly speaking, there are four different approaches to the design of multi-band bandpass filters, each of which can be divided into sub-groups.

The first approach employs classical filter design theory that includes basic concepts such as filter transfer functions, low-pass prototype filters and elements, and frequency and element transformations. This theory is a universal technique that can be applied to any type of filters – waveguide, microstrip, or dielectric. Also, it is an analytical method and thus a very powerful synthesis technique for single-band filters. Since the theory has been widely investigated and applied in single-band filter circuits, it has also been applied in multi-band filter design. In the second section, some classical-theory-based methods for multi-band filter design will be presented and discussed.

The second design approach is based on introducing transmission zeros in the responses of a wideband single-band filter and this method will be presented in the third section.

The third approach employs multi-mode resonators. Since multi-mode structures support several resonant modes, they represent good candidates for miniature multi-band filters. Although the positions of their resonant modes cannot be independently controlled to the full extent, the third approach allows more design freedom in comparison with the previous methods. The fourth section is devoted to multi-band structures that were realized using multi-mode resonators.

Combining two single-band filters to obtain a dual-band response, and single-band and dual-band filters to obtain a response with three or more bands represents the fourth approach to the design of multi-band filters. Since such filters comprise several independent structures, this method gives the most freedom in design in terms of the independent control of passbands. This method will be presented and discussed in the fifth section.

The four methods include design of planar multi-mode bandpass filters. However, there have also been proposed multi-band bandpass filters that are realized in a different manner – using multi-layer architecture or fabrication technologies other than PCB, or using advanced theoretical concepts such as metamaterials. A brief overview of these methods will be given in the sixth section.

Unlike multi-band bandpass filters, multi-band bandstop filters have not been widely explored. Whilst there are four principal and several advanced design methods for multi-band bandpass filters, multi-band bandstop filters have been designed using only some of those approaches. It is also noticeable that most multi-band bandstop filters have been designed to operate at two bands, whilst there have been only a few tri-band bandstop filters. In the last section of this chapter, an overview of multi-band bandstop filters will be given.

2.2 Design based on the classical filter design theory

Filter design theory is an analytical method, and has proven to be a universal and very powerful technique for single-band filter design [2–6]. It has been extensively investigated, and numerous filter transfer functions and topologies have been proposed in the literature. Generally speaking, this design technique includes three major steps:

- filter order and transfer function determination in accordance with predefined specifications,
- network and coupling matrix synthesis,
- design and physical realization of filter.

Behavior of every filtering network can be defined using transfer and characteristic functions which can be defined as

$$H(s) = \frac{E(s)}{P(s)}, \tag{2.1}$$

$$K(s) = \frac{F(s)}{P(s)}, \tag{2.2}$$

where s represents complex frequency and $F(s)$, $P(s)$, and $E(s)$ characteristic polynomials. In low-pass prototypes, $F(s)$ is a polynomial with real coefficients whose roots are positioned on an imaginary axis. Its roots are the frequencies at which there is no reflection and they represents reflection zeros. $P(s)$ is an even polynomial with real coefficients whose roots are the frequencies at which there is no transmission and they represent transmission zeros, whilst $E(s)$ is Hurwitz polynomial.

The most well-known filter functions are Butterworth, Chebyshev, elliptic, and Bessel functions.

Coupling matrices are N x N matrices whose elements represent coupling coefficients between the filter resonators. The main diagonal elements are self-couplings, $M_{i,i+1}$ elements are couplings between adjacent resonators, whilst all other elements are cross-couplings, i.e. couplings between non-adjacent resonators.

The physical layout of the filter is formed in accordance to the coupling matrix. Namely, the coupling matrix determines the filter order as well as the distance between the resonators and ultimately the filter configuration.

The wide application of classical filter design theory has been the main motive to apply it in multi-band filter design.

So far, there have been several design procedures for dual-band and multi-band filters, each of which is characterized by a different approach to transfer function synthesis and the coupling matrix. Some of the procedures are fully analytical yet applicable only to some filter types and topologies, whilst others require demanding optimization methods but at the same time are more universal in terms of filter topology. The common characteristic of the most proposed procedures is that the starting point is the synthesis of a single-band wideband filter. Afterwards, transmission zeros are introduced in the filter response, and passbands are formed. Thus, the passbands cannot be independently formed, which is one of the main drawback of this multi-band filter design approach. In addition, filters designed using this approach have exceedingly large dimensions.

An overview of design procedures for multi-band filters and analysis of their properties are given below.

The first dual-band bandpass filter was proposed in [7], and was realized using classical filter design theory. The proposed procedure allows design of symmetrical dual-band filters, i.e. filters whose passbands are symmetrically positioned around frequency and have equal insertion loss, return loss, and bandwidths.

According to dual-band filter specifications related to in-band and out-of-band characteristics, a low-pass prototype is obtained, Figure 2.1, i.e. the normalized frequencies Ω_a and Ω_s are determined. These frequencies together with number of poles and zeros in bandpass and bandstop regions represent the starting point in the formation of characteristic polynomials $P(s)$, $F(s)$, and $E(s)$. After the characteristic polynomials are synthesized, a coupling matrix is formed, and geometrical parameters of the final filter are determined.

Although the final filter in [7] is realized in the waveguide architecture that does not diminish the applicability of the procedure because the classical theory approach is a universal technique that can be applied to any filter architecture.

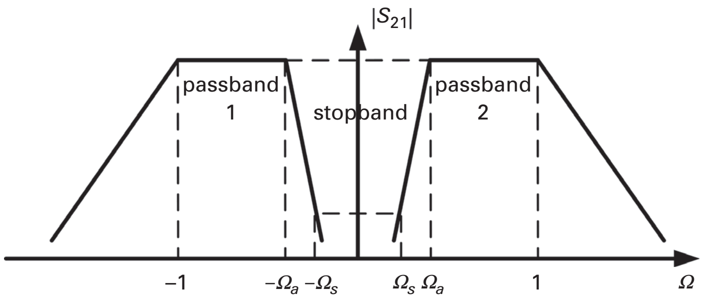

Figure 2.1 Low-pass prototype of the symmetrical dual-band filter.

An advantage of this procedure is the fact that it represents an analytical approach, i.e. an efficient and precise method, as well as the fact that this procedure gives a unique coupling matrix solution. However, its main drawback is the fact that it is applicable only to dual-band filters with symmetrically positioned passbands. In addition, the procedure cannot be readily applied to all filter topologies.

Based on this procedure, in [8] a fully analytical yet simpler method was presented that enables the design of dual-band filters with asymmetrically positioned passbands. However, the two passbands cannot be independently positioned, which is the major drawback. Also, this method cannot be applied to all filter topologies.

Another procedure for synthesis and design of asymmetrical dual-band bandpass filters was presented in [9]. The initial transfer function is formed using the transfer functions of two single-band filters and coupling matrix using optimization procedures. The first step involves an exact and exhaustive synthesis yielding a list of equivalent coupling matrices. In a second step, the proposed approach takes advantage of the multiple solution property by providing some rules for selecting a coupling matrix to be used as the starting point for an approximate synthesis procedure. The approximate synthesis then allows some simplifications of the initial coupling topology by cancelling one or several weak couplings between resonators, which ultimately makes the hardware implementation easier.

Relying on optimization procedures is the major drawback of this procedure, since the convergence time of such procedures is very sensitive to the initial guess. Also, due to the applicability of the method on various filter topologies, optimization methods do not give a unique solution for the coupling matrix.

The three previous procedures can be only used for dual-band filter design, which limits their applicability. In the following, procedures that can be used in the design of filters with a theoretically arbitrary number of passbands will be presented.

A procedure for dual-band and tri-band filter design that can be applied to all filter topologies was presented in [10]. The first step in the procedure is the design of a wideband response which encompasses all passbands of dual-band or tri-band filters. The response is realized by the standard Chebyshev function. Afterwards, the number of transmission zeros is chosen, and they are introduced in the wideband response so as to obtain a dual-band/tri-band response.

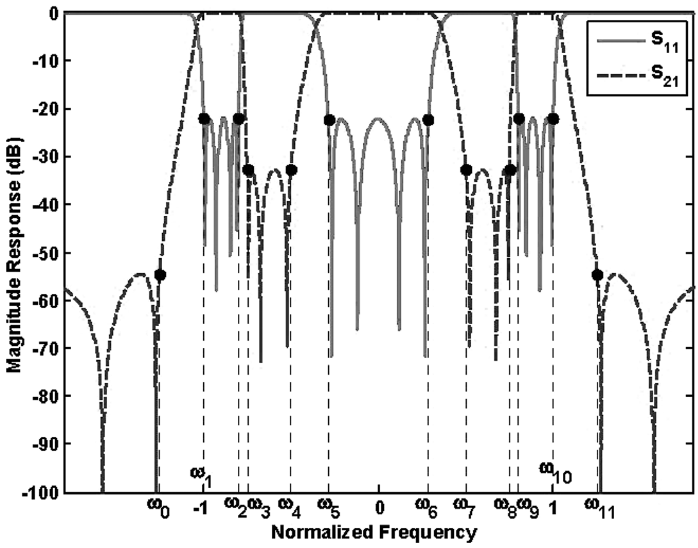

Figure 2.2 Normalized prototype of multi-band filter.

In order to form the coupling matrix, the transfer function needs to be synthesized, which is conventionally achieved using predefined poles and zeros. In this procedure, the transfer function is formed using a different approach. Namely, the transfer function is formed using the transfer functions of two or three single-band filters whose passbands correspond to those of the desired dual-band/tri-band filter. Afterwards, an initial coupling matrix is formed whose non-zero elements are distributed so that it corresponds to the final filter topology. However, the matrix needs to be optimized to obtain the final values that correspond to the filter specifications. The need for optimization, which is sensitive to the initial guess, is the main disadvantage of this procedure. What is more, the optimization may not lead to an optimal response in terms of filter zeros and poles.

The method presented in [11] is the first analytical method for synthesis of symmetrical and asymmetrical multi-band responses with an arbitrary number of passbands and stopbands. Also, it allows synthesis of the transfer function that has both real and imaginary zeros.

According to this method, each passband in the response is defined by two frequencies – ω_1 and ω_2 for the first passband, ω_3 and ω_4 for the second passband, etc., whilst each stopband is defined by one frequency, Figure 2.2.

The transfer function is formed so that it has equal ripple in the passbands, and the first step in its synthesis is to form the initial characteristic function in accordance to passband and stopband specifications. In other words, an initial guess is assigned to zero and pole values in passbands and stopbands.

Figure 2.3 shows an example with two passbands and one stopband, denoted by p_i and z_i, respectively. Each zero and each pole are positioned between two transfer function extrema. For instance, the pole p_2 is positioned between α_1 and α_2. Based on the initial guess of a pole (zero), it is examined whether two extrema in the vicinity of

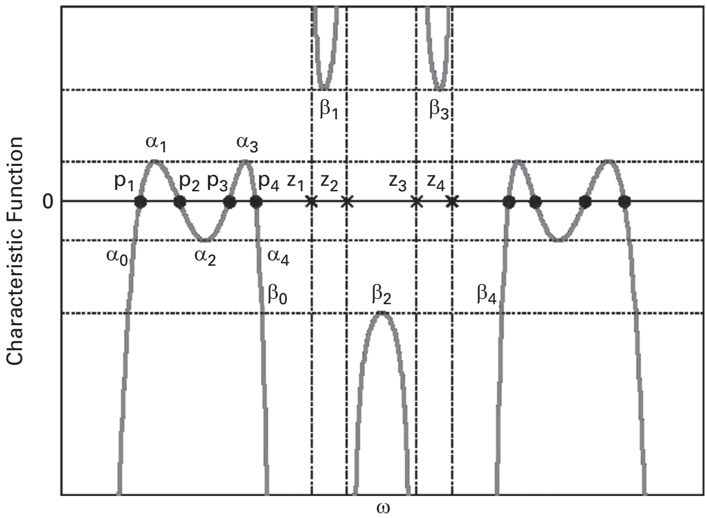

Figure 2.3 Typical filter function with critical frequencies.

the pole (zero) have equal values – if not, a new initial guess is assumed, otherwise the next pole (zero) is determined.

Several tens of iterations are needed to arrive at the final transfer function, which means that this method also requires a certain level of optimization. Yet, the optimization procedures are less demanding than those in [9] and [10].

After the transfer function is obtained, the coupling matrix is formed, and subsequently the geometrical parameters of the filter are determined.

Using this procedure, fourth-order and eighth-order dual-band filters in cul-de-sac topology were designed [12]. Their configurations and responses are shown in Figure 2.4.

The resonators used in the filter configuration were realized using conventional ring-shaped $\lambda/2$ resonators. In both responses, the central frequencies of the passbands are positioned close to each other, and the stopband region has poor performance which is due to the fact that the dual-band response is formed by introducing transmission zeros into the wideband response.

Also, both filters have large overall dimensions, $0.41\lambda_g$ x $0.35\lambda_g$ and $1.18\lambda_g$ x $0.28\lambda_g$, where λ_g represents the guided wavelength at the central frequency of the first passband. Large overall size is a common property of all filters based on classical filter design theory. Namely, the resonators usually employed in filter configuration are conventional $\lambda/2$ resonators and the quality factor and mutual coupling factor are readily determined. In this manner, multiple couplings between resonators are avoided, which is of great importance since the coupling matrix usually foresees only direct couplings and several cross-couplings. On the other hand, such resonators occupy a large area, and thus even low-order filters have large overall size.

In [13], another dual-band filter based on the previous method was proposed, and its configuration and response is shown in Figure 2.5. In this case, dual-mode resonators