SECOND EDITION

# MICROWAVE FILTERS FOR COMMUNICATION SYSTEMS

## FUNDAMENTALS, DESIGN, AND APPLICATIONS

RICHARD J. CAMERON
CHANDRA M. KUDSIA
RAAFAT R. MANSOUR

WILEY

## An in-depth look at the state-of-the-art in microwave filter design, implementation, and optimization

Thoroughly revised and expanded, this second edition of the popular reference addresses the many important advances that have taken place in the field since the publication of the first edition and includes new chapters on Multiband Filters, Tunable Filters, and a chapter devoted to Practical Considerations and Examples.

A critical constraint in the evolution of wireless communication systems is the scarcity of the available frequency spectrum, thus making frequency spectrum a primary resource to be judiciously shared and optimally utilized. This fundamental limitation has long been a driver of intense research and development in the fields of signal processing and filter networks, the two technologies that have a major impact on the information capacity of a given frequency spectrum. Written by distinguished experts with a combined century of industrial and academic experience in the field, *Microwave Filters for Communication Systems:*

- Provides a coherent, accessible description of system requirements and constraints for microwave filters
- Covers fundamental considerations in the theory and design of microwave filters and the use of EM techniques to analyze and optimize filter structures
- Chapters on Multiband Filters and Tunable Filters address the new markets emerging for wireless communication systems and flexible satellite payloads and
- A chapter devoted to real-world examples and exercises that allow readers to test and fine-tune their grasp of the material covered in various chapters. In effect, it provides the methodology, to analyze, design, and perform system level tradeoffs including EM based tolerance and sensitivity analysis for microwave filters and multiplexers for practical applications.

*Microwave Filters for Communication Systems* provides students and practitioners alike with a solid grounding in the theoretical underpinnings of practical microwave filter and its physical realization using state-of-the-art EM-based techniques.

**Richard J. Cameron,** is the former Technical Director at COM DEV International. Visiting Professor at the University of Leeds (UK), and is a Fellow of IEE and IEEE.

**Chandra M. Kudsia, PhD,** is the former Chief Scientist at COM DEV International and currently an Adjunct Professor at the University of Waterloo. He is a Fellow of IEEE, AIAA, CAE, EIC and IETE.

**Raafat R. Mansour, PhD,** is a Professor at the University of Waterloo and a former Director of R&D at COM DEV International. He is a Fellow of IEEE, EIC, and CAE.

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Fundamentals, Design, and Applications

Second Edition

*Richard J. Cameron*
*Chandra M. Kudsia*
*Raafat R. Mansour*

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Microwave Filters for Communication Systems

*The authors wish to acknowledge the many engineers, technologists, and manufacturing staff at COM DEV who contributed in advancing the state of the art and in maintaining sustained leadership position for the design and implementation of microwave filters and multiplexing networks for communication satellite systems from 1970s to 2015.*[1]

1 COM DEV was sold to Honeywell in 2016.

# Preface

Three new chapters are introduced in the second edition. Chapters on multiband filters and tunable filters are added to reflect the emerging markets for wireless systems. The third chapter is devoted to the practical aspects of design and implementation of microwave filters and multiplexing networks. Chapters from edition 1 have undergone a thorough review and minor revisions. New sections have been added in Chapters 1, 6, 8, 16, and 20.

The book begins with a simple model of a communication system. It addresses the issues on: (i) whether there is a limitation on the available bandwidth for a wireless communication system, (ii) what the limitations are for transmitting information in the available bandwidth, and (iii) what the cost-sensitive parameters of a communication system are. Each issue is then addressed to gain understanding of various system parameters with emphasis on the role and requirements of filter networks in different parts of the communication system. This sets the stage to address the fundamentals of filter design based on circuit theory approximation. It continues with a description of classical filters. This is followed by the development of computer-aided techniques to generate a general class of prototype filter functions, exhibiting a symmetrical or asymmetrical frequency response. This general formulation is accomplished by incorporating hypothetical *frequency invariant reactive* (FIR) elements in the lowpass prototype filter design. The FIR elements show up as frequency offsets of resonant circuits in real bandpass or bandstop filters. Absence of FIR elements represents the classical filter function that gives rise to symmetrical frequency response. From this general formulation of the filter function, synthesis techniques are described to realize the equivalent lumped parameter circuit model of filter networks. The next step in the synthesis procedure is to translate the circuit model of the filter into its equivalent microwave structure. As a first approximation, this can be achieved by making use of the extensive existing data that relates circuit models to the physical dimensions and properties of structures used for microwave filters. For more accurate determination of physical dimensions, modern electromagnetic (EM)-based techniques and tools are described to determine filter dimensions with near-arbitrary accuracy. This knowledge is carried through in the design of multiplexing networks having arbitrary bandwidths and channel separations.

Separate chapters are devoted to computer-aided tuning and high-power considerations in filter design. Our goal has been to give the reader a broad view of filter requirements and design and sufficient depth to follow continuing advances in this field. Throughout the book, emphasis has been on fundamentals and practical considerations in filter design. Distinct features of the book include (i) system considerations in the design of filters, (ii) the general formulation and synthesis of filter functions including the FIR elements, (iii) synthesis techniques for lowpass prototype filters exhibiting symmetrical or asymmetrical frequency response in a variety of topologies, (iv) application of EM techniques to optimize physical dimensions of microwave filter structures, (v) design and tradeoffs of various multiplexer configurations,

(vi) computer-aided filter tuning techniques, and (vii) high-power considerations for terrestrial and space applications. The material in the book is organized in 23 chapters:

- Chapter 1 is devoted to an overview of communication systems, more specifically to the relationship between the communication channel and other elements of the system. The intent here is to provide the reader with sufficient background to be able to appreciate the critical role and requirements of radio frequency (RF) filters in communication systems.
  - In the second edition, Digital Transmission, The Channelizer Section, Frequency Plan, and Limitations of Microwave Filter Technology have been revised. The section on RF Filters for Cellular Systems is modified to reflect the requirement of additional frequency bands to meet the explosive growth in wireless services. A section has been added on Ultra Wideband (UWB) Wireless Communication. The summary at the end of the chapter has been revised to reflect the changes.
- The principles that unify communication theory and circuit theory approximations are explained in Chapter 2. It highlights the essential assumptions and the success of the frequency analysis approach that we take for granted in analyzing electrical networks.
- Chapter 3 describes the synthesis of the characteristic polynomials to realize the classical maximally flat, Chebyshev, and elliptic function lowpass prototype filters. It includes a discussion of FIR elements and their inclusion to generate filter functions with asymmetrical frequency response. This leads to transfer function polynomials (with certain restrictions) with complex coefficients, a distinct departure from the more familiar characteristic polynomials with rational and real coefficients. This provides a basis to analyze the most general class of filter functions in the lowpass prototype domain, including minimum and nonminimum phase filters, exhibiting a symmetrical or asymmetrical frequency response.
- Chapter 4 presents the synthesis of characteristic polynomials of lowpass prototype filters with arbitrary amplitude response using computer-aided optimization technique. The key lies in making sure that the optimization procedure is highly efficient. This is accomplished by determining the gradients of the objective function analytically and linking it directly to the desired amplitude response shape. It includes minimum phase and nonminimum phase filters exhibiting a symmetrical or asymmetrical frequency response. To demonstrate the flexibility of this method, examples of some unconventional filters are included.
- Chapter 5 provides a review of the basic concepts used in the analysis of multiport microwave networks. These concepts are important for filter designers since any filter or multiplexer can be divided into smaller two-, three-, or N-port networks connected together. Five matrix representations of microwave networks are described, namely, $[Z]$, $[lY]$, $[ABCD]$, $[S]$, and $[T]$ matrices. These matrices are interchangeable, where the elements of any matrix can be written in terms of those of the other four matrices. Familiarity with the concepts of these matrices is essential in understanding the material presented in this book.
- Chapter 6 begins with a review of some important scattering parameter relations that are relevant for the synthesis of filter networks. This is followed by a discussion of the general kind of Chebyshev function and its application in generating the transfer and reflection polynomials for the equi-ripple class of filter characteristics with an arbitrary distribution of the transmission zeros. In the final part of this chapter, the special cases of predistorted and dual-band filtering functions are discussed.
  - The second edition has two added features: a section for finding the positions of the in-band reflection maxima and the out-of-band transmission maxima of the generalized Chebyshev prototype filter and an appendix extending the two-port $S$-parameter analysis and synthesis to multiport networks with complex terminations. A section has been added describing the relationship between the characteristic polynomials, $S$-parameters, short-circuit admittance, and $[ABCD]$ transfer matrix parameters.

- In Chapter 7, filter synthesis based on the [$ABCD$] matrix is presented. The synthesis procedure is broken down into two stages. The first stage involves lumped element lossless inductors, capacitors, and FIR elements. The second stage includes the immitance inverters. Use of such inverters allows for the prototype electrical circuit in a form suitable for realization with intercoupled microwave resonators. The technique is applicable for synthesizing lowpass prototype filters with symmetrical or asymmetrical response, in ladder form, as well as cross-coupled topologies. A further generalization is introduced to allow the synthesis of singly terminated filters. The synthesis process described in this chapter represents the most general technique for synthesizing lumped element, lowpass prototype filter networks.
- In Chapter 8, the concept of $N \times N$ coupling matrix for the synthesis of bandpass prototype filters is introduced. The procedure is modified by including FIR elements to allow synthesis of asymmetric filter response as well. The procedure is then extended to $N + 2$ coupling matrix by separating out the purely resistive and purely reactive portions of the $N \times N$ matrix. The $N + 2$ coupling matrix allows multiple couplings with respect to the input and output ports, in addition to the main input/output couplings to the first and last resonators as envisaged in the $N \times N$ coupling matrix. This allows synthesis of fully canonical filters and simplifies the process of similarity transformations to realize other filter topologies. This synthesis process yields the general coupling matrix with finite entries for all the couplings. The next step in the process is to derive topologies with a minimum number of couplings, referred to as canonical forms. This is achieved by applying similarity transformations to the coupling matrix. Such transformations preserve the eigenvalues and eigenvectors of the matrix, thus ensuring that the desired filter response remains unaltered. There are two principal advantages of this synthesis technique. Once the general coupling matrix with all the permissible couplings has been synthesized, it allows matrix operations on the coupling matrix to realize a variety of filter topologies. The second advantage is that the coupling matrix represents the practical bandpass filter topology. Therefore, it is possible to identify each element of the practical filter uniquely, including its $Q$ value, dispersion characteristics, and sensitivity. This permits a more accurate determination of the practical filter characteristics and an insight into ways to optimize filter performance.
  - In the second edition, two new sections have been added: (i) $N + 2$ Coupling Matrix Synthesis for Networks with Complex Terminations and (ii) Even and Odd Mode Coupling Matrix Synthesis Technique: The Folded Lattice Array.
- Chapter 9 develops methods of similarity transformations to realize a wide range of topologies appropriate for dual-mode filter networks. Dual-mode filters make use of two orthogonally polarized degenerate modes, supported in a single physical resonator, be it a cavity, a dielectric disc, or a planar structure, thereby allowing a significant reduction in the size of filters. Besides the longitudinal and folded configurations, structures referred to as cascade quartets and cul de sac filters are also included. The chapter concludes with examples and a discussion of the sensitivity of the various dual-mode filter topologies.
- In Chapter 10, we introduce two unusual circuit sections: the extracted pole section and the trisection. These sections are capable of realizing one transmission zero each. They can be cascaded with other circuit elements in the filter network. Application of these sections extends the range of topologies for realizing microwave filters. This is demonstrated by synthesizing filters that include cascaded quartet, quintet, and sextet filter topologies. Lastly, the synthesis of the box section, and its derivative, the extended box configuration, are explained. Examples are included to illustrate the intricacies of this synthesis procedure.
- Theoretical and experimental techniques for evaluating the resonant frequency and unloaded $Q$-factor of microwave resonators are described in Chapter 11. Resonators are the basic building blocks of any bandpass filter. At microwave frequencies, resonators can take

many shapes and forms. The chapter includes two approaches for calculating the resonant frequency of arbitrarily shaped resonators: the eigenmode analysis and the $S$-parameter analysis. Examples are given illustrating the implementation of these two techniques using EM-based commercial software tools such as high frequency system simulator (HFSS). It also includes a step-by-step procedure for measuring the loaded and unloaded $Q$ values using either the polar display of a vector network analyzer or the linear display of a scalar network analyzer.

- Chapter 12 addresses the synthesis techniques for the realization of lowpass filters at microwave frequencies. Typical bandwidth requirements for lowpass filters in communication systems are in the gigahertz range. As a consequence, prototype models based on lumped elements are not suitable for realization at microwave frequencies. It requires the use of distributed elements for the prototype filters. The chapter begins with a description of the commensurate line elements and their suitability for realizing distributed lowpass prototype filters. It then goes into a discussion of characteristic polynomials that are best suited for modeling practical lowpass filters and methods to generate such polynomials. This is followed by a detailed description of the synthesis techniques for the stepped impedance and the lumped/distributed lowpass filters.
- Chapter 13 deals with the practical design aspects of dual-mode bandpass filters. It includes the use of dual-mode resonators that operate in the dominant mode, as well as in the higher order propagation modes. A variety of examples are included to illustrate the design procedure. These examples include longitudinal and canonical configurations, the extended box design, the extracted pole filter, and the filters with all inductive couplings. The examples also include symmetrical and asymmetrical response filters. The steps involved in the simultaneous optimization of amplitude and group delay response of a dual-mode linear phase filter are described. Examples in this chapter span the analysis and synthesis techniques described in Chapters 3–11.
- Chapter 14 presents the use of EM simulator tools for designing microwave filters. It is shown how one can couple the filter circuit models with EM simulation tools to synthesize the physical dimensions of microwave filters with near-arbitrary accuracy. The starting point for such computations is usually the physical dimensions derived from the best circuit model of the filter. Methods are described to compute, with much greater accuracy, the input/output and inter-resonator couplings by using the commercially available EM simulator software. The techniques can be adapted for a direct approach to determine the physical dimensions of filters from the elements of the coupling matrix $[M]$, using $K$-impedance inverter, or $J$-admittance inverter models. Numerical examples are given in this chapter to illustrate, step by step, the application of this approach to the design of dielectric resonator, waveguide, and microstrip filters. For simple geometries with negligible coupling between nonadjacent resonators, this approach yields excellent results. Use of EM tools represents a major advance in the physical realization of microwave filters.
- Chapter 15 presents several techniques for EM-based design of microwave filters. The most direct approach is to combine an accurate EM simulation tool with an optimization software package and then optimize the physical dimensions of the filter to achieve the desired performance. This is effectively a tuning process where the tuning is done by the optimization package rather than a technologist. The starting point for this technique is the filter dimensions obtained using methods described in Chapter 14. Direct optimization approach, without any simplifying assumptions, can be still very computation intensive. A number of optimization strategies including adaptive frequency sampling, neural networks, and multidimensional Cauchy technique are described to reduce optimization time. Two advanced EM-based techniques, the space mapping technique (SM), and the coarse model technique

(CCM), are described in detail, offering a significant reduction in computation time. The chapter concludes with examples of filter dimensions obtained by using aggressive space mapping (ASM) and CCM techniques.

- Chapter 16 develops the design of dielectric resonator filters in a variety of configurations. Commercial software packages such as HFSS and CST Microwave Studio can be readily utilized to calculate the resonant frequency, field distribution, and resonator $Q$ of dielectric resonators having any arbitrary shape. Using such tools, mode charts, along with plots, illustrating the field distribution of the first four modes in dielectric resonators are included. It also addresses the computation of the resonant frequency and the unloaded $Q$ ($Q_0$) of cylindrical resonators, including the support structure. Tradeoffs in terms of $Q_0$, spurious response, temperature drift, and power handling capability are described. The chapter concludes with a detailed description of the design and tradeoffs for cryogenic dielectric resonator filters. Dielectric resonator filters are widely employed in wireless and satellite applications. Continuing advances in the quality of dielectric materials is a good indication of the growing application of this technology.
  - In the second edition, a new section has been added on miniature dielectric resonators illustrating a concept of realizing a quadruple-mode resonator using a traditional cylindrical shape dielectric resonator. It also illustrates how a half-cut dielectric resonator can be used in the realization of dual-mode filters.
- Chapter 17 deals with the analysis and synthesis of allpass networks, often referred to as equalizers. Such external allpass equalizers can be cascaded with filters to improve the phase and group delay response of filter networks. The chapter concludes with a discussion of the practical tradeoffs between the linear phase filters and externally equalized filter networks.
- Chapter 18 presents the design and tradeoffs for multiplexing networks for a variety of applications. It begins with a discussion of tradeoffs among the various types of multiplexing networks, including circulator-coupled, hybrid-coupled, and manifold-coupled multiplexers, employing single-mode or dual-mode filters. It also includes multiplexers based on using directional filters. This is followed by the detailed design considerations for each type of multiplexer. The design methodology and optimization strategy are dealt with in depth for the manifold-coupled multiplexer, by far the most complex microwave network. Numerous examples and photographs are included to illustrate the designs. The chapter is concluded with a brief discussion of the high-power capability of diplexers for cellular applications.
- Chapter 19 is devoted to the computer-aided techniques for tuning microwave filters. From a theoretical standpoint, the physical dimensions of a microwave filter can be perfected using EM-based techniques with near-arbitrary accuracy. In practice, the use of EM-based tools can be very time consuming and prohibitively so for higher-order filters and multiplexing networks. Moreover, owing to manufacturing tolerances and variations in material characteristics, practical microwave filters cannot duplicate the theoretical design. These problems are further exacerbated by the very stringent performance requirements for applications in the wireless and satellite communication systems. As a result, filter tuning is deemed an essential postproduction process. Techniques discussed in this chapter include (i) sequential tuning of coupled resonator filters, (ii) computer-aided tuning based on circuit model parameter extraction, (iii) computer-aided tuning using poles/zeros of the input reflection coefficient, (iv) time domain tuning, and (v) fuzzy logic tuning. The relative advantages of each technique are described.
- Chapter 20 provides an overview of high-power considerations in the design of microwave filters and multiplexing networks for terrestrial and space applications. It describes the phenomena of multipaction and gas discharge based on the classical theory and simple geometries, in particular the two-surface case under single carrier operation on infinite

parallel plates. It highlights the importance of derating factors that can severely degrade the performance of high-power equipment.

- In the second edition, the phenomenon of multipaction is described in depth. In most practical situations, the geometry of high-power RF equipment rarely corresponds to simple parallel-plate conductors, and the high-power equipment must be capable of handling multicarriers. The simple analysis is augmented to include multipaction and gas discharge analysis using numerical techniques. Such methods allow for a more accurate analysis of both single surface and dual surface multipactions in complex structures including nonhomogeneous fields. Although more complex and computer intensive, this analysis is much closer in taking into account the complex geometries of the high-power equipment and the typical operating environment with different numbers of RF carriers and modulations. A description of the classical setup for measuring RF breakdown effects is included. It highlights the efficacy of the industry-accepted methodology of applying the peak power method and the 20-gap crossing rule for the prediction of multipactor discharge in multicarrier operation.
- The chapter also provides guidelines to minimize passive intermodulation (PIM) in the design of high-power equipment.

## Chapter 21

The new Chapter 21 provides an overview of the various techniques for the design of multiband filters, presenting and discussing several examples for dual-band and triple-band filters. The focus in this chapter is on high-$Q$ multiband filters realized in coaxial, waveguide, and dielectric resonator structures. It also presents details of synthesis procedures for multiband filters. The chapter also illustrates how dual-band filters can be employed in realizing miniature diplexers and multiplexers.

## Chapter 22

The new Chapter 22 provides an overview of tunable filter technology. It addresses the main challenges in realizing high-$Q$ tunable filters, which include (i) maintaining constant bandwidth and a reasonable return loss over a wide tuning range, (ii) maintaining a constant high-$Q$ value over a wide tuning range, (iii) integration of tuning elements with 3D filters, and (iv) linearity and power handling capability. It includes an approach for achieving a constant absolute bandwidth over a wide tuning range using only tuning elements for the resonators. A comparison between the various tuning elements (semiconductor, piezomotors, MEMS (microelectromechanical system), BST (barium strontium titanate), and PCM (phase change material)) is described. The chapter shows various examples for realizing tunable combline, dielectric resonator, and waveguide filters. Several examples were given with a focus on the use of MEMS in the design of such filters. Techniques are also presented for realizing filters that are tunable in both center frequency and bandwidth.

## Chapter 23

The new chapter, entitled "Practical Considerations and Design Examples," is aimed at bridging the gap between theory and practical realization of microwave filters and multiplexing networks. A key feature of this chapter is the participation of Professors Vicente Boria and Santiago Cogollos of the Universitat Politecnica de Valencia, Spain, as co-authors. The chapter consists of a series of examples that highlight the methodology for designing and performing tradeoffs for practical filters and multiplexers. This provides a framework to analyze and optimize filtering requirements in communication systems, making use of this information to conduct filter tradeoffs; taking into account the typical operating environment (terrestrial or space), technology limitations, and manufacturing constraints; developing the circuit and quasi-distributed models of the filter topologies; and finally computing the physical dimensions of the structure using EM techniques. The chapter concludes with a brief overview of EM-based tolerance and sensitivity analysis in filter design.

## Appendix E

A new appendix on the Impedance and Admittance Inverters has been added. A simple formulation for the application of inverters in filter design is described in this appendix.

The book is aimed at senior undergraduate and graduate students as well as practitioners of microwave technology. In writing this book, we have borrowed heavily from our industrial experience, giving seminars and teaching courses at universities and interactions with the engineering community at large at various conferences. It reflects a lifetime of experiences in advancing the state of the art in microwave filters and multiplexing networks.