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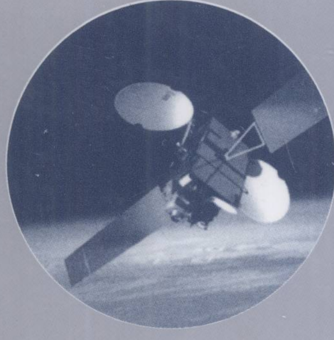
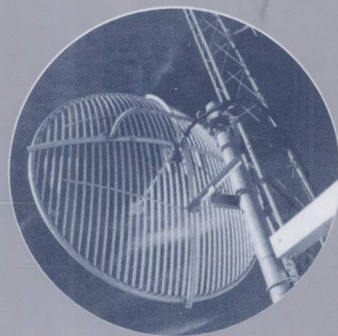
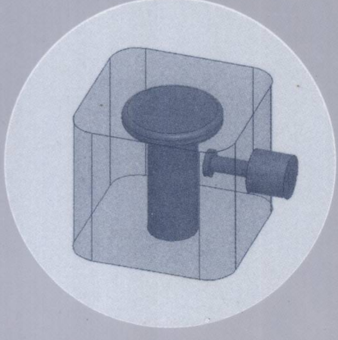
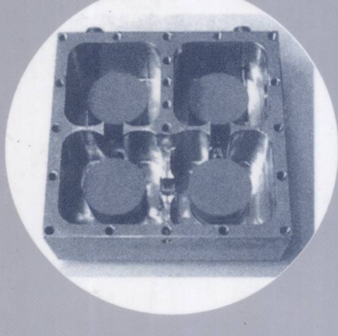
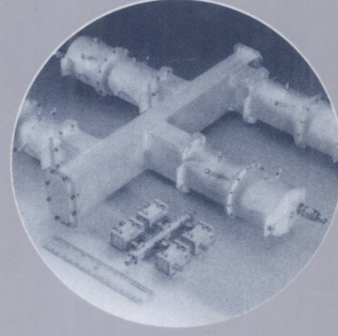



MICROWAVE FILTERS *for* COMMUNICATION SYSTEMS

Fundamentals, Design, and Applications

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MICROWAVE FILTERS FOR COMMUNICATION SYSTEMS: FUNDAMENTALS, DESIGN, AND APPLICATIONS

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To our wives, Patricia, Wendy, and Miranda

FOREWORD

It gives me great pleasure to write a foreword for this monumental work by three of the most prominent contemporary experts in the field of microwave filters. For more than three decades, significant research and development efforts have been focused on improving performance, introducing new concepts, and developing new technologies for microwave filters. As a result, microwave filters available today are significantly better than what was available 30 years ago: much smaller size, lower loss, flat pass bands, very high rejections, extremely steep transition response from pass band to stop band, stop band transmission zeros, symmetrical or asymmetrical responses, and possibility of self equalized group delay. In addition, the design techniques employed today are dramatically different. In the past, microwave filter designers used approximate circuit models and idealized components to produce a design. Such designs required many iterations and empirical adjustments to achieve the desired performance. Today, synthesis techniques coupled with very accurate electromagnetic simulations and sophisticated optimization software algorithms, operating on very fast computers, allow the filter designers to go from the drawing boards almost immediately to the final product, without the need for empirical adjustments or manual tuning. This cuts dramatically the time required for product development cycle. It also allows implementation of much more efficient and enhanced capacity communication systems.

This book captures the fundamentals and practical aspects of modern microwave filter design. It brings in one place a wealth of information that has not been unified before. It is a reference book for the experienced filter designer, and could be an excellent text book for senior level undergraduate or graduate courses on microwave filters. It can also be a guide for researchers in their efforts to advance the state of the art of microwave filters design. And finally, it is quite useful for communications systems designers and planners to learn the current capabilities and limitations of modern microwave filters and multiplexing networks. This book is well balanced between theory and practical implementation.

The vast experience of the authors in industries ranging from satellite communications to cellular base stations is clearly reflected in the book. This experience will no doubt immensely benefit the coming generations of engineering students, practitioners, and the microwave industry as a whole.

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PREFACE

The book begins with a simple model of a communication system. It addresses the issues: (1) whether there is a limitation on the available bandwidth for a wireless communication system, (2) what are the limitations for transmitting information in the available bandwidth, and (3) what are the cost sensitive parameters of a communication system? 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 general class of prototype filter functions, exhibiting 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. 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 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 twenty chapters as follows:

- 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 RF filters in communication systems.
- 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 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 non-minimum phase filters, exhibiting symmetrical or asymmetrical frequency response.
- Chapter 4 presents 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 non-minimum phase filters exhibiting 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], [Y], [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 pre-distorted and dual-band filtering functions are discussed.
- In Chapter 7, filter synthesis based on the [ABCD] matrix is presented. The synthesis procedure is broken 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 inter-coupled microwave resonators. The technique is applicable for synthesising 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 resonator 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 eigen values and eigen vectors 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.

- 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 quartets, quintets and sextets filter topologies. Lastly, the synthesis of the box section, and its derivative, the extended box configuration is 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 eigen-mode analysis and the S-parameter analysis. Examples are given illustrating the implementation of these two techniques using EM-based commercial software tools such as 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 GHz range. As a consequence, prototype models based on lumped elements are not suitable for realization at microwave frequencies. It requires 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 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 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 to 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 multi-dimensional 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. Design considerations 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.

- 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 post-production 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 deals with the high power considerations in the design of microwave filters and multiplexing networks. It includes an overview of the phenomenon of microwave gaseous breakdown for terrestrial applications. It highlights the

importance of various factors that can severely degrade the performance of high power equipment. The phenomenon of multipaction, applicable for space applications, is described in some depth. The topic of design margins, especially when the equipment must handle a number of high power carriers, is discussed in detail. Methods to prevent multipaction are highlighted. Another phenomenon that becomes significant in designing high power equipment is that of passive inter-modulation (PIM). PIM is difficult to analyze and depends upon the choice of materials and workmanship standards. Guidelines to minimize PIM in the design of high power equipment are included.

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.

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