

# ADVANCED DESIGN TECHNIQUES AND REALIZATIONS OF MICROWAVE AND RF FILTERS

---

PIERRE JARRY  
JACQUES BENEAT



IEEE PRESS



WILEY

A JOHN WILEY & SONS, INC., PUBLICATION



**ADVANCED DESIGN TECHNIQUES  
AND REALIZATIONS OF  
MICROWAVE AND RF FILTERS**



# ADVANCED DESIGN TECHNIQUES AND REALIZATIONS OF MICROWAVE AND RF FILTERS

---

PIERRE JARRY  
JACQUES BENEAT



IEEE PRESS



WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2008 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.  
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

***Library of Congress Cataloging-in-Publication Data:***

Jarry, Pierre, 1946–

Advanced design techniques and realizations of microwave and RF filters /

Pierre Jarry, Jacques Beneat.

p. cm.

Includes index.

ISBN 978-0-470-18310-6 (cloth)

1. Microwave filters. I. Beneat, Jacques, 1964– II. Title.

TK7872.F5J37 2008

621.381'3224—dc22

2007050393

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

# CONTENTS

<b>Foreword</b>	<b>xiii</b>
<b>Preface</b>	<b>xv</b>
<b>PART I MICROWAVE FILTER FUNDAMENTALS</b>	<b>1</b>
<b>1 Scattering Parameters and <math>ABCD</math> Matrices</b>	<b>3</b>
1.1 Introduction, 3	
1.2 Scattering Matrix of a Two-Port System, 4	
1.2.1 Definitions, 4	
1.2.2 Computing the $S$ Parameters, 6	
1.2.3 $S$ -Parameter Properties, 10	
1.3 $ABCD$ Matrix of a Two-Port System, 10	
1.3.1 $ABCD$ Matrix of Basic Elements, 11	
1.3.2 Cascade and Multiplication Property, 12	
1.3.3 Input Impedance of a Loaded Two-Port, 14	
1.3.4 Impedance and Admittance Inverters, 14	
1.3.5 $ABCD$ -Parameter Properties, 17	
1.4 Conversion from Formulation $S$ to $ABCD$ and $ABCD$ to $S$ , 18	
1.5 Bisection Theorem for Symmetrical Networks, 18	
1.6 Conclusions, 21	
References, 21	
<b>2 Approximations and Synthesis</b>	<b>23</b>
2.1 Introduction, 23	
2.2 Ideal Low-Pass Filtering Characteristics, 24	

2.3	Functions Approximating the Ideal Low-Pass Magnitude Response, 25	
2.3.1	Butterworth Function, 25	
2.3.2	Chebyshev Function, 26	
2.3.3	Elliptic Function, 27	
2.3.4	Generalized Chebyshev (Pseudoelliptic) Function, 29	
2.4	Functions Approximating the Ideal Low-Pass Phase Response, 30	
2.4.1	Bessel Function, 30	
2.4.2	Rhodes Equidistant Linear-Phase Function, 31	
2.5	Low-Pass Lumped Ladder Prototypes, 32	
2.5.1	General Synthesis Technique, 32	
2.5.2	Normalized Low-Pass Ladders, 36	
2.6	Impedance and Frequency Scaling, 39	
2.6.1	Impedance Scaling, 39	
2.6.2	Frequency Scaling, 40	
2.7	<i>LC</i> Filter Example, 41	
2.8	Impedance and Admittance Inverter Ladders, 41	
2.8.1	Low-Pass Prototypes, 41	
2.8.2	Scaling Flexibility, 42	
2.8.3	Bandpass Ladders, 44	
2.8.4	Filter Examples, 45	
2.9	Conclusions, 46	
	References, 46	
<b>3</b>	<b>Waveguides and Transmission Lines</b>	<b>49</b>
3.1	Introduction, 49	
3.2	Rectangular Waveguides and Cavities, 49	
3.2.1	Rectangular Waveguides, 49	
3.2.2	Rectangular Cavities, 52	
3.3	Circular Waveguides and Cavities, 53	
3.3.1	Circular Waveguides, 53	
3.3.2	Cylindrical Cavities, 55	
3.4	Evanescient Modes, 56	
3.5	Planar Transmission Lines, 57	
3.6	Distributed Circuits, 60	
3.7	Conclusions, 63	
	References, 64	
<b>4</b>	<b>Categorization of Microwave Filters</b>	<b>67</b>
4.1	Introduction, 67	
4.2	Minimum-Phase Microwave Filters, 68	
4.2.1	General Design Steps, 68	

4.2.2	Minimum-Phase Filter Examples, 70	
4.3	Non-Minimum-Phase Symmetrical Response Microwave Filters, 70	
4.3.1	General Design Steps, 71	
4.3.2	Non-Minimum-Phase Symmetrical Response Filter Examples, 73	
4.3.3	Microwave Linear-Phase Filters, 73	
4.4	Non-Minimum-Phase Asymmetrical Response Microwave Filters, 74	
4.4.1	General Design Steps, 74	
4.4.2	Non-Minimum-Phase Asymmetrical Response Filter Examples, 77	
4.4.3	Multimode Microwave Filters by Optimization, 79	
4.5	Conclusions, 79	
	References, 80	
 <b>PART II MINIMUM-PHASE FILTERS</b>		<b>83</b>
 <b>5 Capacitive-Gap Filters for Millimeter Waves</b>		<b>85</b>
5.1	Introduction, 85	
5.2	Capacitive-Gap Filters, 86	
5.2.1	Capacitive-Gap Filter Structure, 86	
5.2.2	Design Procedures, 87	
5.2.3	Step-by-Step Design Example, 91	
5.2.4	Filter Realizations, 93	
5.3	Extension to Millimeter Waves, 95	
5.3.1	Millimeter-Wave Technology, 95	
5.3.2	Fifth-Order Chebyshev Capacitive-Gap Filter at 35 GHz, 96	
5.4	Electromagnetic Characterization of SSS, 99	
5.5	Conclusions, 102	
	References, 102	
 <b>6 Evanescent-Mode Waveguide Filters with Dielectric Inserts</b>		<b>105</b>
6.1	Introduction, 105	
6.2	Evanescent-Mode Waveguide Filters, 106	
6.2.1	Scattering and <i>ABCD</i> Descriptions of the Structure, 108	
6.2.2	Equivalent Circuit of the Structure, 110	
6.2.3	Filter Design Procedure, 115	
6.2.4	Design Examples and Realizations, 117	
6.3	Folded Evanescent-Mode Waveguide Filters, 121	
6.3.1	Scattering and <i>ABCD</i> Descriptions of the Additional Elements, 123	

6.3.2	Filter Design Procedure, 125	
6.3.3	Design Examples and Realizations, 125	
6.4	Conclusions, 127	
	References, 128	
<b>7</b>	<b>Interdigital Filters</b>	<b>131</b>
7.1	Introduction, 131	
7.2	Interdigital Filters, 131	
7.3	Design Method, 135	
	7.3.1 Prototype Circuit, 135	
	7.3.2 Equivalent Circuit, 137	
	7.3.3 Input and Output, 140	
	7.3.4 Case of Narrowband Filters, 141	
	7.3.5 Frequency Transformation, 141	
	7.3.6 Physical Parameters of the Interdigital Filter, 142	
7.4	Design Examples, 145	
	7.4.1 Wideband Example, 145	
	7.4.2 Narrowband Example, 147	
7.5	Realizations and Measured Performance, 148	
7.6	Conclusions, 150	
	References, 151	
<b>8</b>	<b>Comblin Filters Implemented in SSS</b>	<b>153</b>
8.1	Introduction, 153	
8.2	Comblin Filters, 153	
8.3	Design Method, 156	
	8.3.1 Prototype Circuit, 156	
	8.3.2 Equivalent Circuit, 157	
	8.3.3 Input and Output, 159	
	8.3.4 Feasibility, 162	
	8.3.5 Physical Parameters of the Comblin Structure, 162	
8.4	Design Example, 165	
8.5	Realizations and Measured Performance, 168	
8.6	Conclusions, 169	
	References, 170	
<b>PART III</b>	<b>NON-MINIMUM-PHASE SYMMETRICAL RESPONSE FILTERS</b>	<b>171</b>
<b>9</b>	<b>Generalized Interdigital Filters with Conditions on Amplitude and Phase</b>	<b>173</b>
9.1	Introduction, 173	
9.2	Generalized Interdigital Filter, 174	
9.3	Simultaneous Amplitude and Phase Functions, 175	

9.3.1	Minimum-Phase Functions with Linear Phase, 175	
9.3.2	Non-Minimum-Phase Functions with Simultaneous Conditions on the Amplitude and Phase, 177	
9.3.3	Synthesis of Non-Minimum-Phase Functions with Simultaneous Conditions on the Amplitude and Phase, 180	
9.4	Design Method, 182	
9.4.1	Even-Mode Equivalent Circuit, 182	
9.4.2	Frequency Transformation, 186	
9.4.3	Physical Parameters of the Interdigital Structure, 187	
9.5	Design Example, 191	
9.6	Realizations and Measured Performance, 194	
9.7	Conclusions, 195	
	References, 197	
<b>10</b>	<b>Temperature-Stable Narrowband Monomode TE<sub>011</sub> Linear-Phase Filters</b>	<b>199</b>
10.1	Introduction, 199	
10.2	TE <sub>011</sub> Filters, 200	
10.3	Low-Pass Prototype, 200	
10.3.1	Amplitude, 200	
10.3.2	Delay, 201	
10.3.3	Synthesis of the Low-Pass Prototype, 202	
10.4	Design Method, 204	
10.4.1	Matching the Coupling, 204	
10.4.2	Selecting the Cavities, 207	
10.4.3	Defining the Coupling, 208	
10.5	Design Example, 210	
10.6	Realizations and Measured Performance, 213	
10.6.1	Amplitude and Phase Performance, 213	
10.6.2	Temperature Performance, 214	
10.7	Conclusions, 215	
	References, 217	
<b>PART IV</b>	<b>NON-MINIMUM-PHASE ASYMMETRICAL RESPONSE FILTERS</b>	<b>219</b>
<b>11</b>	<b>Asymmetrical Capacitive-Gap Coupled Line Filters</b>	<b>221</b>
11.1	Introduction, 221	
11.2	Capacitive-Gap Coupled Line Filters, 222	
11.3	Synthesis of Low-Pass Asymmetrical Generalized Chebyshev Filters, 222	
11.3.1	In-Line Network, 225	
11.3.2	Analysis of the In-Line Network, 226	

11.3.3	Synthesis of the In-Line Network, 229	
11.3.4	Frequency Transformation, 232	
11.4	Design Method, 233	
11.5	Design Example, 238	
11.6	Realization of the CGCL Filter, 243	
11.7	Conclusions, 244	
	References, 245	
<b>12</b>	<b>Asymmetrical Dual-Mode <math>TE_{102}/TE_{301}</math> Thick Iris Rectangular In-Line Waveguide Filters with Transmission Zeros</b>	<b>247</b>
12.1	Introduction, 247	
12.2	$TE_{102}/TE_{301}$ Filters, 248	
12.3	Synthesis of Low-Pass Asymmetrical Generalized Chebyshev Filters, 248	
12.3.1	Fundamental Element, 249	
12.3.2	Analysis of the In-Line Network, 250	
12.3.3	Synthesis by Simple Extraction Techniques, 252	
12.3.4	Frequency Transformation, 254	
12.4	Design Method, 256	
12.4.1	Equivalent Circuit of Monomode and Bimode Cavities, 256	
12.4.2	Optimization Approach, 256	
12.5	Design Example, 262	
12.6	Realizations and Measured Performance, 266	
12.6.1	Third-Order Filter with One Transmission Zero, 266	
12.6.2	Fourth-Order Filter with Two Transmission Zeros, 268	
12.7	Conclusions, 269	
	References, 270	
<b>13</b>	<b>Asymmetrical Cylindrical Dual-Mode Waveguide Filters with Transmission Zeros</b>	<b>273</b>
13.1	Introduction, 273	
13.2	Dual-Mode Cylindrical Waveguide Filters, 274	
13.3	Synthesis of Low-Pass Asymmetrical Generalized Chebyshev Filters, 275	
13.3.1	Synthesis From a Cross-Coupled Prototype, 275	
13.3.2	Extracting the Elements from the Chain Matrix, 277	
13.3.3	Coupling Graph and Frequency Transformation, 281	
13.4	Design Method, 284	
13.4.1	Rotation Matrix, 284	
13.4.2	Cruciform Iris, 286	
13.4.3	Physical Parameters of the Irises, 290	
13.5	Realizations and Measured Performance, 292	

13.5.1	Fourth-Order Filter with One Transmission Zero on the Left, 292	
13.5.2	Fourth-Order Filter with Two Transmission Zeros on the Right, 293	
13.5.3	Sixth-Order Filter with One Transmission Zero on the Right, 295	
13.6	Conclusions, 296	
	References, 296	
<b>14</b>	<b>Asymmetrical Multimode Rectangular Building Block Filters Using Genetic Optimization</b>	<b>299</b>
14.1	Introduction, 299	
14.2	Multimode Rectangular Waveguide Filters, 300	
14.3	Optimization-Based Design, 302	
	14.3.1 Genetic Algorithm, 302	
	14.3.2 Example, 308	
14.4	Realizations, 313	
	14.4.1 Fourth-Order Filter with Two Transmission Zeros, 313	
	14.4.2 Seventh-Order Filter with Four Transmission Zeros, 314	
	14.4.3 Extension to a Tenth-Order Filter with Six Transmission Zeros, 318	
14.5	Conclusions, 320	
	References, 320	
	<b>Appendix 1: Lossless Systems</b>	<b>323</b>
	<b>Appendix 2: Redundant Elements</b>	<b>325</b>
	<b>Appendix 3: Modal Analysis of Waveguide Step Discontinuities</b>	<b>328</b>
	<b>Appendix 4: Trisections with Unity Inverters on the Inside or on the Outside</b>	<b>338</b>
	<b>Appendix 5: Reference Fields and Scattering Matrices for Multimodal Rectangular Waveguide Filters</b>	<b>340</b>
	<b>Index</b>	<b>353</b>



# FOREWORD

Being asked to review the manuscript of *Advanced Design Techniques and Realizations of Microwave and RF filters* was an honor. The title truly represents the book's focus and its contents.

Filters are the most important passive components used in RF and microwave subsystems and instruments to obtain a precise frequency response. In the early years of filter development, significant progress was made in waveguide and planar TEM filters. During the past two decades, filter technology has advanced in the area of emerging applications for both military and commercial markets. Several major developmental categories in filter technology are included: performance improvement, development of CAD tools, full-wave analysis, new structures and configurations, and advanced materials and associated technologies. Advanced materials/technologies such as high-temperature superconductor substrates, micromachining, multilayer monolithic, low-temperature co-fired ceramic, and liquid-crystal polymer are commonly used in the development of advanced filters. Some recent applications of filters include dual-band communication, such as wireless local area networks and ultrawideband communication and imaging.

This book treats the subject to meet the needs for advanced filter design based on planar and waveguide structures that can satisfy the ever-increasing demand for design accuracy, reliability, fast development times, and cost-effective solutions. The topics discussed include analyses, design, modeling, fabrication, and practical considerations for both ladder and bridged filters. Modern design techniques are discussed for a wide variety of microwave filters, including comprehensive analyses and modeling of structures. These topics are self-contained, with practical aspects addressed in detail. Extensive design information in the form of equations, tables, graphs, and solved examples are included. To aid in solving filter-related design problems from specifications to realization of the end-product, the book provides a unique integration of theory and practical aspects of filters. Simple design equations and numerous practical examples are included which simplify the concepts of advanced filter design. With emphasis on theory,

design, and practical aspects geared toward day-to-day applications, the book is suitable for students, teachers, scientists, and practicing engineers.

Overall, the book is well balanced and includes exhaustive treatment of relevant topics important to a filter designer. I congratulate the authors on an outstanding book that I am confident will be very well received in the RF and microwave community.

Dr. INDER BAHL

*Roanoke, Virginia*  
*November 2007*

# PREFACE

Microwave and RF filters play an important role in communication systems, and due to the proliferation of radar, satellite, and mobile wireless systems there is a need for design methods that can satisfy the ever-increasing demand for accuracy, reliability, and fast development times. This book, which provides modern design techniques for a wide variety of microwave filters operating over the frequency range 1 to 35 GHz, has grown out of the authors' own research and teaching and thus can present a unity of methodology and style, essential for a smooth reading.

The book is intended for researchers and for radio-frequency (RF) and microwave engineers, but is also suitable for an advanced graduate course in the subject area. Furthermore, it is possible to choose material from the book to supplement traditional courses in microwave filter design. The fundamental principles that can be applied to the synthesis and design of microwave filters are first recalled in a concise manner. Each of the 10 design chapters provides a complete analysis and modeling of the microwave structure used for filtering, as well as the design methodology. We hope that this will provide researchers with a set of approaches that can be used for current and future microwave filter designs. We also emphasize the practical nature of the subject by summarizing the design steps and giving numerous examples of filter realizations and measured responses so that RF and microwave engineers can have an appreciation of each filter in view of their needs. This approach, we believe, has produced a coherent, practical, and real-life treatment of the subject. The book is therefore theoretical but also experimental, with over 20 microwave filter realizations.

The book is divided into four parts. In Part I comprising the first four chapters, fundamental concepts and equations for microwave filter analysis and design are provided. Chapter 1 covers definitions and examples of the scattering and *ABCD* parameters of two-port systems. Classical elements used in microwave filter design, such as impedance and admittance inverters, are reviewed. The bisection theorem, which is often very useful to simplify the synthesis of microwave

filters, is presented. Chapter 2 summarizes filter approximations and synthesis. Several functions, such as the Butterworth, Chebyshev, elliptic, and pseudoelliptic, are given for amplitude-oriented filters. The Bessel and Rhodes equidistant linear-phase functions are provided for phase-oriented filters. The general synthesis method for some of these functions is discussed in terms of lumped ladder realizations. The chapter ends with useful properties and equations related to realizations based on impedance and admittance inverters. In Chapter 3 we recall the fundamental equations for waveguides, striplines, suspended substrate striplines, and distributed circuits. The general design approaches used for the filters presented in the book are given in Chapter 4. The filters are regrouped in terms of minimum or non-minimum-phase microwave filters. The latter being regrouped according to the low-pass symmetry of their magnitude response around 0 Hz, referred to as non-minimum-phase symmetrical or asymmetrical microwave filters.

Part II consists of Chapters 5 through 8, corresponding to the analysis and design of four minimum-phase filters. In Chapter 5 we describe the analysis and modeling of capacitive gap filters implemented using suspended substrate stripline. A straightforward design technique is presented and actual realizations and measured responses are given for narrow- and wideband filters in the range 8 to 16 GHz. The chapter concludes with preliminary results showing that this technique can be extended to the design of millimeter-wave filters. An example of a 35-GHz suspended substrate stripline filter is given. It becomes clear, however, that more rigorous electromagnetic analysis and treatment of problems will be needed to improve the performance of filters at these frequencies. In Chapter 6 we present a design technique for evanescent-mode waveguide filters, which can have either rectangular or circular cross sections and include a number of dielectric inserts. These filters can be smaller than traditional waveguide filters, since the cutoff frequency of the guide can be increased even if this means that the fundamental mode will be evanescent in part of the structure.

Several realizations showing the reliability of the technique are given at 14 GHz. In an attempt to reduce the form factor of these filters, the design of folded evanescent mode waveguide filters is introduced. Two realizations with different angles of curvature around 8.4 and 14.6 GHz are described. In Chapter 7 we present the design of interdigital filters, structures modeled using the method of graphs rather than the admittance matrix approach. The design is based on the use of a low-pass prototype circuit, due to the periodic nature in frequency of interdigital line segments. Two realizations around 1 and 2 GHz made using suspended substrate stripline are shown. In Chapter 8 an exact design procedure for combline filters is provided. The technique is applied to a filter at 1.2 GHz using suspended stripline.

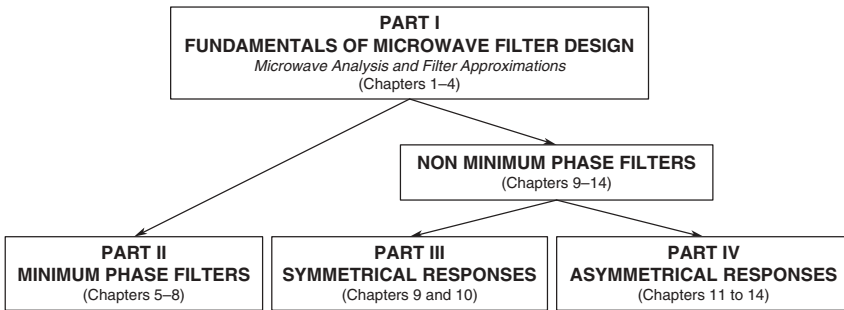
Part III which includes Chapters 9 and 10, provides two techniques for designing non-minimum-phase symmetrical response filters. In the case of symmetrical responses, the bisection theorem can be used to reduce the complexity of the design method. The filters presented in this part are concerned primarily with phase characteristics. The non-minimum-phase condition leads to additional

degrees of freedom that can be used to shape the frequency response of the filter. However, this also requires microwave structures that can accommodate the non-minimum-phase condition, and the design techniques are usually more complex. Chapter 9 makes use of the additional degrees of freedom to design filters that have good group delay characteristics. The filters are implemented using a generalized interdigital structure. A realization at 2.7 GHz based on interdigital bars is shown to give a group delay variation of 2 ns in the pass-band. In Chapter 10 we present very narrowband (e.g., 1%) circular monomode  $TE_{011}$  cavity filters. A method for optimizing the group delay is introduced. A monomode filter design and realization is given at 14.5 GHz. These filters are also suited for temperature variations. The stability of filter responses from  $-10$  to  $+20^\circ\text{C}$  is demonstrated.

Part IV groups Chapters 11 through 14 and deals with non-minimum-phase asymmetrical response filters. The filters in this chapter present generalized Chebyshev or pseudoelliptic bandpass responses with a given number of transmission zeros. In the case of asymmetrical responses, the lowpass prototype is imaginary, and neither the bisection theorem nor traditional frequency transform techniques can be used. The microwave structures must also be able to generate zeros of transmission. In Chapter 11 we describe the design technique for capacitive-gap coupled line filters that have generalized Chebyshev asymmetrical responses. A third-order realization in suspended stripline at 10 GHz shows an asymmetrical response with a zero of transmission at a frequency above the passband. Chapter 12 deals with a state-of-the-art family of in-line dual-mode rectangular structures using resonant  $TE_{102}$  and  $TE_{301}$  modes. Two realizations are given for frequencies around 12 GHz. In Chapter 13 we describe a technique used to design cylindrical dual-mode cavity filters with asymmetrical responses. Good amplitude characteristics are obtained using the  $TE_{113}$  resonant mode. Several realizations using a dual-mode cavity are given around 8.5 GHz. The responses show that various combinations of the zeros of transmission can be obtained.

In Chapter 14 we introduce a new concept for the design of non-minimum-phase microwave filters. The filters are made of basic rectangular waveguide building blocks, and the filters can be designed by using a powerful optimization algorithm called the genetic algorithm. Use of this method makes it possible to design rectangular multimode cavity filters with generalized Chebyshev responses. The realization of a fourth-order filter at 14 GHz with two zeros of transmission using one building block ( $TE_{100}$ ,  $TM_{120}$ , and  $TM_{210}$  modes), and a seventh-order filter at 20 GHz with four zeros of transmission using two building blocks are given. Due to the simplicity of the building blocks, these filters are also easy to manufacture.

The plan of the book is summarized in Figure P1. It shows that we begin in Part I with fundamental concepts and equations useful for designing microwave filters. The reader can stop after Part II which provides a synthesis of minimum-phase microwave filters. The reader could also go directly to more advanced filters known as non-minimum-phase filters. Part III provides the design techniques



**Figure P1** Summary of the organization of the book.

used for non-minimum-phase filters with symmetrical responses, and Part IV covers approaches for designing non-minimum-phase filters with asymmetrical responses. The difference between the latter two types of filters depends on the low-pass network being considered (real or imaginary).

We would like to acknowledge the contributions of our past and present research students whose collaboration has resulted in much of the material in the book. In particular, we would like to mention Professor Humberto Abdalla Junior and Professor Horacio Tertuliano from Brazil, Professor G. Tanné and Associate Professors J.F. Favennec and F. Le Pennec from France, Professor C. Djoub from Ivory Coast, Engineer M. Lyakoubi from Canada, and Engineers N. Boutheiller, CL. Guichaoua, E. Hanna, M. Lecouve, D. Lo Line Tong and O. Roquebrun from France.

The book is based on the authors' research under the sponsorship of the European Space Agency (ESA), France Telecommunications Research & Development (CNET), National Center of Spatial Studies (CNES), ALCATEL SPACE, PHILIPS and THOMSON, French Ministry of Research and Technology (MRT), French Delegation of Research in Science and Techniques (DGRST).

The work resulted in 2 patents with ESA, 3 patents with ALCATEL SPACE and approximately 16 contracts with the different agencies and companies.

## ACKNOWLEDGMENTS

The authors are deeply indebted to Dr. Inder J. Bahl of Tyco Electronics M/A-COM (USA), editor of the *International Journal of RF and Microwave Computer-Aided Engineering*. The book couldn't have been written without his help, and he is acknowledged with gratitude.

Our sincere thanks extend to George Telecki of Wiley-Interscience, and the reviewers, for their support in writing the book. The help provided by Rachel Witmer and Melissa Valentine of Wiley is very much appreciated.

Pierre Jarry wishes to thank his colleagues at the University of Bordeaux, including Professors Pascal Fouillat, Eric Kerherve, and André Touboul, as well

as Professor Yves Garault at the University of Limoges. Finally, he would like to express his deep appreciation to his wife, Roselyne, and his son, Jean-Pierre, for their tolerance and support.

Jacques Beneat is very grateful to Norwich University, a place conducive to trying new endeavors and succeeding. He particularly wants to thank Professors Ronald Lessard and Steve Fitzhugh for their support during the writing of the book; Bjong Wolf Yeigh, Vice President for Academic Affairs and Dean of the Faculty; and Bruce Bowman, Dean of the David Crawford School of Engineering, for their encouragement in such a difficult enterprise.

PIERRE JARRY  
JACQUES BENEAT



# **PART I**

---

## **MICROWAVE FILTER FUNDAMENTALS**



---

# 1

---

## SCATTERING PARAMETERS AND *ABCD* MATRICES

1.1	Introduction	3
1.2	Scattering matrix of a two-port system	4
1.2.1	Definitions	4
1.2.2	Computing the <i>S</i> parameters	6
1.2.3	<i>S</i> -parameter properties	10
1.3	<i>ABCD</i> Matrix of a two-port system	10
1.3.1	<i>ABCD</i> matrix of basic elements	11
1.3.2	Cascade and multiplication property	12
1.3.3	Input impedance of a loaded two-port	14
1.3.4	Impedance and admittance inverters	14
1.3.5	<i>ABCD</i> -parameter properties	17
1.4	Conversion from formulation <i>S</i> to <i>ABCD</i> and <i>ABCD</i> to <i>S</i>	18
1.5	Bisection theorem for symmetrical networks	18
1.6	Conclusions	21

### 1.1 INTRODUCTION

In this chapter we recall the most important characterization techniques used in the design of microwave filters [1.1]. These consist of the scattering parameters, which are often based on electromagnetic analysis of the microwave structures, and the *ABCD* parameters, which are useful to make the link with two-port systems and have been studied exhaustively over the years. Several examples are presented to better understand the relations between the two formalisms. The bisection (or Bartlett) theorem is also reviewed and proves to be very useful in the case of symmetrical networks.

## 1.2 SCATTERING MATRIX OF A TWO-PORT SYSTEM

### 1.2.1 Definitions

The scattering matrix [1.2] of a two-port system provides relations between the input and output reflected waves  $b_1$  and  $b_2$  and the input and output incident waves  $a_1$  and  $a_2$  when the structure is to be connected to a source resistance  $R_G$  and a load resistance  $R_L$ , as depicted in Figure 1.1. The notion of waves rather than voltages and currents is better suited for microwave structures.

For a two-port system, the equations relating the incident and reflected waves and the  $S$  parameters are given by

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned}$$

These equations can be summarized in the matrix form  $(b) = (S)(a)$ , where

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

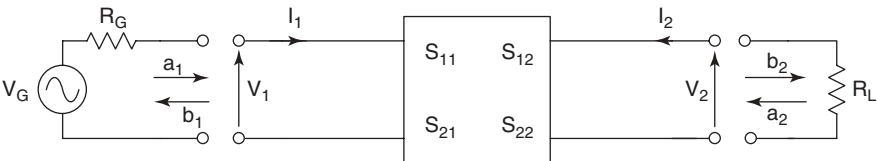
The parameter  $S_{11}$ , called the *input reflection coefficient*, can be computed by setting the output incident wave  $a_2$  to zero and taking the ratio of the input reflected wave over the input incident wave:

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0}$$

The output incident wave  $a_2$  is set to zero by connecting the output of the system to the reference resistor  $R_L$ . The parameter  $S_{11}$  provides a measure of how much of the input incident wave does not reach the output of the system and is reflected back at the input. For microwave filters, ideally,  $S_{11}$  should be equal to zero in the passband of the filter.

The parameter  $S_{21}$ , called the *forward transmission coefficient*, can be computed by setting the output incident wave  $a_2$  to zero and taking the ratio of the output reflected wave over the input incident wave:

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0}$$



**Figure 1.1** Notation used in defining the scattering matrix of a two-port system.

The output incident wave  $a_2$  is set to zero by connecting the output to the reference resistor  $R_L$ . The parameter  $S_{21}$  provides a measure of how much of the input incident wave reaches the output of the system. For microwave filters, ideally,  $S_{21}$  should be equal to 1 in the passband of the filter.

The parameter  $S_{22}$ , called the *reflection coefficient at the output of the system*, can be computed by setting the input incident wave  $a_1$  to zero and taking the ratio of the output reflected wave over the output incident wave:

$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0}$$

The input incident wave  $a_1$  is set to zero by connecting the input of the system to the reference resistor  $R_G$ . As in the case of  $S_{11}$ , it is desirable that  $S_{22}$  be kept close to zero in the passband of the filter.  $S_{11}$  and  $S_{22}$  provide a measure of how well the system impedances are matched to the reference terminations.

The parameter  $S_{12}$ , called the *reverse transmission coefficient*, can be computed by setting the input incident wave  $a_1$  to zero and taking the ratio of the input reflected wave over the output incident wave:

$$S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0}$$

The input incident wave  $a_1$  is set to zero by connecting the input of the system to the reference resistor  $R_G$ . The parameter  $S_{12}$  provides a measure of how much of an incident wave set at the output of the system would reach the input. Due to symmetries in the system,  $S_{21}$  and  $S_{12}$  can have similar values. Since there are no generators at the output of the system, an output incident wave could appear due to a poor  $S_{22}$ .

The scattering parameters can be illustrated using a graph, as shown in Figure 1.2. The graph shows that part of the incident wave  $a_1$  results in a reflected wave  $b_1$  through the parameter  $S_{11}$ , and in a transmitted wave  $b_1$  through the parameter  $S_{21}$ . Similar descriptions can be given for  $a_2$  and the parameters  $S_{22}$  and  $S_{12}$ . It is always important to remember that the  $S$ -parameter values are associated with a given set of termination values. Changing the termination values will change the  $S$ -parameter values.

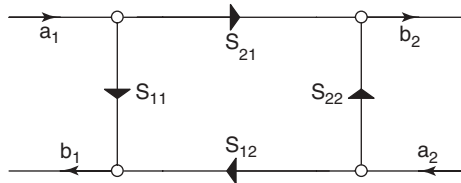


Figure 1.2 Graph of a two-port scattering matrix.

### 1.2.2 Computing the $S$ Parameters

A common example of a scattering matrix in microwave is that of a waveguide of length  $l_0$  and characteristic impedance  $Z_0$ , as shown in Figure 1.3. When the structure is to be connected to a source and load resistance equal to the characteristic impedance of the waveguide, the scattering matrix is given by

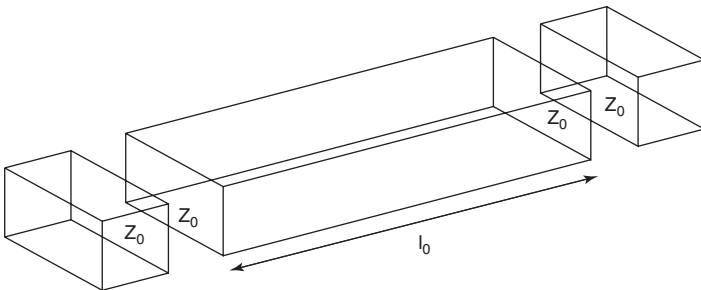
$$(S) = \begin{pmatrix} 0 & e^{-j\beta l_0} \\ e^{-j\beta l_0} & 0 \end{pmatrix}$$

where  $j\beta$  is the propagation function of a given mode above the cutoff frequency of the waveguide. This matrix tells us that the structure will be perfectly matched to the terminations since  $S_{11}$  and  $S_{22}$  are equal to zero. It also tells us that  $b_1$  the wave transmitted, will simply be a delayed version of  $a_1$ , the incident wave, since the forward transmission coefficient,  $S_{21}$ , has a magnitude of 1 and a linear phase of  $-\beta l_0$ , and the longer the length, the longer the delay. Since we cannot differentiate one end of a waveguide from the other, we would have similar results if connecting the source to the output and the load to the input (e.g.,  $S_{12} = S_{21}$ ).

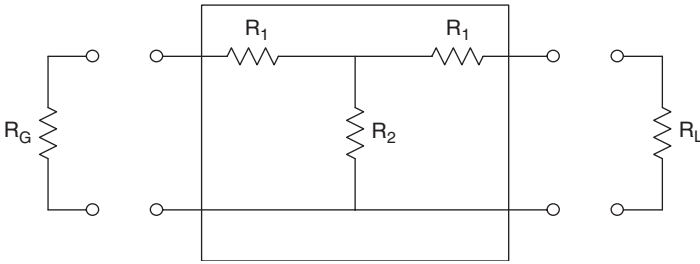
As will be seen, microwave structures will at times have discontinuities that result in the apparition of “scattered” and unwanted electromagnetic fields. For these cases, matching the electromagnetic fields on each side of the discontinuity will provide relations that can be used for defining the scattering parameters of the discontinuity. In that case, the scattering parameters will be defined directly from electromagnetic wave equations. It should be noted, however, that scattering parameters are not limited to microwave structures and electromagnetic field equations.

The incident and reflected waves can be expressed in terms of voltages and currents, as shown in Figure 1.1.

$$\begin{aligned} a_1 &= \frac{V_1 + R_G I_1}{2\sqrt{R_G}} & a_2 &= \frac{V_2 + R_L I_2}{2\sqrt{R_L}} \\ b_1 &= \frac{V_1 - R_G I_1}{2\sqrt{R_G}} & b_2 &= \frac{V_2 - R_L I_2}{2\sqrt{R_L}} \end{aligned}$$



**Figure 1.3** Waveguide of length  $l_0$  and characteristic impedance  $Z_0$ .



**Figure 1.4** Defining the scattering parameters of a resistive two-port system.

For example, the scattering parameters of the resistive two-port system in Figure 1.4 can be defined from these voltages and currents.

The input reflection coefficient  $S_{11}$  is defined from the input incident and reflected waves when the system is connected to the reference resistor  $R_L$ , as shown in Figure 1.5. Also shown in the figure, the system connected to resistor  $R_L$  can be modeled as  $Z_{in}$ , an input impedance of the system. In this case,  $V_1 = Z_{in}I_1$  and  $S_{11}$  is given by

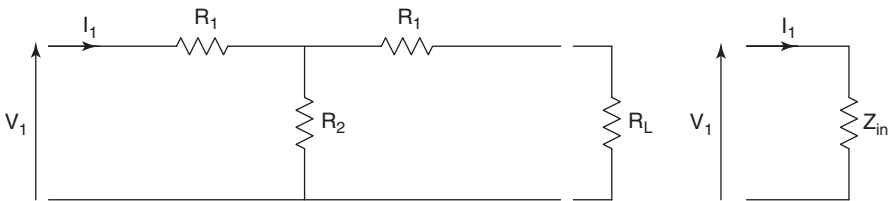
$$S_{11} = \frac{V_1 - R_G I_1}{V_1 + R_G I_1} = \frac{Z_{in} I_1 - R_G I_1}{Z_{in} I_1 + R_G I_1} = \frac{Z_{in} - R_G}{Z_{in} + R_G}$$

This gives  $Z_{in} = R_1 + R_2 || (R_1 + R_L)$  for the input impedance of the system. For  $S_{11}$  to be equal to zero, the input impedance  $Z_{in}$  should be equal to the source resistor  $R_G$ .

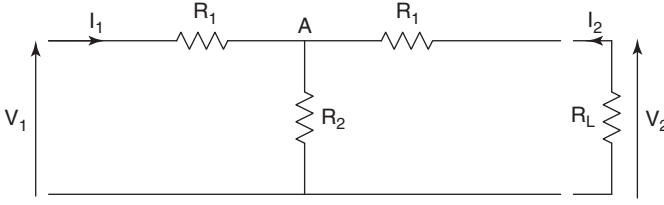
The forward transmission coefficient  $S_{21}$  is defined from the input incident wave and output reflected wave when the system is connected to the reference resistor  $R_L$ , as shown in Figure 1.6. Replacing the incident and reflected waves by their voltage and current expressions,  $S_{21}$  is given by

$$S_{21} = \sqrt{\frac{R_G}{R_L}} \frac{V_2 - R_L I_2}{V_1 + R_G I_1}$$

Also from the computations of  $S_{11}$ ,  $V_1 = Z_{in}I_1$  when the system is connected to  $R_L$ . From Figure 1.6 it is also seen that  $V_2 = -R_L I_2$ . Therefore,  $S_{21}$  will be



**Figure 1.5** Defining the input reflection coefficient  $S_{11}$ .



**Figure 1.6** Defining the forward transmission coefficient  $S_{21}$ .

given by

$$S_{21} = \sqrt{\frac{R_G}{R_L}} \frac{V_2 - (-V_2)}{V_1 + (R_G/Z_{in})V_1} = 2\sqrt{\frac{R_G}{R_L}} \frac{1}{1 + R_G/Z_{in}} \frac{V_2}{V_1}$$

Note that in the case where  $Z_{in} = R_G$  (input impedance matching) and  $R_G = R_L$  (similar source and load terminations), the forward coefficient reduces to

$$S_{21} = \frac{V_2}{V_1}$$

In Figure 1.6,

$$V_2 = \frac{R_L}{R_L + R_1} V_A \quad \text{and} \quad V_A = \frac{R}{R + R_1} V_1$$

where  $R = R_2 || (R_1 + R_L)$ , so that

$$V_2 = \frac{R_L}{R_L + R_1} \frac{R}{R + R_1} V_1$$

and a general expression for  $S_{21}$  is given by

$$S_{21} = 2\sqrt{\frac{R_G}{R_L}} \frac{1}{1 + R_G/Z_{in}} \frac{R_L}{R_L + R_1} \frac{R}{R + R_1}$$

The  $S_{22}$  and  $S_{12}$  parameters can be defined using a similar process, where the input is now connected to the reference resistor  $R_G$ . In the resistive example above, the  $S$  parameters are independent of frequency since the impedances of the resistors are independent of frequency. However, the results can be used to define the  $S$  parameters of a more general case, as shown in Figure 1.7. The input reflection coefficient  $S_{11}$  will now be a function of the impedances of the system and therefore depend on the frequency of application through the Laplace variable  $s$ :

$$S_{11}(s) = \frac{Z_{in}(s) - R_G}{Z_{in}(s) + R_G}$$