

Advanced Series in Electrical and Computer Engineering – Vol. 18

BROADBAND MATCHING

THEORY AND IMPLEMENTATIONS

Third Edition



WAI-KAI CHEN

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BROADBAND MATCHING

THEORY AND IMPLEMENTATIONS

Third Edition

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THEORY AND IMPLEMENTATIONS

Third Edition

WAI-KAI CHEN

University of Illinois at Chicago, USA

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(3rd Edition)

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To Shiao-Ling and Jerome and Melissa

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Contents

<i>Preface to the 3rd Edition</i>	xvii
<i>Preface to the 2nd Edition</i>	xix
<i>Preface to the 1st Edition</i>	xxi
Chapter 1. Foundations of Network Theory	1
1. Basic network postulates	2
1.1. Real-time function postulate	3
1.2. Time-invariance postulate	4
1.3. Linearity postulate	5
1.4. Passivity postulate	6
1.5. Causality postulate	9
1.6. Reciprocity postulate	10
2. Matrix characterizations of n -port networks	11
2.1. The impedance matrix	12
2.2. The admittance matrix	13
2.3. The hybrid matrix	14
2.4. The indefinite-admittance matrix	15
3. Power gains	21
4. Hermitian forms	23
5. The positive-real matrix	28
6. Frequency-domain conditions for passivity	39
7. Conclusions	43
Problems	45
References	47

Chapter 2. The Scattering Matrix	48
1. A brief review of the transmission-line theory . . .	49
2. The scattering parameters of a one-port network . .	50
2.1. Basis-dependent reflection coefficients . . .	52
2.2. Basis-independent reflection coefficient . .	54
2.3. The factorization of the para-hermitian part of $z(s)$	57
2.4. Alternative representation of the basis-independent reflection coefficient . . .	62
2.5. The normalized reflection coefficient and passivity	64
3. The scattering matrix of an n -port network	66
3.1. Basis-dependent scattering matrices	70
3.2. Basis-independent scattering matrix	74
3.3. The scattering matrices and the augmented n -port networks	77
3.4. Alternative representation of the basis-independent scattering matrix	80
3.5. Physical interpretation of the normalized scattering parameters	82
3.6. The normalized scattering matrix and passivity	88
3.7. The normalized scattering parameters of a lossless two-port network	90
4. The bounded-real scattering matrix	91
5. Interconnection of multi-port networks	98
6. Conclusions	107
Problems	108
References	114
 Chapter 3. Approximation and Ladder Realization	 116
1. The Butterworth response	117
1.1. Poles of the Butterworth function	119
1.2. Coefficients of the Butterworth polynomials	121

1.3.	Butterworth networks	124
1.4.	Butterworth <i>LC</i> ladder networks	126
2.	The Chebyshev response	133
2.1.	Chebyshev polynomials	133
2.2.	Equiripple characteristic	135
2.3.	Poles of the Chebyshev function	139
2.4.	Coefficients of the polynomial $p(y)$	142
2.5.	Chebyshev networks	144
2.6.	Chebyshev <i>LC</i> ladder networks	146
3.	Elliptic functions	152
3.1.	Jacobian elliptic functions	152
3.2.	Jacobi's imaginary transformations	154
3.3.	Periods of elliptic functions	155
3.3.1.	The real periods	157
3.3.2.	The imaginary periods	158
3.4.	Poles and zeros of the Jacobian elliptic functions	159
3.5.	Addition theorems and complex arguments	162
4.	The elliptic response	166
4.1.	The characteristic function $F_n(\omega)$	167
4.2.	Equiripple characteristic in passband and stopband	174
	A. Maxima and minima in the passband	177
	B. Maxima and minima in the stopband	178
	C. Transitional band	179
4.3.	Poles and zeros of elliptic response	184
4.4.	Elliptic networks	191
5.	Frequency transformations	198
5.1.	Transformation to high-pass	199
5.2.	Transformation to band-pass	202
5.3.	Transformation to band-elimination	205
6.	Conclusions	207
	Problems	209
	References	217

Chapter 4. Theory of Broadband Matching:	
The Passive Load	220
1. The Bode–Fano–Youla broadband matching problem	221
2. Youla’s theory of broadband matching: preliminary considerations	222
3. Basic constraints on $\rho(s)$	225
4. Bode’s parallel RC load	227
4.1. Butterworth transducer power-gain characteristic	228
4.2. Chebyshev transducer power-gain characteristic	239
4.3. Elliptic transducer power-gain characteristic	252
4.4. Equalizer back-end impedance	262
5. Proof of necessity of the basic constraints on $\rho(s)$	265
6. Proof of sufficiency of the basic constraints on $\rho(s)$	269
7. Design procedure for the equalizers	272
8. Darlington type-C load	279
8.1. Butterworth transducer power-gain characteristic	279
8.2. Chebyshev transducer power-gain characteristic	287
8.3. Elliptic transducer power-gain characteristic	293
8.4. Equalizer back-end impedance	296
9. Constant transducer power gain	298
10. Conclusions	312
Problems	313
References	317

Chapter 5. Theory of Broadband Matching:	
The Active Load	320
1. Special class of active impedances	321
2. General configuration of the negative-resistance amplifiers	323
3. Nonreciprocal amplifiers	325
3.1. Design considerations for N_α	328
3.2. Design considerations for N_β	330
3.3. Design considerations for N_c	330
3.4. Illustrative examples	333
A. Realization of N_α	336
B. Realization of N_β	341
C. Realization of N_c	342
3.4.1. The tunnel diode amplifier: maximally-flat transducer power gain	344
A. Realization of N_α	346
B. Realization of N_β	348
3.4.2. The tunnel diode amplifier: equiripple transducer power gain	352
A. Realization of N_α	353
B. Realization of N_β	357
3.5. Extension and stability	361
4. Transmission-power amplifiers	363
4.1. Tunnel diode in shunt with the load	364
4.1.1. Transducer power gain: $R_2 > R$	365
A. Maximally-flat low-pass amplifiers	367
B. Equiripple low-pass amplifiers	370
4.1.2. Transducer power gain: $R_2 < R$	374
4.2. Tunnel diode in shunt with the generator	376
4.2.1. Transducer power gain: $R_1 > R$	378
4.2.2. Transducer power gain: $R_1 < R$	378

4.3.	Stability	379
4.4.	Sensitivity	380
4.4.1.	Tunnel diode in shunt with the load	381
4.4.2.	Tunnel diode in shunt with the generator	383
5.	Reciprocal amplifiers	384
5.1.	General gain-bandwidth limitations	385
5.2.	Cascade connection	388
6.	Amplifiers using more than one active impedance .	393
6.1.	Nonreciprocal amplifiers	396
6.2.	Reciprocal amplifiers	399
7.	Conclusions	401
	Problems	403
	References	414

Chapter 6. Explicit Design Formulas for Broadband Matching Networks 416

1.	Low-pass Butterworth networks	417
1.1.	Basic constraints for low-pass Butterworth response	417
1.2.	Explicit design formulas for low-pass Butterworth response	425
1.3.	General explicit formulas for low-pass Butterworth networks	433
1.3.1.	Explicit formulas for the Darlington type-C section	439
1.3.2.	Illustrative examples	442
2.	Low-pass Chebyshev Networks	448
2.1.	Basic constraints for low-pass Chebyshev response	448
2.2.	Explicit formulas for low-pass Chebyshev response	453
2.3.	General Explicit Formulas for Low-pass Chebyshev Networks	459

2.3.1.	Explicit formulas for the Darlington type-C section	461
2.3.2.	Illustrative examples	464
3.	Band-pass Butterworth networks	470
3.1.	Basic constraints for band-pass Butterworth response	470
3.2.	Explicit formulas for band-pass Butterworth response	478
4.	Band-pass Chebyshev networks	488
4.1.	Basic constraints for band-pass Chebyshev response	488
4.2.	Explicit formulas for band-pass Chebyshev response	494
5.	Conclusions	500
	References	500

Chapter 7. Broadband Matching of Frequency-Dependent Source and Load 502

1.	The problem of compatible impedances	503
1.1.	Wohlers' compatibility theorem	506
1.2.	Equivalency of conditions	517
2.	Broadband matching of frequency-dependent source and load	531
2.1.	Method of synthesis	537
2.2.	Illustrative examples	538
3.	Coefficient realizability conditions of a scattering matrix	548
3.1.	Basic coefficient constraints	551
3.2.	Coefficient realizability conditions	553
3.3.	Illustrative example	564
3.4.	Realization of the matching networks	575
4.	General scattering matrix realizability	579
5.	Conclusions	590
	References	590

Chapter 8. Real-Frequency Solutions of the Broadband Matching Problem	592
1. Direct real-frequency approach	593
2. Piecewise linear approximation	596
3. Piecewise linear Hilbert transforms	599
4. Gain objective function	610
5. Rational representation of $R_{22}(\omega)$	617
6. Rational least-squared-error approximation of $R_{22}(\omega)$	622
7. Calculation of the network function from a given real part	634
7.1. Bode method	635
7.2. Brune-Gewertz method	636
8. Double matching problems	643
8.1. Basic equations	643
8.2. Computational algorithm	647
8.3. Realizability of $R_{20}(\omega)$	650
8.4. Illustrative examples	652
9. The complex-normalized reflection coefficients	657
9.1. Main theorem	658
9.2. Illustrative examples	663
10. Analytic solution of the matching problem of Fig. 8.12.	673
10.1. Coefficient constraints imposed by $z_1(s)$	675
10.2. Coefficient constraints imposed by $z_2(s)$	677
10.3. Equalizer back-end impedance	681
10.4. Realization of the Darlington type-C section	682
10.5. Verification of design	686
11. Conclusions	689
References	691

Chapter 9. The Maximally-Flat Time Delay Approximation: The Bessel–Thomson Response	693
1. The Bessel–Thomson response	693
2. Maximally-flat group delay characteristic	694
3. Poles of the Bessel–Thomson function	701
4. Synthesis of the Bessel–Thomson filters with prescribed <i>RLC</i> load	703
4.1. Basic constraints for the Bessel–Thomson response	703
4.2. Design procedure for the Bessel–Thomson response	712
5. Synthesis of the Bessel–Thomson filters with general loads	717
5.1. Scattering representation with indeterminate coefficients	718
5.2. The system transmission function	721
5.3. Realizability conditions	725
5.4. Illustrative examples	728
5.5. Appendix	738
References	742
 Chapter 10. Diplexer and Multiplexer Design	 743
1. Diplexer having Butterworth characteristic	743
2. Symmetrical diplexer having Butterworth characteristic	752
3. Real-frequency approach to the design of a reactance-ladder diplexer	767
3.1. Real-frequency approach to the design of a low-pass high-pass reactance-ladder diplexer	769

3.2.	Optimization procedure	776
3.3.	Butterworth diplexer	779
3.4.	Elliptic response diplexer	787
3.5.	Appendix: Derivatives required in the formation of Jacobian matrix	793
4.	Design of a multiplexer with a common junction . .	794
4.1.	Formulas for the scattering parameters . . .	795
4.2.	Derivations of formulas	801
4.3.	Design method	805
4.4.	Illustrative examples	808
5.	Design of a singly-matched multiplexer with a common junction	818
5.1.	Design formulas	821
5.2.	Design approach	824
5.3.	Illustrative example	826
	References	832
	Appendices	835
	Appendix A. The Butterworth Response	835
	Appendix B. The Chebyshev Response	837
	Appendix C. The Elliptic Response	840
	<i>Symbol Index</i>	845
	<i>Subject Index</i>	848

Preface to the 3rd Edition

OVER the years, the fundamentals of broadband matching have evolved to include a wide range of topics and a broad range of practice. To encompass such a wide range of knowledge, the book focuses on the key concepts, models, and equations that enable the electrical engineer to analyze, design, and predict the behavior of broadband circuits. While design formulas and tables are listed, emphasis is placed on the key concepts and theories underlying the applications. The purpose of the book is to provide in a single volume a comprehensive reference work covering the broad spectrum of mathematics for circuits and filters; circuits configurations, devices, and their models. The book is written and developed for the practicing electrical engineers in industry, government, and academia. The goal is to provide the most up-to-date information in the field.

The book stresses fundamental theory behind professional applications. In order to do so, it is reinforced with frequent examples. The reader is assumed to have a certain degree of sophistication and experience. However, brief reviews of theories, principles, and mathematics of some subject areas are given. These reviews have been done concisely with perception.

The third edition presents a unified, up-to-date, and detailed account of broadband matching theory and its applications to the design of broadband matching networks, multiplexers, and amplifiers. A special feature is the addition of results that are of direct practical value. They include design curves, tables, and explicit formulas for designing networks having Butterworth, Chebyshev, elliptic or

maximally-flat group-delay response as well as for designing diplexer and, in general, multiplexer having these responses. The results are extremely useful as the design procedures can be reduced to simple computer routines. Several illustrative examples given at the last two new chapters are intended to demonstrate the applications to the practical design of modern filter circuits.

The compilation of this book would not have been possible without the contribution of my visiting scholars Professors Zhao-Ming Wang and Yi-Sheng Zhu and my doctoral student Dr Ji-An Gong. In fact, the last two chapter material is mostly based on their research work. I wish to thank them all.

May 27, 2014

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Preface to the 2nd Edition

THE BOOK was initially conceived as a revision of the original volume. Since then it evolved and was modified to such a great extent that more than one-third of the material is new. As a result, the title of the new edition has been changed to reflect more accurately its contents. Most of the new material appeared after the publication of the first edition in 1976, which was translated to Russian in 1979, and to Chinese in 1982.

In revising the first edition, I can think of many items that should be added. Judging from the interest of readers and the practical applications of the subject to engineers, I have decided to concentrate on areas that have received wide attention in recent years. The purpose of the new edition is to present a unified, up-to-date, and detailed account of broadband matching theory and its applications to the design of broadband matching networks and amplifiers. The book can be used as a later text in network theory as well as a reference for practicing engineers who wish to learn how the modern network theory can be applied to the design of many practical circuits. A special feature of this new edition is that results of direct practical value are included.

The new material starts in Chapter 6 with the presentation of explicit design formulas for broadband matching networks having low-pass or bandpass Butterworth or Chebyshev response of arbitrary order. The significance of these results is that they reduce many of the design procedures to simple arithmetic. Chapter 7 extends the classical single match to double match where both the source and

load impedances are frequency dependent. This is important because in many practical applications, the internal impedances of the available electronic sources are not purely resistive, especially at high frequencies for which the broadband matching theory is most needed. Finally, we present the real-frequency technique in Chapter 8 for both the single match and the double match. The method is a numerical one, and only utilizes real-frequency data of the load and/or source impedance. No model or analytic impedance function for the load and/or source is required. Nor is the equalizer topology or analytic form of the system transfer function assumed.

This edition contains a significant number of corrections that have been incorporated throughout the text. One inevitable result in adding new material is that the book has grown longer. It contains more material than can be adequately presented in a one-semester or two-quarter three hours-per-quarter course in network theory. This added flexibility will allow instructors to select subjects and sections to meet their needs and environment.

Since the publication of the first edition, many people have been kind enough to give me the benefit of their comments and suggestions, often at the expense of a very considerable amount of their time and energy. In particular, I am indebted to my graduate students, visiting scholars and those users of the book who have contributed to the improvement of this edition. Special thanks are due to Mr. Yi-Sheng Zhu of Dalian Marine College and my doctoral students Ms. Hui Tang and Mr. Qiang-Zhong Zha, who gave the new chapters a careful and critical reading and assisted me in preparing the index. Finally, I express my appreciation to my wife, Shiao-Ling, and children, Jerome and Melissa, for their patience and understanding during the preparation of the book.

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Naperville, Illinois

Preface to the 1st Edition

OVER the past two decades, we have witnessed a rapid development of solid-state technology with its apparently unending proliferation of new devices. In order to cope with this situation, a steady stream of new theory, being general and independent of devices, has emerged. One of the most significant developments is the introduction of scattering techniques to network theory. The purpose of this book is to present a unified and detailed account of this theory and its applications to the design of broadband matching networks and amplifiers. It was written primarily as a late text in network theory as well as a reference for practicing engineers who wish to learn how the modern network theory can be applied to the design of many practical circuits. The background required is the usual undergraduate basic courses in networks as well as the ability to handle matrices and functions of a complex variable.

In the book, I have attempted to extract the essence of the theory and to present those topics that are of fundamental importance and that will transcend the advent of new devices and design tools. The guiding light throughout the book has been mathematical precision. Thus, all the assertions are rigorously proved; many of these proofs are believed to be new and novel. I have tried to give a balanced treatment between the mathematical aspects and the physical postulates which motivate the work, and to present the material in a concise manner; using discussions and examples to illustrate the concepts and principles involved. The book also contains some of the personal contributions of the author that are not available elsewhere in the literature.

The scope of this book should be quite clear from a glance at the table of contents. Chapter 1 introduces many fundamental concepts related to linear, time-invariant n -port networks, defines *passivity* in terms of the universally encountered physical quantities *time* and *energy*, and reviews briefly the general characterizations of an n -port network. Its time-domain passivity conditions are then translated into the equivalent frequency-domain passivity criteria, which are to be employed to obtain the fundamental limitations on its behavior and utility. Thus, this chapter, as the title implies, may be taken as the foundation for any subsequent network study as well as for the material treated in the remainder of the book.

Chapter 2 gives a fairly complete exposition of the scattering matrix associated with an n -port network, starting from a one-port network and using the concepts from transmission-line theory. Fundamental properties of the scattering matrix and its relation to the power transmission among the ports are then derived. The results are indispensable in developing the theory of broadband matching to be treated in the last two chapters.

In seeking fundamental limitations on network or device behavior, performance criteria are often overly idealistic and are not physically realizable. To avoid this difficulty, Chapter 3 considers the approximation problem along with a discussion of the approximating functions. It is shown that the ideal low-pass brick-wall type of gain response can be approximated by three popular rational function approximation schemes: the maximally-flat (Butterworth) response, the equiripple (Chebyshev) response, and the elliptic (Cauer-parameter) response. This is followed by presenting the corresponding ladder network realizations which are attractive from an engineering viewpoint in that they are unbalanced and contain no coupling coils. Explicit formulas for element values of these ladder networks with Butterworth or Chebyshev gain characteristic are given, which reduce the design of these networks to simple arithmetic. Confining attention to the low-pass gain characteristic is not to be deemed restrictive as it may appear. This is demonstrated by considering frequency transformations that permit low-pass characteristic to be converted to a high-pass, band-pass, or band-elimination characteristic.

Using the results developed in the first three chapters, Chapter 4 treats Youla's theory of broadband matching in detail, illustrating every phase of the theory with fully worked out examples. In particular, the fundamental gain-bandwidth limitations for Bode's parallel RC load and Darlington's type-C load are established in their full generality. The extension of Youla's theory to active load impedance is taken up in Chapter 5. It is demonstrated that with suitable manipulations of the scattering parameters, the theory can be applied to the design of negative-resistance amplifiers. This is especially significant in view of the continuing development of new one-port active devices such as the tunnel diode. Many readers will find the perusal of this chapter to be a gratifying and stimulating experience.

In selecting the level of presentation, considerable attention has been given to the fact that many readers may be encountering these topics for the first time. Thus basic introductory material has been included. For example, since many readers are not familiar with the subject of elliptic functions in Chapter 3 on Approximation and Ladder Realization, an entire section is devoted to the discussion of elliptic functions and some of their fundamental properties that are needed in subsequent analysis. In fact, the section on elliptic response has never been so concisely and systematically treated elsewhere.

The text has grown out of a graduate course entitled "Linear Network Theory" organized at Ohio University. Over the period of years, the material has naturally evolved and up-dated into a shape quite different from the original. However, the basic objective of establishing the fundamentals in this area has remained unchanged throughout. There is little difficulty in fitting the book into a one-semester, or two-quarter course in linear network theory and design. It can be used equally well as a text in advanced network synthesis. For example, as an advanced text in modern network synthesis, Chapters 2, 4 and 5 plus some sections of Chapter 3 would serve for this purpose. Some of the later chapters are also suitable as topics for advanced seminars.

A special feature of the book is that results of direct practical value are included. They are design curves and tables for networks having Butterworth, Chebyshev or elliptic response. These results

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