Linear Integrated Networks Design

George S. Moschytz

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GEORGE S. MOSCHYTZ

Bell Telephone Laboratories
presently professor,
Swiss Federal Institute of Technology,
Zurich, Switzerland

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VAN NOSTRAND REINHOLD COMPANY

New York/Cincinnati/Toronto/London/Melbourne

Van Nostrand Reinhold Company Regional Offices:
New York Cincinnati Chicago Millbrae Dallas

Van Nostrand Reinhold Company International Offices:
London Toronto Melbourne

Library of Congress Catalog Card Number: 74-13707
ISBN: 0-442-25582-9

Manufactured in the United States of America

Published by Van Nostrand Reinhold Company
450 West 33rd Street, New York, N.Y. 10001

Published simultaneously in Canada by Van Nostrand Reinhold Ltd

15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging in Publication Data

Moschytz, George S
Linear integrated networks: design.

(Bell Telephone Laboratories series)
Includes bibliographical references.
1. Linear integrated circuits. 2. Hybrid integrated circuits. 3. Electronic circuit design.
I. Title.
TK7874.M5344 621.381'73 74-13707
ISBN 0-442-25582-9

FOREWORD

It is quite timely for a work to appear on the theory and design of linear integrated networks which emphasizes the growing recognition and importance of hybrid integrated circuits based on silicon semiconductor technology and precision passive film technology. Dr. Moschytz has undertaken a project which provides a sound theoretical basis for understanding linear active networks while stressing the practical active network realizations which were achieved during recent years, particularly at Bell Laboratories where he supervised much of the advanced development and design effort on active linear networks. Many of the examples and illustrations in the work are based on these designs, with careful consideration given to the numerous design and performance trade offs involved in developing high performance active networks using a hybrid technology.

This work will improve the communications and understanding necessary among the specialists in semiconductor device, component, and network technologies, and it effectively complements other recent books by providing practical illustrations of active networks designed to meet special requirements. The author gives special consideration to the unique features of hybrid integrated circuits with regard to small size, low power dissipation, batch fabrication, parasitic effects, network and device sensitivity, functional adjustment, and network performance.

The two volumes, devoted respectively to fundamentals and design, should become a valuable addition to the literature, and will be of considerable benefit to students and to practicing industry engineers and scientists. The volumes are the latest in the Bell Telephone Laboratories series, in which we attempt to bring the engineering and scientific community up to date on subjects of major current interest.

David Feldman
Director
Film and Hybrid Technology Laboratory
Bell Telephone Laboratories

PREFACE

A new technology has emerged with hybrid integrated circuit technology, and it has already drastically affected the design of linear networks such as frequency selective filters, shaping networks, and delay lines. The need to eliminate inductors from these networks has had particularly far-reaching consequences in that much of the classical filter theory and conventional filter know-how that was previously at the designer's disposal can no longer be directly applied. More and more, *active filters* in hybrid integrated form are replacing their passive LCR counterparts in modern communication and control systems, and the need has become evident of documenting the new design rules and guidelines necessary to perform this transition from the old to the new. This transition is, of course, motivated by such very real incentives as more economical (batch) production methods, higher reliability, smaller size, manufacturing processes that are compatible with other (e.g. digital) integrated circuit production methods, and so on. These benefits of the new technology are well known at the present time, and the need to justify more elaborately the trend toward inductorless networks (of which linear integrated networks belong to the most important exponents) should no longer be necessary.

This book attempts to fill the need, expressed above, of documenting the design rules and guidelines necessary for the design, development, and manufacture of linear networks—and in particular of active filters—realized in hybrid integrated form. To do so, it draws heavily on the companion book *Linear Integrated Networks: Fundamentals* in which the prerequisites necessary for the understanding of the material presented here are covered in detail. To facilitate the coordination between the two books, and to provide a self-contained, comprehensive work on the subject of linear integrated networks (LINs), cross references are given wherever necessary.

This book covers the theory of LIN design, while at the same time blending with it the practical aspects of LIN development and manufacture, as encountered by the author in an industrial environment. The close interrelationship between the theory and practice of LIN design is considered a vital aspect of the book; wherever possible practical considerations are given a sound theoretical foundation; likewise, theoretical discussions are firmly tied to practical experience. Development steps that have been successfully proven in practice are enumerated in easy to follow fashion. These steps are based on the detailed theoretical considerations preceding them, as well as on the experience acquired during implementation in practice.

Most of the material covered here appears in book form for the first time; much of it has not been published in any form before. The material has been divided into two parts. Part I, comprising the first three chapters, deals with the synthesis of active networks. This part is essentially independent of the technology utilized for the actual realization and covers the general theory of active network design. After briefly discussing the filter approximation problem, those aspects peculiar to *active* filter design are covered. These encompass the problem of optimum pole-zero pairing, the sensitivity of cascaded second- and third-order networks, the general realization of such networks, as well as their realization in building-block form. A comprehensive classification of active networks using single active devices is given and the most useful multi-amplifier configurations are discussed in detail. Part II, comprising the remaining four chapters, specifically deals with the design of active networks in ***hybrid-integrated*** form. Here the almost unlimited variety of active networks encompassed in the general treatment of Part I are reconsidered with a view to hybrid-integrated circuit realization. This review takes the parasitic and other nonideal effects inherent in hybrid-integrated circuit technology into account. Using a suitable active network type as an illustrative example, the step-by-step design and development procedure necessary for the realization of hybrid-integrated filter building blocks is covered in detail. The capabilities of such filters are compared with those of other inductorless-filter techniques, and those areas in which active filters seem to hold most promise are mapped out. Finally, modifications necessary to extend the capabilities of hybrid-integrated networks such that they can be fully utilized in, and beyond, those areas are covered in detail.

The material covered in this book is directed at student and engineer alike, and is presented such as to permit self study. For this reason numerous examples are worked out in detail and liberal use is made of figures.

Chapter 1 covers those design aspects common to all active networks, irrespective of the technology used for their realization. These include optimization for maximum inband gain and minimum sensitivity, the sensitivity of cascaded and inductor-simulated active networks and the characterization and sensitivity of second and third-order networks. *Chapter 2* contains a unified theory and classification of all second-order active networks comprising a single active element. This classification permits conclusive generalizations to be made with respect to characteristics, sensitivity, etc., for each network class. In *Chapter 3* the most useful and proven single and multiple-amplifier second-order active filter building blocks are presented in detail. The two topologies (cascade and parallel) in which these building blocks can be used are discussed. In *Chapter 4* those practical aspects are considered that enter the design process when linear active networks are to be realized using hybrid integrated circuit technology. The multitude of active circuits that emerge from the classifications in Chapters 2 and 3 are evaluated from the point of view of hybrid integrated circuit technology, and the interrelationship between network class and technology is demonstrated. The effects of parasitics and other nonideal characteristics are analyzed and tuning methods that enable the ensuing initial errors to be compensated for (or "tuned out") are considered. *Chapter 5* deals with the actual design and development of filter building blocks in hybrid integrated circuit form. This chapter deals with such topics as layout, substrate and film materials, single- and double-substrate assemblies, scribing methods, and the like. Other inductorless filter methods are also reviewed and, based on this review, areas of applications where active filters appear particularly useful are pointed out. In this context the economics of hybrid-integrated circuits are also considered. *Chapter 6* presents the step-by-step optimization and design of a family of hybrid integrated filter building blocks that have proved themselves in production and practice. Partly in cook book fashion, and with extensive tabulated material, this chapter has sufficient detailed design information to permit the reader to follow and understand the intricacies of hybrid integrated building block design. Finally, in *Chapter 7*, some of the latest methods used to extend the frequency and selectivity capabilities of hybrid integrated networks are covered. Methods are discussed of designing hybrid integrated active filters for extreme low, and very high frequency applications (compared to presently available frequency ranges). The various methods of inductor simulation are elaborated on and optimization methods for networks with maximum dynamic range and minimized sensitivity are given. Furthermore some of the latest results are given with respect to negative-feedback-coupled active filter building blocks, and methods are presented of analyzing the improved filter stability thereby obtainable.

Much of the material covered in this book and the companion book (*LINs: Fundamentals*) has been "class-room tested" as a two-semester course with two rather different types of students. First given as an out-of-hours course at Bell Telephone Laboratories, Holmdel, N.J., the students were exclusively engineers who, in some way or another, had use for certain aspects, if not for the outright design, of hybrid-integrated networks in the course of their daily work. The second time the material was taught as a first year graduate course at the Swiss Federal Institute of Technology, Zurich, Switzerland (while on leave of absence from Bell Telephone Laboratories as a visiting professor at the Institute of Telecommunications).

In teaching the material covered in this and the companion book in a two-semester course the following sequence has been found useful:

Chapters 1 to 4 (*Fundamentals*) as well as Chapter 2 (*Design*) are covered in the first semester in order to provide a somewhat rounded off treatment of linear active networks in general. Chapters 5 (*Fundamentals*) and selected topics of chapters 1, 3, 4, 6 and 7 (*Design*) are then dealt with in the second semester, whereby chapters 6, 7 and 8 (*Fundamentals*) are suggested as additional reading material. In this way the second semester covers the integrated circuit aspects of linear network design. Depending on how much of *Fundamentals* it is deemed necessary to teach, this program can, of course, be drastically shortened—if need be to a one semester course.

GEORGE S. MOSCHYTZ

ACKNOWLEDGMENTS

Many of the ideas presented in this book were formed during the exciting and stimulating experience of designing and getting into production hybrid integrated filters for the Bell System in a team effort in which I was involved with numerous colleagues on the staffs of the Bell Telephone Laboratories and the Western Electric Company. To name all the people who contributed to that successful effort is practically impossible, and I must acknowledge my indeptedness to them collectively. However, I wish to acknowledge specifically D. Hirsch and N. E. Snow as well as D. Feldman, C. T. Goddard and D. A. McLean for their encouragement and support during the whole project. Furthermore I wish to acknowledge the main contributors to that project namely W. L. Barton, W. H. D'Zio, J. S. Fisher, M. C. Kolibaba, J. A. Krayesky, E. Lueder, G. Malek, D. G. Marsh, D. R. Means, D. G. Medill, D. O. Melroy, W. H. Orr, N. P. Palumbo, A. L. Pappas, C. J. Steffen, S. E. Sussman, W. Thelen and R. M. Zeigler, of Bell Telephone Laboratories and G. Allerton, T. Breisch, S. Hause, and W. B. Reichard of the Western Electric Company.

I am greatly indebted to T. F. Epley, formerly of the Van Nostrand Reinhold Co., whose enthusiasm and encouragement provided the necessary motivation for this book and the companion book *Linear Integrated Networks: Fundamentals*, and whose guidance through the early stages was invaluable; and to his successor B. R. Nathan, and his colleagues Mrs. A. W. Gordon, J. Stirbis and Mrs. F. Landau, whose much appreciated advice assisted me up to the completion of both books.

I am indebted to many friends, colleagues and students for their valuable comments and suggestions during the preparation of this book. I am grateful for the constructive criticisms of the reviewers at Bell Telephone Laboratories (BTL), in particular to R. K. Even, D. R. Means, E. Lueder, C. J. Steffen and G. Malek. I am especially indebted to R. K. Even and D. R. Means for their very thorough review of the entire manuscript and for their numerous constructive criticisms and helpful advice regarding organization and presentation of the book. I also greatly appreciate the numerous helpful comments from my students at the Swiss Federal Institute of Technology (SFIT) in Zurich, in particular from R. Hammer, P. Horn and M. Kuenzli.

I am most grateful for the kind cooperation of D. Hirsch and E. R. Kretz mer of BTL and of Professor H. Weber of the SFIT for making it possible for the manuscript to progress smoothly while I was in Zurich on a leave of absence from Bell Telephone Laboratories. My deep appreciation also goes to the extensive secretarial assistance of Miss P. Jobes at BTL and Mrs. A. Huebscher and Mrs. L. Hubmann at the SFIT, as well as to the excellent typing skills of Mrs. M. Taolise. Finally, my thanks go to my wife Doris and my daughters Joy, Helen and Miriam for the interest and understanding they showed during this undertaking.

G. S. MOSCHYTZ

CONTENTS

PART I:

FUNDAMENTALS OF ACTIVE NETWORK SYNTHESIS

CHAPTER

1

LINEAR ACTIVE NETWORK DESIGN

INTRODUCTION

In this chapter we first consider the so-called approximation problem briefly, that is, the problem of determining a rational transfer function that will satisfy our system requirements in terms of a frequency response or in the time domain. Having done so, the question must then be answered, how to translate the given transfer function into a suitable active network that not only responds in the required manner but also satisfies various additional constraints such as, for example, providing a specified stability over given ambient conditions, a specified signal-to-noise ratio over a given dynamic range, or a specified current drain over a given supply voltage range. Some answers to these and related questions will be given in this and the following chapters.

1.1 THE THREE STEPS IN LINEAR ACTIVE NETWORK SYNTHESIS

Network synthesis is the process by which a network is obtained that satisfies a set of prescribed electrical characteristics. The required characteristics may be specified in either the frequency domain, the time domain, or possibly even in both. In the case of active network synthesis, a three-step process is used to obtain a desired network (see Fig. 1-1).

Step 1. Approximation. Obtain a rational transfer function in s which approximates with acceptable accuracy the prescribed electrical charac-

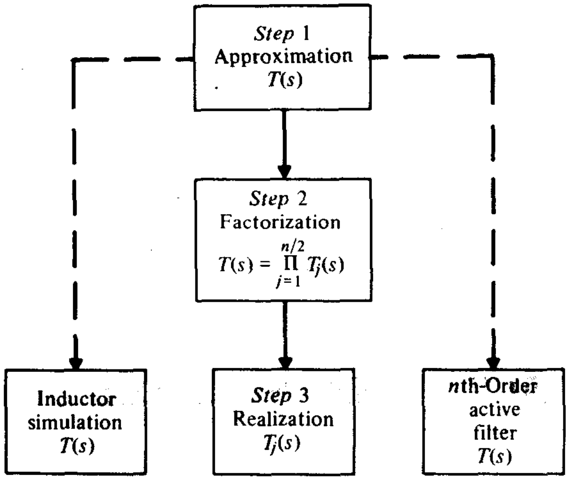

FIG. 1-1. The various approaches to active filter design.

teristics. In the case of a voltage transfer function, for example, this function is of the form

$$T(s) = \frac{\text{output}}{\text{input}} = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_1 s + b_0}{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_1 s + a_0} \tag{1-1}$$

where $s = \sigma + j\omega$ and $n \geq m$.

In most cases such a ratio of polynomials with real coefficients can readily be found. In some cases, however, particularly when designing pulse-shaping networks, the required characteristics are either specified in the time domain or in the form of a transcendental function in s. In such cases the approximation of "nonrational" specifications by a rational function of the type represented by (1-1) may cause some difficulties. If the response of the initially obtained rational function does not lie within the specified limits, optimization techniques[1] must be used, which perturb the individual poles and zeros of the rational function until its response falls within the tolerances specified.

Step 2. Decomposition. Obtain the roots of the numerator polynomial (the zeros) and of the denominator polynomials (the poles). The desired transfer function can then be written as the product of second-order subfunctions as follows:

$$T(s) = \prod_{j=1}^{n/2} T_j(s) = \prod_{j=1}^{n/2} K_j \frac{(s - z_{j1})(s - z_{j2})}{(s - p_j)(s - p_j^*)} \tag{1-2}$$

1. G. Szentirmai, Computer aids in filter design: A review, *IEEE Trans. Circuit Theory*, **CT-18**, 35–40 (1971).

Note that odd polynomials have single negative real roots in addition to the conjugate complex pairs.

Step 3. Realization. Select an appropriate synthesis method to realize the individual subfunctions $T_j(s)$.

As simple as these three rules may seem at first sight, putting them into effect may be quite difficult. The approximation problem (step 1) alone warrants extensive treatment far beyond the scope of this book. Detailed information on this subject can be found in the references for this chapter listed at the end of the book. Furthermore, numerous computer programs are now available that match the coefficients of a rational transfer function to the prescribed electrical requirements of a network. Thus, we shall assume in the following that a network function in s as given by (1-1) is at hand; our problem of designing the corresponding active network then takes off from there.

Steps 2 and 3 also require considerable elaboration, which will follow in this and the following chapters. First, however, we shall pursue an alternative path (see Fig. 1-1) that takes off (as do steps 2 and 3) from the existing function $T(s)$ and attempts to realize the corresponding *LCR* network in active, inductorless form, by inductor simulation.

1.2 INDUCTOR SIMULATION

A gyrator is a two-port device with an impedance-inversion property that converts a capacitive load into a simulated inductive reactance at its input terminals.[2]

In Fig. 1-2 a configuration providing the simulation of a grounded inductor is shown; a floating inductor requires two gyrators, as shown in Fig. 1-3.[3] Inductor simulation using a silicon integrated gyrator combined with a chip or thin-film capacitor therefore comes closest to the practical realization of a

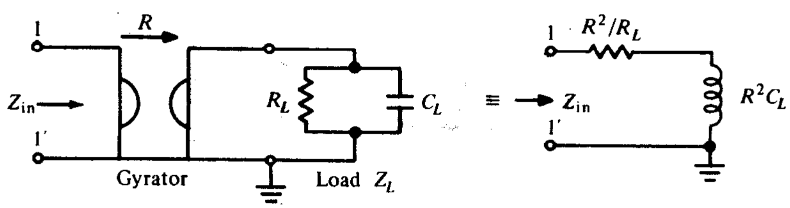

FIG. 1-2. Simulation of a grounded inductor by a gyrator–capacitor combination; R = gyration resistance.

2. See, for example, Chapter 5, Section 5.4.2 of *Linear Integrated Networks: Fundamentals.*
3. If $R_1 \neq R_2$ in the figure, then a transformer must be added to the equivalent circuit (see, for example, Chapter 5, Fig. 5-22 of *Linear Integrated Networks: Fundamentals*).