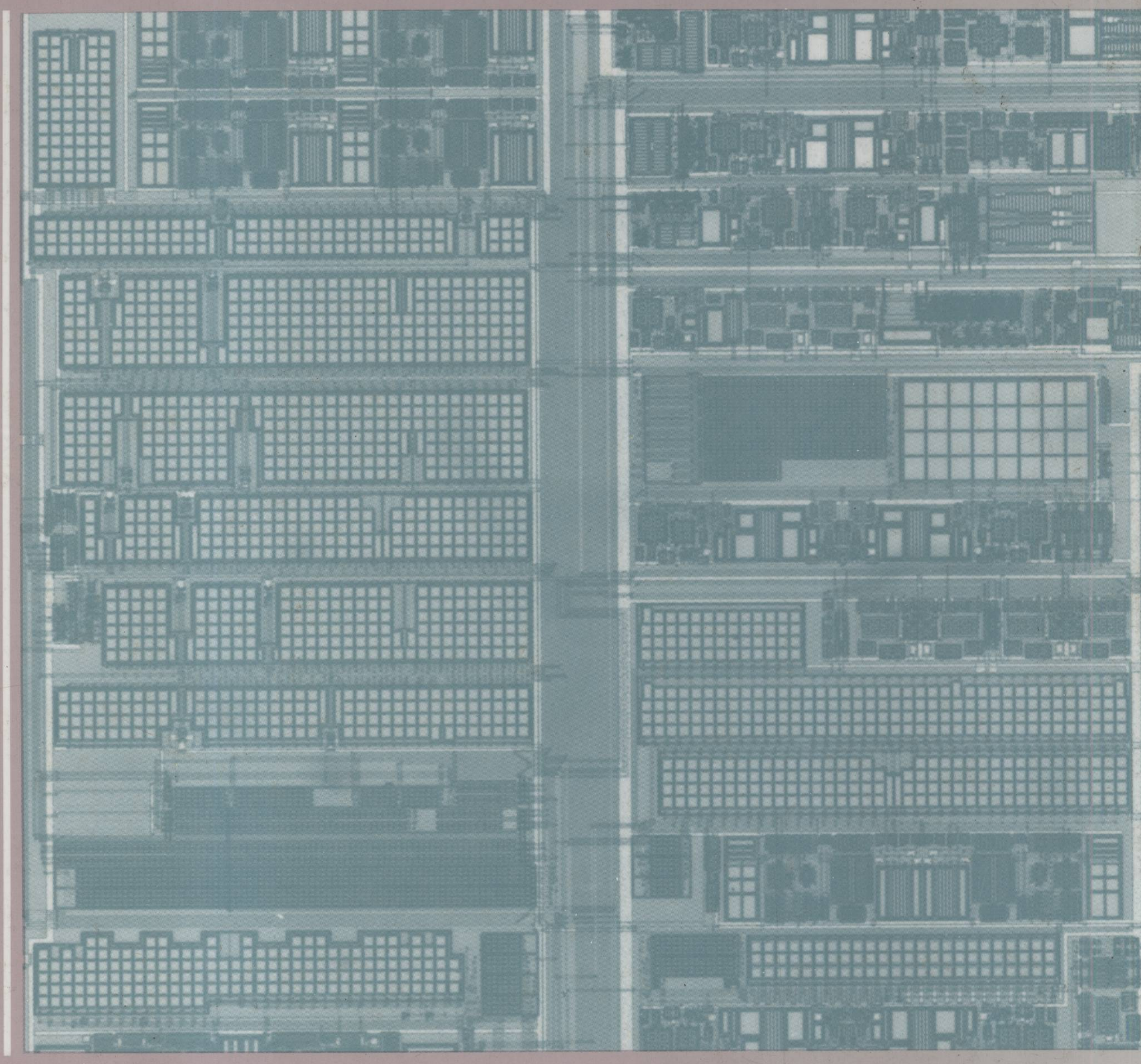
INTEGRATED CONTINUOUS-TIME FILTERS

PRINCIPLES, DESIGN, AND APPLICATIONS



IEEE PRESS

A SELECTED REPRINT VOLUME

Edited by Y. P. Tsividis and J. O. Voorman

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Integrated Continuous-Time Filters

Principles, Design, and Applications

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A Selected Reprint Volume
IEEE Circuits and Systems Society, *Sponsor*

The Institute of Electrical and Electronics Engineers, Inc., New York

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Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-7803-0425-X

IEEE Order Number: PC0321-0

Library of Congress Cataloging-in-Publication Data

Integrated continuous-time filters / [edited by] Yannis P. Tsividis, J. O. Voorman.
p. cm.
Includes bibliographical references and index.
ISBN 0-7803-0425-X
1 Electric filters. I. Tsividis, Yannis. II. Voorman, J. O.
TK7872.F5I55 1993
621.3815′324—dc20 92-53216
CIP

Integrated Continuous-Time Filters

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Preface

AMONG several electronic filter types, continuous-time filters were the first to be invented and the last to be established in integrated form on a massive scale. Thus, we saw digital and switched-capacitor filters (both discrete-time types) develop and mature in integrated form, while researchers attempting to place continuous-time filters on chips were still tackling severe issues related to precision, noise, and signal swing. Nevertheless, today integrated continuous-time filters are a reality, having finally reached the stage of commercial exploitation in such products as TVs, VCRs, disk drive electronics, line equalizers for computer networks, and telephony circuits, to name a few. The recent excitement in industry and academia about this form of integrated filters prompted us to assemble this volume.

This volume is one of three on continuous-time filters published by IEEE Press, with one volume appearing about every ten years. The first volume, *Active Inductorless Filters*, edited by S. K. Mitra in 1971, and the second, *Modern Active Filter Design*, edited by R. Schaumann, M. A. Soderstrand, and K. R. Laker in 1981, dealt almost exclusively with "active" filters assembled from discrete components. A large amount of work, which took place mostly since the publication of the second volume, led to the successful integration of continuous-time filters and their incorporation into large integrated systems implemented in VLSI technology. The present volume puts together key papers describing such work.

In light of the numerous high-quality papers on many aspects of integrated continuous-time filters, we had to make choices. To provide a concise volume, we decided to focus on papers that emphasize real integrated implementations of complete filters. Thus, with the exception of some studies on automatic tuning, practically every paper in this volume reports on results from fabricated chips. The very few exceptions are papers that complete or expand on material of other companion papers that do report on chips. Our emphasis on complete filter chip implementation meant that two categories of valuable papers had to be excluded: those dealing with network-theoretic aspects and those dealing with the design of active elements (operational amplifiers and transconductors). Nevertheless, several issues from these two excluded categories are considered both in the papers we did include, and, of course, in the references.

Even among the papers reporting on real chips, the selection was difficult. We tried to include papers that describe time-enduring or promising techniques, or at least contain considerations of value to the design of successful chips. We tried to have all major filter types represented. Still, not every high-quality paper that met the above criteria could be included because of space limitations, IEEE Press editorial policy, visual appearance, reviewers' suggestions, and the need of these editors to compromise with each other. We apologize to our colleagues whose good work could not be included.

This volume contains 64 papers and is divided into seven parts. Part 1 is an overview of the field and includes original material unique to this volume. Part 2 deals with integrated filters most closely resembling classic active filters, namely MOSFET-C circuits that use operational amplifiers, capacitors, and MOS transistors implementing resistors. Original material is also included in Part 2. Parts 3 and 4 concentrate on filters using transconductors instead of resistors. The filters described in Part 3 use only transconductors and capacitors, while those in Part 4 use operational amplifiers in addition. In Part 5 we have included papers reporting on several other types of integrated filters, namely active *R*, distributed, NIC, and true active *RC* and passive filters which can, in some cases, be advantageously integrated. Part 6 is devoted to the study of on-chip automatic tuning of filters and to the related subject of adaptivity; it augments on related discussions in many of the papers elsewhere in the volume. Finally, the use of integrated filters is illustrated in Part 7, which contains papers on representative applications and application studies, including an original paper. In all, over 15% of the pages contain original material written specifically for this volume and not published elsewhere.

We hope this book will be useful as a reference for practicing engineers and researchers and as material accompanying industrial courses on the subject. It can also serve as a companion book for senior-year and graduate courses, supplementing a main text on discrete-component filter design. We hope the volume will be a good starting point for newcomers, some of whom will eventually make further advances in this exciting field.

We want to thank A. van Bezooijen, N. Ramalho, R. Schaumann, G. J. Smolka, U. Riedle, U. Greje, B. Jahn, F. Parzefall, W. Veit, and H. Werker, who wrote original material for this volume and V. Gopinathan, J. Khoury, D. Rich, R. Schaumann, E. Seevinck, K.-S. Tan, and G. Temes for their valuable comments on the original material and on the proposed list of publications and book format. We also want to thank IEEE Press Executive Editor Dudley Kay who, through all communication channels known to man (mostly electronic mail), kept after us and helped us produce what we hope is a concise, focused and useful book.

Y. Tsividis
J. Voorman

Contents

Part 1
Overview

THIS part is an overview of integrated continuous-time filters. The tutorial paper by Schaumann was written specifically for this volume, and will probably be especially appreciated by newcomers; it explains why integrated continuous-time filters are needed and how they are designed, gives examples of various types of such filters, and discusses their tuning by automatic means. The next paper, by Voorman, discusses the same issues at a more advanced level and in much more detail. It also has been written specifically for this volume, and includes original material. Although this is the longest paper in the volume, it is nevertheless dense because of the large amount of information it contains. Hence it may not be easy reading for newcomers, who may want to defer reading it until they have read other papers in the volume; this paper can then really help put things together, in addition to providing much extra information. Useful general introductions to integrated continuous-time filters can also be found in the beginning of other, more specialized papers in this volume.

Although the overview papers in this part summarize relevant topics from classical filter theory and design, much more detailed discussions can be found in textbooks (see, for example, [1–4]). An in-depth review of classical results on active filters, covering the period up to the early 1970s, can be found elsewhere [5]; many of these results are, or may become in the future, relevant in the context of fully integrated filters.

References

[1] G. C. Temes and J. W. LaPatra, *Introduction to Circuit Synthesis and Design*, New York: McGraw-Hill, 1977.

[2] A. S. Sedra and P. O. Brackett, *Filter Theory and Design: Active and Passive*, Chesterfield, Ohio: Weber Systems Inc., 1978.

[3] R. R. Schaumann, M. Ghausi, and K. R. Laker, *Design of Analog Filters*, Englewood Cliffs, NJ: Prentice-Hall, 1990.

[4] M. Herpy and J.C. Berka, *Active RC Filter Design*, Amsterdam: Elsevier, 1986.

[5] W. E. Heinlein and W. H. Holmes, *Active Filters for Integrated Circuits: Fundamentals and Design Methods*, New York: Springer-Verlag, 1974.

Paper 1-1

Continuous-Time Integrated Filters—A Tutorial[1]

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***Abstract*—This paper summarizes the fundamental concepts and methods used for designing continuous-time (CT) signal-processing circuits (i.e., filters) in fully integrated form. The resulting filter structures can be integrated together with other parts of the system on the same chip and are compatible with any desired IC technology. The two main design procedures are the promising MOSFET-C approach that is closely based on classical active *RC* concepts, and the currently dominant transconductance-C method, which uses only capacitors and transconductors for the implementation of monolithic CT filters. The critically important problem of automatic tuning against fabrication tolerances and component drifts during operation is discussed in detail.**

1. Introduction

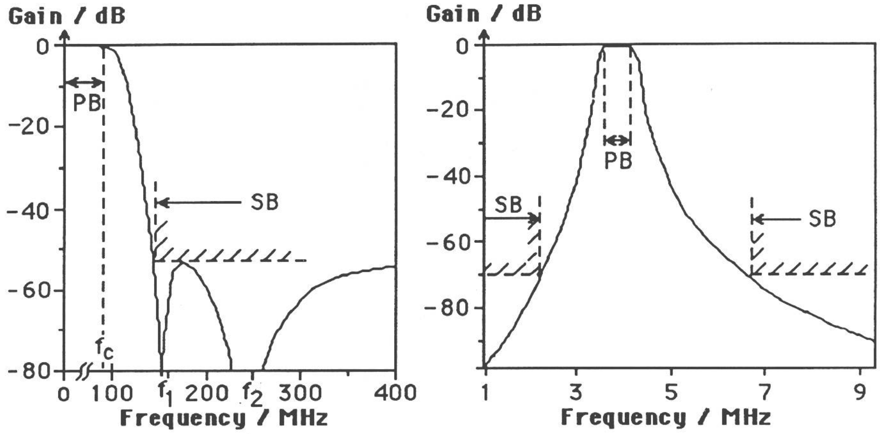
ALL modern communication systems and most measuring equipment contain various types of electrical filters that the designer has to realize in an appropriate technology. In general, a filter is a two-port circuit designed to process the magnitude and/or phase of an input signal in some prescribed way in order to generate a desired output signal. For example, the filter may transmit (pass) the desired frequency components in the spectrum of an input signal with little or no change, and reject (stop) the remaining components interfering with the signal processing task at hand. In this sense, *passbands* (PB) and *stopbands* (SB) can be defined as illustrated in Fig. 1 for a lowpass and a bandpass characteristic. The literature contains many well-defined techniques and computer programs to help the designer find the appropriate transfer function that a filter must realize to satisfy the required behavior [2–6].

Once the filter's transfer function is obtained, implementation methods must be found that are compatible with the technology selected for the design of the total system. In some situations, dictated by such factors as power consumption, frequency range, signal level, or production numbers, discrete (passive or active) filter realizations may be the appropriate choice. In many circumstances, however, the goal will be to realize as much as possible of the total system, fully integrated in microelectronic form, so that naturally the question arises whether the filters can be implemented in the same technology.

In many signal processing situations, filters must interface with the real world where the input and output signals take on continuous values as functions of the continuous variable time; that is, they are *continuous-time* (CT) signals. Because it is the performance of the total system that is relevant and not just that of the intrinsic filter, the designer may have to consider whether it might not be preferable to implement the entire system in the CT domain rather than as a digital or sampled-data system. Although at least at low frequencies, the latter methods have the advantages of being able to attain very high accuracy and little or no parameter drifts, they entail a number of peripheral problems connected with analog-to-digital (A/D) and digital-to-analog (D/A) conversion, sample-and-hold, switching, antialiasing, and reconstruction circuitry. For the implementation of digital and sampled-data switched-capacitor filters, the reader is urged to consult the literature [6–12]. In this paper, only

[1] The paper is a revised and updated version of [1] and was written especially for this volume.

Reprinted from *IEE Proceedings,* vol. 136, Pt. G, pp. 184–190, Aug. 1989.



(a) (b)

Fig. 1. (a) fifth-order elliptic lowpass and (b) eight-order Chebyshev bandpass characteristics.

those cases are considered where the signals must be CT in nature.

2. Implementation Methods

Traditionally, the implementation of CT filters has relied on discrete designs. Well-defined procedures exist for deriving passive *LC* networks or active *RC* circuits from a given transfer function [2, 3, 6]. If, however, a microelectronic realization with full integration is the goal, inductors usually are not used because there is no practical method for realizing high-quality inductors on an integrated circuit (IC) chip. Thus, to realize the required complex natural frequencies, the designer of an IC filter is forced to use active devices. As is well known, active filters can realize complex poles by using gain, for example, an operational amplifier (op amp) or an operational transconductance amplifier (OTA) embedded in an *RC* feedback network [2, 3, 6, 13–18].

Consider, for example, a fully differential transconductor whose simplified model[2] and the circuit symbol employed in this paper are shown in Fig. 2. Many realizations of such cells exist in CMOS [9, 18, 19–24, 26, 27, 29, 35–37, 48, 49, 57, 59], bipolar, or in BiCMOS technologies, and even in GaAs [20–38, 47, 51]. Because op amps and OTAs are electronic circuits, it becomes apparent that the problem of monolithic filter design is solved in principle—all active devices and any necessary capacitors and resistors can be integrated together on one silicon chip. Although this conclusion is correct, three other factors that are peculiar to integrated CT filters and perhaps are not immediately obvious must be addressed. The first concerns probably the most formidable obstacle to achieving commercially practical designs—integrated filters must be *electronically tunable* [6, 39]. Because of its importance, this topic is discussed separately elsewhere in this paper. The second factor deals with the economics of practical implementations of active filters—in discrete designs, the cost of acquiring and stocking components usually necessitate designing the filter with a minimum number of active devices, such as one or possibly two op amps per pole pair, and using the smallest number of different (if possible, all identical) capacitors. In integrated realizations, capacitors are determined by processing mask dimensions and the number of different capacitor values is unimportant as long as the spread is not excessive. Furthermore, active devices frequently occupy less chip area than passive elements so it is often preferable to use active elements. In particular, for the problem at hand (i.e., integrated CT filters), frequency parameters are set by *RC* products or, equivalently, by C/g_m ratios [see Equation (2a)] and

[2] The linear OTA model in Fig. 2(a) is valid for signals in the linear range of the respective electronic implementation. The model also shows the dominant parasitics, the input and output capacitors, and conductors c_i, g_i, and c_o, g_o, respectively. Although their effects and those of transconductance phase errors, modeled as $g_m(j\omega)e^{j\Phi(\omega)}$ [6, 19, 20, 38] are neglected in this tutorial paper, the designer is well advised to investigate their effects carefully when designing monolithic filters at high frequencies and with large quality factors, Q_i. The most troublesome effects are that phase errors tend to increase Q_i above the design values, whereas g_i and g_o cause Q_i to decrease.

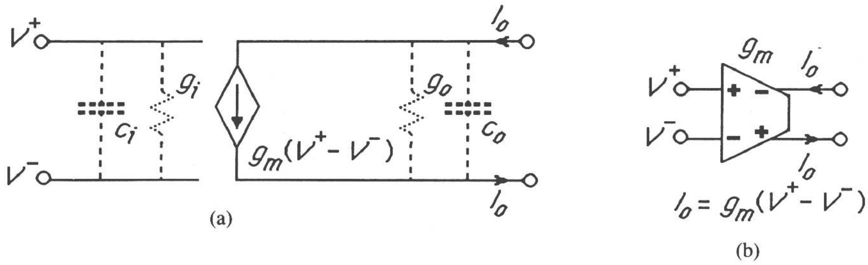


Fig. 2. Fully differential transconductor. (a) Small-signal model with the main parasitic components shown in dashed form; (b) circuit symbol.

the dimensionless quality factors are determined by ratios of like components [see Equation (2b)]. Also, as was pointed out earlier, gain is needed to realize complex poles. Recalling further that the function of resistance can be obtained from transconductors[3] leads to the important conclusion that capacitors and transconductors ($C - g_m$) form a minimal irreducible set of elements necessary for the realization of integrated CT filters. Finally, the third factor pertains to the fact that filters usually have to share an integrated circuit with other, possibly switched or digital systems, so that the AC ground lines (power supply and ground wires) are likely to contain switching transients and are generally noisy. Measuring the analog signals relative to AC ground, therefore, results in designs with poor signal-to-noise ratio and low power supply rejection. The situation is remedied in practice by building the continuous-time filter in fully differential, balanced form where the signals are referred to each other as $V = V^+ - V^-$ as shown in Fig. 2. An additional advantage of this arrangement is that the signal range is doubled (for an added 6 dB of signal-to-noise ratio) and that the even-order harmonics of the in principle nonlinear operation of the transconductors cancel. The examples in this paper are, therefore, drawn as fully differential designs.

[3] Note that an inverting transconductor g_m with its output connected to its input simulates a grounded resistor of value $1/g_m$. See the left OTA g_{m2} in Fig. 3.

The transconductor model and the symbol in Fig. 2 are used in the circuit in Fig. 3. By writing node equations at the nodes labeled V_{LP} and V_{BP} and observing that the left transconductor g_{m2} implements a resistor of value $1/g_{m2}$, the reader can verify that the circuit realizes the second-order bandpass and lowpass functions.

$$H_{BP}(s) = \frac{V_{BP}}{V_i} = \frac{sC_2 g_{m1}}{C_1 C_2 s^2 + sC_2 g_{m2} + g_{m1} g_{m2}} = \frac{sM\omega_o/Q_o}{s^2 + s\omega_o/Q_o + \omega_o^2} \tag{1a}$$

$$H_{LP}(s) = \frac{V_{LP}}{V_i} = \frac{g_{m1} g_{m2}}{C_1 C_2 s^2 + sC_2 g_{m2} + g_{m1} g_{m2}} = \frac{\omega_o^2}{s^2 + s\omega_o/Q_o + \omega_o^2} \tag{1b}$$

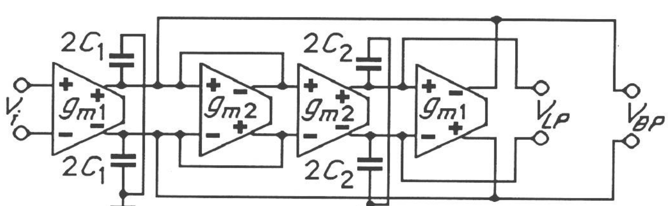


Fig. 3. Second-order active $g_m - C$ filter with lowpass and bandpass outputs.