ANALOG MOS INTEGRATED CIRCUITS FOR SIGNAL PROCESSING

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SERIES PREFACE

The primary objective of the Wiley Series On Filters is to bring together theory and industrial practice in a series of volumes written for filter users as well as those involved in filter design and manufacturing. Although this is a difficult task, the authors in this series are well qualified for the job. They bring both strong academic credentials and many years of industrial experience to their books. They have all designed filters, have been involved in manufacturing, and have had experience in interacting with the filter user.

Each of the books covers a wide range of subjects including filter specifications, design, theory, parts and materials, manufacturing, tuning, testing, specific applications, and help in using the filter in a circuit. The books also provide a broad view of each subject based on the authors' own work and involvement with filter experts from around the world.

The most outstanding feature of this series is the broad audience of filter builders and users, which it addresses. This includes filter research and development engineers, filter designers, and material specialists, as well as industrial, quality control, and sales engineers. On the filter user's side, the books are of help to the circuit designer, the system engineer, as well as applications, reliability, and component test experts, and specifications and standards engineers.

ROBERT A. JOHNSON
GEORGE SZENTIRMAI

PREFACE

The purpose of this book is to describe the operating principles of analog MOS integrated circuits and to teach the reader how to design and use such circuits. Examples of these devices include switched-capacitor filters, analog-to-digital and digital-to-analog converters, amplifiers, modulators, oscillators, and so on. The main emphasis is on the physical operation and on the design process. It is hoped that the book will be used as a senior- or graduate-level text in the electrical engineering curriculum of universities and also as training and reference material for industrial circuit designers. To increase the usefulness of the book as a text for classroom teaching, numerous problems are included at the end of each chapter; these problems may be used for homework assignments. To enhance its value as a design reference, tables and numerical design examples are included to clarify the step-by-step processes involved. The first three chapters provide a concise, basic-level, and (we hope) clear description of the general properties of analog MOS integrated circuits, and the required background in mathematics and semiconductor device physics. The remainder of the book is devoted to the design of the actual circuits, the practical problems encountered and their solutions, and some examples of system applications.

This book evolved from a set of lecture notes written originally for short courses presented several times annually since 1979 in the United States and in Western Europe, both as a public offering at UCLA, the Federal Institute of Technology of Switzerland, the University of Stuttgart, and so on, and as an in-house training course for high-technology semiconductor, communication, and computer companies, offered through the Continuing Education Institute of Los Angeles. Later, this material formed the basis of a graduate course offered on analog MOS integrated circuits at UCLA. The organization of the material was therefore influenced by the need to make the presentation suitable for audiences of widely varying backgrounds. Hence, we tried to make the book reasonably self-contained, and the presentation is at the simplest level afforded by the topics discussed. Only a limited amount of preparation was assumed on the part of the reader: mathematics on the junior level, and one or two introductory-level courses in electronics and semiconductor physics are the minimum requirements.

The origin of the book also influenced the detailed choice of its subject matter. Since the original short course was intended to train industrial engineers in the design of analog MOS circuits, the theoretical topics discussed were restricted to the minimum needed for the practical design process. Also, in those situations where a number of design techniques were available to accomplish a given task, we described only the one that was most extensively tested in practical applications. Hence many ingenious and effective design procedures were ignored.

Both authors have had considerable industrial experience and also extensive teaching background. We hope that this experience is detectable in our approach to the treatment of our subject.

The book contains eight chapters. Chapter 1 gives a basic introduction to switched-capacitor circuits, compares the analog MOS circuits with other signal processor implementations, and describes (but does not explain in any detail) some typical applications. This material can be covered in one lecture (two-hour lectures are assumed here and throughout this preface).

Chapter 2 describes the Laplace, Fourier, and z-transforms, and introduces the important s-to-z transformations needed to design a sampled-data system from an analog "model." Depending on the mathematical background of the students, this material may require two to three two-hour lectures.

Chapter 3 gives a brief description of the physics of MOS devices, discusses the linearized models of MOSFETs, and describes MOS capacitors and switches. The technology used to fabricate MOS devices is also briefly described. Once again, depending on the background of the audience, two or three lectures should suffice to cover the content of this chapter.

Chapter 4 discusses the circuit design techniques for realizing MOS operational amplifiers. The most common circuit configurations, as well as their design and limitations, are included, and a design example is worked out in detail. Complete coverage of all topics in this chapter requires about five lectures; this time can be reduced by restricting the discussions, leaving out some specialized subjects such as those discussed in Sections 4.10, 4.11, and 4.13, and assigning the design example for reading.

Chapter 5 deals with switched-capacitor filter design and hence represents the focal point of the book. As already mentioned, the design techniques discussed are restricted to the "mainstream" ones: those that have been most thoroughly tested in practical applications. The design of the two commonly used configurations—cascade and ladder circuits—is discussed in detail and illustrated with a numerical design example. Some special circuits, such as switched-capacitor N-path filters and simulated-resistor active-RC filters, are also described. A full coverage of all topics in this chapter needs about five lectures; by omitting Sections 5.8 and 5.9, this number can be reduced to three.

Chapter 6 deals with nonfiltering applications of switched-capacitor circuits. Such important circuits as voltage amplifiers, digital-to-analog and analog-to-digital converters, comparators, modulators, and oscillators are discussed on an introductory level. A complete coverage of all topics may require four lectures; it can be presented in two lectures if the detailed discussions of Sections 6.3 and 6.5 are condensed.

Chapter 7 contains a detailed discussion of the nonideal effects occurring in switched-capacitor circuits. This material is of utmost importance to the industrial designer of practical circuits and hence (in spite of its seemingly mundane subject matter) should be covered at least briefly even in an undergraduate lecture class. Two lectures should be sufficient for a brief presentation.

Chapter 8 discusses some of the systems aspects of analog MOS signal processors and illustrates their use in commercial integrated systems. The first two sections, which deal with the prefiltering and postfiltering requirements of analog MOS circuits, should be discussed in the classroom. The remainder of the chapter discusses, on a descriptive level, some specific applications and can thus be assigned for reading. Hence the material in this chapter may be presented in one or two lectures, depending on how the application examples are treated.

Thus, depending on the depth of the presentation, the full coverage of all material in the book may require as many as 25 two-hour lectures or as few as 16. In intensive presentations (such as a short course or a training course), the complete book has been covered in four days, with six lecture hours per day.

We are grateful to our colleagues Drs. Du Xi-Yu, S. C. Fan, B. Fotouhi, B. Ghaderi, S. Law, K. Martin, T. Cataltepe, and H. J. Orchard, as well as our present and former students, J. N. Babanezhad, F. Dunlap, T. H. Hsu, L. Larson, J. B. Shyu, and F. J. Wang for discussions, review, and criticism. Most of the difficult typing task was done by Ms. Loetitia Loberman. We are grateful for her excellent and painstaking help. The artwork was done (excellently) by Mr. Kayvan Abolhassani of the Department of Electrical Engineering at UCLA. Last, but not least, we would like to express our gratitude to our wives for graciously suffering neglect during the writing of this work.

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Chapter One

INTRODUCTION

In this chapter, the basic concept of a switched capacitor performing as a simulated resistor is introduced. Some of the physical properties of switched-capacitor circuits are also briefly discussed. Then, a comparison is made between signal processors using switched-capacitor circuits and some alternative implementations, such as discrete analog circuits, digital filters, and analog bipolar integrated circuits. Finally, a few representative examples are given of circuits and systems utilizing MOS analog signal processing techniques, to illustrate the great potential of these circuits in telecommunication systems and related applications.

1.1. THE USE OF ANALOG MOS INTEGRATED CIRCUITS FOR SIGNAL PROCESSING.[1-4]

Electrical signal processors are usually divided into two categories: analog and digital systems. An *analog system* carries signals in the form of voltages, currents, charges, and so on, which are *continuous* functions of the *continuous* time variable. Some typical examples of analog signal processors are audio amplifiers, passive- or active-RC filters, and so on. By contrast, in a *digital system* each signal is represented by a sequence of numbers. Since these numbers can only contain a finite number of digits (typically, coded in the form of binary digits or *bits*) they can only take on *discrete values*. Also, these numbers are the *sampled* values of the signal, taken at *discrete time* instances. Thus, both the dependent and independent variables of a digital signal are discrete. Since the processing of the digital bits is usually performed synchronously, a timing or *clock* circuit is an important part of the digital system. The clock provides one or more clock signals, each containing accurately timed pulses which operate or synchronize the operation of the components of the system. Typical examples of digital systems are a general-purpose digital computer, or a special-purpose computer dedicated to (say) calculating the Fourier transform of a signal via the fast Fourier transform (FFT), or a digital filter used in speech analysis, and so on.

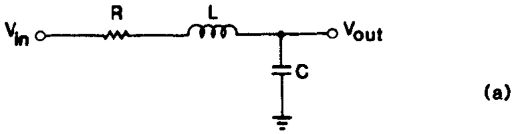
Most of the circuits considered in this book fall into a category which is in between the two main classifications described above. This is the category of *sampled-data analog systems*. For such systems, the signal is represented by the uncoded amplitude of an electrical quantity (normally, a voltage) as in an analog system. However, the system contains a clock, and the signal amplitude is sensed only at discrete time instances, as in a digital system. Prior to the development of the MOS circuits discussed in this work, the most important sampled-data analog systems were the charge-transfer devices, such as charge-coupled devices (CCDs) and bucket-brigade devices (BBDs). In these, the signal amplitude is represented by the amount of charge shifted from cell to cell. Since, with very few exceptions, these devices did not contain feedback loops, they were inherently nonrecursive in nature. Therefore, they were more suited for such applications as sampled-data delay lines, multiplexers, correlators, and so on which did not require accurately controlled poles as well as zeros, than for the commonly needed frequency-selective filtering tasks. Also, they require special fabrication technology, rather than the standard MOS process used to manufacture digital MOS circuits, and usually need some specialized peripheral (input and output) circuitry. For these reasons, their uses were restricted to a relatively few large companies, where the requisite special design background and technology could be developed and maintained.

By contrast, the circuits considered in this book can be fabricated utilizing standard digital MOS technology, and hence can also be placed on the same chip with digital circuitry. This latter aspect is of great importance, for example, in modern telecommunication systems, where both analog and digital functions are often needed within the same functional block. Furthermore, these circuits contain only a few standard building blocks: amplifiers, switches, capacitors, and, in rare instances, resistors. Once these have been developed and standardized in the locally available technology, a large number of applications can be accommodated using only slightly different configurations and/or dimensions.

To understand the basic concepts of the most commonly used configurations of analog MOS circuits, consider the simple analog transfer function

$$\frac{V_{\text{out}}(s)}{V_{\text{in}}(s)} = \frac{b}{s^2 + as + b}. \tag{1.1}$$

It is easy to verify that the RLC circuit shown in Fig. 1.1*a* can realize this function (Problem 1.1). While this circuit is easy to design, build, and test, the presence of the inductor in the circuit makes the fabrication in an integrated form impractical. In fact, for low-frequency applications, this circuit may well require a very large-valued, and hence bulky, inductor and capacitor. To



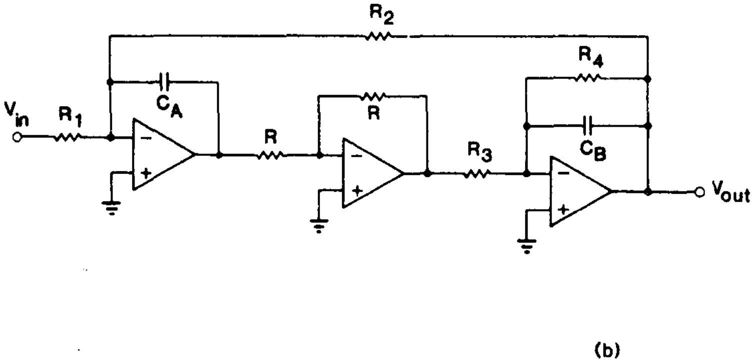


FIGURE 1.1. Second-order filter realizations; (*a*) passive circuit; (*b*) active-RC circuit.

overcome this problem, the designer may decide instead to realize the desired transfer function using an active-RC circuit. It can readily be shown that the circuit of Fig. 1.1*b*, which utilizes three *operational amplifiers*, is capable of providing the transfer function specified in Eq. (1.1). This circuit needs no inductors and may be realized with small-sized discrete components for a wide variety of specifications (Problem 1.2). It turns out, however, that while the integration of this circuit on an MOS chip is, in principle, feasible (since the amplifiers, resistors, and capacitors needed can all be integrated), there are some major practical obstacles to integration. These include the very large chip area needed by the RC components, as well as the stringent accuracy and stability requirements for these elements. These requirements cannot be readily satisfied by integrated components, since neither the fabricated values nor the temperature-induced variations of the resistive and the capacitive elements track each other. The resulting pole/zero variations are too large for most applications. (This subject will be discussed in detail in Section 5.1 of Chapter 5.)

An effective strategy which can solve both the area and the matching problems is to replace each resistor in the circuit by a combination of a capacitor and a few switches. Consider the branch shown in Fig. 1.2. Here, the four switches S_1, S_2, S_3, and S_4 open and close periodically, at a rate which is much faster than that of the variations of the terminal voltages v_A and v_B. Switches S_1 and S_4 operate synchronously with each other, but in opposite phase with S_2 and S_3. Thus, when S_2 and S_3 are closed, S_1 and S_4 are open,

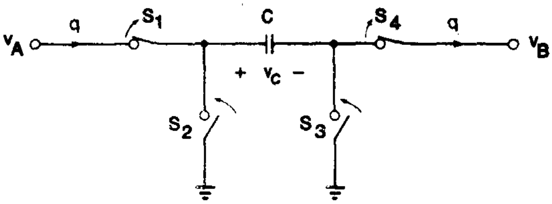


FIGURE 1.2. Switched-capacitor realization of a resistive branch.

and vice versa. Now when S_2 and S_3 close, C is discharged. When next S_2 and S_3 open, and S_1 and S_4 close, C is recharged to the voltage $v_C = v_A - v_B$. This causes a charge $q = C(v_A - v_B)$ to flow through the branch of Fig. 1.2. Next, C is again discharged by S_2 and S_3, and so on. If this cycle is repeated every T seconds (where T is the *switching period* or *clock period*) then the average current through the branch is therefore

$$i_{av} = \frac{q}{T} = \frac{C}{T}(v_A - v_B). \tag{1.2}$$

Thus, i_{av} is *proportional* to the branch voltage $v_A - v_B$. Similarly, for a branch containing a resistor R, the branch current is $i = (1/R)(v_A - v_B)$. Thus, the average current flows in these two branches are the same if the relation $R = T/C$ holds.

It is plausible therefore that the branch of Fig. 1.2 can be used to replace all resistors in the circuit of Fig. 1.1*b*. The resulting stage[3] is shown in Fig. 1.3. In this circuit, switches which belong to different "resistors," but perform identical tasks, have been combined. Furthermore, the second operational amplifier

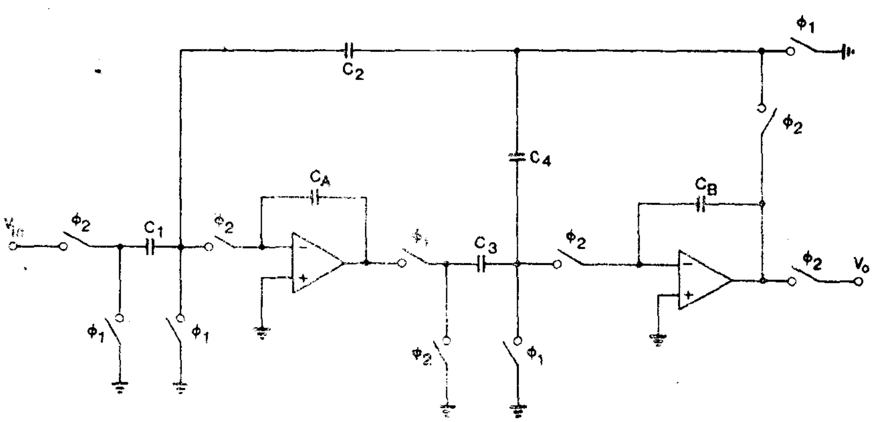


FIGURE 1.3. Second-order switched-capacitor filter section.

(op-amp) in Fig. 1.1*b*, which acted merely as a phase inverter, has been eliminated. This was possible since by simply changing the phasing of two of the switches associated with capacitor C_3, the required phase inversion could be accomplished without an op-amp. The details of the transformation of the circuit of Fig. 1.1*b* to that of Fig. 1.3 are discussed in Chapter 5, Section 5.4.

As Fig. 1.3 illustrates, the transformed circuit contains only capacitors, switches, and op-amps. A major advantage of this new arrangement is that now all time constants, previously determined by the poorly controlled RC products, will be given by expressions of the form $(T/C_1)C_2 = T(C_2/C_1)$. Here, the clock period T is usually determined by a quartz-crystal-controlled clock circuit, and is hence very accurate and stable. The other factor of the time constant is C_2/C_1, that is, the *ratio* of two on-chip MOS capacitances. Using some simple rules in the layout of these elements (described in Section 3.5), it is possible to obtain an accuracy and stability of the order of 0.1% for this ratio. The resulting overall accuracy is at least a hundred times better than what can be achieved with an on-chip resistor and capacitor for the RC time constant.

A dramatic improvement is also achievable for the area required by the passive elements. To achieve a time constant in the audio-frequency range (say 10 krad/s), even with a large (10 pF) capacitor a resistance of 10 MΩ is required. Such a resistor will occupy an area of about 10^6 μm^2, which is prohibitively large; it is nearly 10% of the area of an average chip. By contrast, for a typical clock period of 10 μs, the capacitance of the switched capacitor realizing a 10-MΩ resistor is $C = T/R = 10^{-5}/10^7 = 10^{-12}$ F = 1 pF. The area required to realize this capacitance is about 2500 μm^2, or only 0.25% of that needed by the resistor which it replaces.

Using the three types of components (op-amps, capacitors, and switches) shown in Fig. 1.3, a large quantity of signal processing circuitry can be placed on a single chip. A high-quality op-amp can be fabricated on an area of 5×10^4 to 10^5 μm^2, while a switch needs typically only about 50 μm^2. Since the area of a large chip may be around 5×10^7 μm^2, such a chip can readily accommodate, say, 100 op-amps, 300 capacitors, and 500 switches. Extrapolating from the circuit of Fig. 1.3 which realizes the second-order transfer function given in Eq. (1.1), it can be seen that the signal processing capability of such a chip is sufficient to implement transfer functions with a combined order of 100. In fact, since the op-amps can be time shared (multiplexed) for low-frequency signals, even higher-order functions may be realized: a speech analyzer chip[5] implementing switched-capacitor filters with a total of 308 poles, in addition to a substantial quantity of on-chip digital circuitry was recently described!

In addition to frequency-selective filtering which has been the most common application of the switched-capacitor (SC) circuits introduced in Fig. 1.3, there are many other functions which such circuits can perform. These include analog-to-digital (A/D) and digital-to-analog (D/A) data conversion, programmable-gain amplification for AGC and other applications, as well as such nonlinear operations as multiplication, modulation, detection, rectification, zero-crossing detection, and so on. They have also been used extensively in large mixed analog–digital systems such as codecs, modems, and speech processors. It is expected that this range will expand further, as the quality (bandwidth, dynamic range, etc.) of the components, especially op-amps, improves, and as better circuit techniques are introduced.

1.2. COMPARISON OF ANALOG MOS SIGNAL PROCESSORS WITH OTHER IMPLEMENTATIONS

It is important to define the areas of applications in which analog MOS signal processors are competitive with, or even superior to, earlier implementations of signal processing systems. To do that, we list below some salient features of analog MOS (typically, switched-capacitor) circuits, and contrast them with those of alternative realizations.

1. *Switched-Capacitor Circuits Are Integrated Circuits.* This property has a profound effect on the economy of its applications. The development (theoretical design, computer simulation, layout and fabrication, testing and troubleshooting) of such a circuit may require a combined initial design effort of one or more man-years, at a cost of $50,000 or more. After this initial expenditure, the devices can be mass produced at a low per-unit cost, say $5 or less. Hence, compared to a discrete implementation costing (say) $15 and having a negligible design expenditure, the integrated realization is economical if the inequality

$$50{,}000 + 5N < 15N \tag{1.3}$$

holds. Here, N is the total number of units required. For the values used, this gives $N > 5000$. Clearly, the actual figures depend on the experience, equipment, application, and so on; however, the orders of magnitude given are fairly typical.

Other features associated with the integrated-circuit (IC) character of SC circuits are small size, light weight, high reliability, and small dc bias power required. These may also have a great importance in, say, aerospace applications.

2. *Switched-Capacitor Circuits Are Sampled-Data Systems.* As mentioned before, the signal values are evaluated only at periodic time instants in an SC circuit, and the sampling period is determined by a crystal-controlled clock. This feature makes it possible to have all pole and zero values dependent only on capacitance *ratios* (rather than on absolute values); it thus permits the realization of high-selectivity responses with good accuracy and stability. Furthermore, since only periodic samples of the signal are of interest, it is possible to time share (multiplex) the whole circuit, or parts such as the

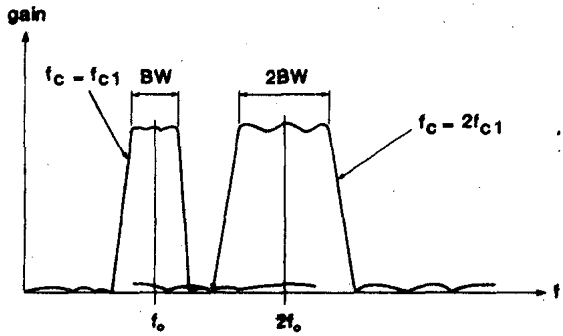


FIGURE 1.4. Switched-capacitor bandpass filter responses for $f_c = f_{c1}$ and $f_c = 2f_{c1}$. Both the center frequency f_0 and the bandwidth BW are doubled when f_c doubles.

op-amps of the circuit, among several signal channels resulting in highly efficient multichannel systems.

Finally, all time constants of an SC circuit are proportional to the clock period T. As a result, the overall gain versus frequency response $H(f)$ can readily be scaled by changing the *clock frequency* $f_c = 1/T$. As an illustration, Fig. 1.4 shows the responses of an SC bandpass filter for two different clock frequencies. Clearly, changing the value of f_c from f_{c1} to $2f_{c1}$ simply expands the response curve horizontally by the same factor 2. This gives a valuable tool for the fine tuning of the response for applications such as voltage-controlled oscillators (VCOs), adaptive filters, tracking filters, and so on.

The above features (integrated realization, clock-controlled sampled-data operation) are shared with charge-transfer devices such as CCDs and BBDs, as well as with digital filters, but not with the other commonly used signal processor implementations.

3. *Switched-Capacitor Circuits Are Analog Systems.* In spite of their sampled-data characters, SC circuits handle signals in analog forms; thus, the amplitudes of the sampled voltages are the signal values, without the use of any encoding. This makes the basic operations (multiplication, addition, delay) needed in signal processing much simpler to perform than in digital circuits. Hence, the density of operations on the chip can be much higher than for digital signal processors. Without any multiplexing, linear filter sections realizing 100 or even more poles can be accommodated on a single chip.

Due to the basic simplicity of the circuits used in SC systems, the speed with which the signal processing tasks can be accomplished is much higher than for digital systems. The real-time filtering of signals with frequencies up to about 0.5 MHz is possible currently, and this figure is continuously rising as improved technology and design techniques become available.

Due to its much simpler structure, along with the chip area needed, the dc power required for a given signal processing task is also considerably less for a