Linear Integrated Circuits

Practice and Applications

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In memory of Sol D. Prensky

teacher, writer—a warm and generous human being

Preface

In considering the sustained progress of the field of integrated circuits, we find important major advances that have been made over a relatively short period. Most outstanding has been the dramatic development of the microprocessor (μP) in the digital IC field, accompanied by supplemental progress in the linear IC group. This significant progress has been sparked by important advances in large-scale-integration (LSI) technology in achieving considerably greater density of active devices on the IC chip, including both the bipolar and the MOS field-effect types of transistors, and also the new combination of both devices (called a BiMOS or BiFET chip). Combined with these improved fabrication techniques, we find clever circuit designs within the denser IC chip that offers a choice of various monolithic microprocessor units, which merit the proud description of "computer-on-a-chip."

This active development of microprocessors and their attendant memory circuits in the digital division has fostered a corresponding upsurge of advanced devices in the linear IC field. Exploiting the broad flexibility of the microprocessor, we find innovative designs that include linear ICs diverse areas, ranging from the automotive field for engine controls to the electronic-instruments field for various automatic testing functions. In these new functions, many advanced forms of linear ICs are employed to handle the analog signals that feed the digital processing.

Other linear IC developments, such as in the consumer-communication areas, all emphasize the continuing trend for replacing discrete circuits (with their multiplicity of individual transistors and their numerous interconnections) with the more compact and reliable ICs. In the broad view, it is fair to say that the process of supplanting discrete transistor circuits by the emergent ICs is now as much a revolutionary development as was the previous upheaval that supplanted vacuum tubes with transistors.

For the linear IC field, advanced developments include newer versions of OP AMPS (including the previously mentioned BiFET types), increased utilization of the phase-locked-loops (PLL) units in the communications area, and a proliferation of devices interfacing with the newer digital developments. To cite some additional examples, we find more versatile A/D and D/A converters, more multipliers for signal conditioning and a greater variety of peripheral drivers for various interface and display purposes.

This work is an updating and expansion of Prensky's well-received *Manual of Linear Integrated Circuits: Operational Amplifiers and Analog ICs* published by Reston Publishing Company in 1974. Its aim is to provide the technician and engineer with practical information on the selection of linear ICs for use in a large variety of applications which include dc and audio amplifiers, waveform generation, D/A and A/D conversion, active filters, voltage regulators, and communication systems.

In keeping with the original theme of representing well-accepted linear IC models from all the major manufacturers, considerable care has been taken in presenting the extensive cross-reference list in Appendix III. This listing of around 400 frequently used model numbers is an important practical feature; it allows the user, often confronted with a clutter of type numbers, to rapidly identify a particular manufacturer's designation, and also to characterize it in relation to its general class (often as a second source of a better-known type).

This same feature of including types from all the major manufacturers has been carried out in the presentation of the selection guide for OP AMPS (Appendix II). Further, as a source for obtaining greater details on particular models that are available from the comprehensive data sheets supplied by the manufacturers, a current list of their addresses is given in Appendix IV.

The maturing growth of the semiconductor industry strengthens the trend toward "standardized" types, both for OP AMPS and for the other forms of linear ICs; to this desirable end, the manual serves as a practical tool to highlight such specific types, by illustrating selected applications of these versatile devices.

The authors are grateful to the many manufacturers who supplied us with material. Any errors, however, that may appear in the text are our responsibility.

SOL D. PRENSKY
ARTHUR H. SEIDMAN

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Chapter 1

Introduction to Linear Integrated Circuits

1-1 GENERAL SIGNIFICANCE OF LINEAR INTEGRATED CIRCUITS

The category of *linear integrated circuits* (LICs) can be distinguished, in a broad sense, from the category of digital integrated circuits (DICs); thus the numerous and diverse types of integrated circuits can be classified into these two large groups. Both forms of ICs (also known as *microcircuits*) have proved immensely popular, and they are rapidly supplanting circuits using discrete transistors. This stems from the greater convenience and increased reliability offered by these small devices.

The linear IC group encompasses circuits of the *analog type*, where the input, in general, is in the form of a smoothly varying signal and the output usually is an amplified version of the input signal. This is in contrast to the zero-one switching action of the digital IC. The *operational* amplifier (OP AMP) is an outstanding and popular example of the analog group, which, in addition, includes other nondigital types (even though the operation may be nonlinear). Thus the LIC group includes regulators and other forms of signal conditioners that are designated "linear" or analog, as opposed to the digital types. The DIC, on the other hand, depends essentially on its switching function, and this group encompasses a large number of devices, such as gates, flip-flops, memories, and microprocessors.

As might be expected, with the wide diversity of ICs there are some devices that possess characteristics of both groups, as in the case of *interface circuits*. Examples of interface circuits include the analog-to-digital (A/D) converter and its counterpart, the digital-to-analog (D/A) converter. In addition, important use is made of these "in-between" types in providing a great variety of control circuits using the highly versatile microprocessor, where analog sensing elements are conditioned to work with the digital processing of microcomputers. These special types are generally classified as belonging to the linear group. Nevertheless, there need be no confusion about these classifications, as long as we do not interpret the designation of linear in too literal a fashion.

Thus the linear group may include devices that exhibit nonlinear transfer characteristics but that still are of an analog nature (such as the logarithmic amplifier). Keeping in mind the broad interpretation of these classifications, this text concentrates on the entire linear group as opposed to the other major (and very large) group of digital ICs.

1-2 DEVELOPMENT OF LINEAR INTEGRATED CIRCUITS

The linear group of ICs attained its importance and prominence when it eventually became possible to provide, at a reasonably low cost, amplifiers of the *operational-amplifier type*. The development can be traced from the time (approximately 1964) when pairs of transistors, forming *integrated differential amplifiers*, were first fabricated on a single silicon chip. This step represented a significant advance over the use of discrete transistors in the basic circuit; it demonstrated the ability of the IC to greatly reduce the troublesome temperature dependence of discrete transistors, even when the separate transistors were laboriously matched (as discussed later). Since both transistors of the differential pair could be fabricated simultaneously on the same IC chip, it was possible, by this step alone, to make an improvement by whole orders of magnitude in alleviating the temperature-drift problem—from millivolts for the discrete transistor to just microvolts per degree Celsius for the integrated pair.

About a year later, another enormous step forward was taken with the introduction of the *integrated general-purpose operational amplifier*. This IC was able to take good advantage of the integrated differential-amplifier stage for the first stage of a multistage amplifier and was capable of open-loop gains well beyond 10,000—all in a very compact package. By the use of an external feedback resistor, the IC operational amplifier (of the 709[1] type, for example) became a low-cost and highly versatile amplifier that incorporated 9 transistors and 12 associated resistors in a conveniently small package. This relatively simple operational amplifier could easily perform many of the functions of discrete amplifiers and could do so at a lower cost and in a much more reliable

[1] A popular IC type.

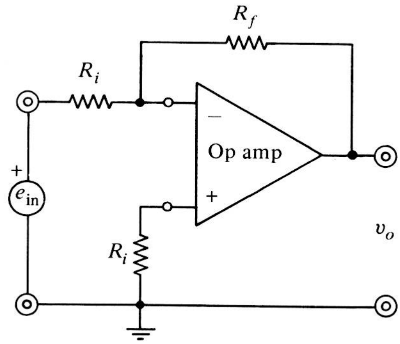
and versatile form. The IC operational amplifier offered designers a highly flexible tool that approached a *basic building block* around which a great number of desired circuits could be devised quite simply.

1-3 USING A SIMPLE LINEAR INTEGRATED CIRCUIT

The ease of use and the great utility of LICs can be illustrated by selecting a simple example in the form of a general-purpose operational amplifier (commonly called an OP AMP). Contrasted with the use of discrete components (such as transistors, resistors, and small capacitors) in a multistage amplifier, the use of an OP AMP can often make the design of a desired amplification function (either direct or alternating current) a straightforward operation; in many cases it would simply mean choosing values for two external resistors (R_f and R_i) to use with a general-purpose OP AMP, such as the very popular 741 type[2] illustrated in Fig. 1.1.

To gain a clear appreciation of the superior convenience and flexibility offered by the IC OP AMP compared to a traditional amplifier made up of discrete components, it is instructive to trace the steps needed in the case of both amplifiers to accomplish a typical amplification function.

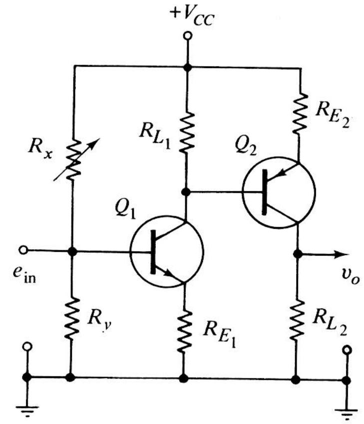
Let us assume a project requiring a direct-coupled amplifier with a stable gain of, say, 500, where the input comes from a light sensor that provides a slowly varying dc signal ranging from 1 to 10 mV. (This would call for an output from the amplifier of $\frac{1}{2}$ to 5 V, as displayed on a dc voltmeter.) In the next two paragraphs we can follow the necessary procedures to accomplish the same purpose in each case.



$$v_o = -\left[\frac{R_f}{R_i}\right] e_{in}$$

Figure 1.1 Functional symbol diagram of an operational amplifier (OP AMP); the simple gain formula applies to a typical operational amplifier used as an inverting amplifier.

[2] Another very popular IC type with internal compensation.



$$v_o \approx 0.7 \left[\left(\frac{R_{L_2}}{R_{E_2}}\right)\left(\frac{R_{L_1}}{R_{E_1}}\right)\right] e_{in}$$

Figure 1.2 Discrete form of direct-coupled amplifier: it requires calculation of proper values of at least six resistors to accomplish desired gain; compare this to a simple ratio of two resistors for the OP AMP in Fig. 1.1.

In the case of the *discrete amplifier*, we might choose the circuit of Fig. 1.2, calling for an *NPN* transistor (Q_1) followed by a *PNP* type (Q_2), arranged in the "compound" type of circuit, where the bias voltages can be handled more conveniently in this type of complementary transistor connection. Making use of simplified design relations, we would first establish the *Q*-point for the output stage to ensure that we stay within the linear operating range. With a supply voltage of around 20 V, this would call for a collector voltage of about half the supply, or approximately 10 V, for V_{CE2} at the *Q*-point, ensuring no distortion. Then, as suggested by Lenk,[3] we would choose proper values for the resistors; for example, we might choose R_{L_2} as 1 kΩ, requiring collector current of Q_2 to be about 10 mA. Proceeding from this, values of R_{E_2} and then of R_{L_1} and R_{E_1} are selected for the proper gain relationship of R_L/R_E for each stage; then the selection of approximate values of R_x and R_y is made for obtaining proper bias currents. As an additional simplification, R_x is shown to be variable, so that it may be easily set to obtain the correct meter reading for collector current of Q_2; finally, a final adjustment of R_x is again made, if required, so that the full output range is obtained without distortion. It will be noted that even when a bit of cut-and-try process is used here to reduce unnecessarily precise calculations, the simplified procedure still involves working with six resistor values to accomplish the proper operation of the amplifier in producing a direct-coupled gain of about 500, together with a satisfactory output swing between $\frac{1}{2}$ and 5 V, as desired.

[3] J. D. Lenk, *Handbook of Simplified Solid-State Circuit Design*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1971.