Circuits for electronic instrumentation

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1.1 Introduction

This book is concerned with the electronic circuits which are found in instrumentation systems. The interest here is with circuit detail. What might be called the 'difficult' circuits of instrumentation are those circuits which deal with the signals of interest *before* these are digitised. These are analog circuits, as a rule, and can involve problems associated with very high frequency technique, low noise level, d.c. stability, and so on.

Electronic instrumentation has developed greatly over the past half century. This development will be reviewed in the next section. Inside the instrument, however, at the level of circuit detail, it is interesting to see how often the same kind of circuit problem comes up again and again. This fact seems to suggest that circuit designers should take some interest in the history of their subject, and have a good knowledge of past technique as well as current technique. For this reason this book gives numerous references to the literature and, when possible, a note is given of the apparent origin of any widely used circuit technique.

The point about circuit detail, a particular circuit idea or what kind of circuit to use, also seems very important in electronic circuit design. It is impossible to calculate component values, device specifications or tolerances, before the circuit *shape* is fairly well determined. For example, in the trivial case of a single stage of amplification, is this to be grounded emitter, grounded base, or grounded collector? Is the stage to use a bipolar transistor anyway? Would a JFET be better? Why not choose an MOST? This initial step in the design process is often glossed over as being obvious or unimportant, but it is not. The really new ideas in electronics are often precisely within this field of circuit shape, and this concept is considered in detail in a separate section below.

Finally, one does not learn to be a circuit designer in the lecture theatre but in the laboratory. The most satisfying way to learn electronics is to build circuits and make measurements on these circuits. This may well mean restricting experimental work to the lower frequencies, simply because the most advanced constructional techniques and the latest test equipment may not be available to the student. Such restrictions should never deter the experimentalist in electronic circuits, and this book lays great emphasis on experimental work. Each chapter gives full details of experimental circuits which should be put together in order to see the full implications of the text.

1.2 Electronic instrumentation

The circuits which are discussed in the following chapters of this book have been taken from the field of electronic instrumentation. The main reason for this is that students should always have access to a circuits laboratory where test instruments are available, and they should be able to examine these closely. The handbooks of these instruments give the circuit detail of what might be called 'real' circuits, in contrast to the idealised circuits of the majority of text books, while the instruments themselves give examples of the hardware realisations of these circuits, probably using techniques which are more or less up to date.

A great deal can be learnt from this kind of close examination of the test equipment in a circuits laboratory. As mentioned above, however, the real business of the student of electronic circuit design is to build circuits and make measurements.

The development in electronic instrumentation over the past half century can be illustrated by choosing just one kind of instrument: the oscilloscope. In fact, the majority of the circuits in this book have been taken from this example, which covers a very wide field: the analog, sampling, and digitising forms of the oscilloscope.

The analog oscilloscope, in the form known today, was introduced in the early 1930s. The source of most of the ideas in this area, at that time, seems to have been Manfred von Ardenne [1], whose laboratory in Germany provided the cathode ray tubes (CRTs) for these first instruments, and also many of the circuit ideas. These early instruments gave bandwidths of only a few megahertz, used *RC* coupled amplifiers, and were difficult for one person to lift. Today, instruments with direct-coupled amplifiers, having millivolt sensitivity and bandwidths well over 100 MHz, are available, and weigh only a few kilograms. The deflection amplifier circuits and the waveform generating circuits of the analog oscilloscope have been chosen for study in chapters 6 and 7 of this book.

In the 1950s, an analog oscilloscope with a bandwidth of 30 MHz was considered to be a top of the line research instrument. This limited bandwidth was a severe restriction to engineers working in the rapidly developing field of digital electronics, where circuits were beginning to work at nanosecond speeds. There was also a great demand for a high speed oscilloscope from workers in the field of digital memories, and in nuclear physics. These pressures may have helped to bring about the development of the sampling oscilloscope.

The sampling oscilloscope uses an idea which is quite old. It is really like a stroboscope where a high speed repetitive event is viewed by means of a short flash of light, and this flash is made to occur at a slightly later time during each repetition. The technique was used by Lenz to view electrical waveforms, by taking a sample of the waveform with a contact that closed for a very short time, as early as 1849 [2].

The first commercial sampling oscilloscope appeared in 1950 [3] and had a bandwidth of 50 MHz. This was closely followed, in 1952, by a 300 MHz instrument [4]. The development of a solid state sampling oscilloscope by Chaplin, Owens and Cole [5], in 1959, marked the beginning of a radical change in technique, leading to the digitising oscilloscope of today.

The digitising oscilloscope, like the sampling oscilloscope, uses a sampling gate to take a measurement of the incoming signal over a very short time. This measurement is then put into the memory of the instrument, the next measurement is put into another memory location, and so on. In this way, a record of the incoming signal is built up, and this may be displayed later on, or as the data comes in, according to whatever program the user may decide. In what may be its most sophisticated form, the digitising oscilloscope is simply a small box with only coaxial sockets on the front, for *Y* inputs and trigger signals, and a connector on the back which links the digitising oscilloscope to a personal computer (PC) [6]. The VDU of the PC will then be a 'soft front panel' giving the oscilloscope display and all the 'controls', which are now accessed from the keyboard or from some other user interface. The most advanced digitising oscilloscopes, which may be able to accept data at up to one billion samples per second [7], are too fast to work directly with a PC and are stand-alone instruments.

Both the sampling oscilloscope and the digitising oscilloscope call for very short pulse generator circuits, and for high speed sample and hold circuits. These are, at first sight, very simple circuits which involve only a few components. For this reason they have been chosen to be the subjects of the next two chapters of this book. Chapter 4 deals with comparator circuits, which are a key feature of the very fast analog to digital converters (ADCs) found in the digitising oscilloscope. Chapter 5 considers circuits which are common to analog, sampling, and digitising oscilloscopes: the probe and input circuits which are needed to connect these instruments to the outside world.

The book closes with three chapters that consider circuit design problems from other areas of instrumentation. Chapter 8 deals with switched capacitor circuits, chapter 9 considers phase locked loop circuits, and chapter 10 looks at the circuit techniques which are used to obtain low noise. In every chapter there are experimental circuits which may be built.

1.3 Circuit shapes and circuit ideas

To return to the idea that was put forward at the beginning of this chapter, there seem to be two quite separate steps in the circuit design process, as there are in any design process. Designers first sketch out what kind of circuit they plan to build, they sketch out its general shape, their circuit ideas. No values, power supplies, device types, no *numbers*, are involved at this stage. The *Gestalt* is the problem here, and this is why the term circuit *shape* is chosen to express this stage in the design process. Only when this circuit shape has been decided can any calculation of component values, and then performance, be made. Certainly, the results of these calculations may well cause the designer to go back and think about new possibilities, new circuit shapes, but this does not alter the fact that the first step in the design process is one of imagination and intuition. There is no *algorithm* [8] which can be used to come up with a new circuit idea.

The process of invention, the way in which circuit designers arrive at really new ideas, often seems to be a process of imaginatively combining ideas that were new at some earlier time. Two examples of this will be given in the next two sections. The first is from the late 1960s, when electronic circuit design in monolithic silicon bipolar circuits was by far the most active branch of the subject. The second example concerns today's interest in gallium arsenide integrated circuits.

1.4 A new circuit shape in bipolar silicon

Gilbert has given a very interesting account of the way in which old and well-established circuit ideas, which were, of course, once quite new and even revolutionary, may be combined to provide a completely new circuit

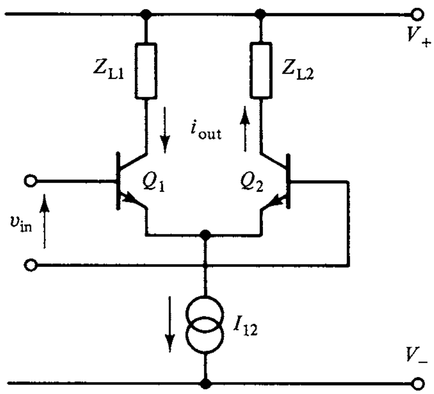

Fig. 1.1. *The long tailed pair.*

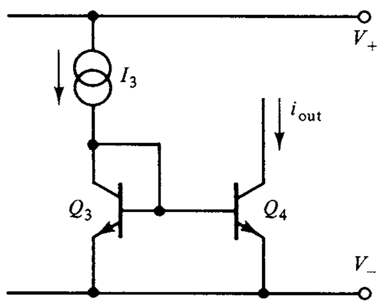

Fig. 1.2. *The Widlar current mirror.*

shape [9]. The process of invention which Gilbert describes is shown here in Figs 1.1–1.3.

In Fig. 1.1, the well-known long tailed pair circuit is shown. This is a very old circuit idea, first introduced by Blumlein [10] in 1936, which is now used for the input circuit of nearly all operational amplifiers. Attention is directed towards the output currents in Fig. 1.1, and the collector loads are represented by quite general impedances. As it stands, the long tailed pair provides a very non-linear and temperature dependent transconductance, di_{out}/dv_{in}, and this was one property which Gilbert [9] aimed to improve.

Fig. 1.2 shows another very well-known circuit shape: the Widlar current mirror. Again, this is an old circuit idea, which originated in 1965 [11]. In this circuit, Q_3 is clamped active by the simple expedient of connecting its base to its collector. Because the emitter junctions of Q_3 and Q_4 are in parallel, both devices must have the same V_{BE}, so that, provided they are identical devices and are both at the same temperature, as they would be in one and the same integrated circuit, i_{out} must equal I_3. The

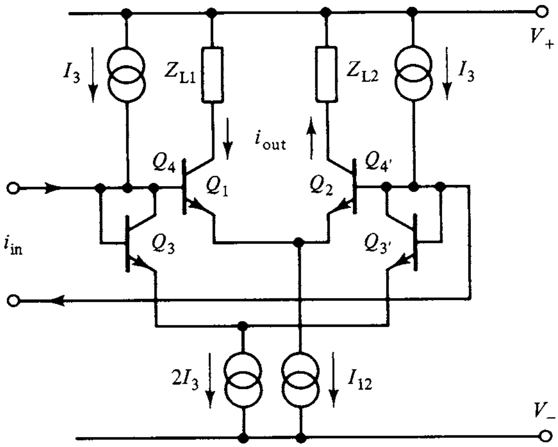

Fig. 1.3. *Gilbert's 'marriage' of Figs.* 1.1 *and* 1.2.

collector of Q_4 may be connected to any potential above V_{BE}, always bearing $V_{CE(max)}$ in mind.

Fig. 1.3 shows what Gilbert [9] called the 'marriage' of Figs. 1.1 and 1.2. The circuit shown in Fig. 1.2 is introduced into the circuit shown in Fig. 1.1 as an input circuit, on both sides, so that the new circuit, shown in Fig. 1.3, accepts a current as its input signal. In fact, the current gain, i_{out}/i_{in}, is given by I_{12}/I_3 [12], and is linear over the range $-I_3 < i_{in} < +I_3$ as well as being temperature independent. The gain–bandwidth product of the new circuit is essentially equal to that of the transistors used, and Gilbert's paper [9] described an integrated circuit using five such stages of amplification.

Gilbert's circuit has not been widely adopted as a wide-band current amplifier [13], and this is precisely the reason it has been chosen here as an example of a new circuit shape. Although the circuit uses the well-established bipolar technology, and is over 20 years old, it may well be unfamiliar to many readers, whereas the circuits shown in Figs. 1.1 and 1.2 will be absolutely familiar and are circuit shapes which are accepted today without question. This was certainly not the case when these circuits were first published, however.

To find a second example of a new circuit shape, which may strike many readers as a new and interesting circuit idea, it is only necessary to look at the kind of circuit design work that is taking place today in the field of gallium arsenide integrated circuits.

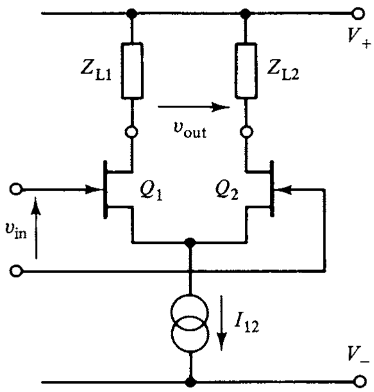

Fig. 1.4. The long tailed pair in gallium arsenide.

1.5 A new circuit shape in gallium arsenide

Gallium arsenide integrated circuits make use of n-channel field effect transistors (FETs). The gates of these devices are Schottky barriers, hence the use of the usual JFET symbol, and the devices have excellent high frequency properties due to the high electron mobility in gallium arsenide, as well as the possibility of making FETs with very short channels.

Fig. 1.4 shows the long tailed pair circuit again, this time drawn using a pair of gallium arsenide FETs. The intention of the circuit designer is to make a high gain voltage amplifier from this well-known circuit shape. This is not easy in gallium arsenide because the FETs have modest transconductance, dI_d/dV_{gs}, coupled with a rather high output conductance, dI_d/dV_{ds}. The voltage gain, of course, can never exceed $(dI_d/dV_{gs})/(dI_d/dV_{ds})$, no matter what values are chosen for Z_{L1} and Z_{L2}.

Fig. 1.5 shows another classical electronic circuit, the cascode [14], now drawn in gallium arsenide technology. This well-known amplifier circuit provides a high input impedance, at high frequency, compared to a single grounded source stage, because Q_3 has its gate connected to a constant bias voltage, V_B, and thus holds the drain of Q_4 at a fairly constant level. The output signal appears at the drain of Q_3, and this means that the feedback capacitance from output to input, in Fig. 1.5, should be very small.

The cascode has been the subject of a paper by Abidi [15], who shows that there is a great deal more involved in understanding this circuit than is generally thought. In this paper [15], and in an earlier paper [16], Abidi discusses the circuit shown in Fig. 1.6. This circuit has become widely used in gallium arsenide integrated circuits, and it is possible to argue that its origin is a combination of the two classical circuits shown in Figs. 1.4 and

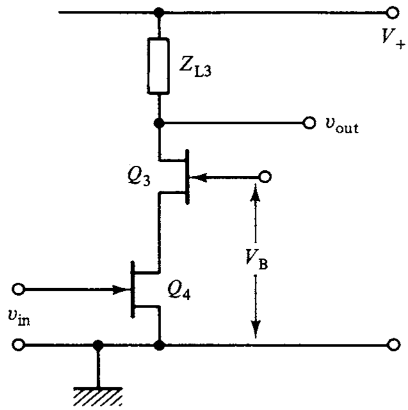

Fig. 1.5. *The cascode circuit.*

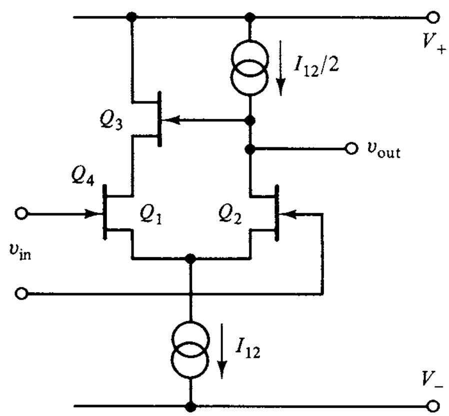

Fig. 1.6. *The gain enhanced circuit in gallium arsenide, formed by the combination of Figs.* 1.4 *and* 1.5.

1.5. As far as the two circuit shapes are concerned, this argument seems sensible. However, some very interesting changes in the function of the two transistors, Q_3 and Q_4, which came into the new circuit from the cascode circuit shape, may be seen. In Fig. 1.6, Q_3 is now driving the drain of Q_4, which is, of course, the Q_1 of the original long tailed pair shown in Fig. 1.4. The drain of this Q_1 is now 'bootstrapped' [16], in that its voltage rises as v_{out} rises, whereas, in the original long tailed pair circuit, Fig. 1.4, the drain of Q_1 falls when the drain of Q_2 rises.

Some kind of d.c. feedback must be arranged across the new circuit, shown in Fig. 1.6, in order to define the d.c. level at the drain of Q_2. The final result then *is* a high gain voltage amplifier with a gain of the order of the *square* of the gain of the simple circuit shown in Fig. 1.4, and this may be taken as a good example of invention in the field of electronic circuit design. A similar gain enhancement idea, coming from the same combination of the cascode and long tailed pair circuits, is found in CMOS integrated operational amplifier design [17].

1.6 Method in design

The circuits which feature in the following chapters of this book are presented in the light of the above discussion. For example, in chapters 2 and 3, where the circuits are fairly simple, the search for a good circuit shape, a good circuit idea, appears to involve a choice of a circuit from the past literature. In chapter 4, where the fast comparator circuits of the flash ADC are considered, the problem of circuit shape should come over more in the spirit of Figs. 1.1–1.6. The comparator circuit finally chosen for experimental work is a combination of two long tailed pairs, the circuit shown in both Figs. 1.1 and 1.4. The same story appears in chapter 6, where series and shunt feedback circuits are combined to give wide-band amplifier circuits; and in chapter 8, where a voltage controlled oscillator (VCO) circuit from chapter 7 is combined with a simple charge pump to give an ultra-linear VCO.

When such a variety of circuit shapes is presented, the question of method in design should be brought up again. Is there, in fact, a method which is followed when a designer comes up with a new circuit shape, like the circuits shown in Figs. 1.3 and 1.6, or must this be accepted as an intuitive or imaginative process, as it was above in sections 1.3–1.5? The answer to this important question is obscured by the fact that, once the new circuit shape is known, it *is* possible to give an account of the reasoning that might have led to this new idea. This is done in many of the examples which are given in the following chapters.

Finally, it must be remembered how the new and unexpected can turn up regularly, in any field of technology, and make the technique of the recent past look quite outmoded. In electronics there are many examples: the transistor of the mid-1950s, the silicon integrated circuit of the mid-1960s, the VLSI circuits, particularly the microprocessor, of the mid-1970s, and recently the gallium arsenide integrated circuits of the mid-1980s. All these revolutions have caused people to think about circuits in a new way, to think of quite new circuit shapes, as sections 1.4 and 1.5 illustrated. These same sections, however, showed that circuit ideas from earlier times were still influencing the process of invention.

1.7 Experimental circuits

The experimental circuits, which are given in the following chapters, have been chosen so that they may be put together in the simplest kind of circuits laboratory. Very fast, and very high frequency, circuits are slowed down to make construction quite straight-forward. This is also necessary because it is assumed that readers may only have fairly modest test equipment available.

In cases where the circuit interest is in the detail of, what would be, a large scale integrated circuit, as it is in chapters 4 and 9, it is possible to do very instructive experimental work by using transistor arrays, or by using an example of the integrated circuit itself which happens to have a pin-out that provides access to the signals needed.

The constructional methods which are used for experimental work are left fairly undefined in most cases because these must depend upon what the reader has available. One general rule which must be followed is that the layout of the experimental circuit must be thought about very carefully before construction begins. In this connection, the fact that these circuits are intended for experimental work, which means access for measurement, as well as a need to add or change a few components, must be borne in mind. Horowitz and Hill have a useful chapter on constructional techniques in their book [18], but their advice is directed more towards circuits that are built with the confidence that these circuits will form part of a finished product.

1.8 Symbols and abbreviations

Finally, a note on the symbols and abbreviations which will be used in the following chapters.

Voltages and currents are represented by upper case letters (V and I) when these are constant levels. The same rule applies for subscripts, so that V_{BE} is the bias voltage across a base-emitter junction, V_{DS} the voltage from drain to source, and so on. Small signals, which are superimposed upon such constant levels, appear in the text as lower case letters, both v and i, and the subscripts, v_{be} and v_{ds} for example. The use of lower case subscripts with upper case letters means a level which is changed by the experimentalist, for example, V_{c} would be a control voltage, I_{in} would be a direct current that might be varied from run to run, and so on.

When circuits involve many components, symbols like I_{C3} appear for the collector current of transistor Q_3 and, less elegantly, I_{R_3} for the current in R_3. With these conventions in mind, the reader should find the symbolism straightforward. All other symbols are defined when they first appear.

Abbreviations, like ADC, PLL, and so on, are defined when they first appear. The only one which deserves special comment is the troublesome 'd.c. level'. In this text, d.c. means direct current and d-c means direct-coupled. The term d.c. level is so widely used to mean the constant voltage level, or the mean voltage level, which appears at some point in a circuit, that to avoid its use seems to be pedantic.

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