LOW CURRENT/LOW VOLTAGE BIAS TECHNIQUES

Many system requirements may dictate a circuit design which is required to work under low current/low voltage bias conditions. There may be simply a requirement for low power consumption to minimize power costs in a very complex system. Or there may be a problem of power availability, portability and longevity such as in battery powered devices (for example, hearing aids and pacemakers) where battery size and lifetime are paramount considerations. Last, but certainly not least, low current/low voltage biasing may be dictated by circuit noise contributions to signal-to-noise ratio (usually in the form of current induced shot-noise).

How Much Current?

At first glance it would appear desirable to set bias currents as low as practical within the physical capabilities of the process utilized. While extremely low currents are practical in many functional circuits such as timers, low speed logic arrays and comparators, some practical limitations appear when our primary circuit consideration is the processing (amplification) of low-level signals.

At low currents predictability and repeatability vanish. Noise abruptly rises (particularly popcorn noise), transistor V_{be}'s and base currents become unpredictable and f_T is reduced so drastically that stable operation in feedback configurations becomes virtually impossible. Interstage coupling problems also appear in the form of impedance mismatching and power gain losses in the biasing systems.

An experimentally determined lower limit on bias current that prevents the above list of problems has been found to be (with some safety margin) about 20μA. The discussions and hearing aid circuit examples that follow will be developed with this limit in mind.

Current Setting Methods

The first problem confronting the circuit designer is how to establish, reliably, a low level of operating current. Obviously currents are established by resistors applied between voltage potentials. Resistors in an integrated circuit are primarily of two types: diffused and ion-implanted.

Diffused resistors are convenient to process but have some disadvantages in low current circuits. The resistivity of these resistors is typically 100 to 300 $\Omega/\square$, thus the large values of resistance needed to establish low currents can use up a considerable area on the integrated circuit chip.

A form of diffused resistor, the emitter diffusion over base diffusion "pinch" resistor exhibits 5 to 15K/$\square$ resistivity but its tolerance is generally unacceptable for good predictability of circuit performance.

Ion-implanted resistors provide approximately 6K/$\square$ resistivity with good tolerance and are a desirable choice for use in low-current circuits. Also they exhibit less excess noise than standard diffused types.

Current Sources

As in the design of standard integrated circuits, current sources are a "natural" for low current designs. The only problems that commonly occur are 1) insufficient supply voltage to allow "headroom" for the current source and 2) current sources should not be used to bias low noise stages since they can contribute a substantial amount of shot noise into the stage. In both these cases resistors should be used for the biasing requirements.

Current source levels can be established by on-chip resistors, as in conventional designs, or if this requires too large a value of resistance on the chip the bias can be established by an external resistor and forming a bias buss. If it is desirable to utilize only on-chip resistors, then logarithmic biasing systems can be used. This approach can waste a substantial amount of current, however, and may be unsuitable in battery powered, long-lifetime equipment.

Gain Stages and Interstage Problems

In most IC designs that process analog signals the natural choice for an input stage is the commonly used differential amplifier. The reason for this choice is that large gain is obtained along with ease of feedback application, both DC and AC. Unfortunately it doesn't fit too well into a system with a 1 volt power supply (such as a hearing aid).

What do we do, then, to obtain gain with reasonable bias stability? Recall how a transistor can be biased with a diode (see Figure 1);

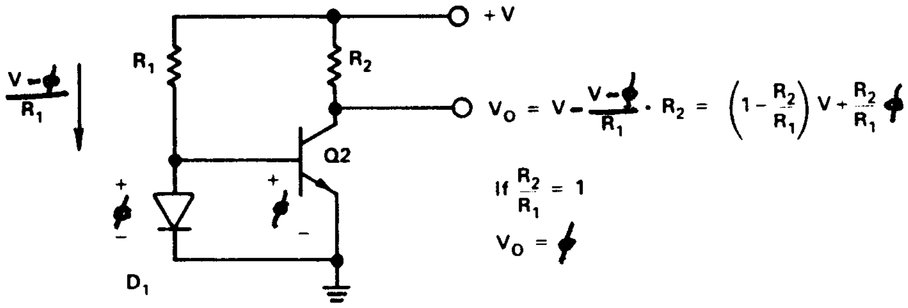


FIGURE 1

Note that the DC output potential is easily forced to be ϕ, independent of power supply potential, V. (Keep in mind, also, that operation at zero volts collector-to-base is perfectly satisfactory at small signal levels.) For this simple bias scheme we then need to find a way to introduce a signal.

Recall for a moment that a diode is a transistor with a base-collector short (Figure 2):

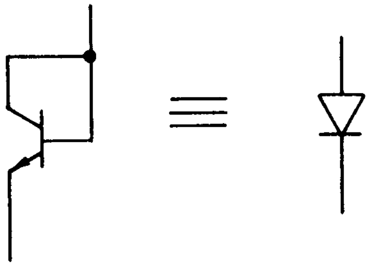


FIGURE 2

With this in mind consider now the configuration in Figure 3. We have recreated the bias arrangement of Figure 1, but with balanced base resistors, R_B.

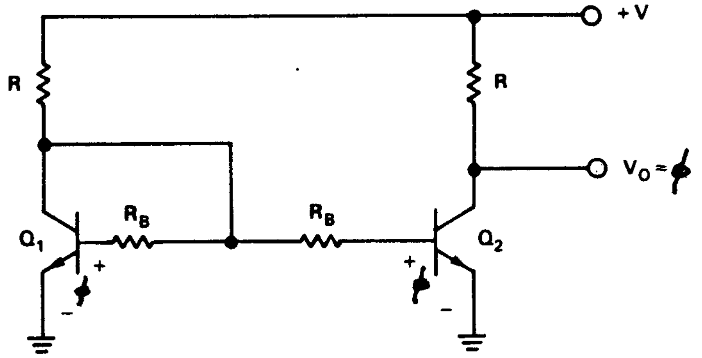


FIGURE 3

We can now do something with the circuit of Figure 3 that couldn't be done with the configuration of Figure 1. Consider the impedance at the base of Q_2 in Figure 1 —it is the impedance of diode D_1, too low and too nonlinear to couple into with a capacitor. In Figure 3, the impedance at the base of Q_2 is R_B in parallel with the input impedance of Q_2, fairly high and essentially linear. Thus AC gain may be taken as in Figure 4. This stage, as shown, has been used as the first stage in a hearing aid IC.

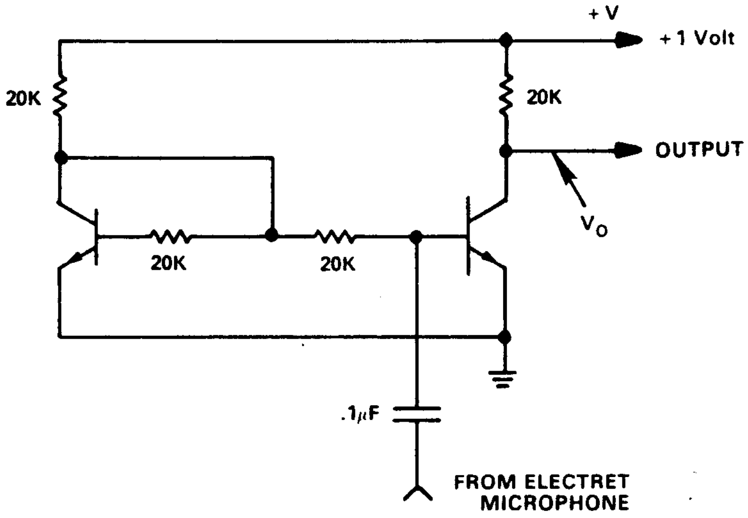


FIGURE 4

The voltage gain of this amplifier (neglecting the loading from a following stage) can be estimated at $G \cong 40(V - V_O) = 40(1 - .6) = 40(.4) = 16$ or 24 dB.

This biasing "trick" can be extended further by adding a feedback triple as shown in Figure 5. Here the voltage gain is given by $G = 20K/300\Omega = 66.7$ or 36.5 dB This stage has also been used within a hearing aid IC.

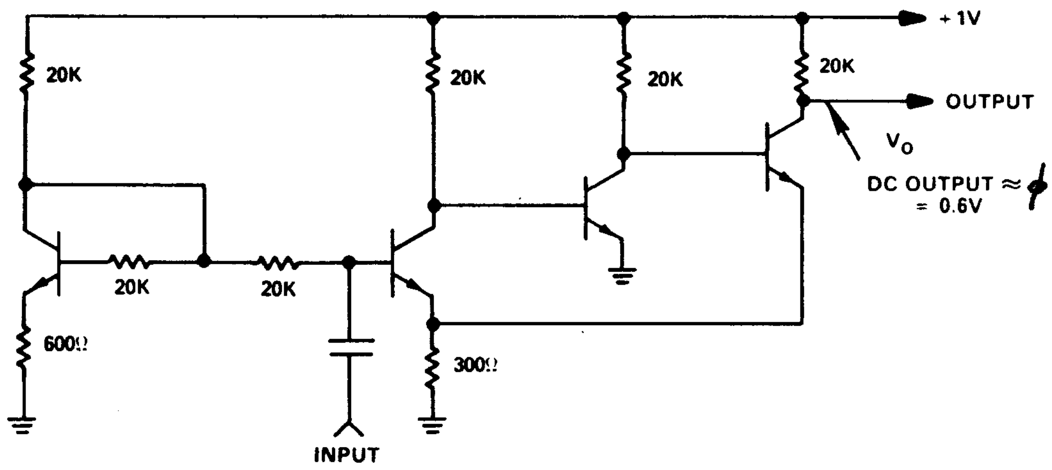


FIGURE 5

If we try to extend these techniques too far the DC predictability of V_O begins to suffer. We have two choices, depending on application—we can AC couple between stages with a capacitor, or we can utilize an overall DC feedback loop to establish bias stability. (DC loops in hearing aid applications generally require too large a value of capacitor for decoupling and are to be avoided in most cases.)

Output Stages

Most low level designs end up with the requirement for an output stage capable of delivering a significant amount of power. At the low battery potentials usually available in these designs the choices are few—class A outputs which waste a significant amount of power when signal levels are low or class B outputs which require transformer coupling and which have difficult distortion control problems.

Consider, however, a possible alternative. Suppose that we could design a class A output stage that did not idle at full power capability but instead drew only minimal power when no signal was applied. As signal was applied the bias would rise to accomodate the driving signal level (and thus also avoiding distortion). This conceptual circuit idea is called "Sliding-Class-A" bias. Consider the block diagram of Figure 6.

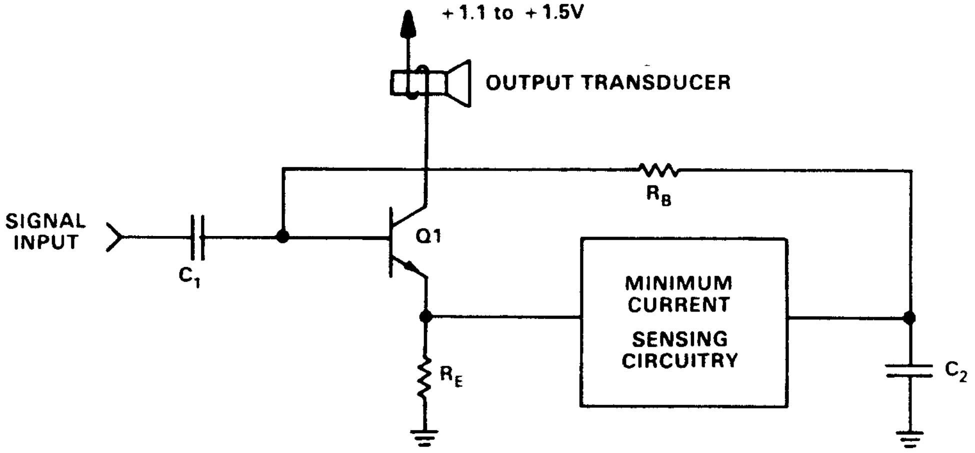
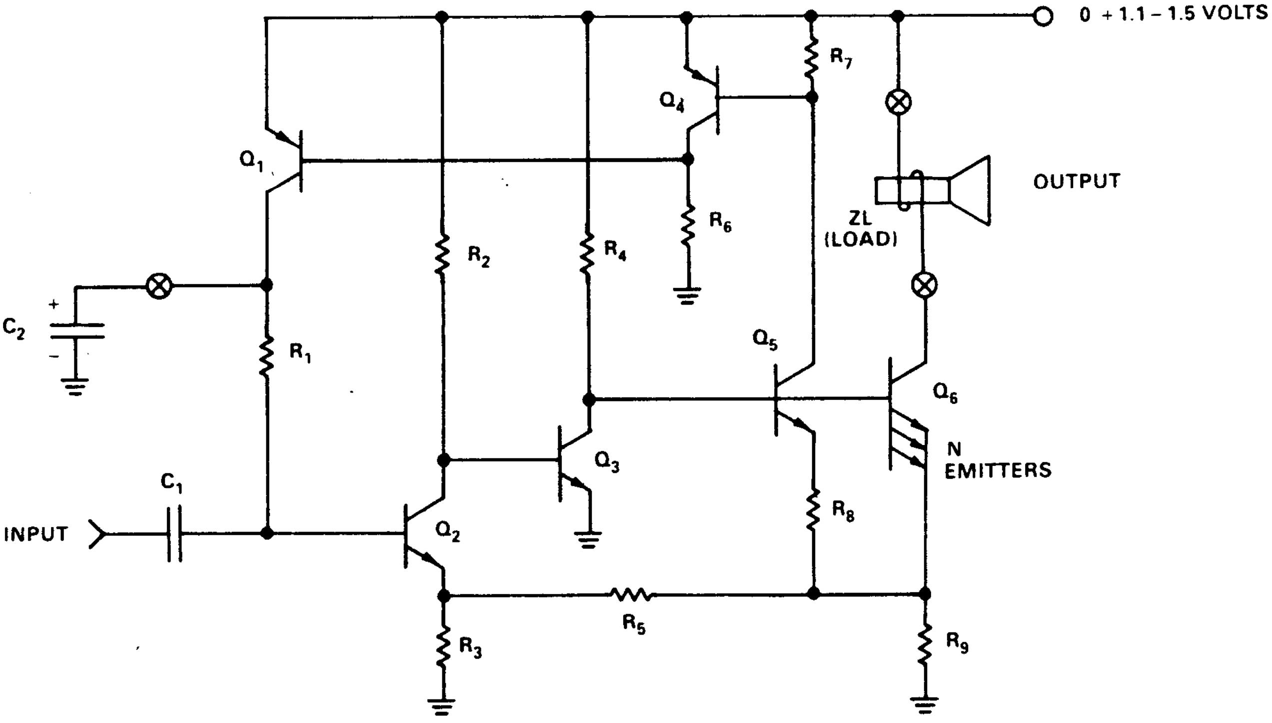


FIGURE 6

Assume that transistor Q1 idles at some small bias current. As we apply a signal that swings positive there is no problem—the current in Q1 will increase linearly with signal, driving the output transducer. As the signal swings in the negative direction, however, Q1 will be cut-off and distortion will result. If we utilize a current detection scheme, as shown, which senses that Q1's current has fallen below a minimum settable level we can "pump-up" the voltage on C_2, increasing the quiescent bias on Q2. Thus clipping will be avoided. By proper choice of attack and decay time constants, distortion for audio frequency signals can be made exceptionally low (.3% in one design). At the low voltage supplies typically found in hearing aids the efficiency of a Sliding-Class-A stage may actually exceed that of Class-B designs.

The full implementation of a typical Sliding-Class-A output stage is shown in Figure 7. The configuration of Figure 6 suffers from considerable gain variation (and thus distortion) with signal swing, thus, in Figure 7 a feedback triple composed of Q2, Q3 and Q6 has been used to stabilize gain independent of bias current. Q5 senses the current in Q6, turning off Q4, turning on Q1 to pump up C_2 to increase the bias to Q2 and thus Q6, to provide the sliding bias action.

Output stages of this type have been designed with quiescent current levels of approximately 100μA, yet with peak current capability to 6mA.



SLIDING—CLASS-A OUTPUT AMPLIFIER
FOR HEARING AID

FIGURE 7

Low Voltage Regulators

A typical hearing aid battery may be specified at 1.5 volts when new and may discharge to approximately a 1.1 volt level before "end-of-life" may be assumed to have been reached.

This variation in voltage presents several problems. Voltage changes manifest themselves as current changes, then gain changes with battery age—this is an undesirable product attribute. Electret microphones used with hearing aids also prefer constant potential. In addition, battery impedance rises as the battery discharges, causing decoupling problems which usually manifest themselves as "motorboating" or overall low frequency oscillations

For these reasons it is desirable to consider a voltage regulator in low voltage designs. The conventional approach (using NPN devices) shown in Figure 8 is undesirable for low voltage applications since $V_{OUT} \leq V_{IN} - \phi$. (Thus if $V_{IN} = 1.5$ volts, $V_{OUT} \approx 1.5 - .6 = .9$ and if $V_{IN} = 1.1$ volts, $V_{OUT} \leq 1.1 - .6 = .5$).

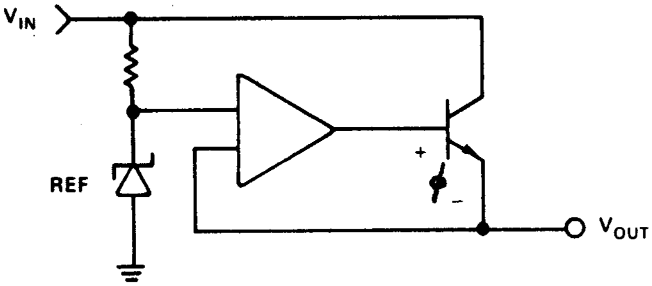


FIGURE 8

Therefore we must consider PNP approaches as in Figure 9. This approach has the advantage that $V_{OUT} \leq V_{IN} - V_{SAT}$. (The PNP must be specially designed for low saturation, but this is not difficult at low currents). Note that the output is referenced to ϕ and thus at first glance would appear to be too temperature sensitive. In personal equipment, such as hearing aids, this is alleviated by the temperature referencing effect of the body.

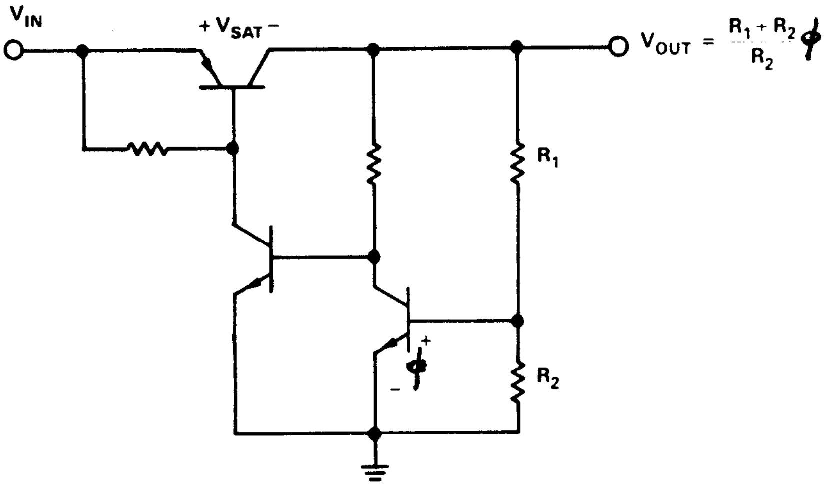


FIGURE 9

The circuit of Figure 9 does have one problem, however—it is not self-starting. Unless V_{OUT} is present, there is no bias source for the PNP—with no bias on the PNP V_{OUT} does not exist. This problem is solved with a starting circuit as shown in Figure 10.

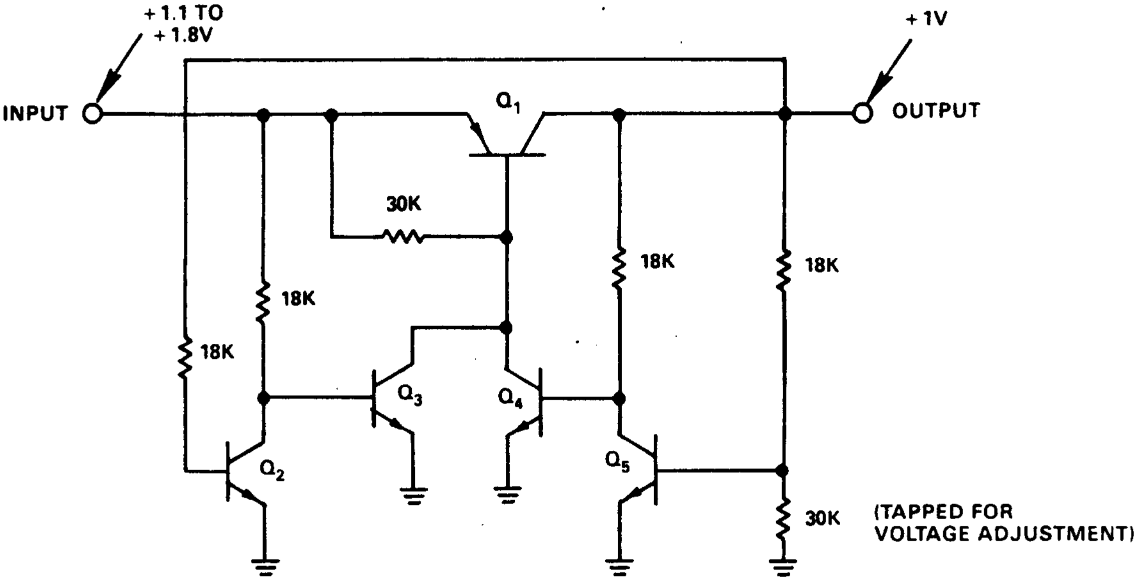


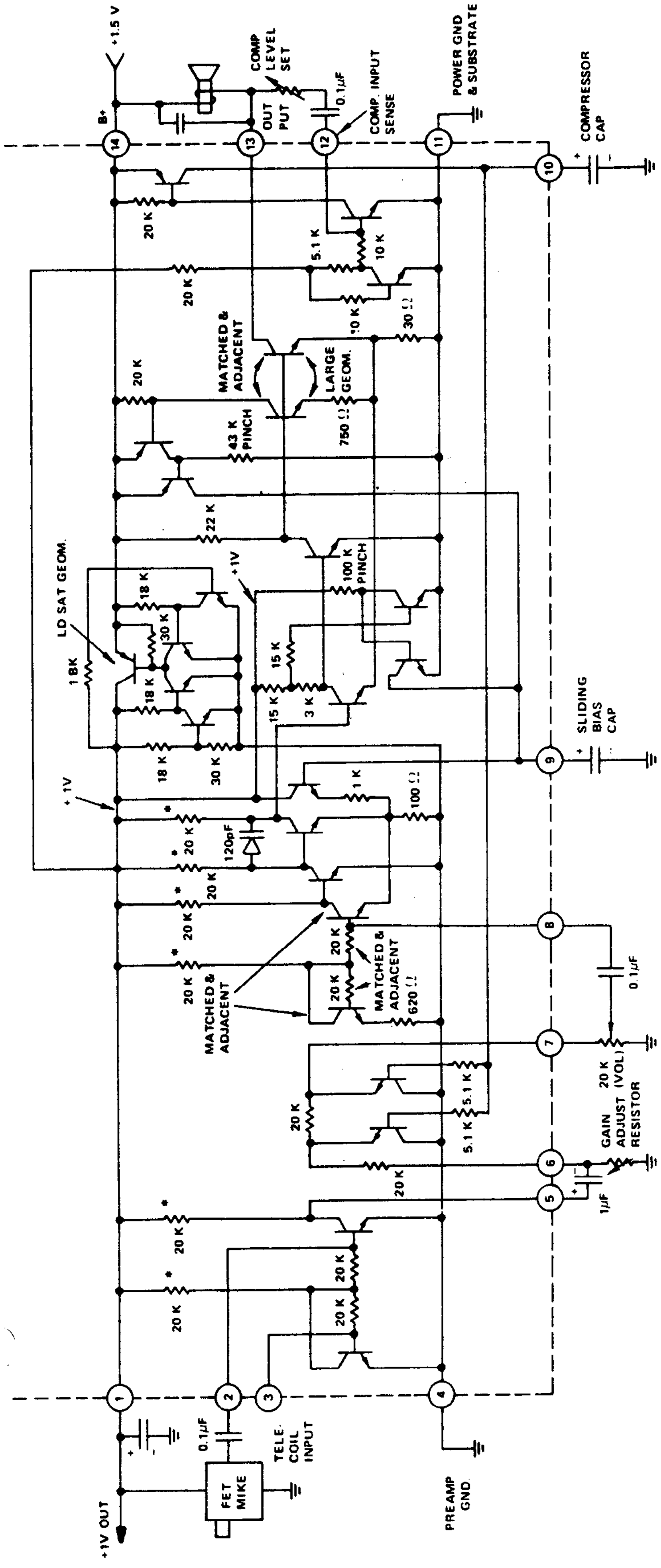
FIGURE 10

Initial start-up bias is provided by Q3. When the output reaches +ó, Q2 turns on, turning off Q3, the feedback loop through Q4 and Q5 then takes over.

Hearing Aid Example

The complete schematic of a hearing aid amplifier is shown in Figure 11. The performance of this device may be summarized as follows:

Gain from microphone input	78 dB
Microphone terminal input impedance	20K
Gain from telecoil input	90 dB
Telecoil terminal input impedance	≈2K
Gain variation +1.5V to +1.1V	−3 dB
Gain adjustment range (external R)	> 20 dB
Quiescent current (including microphone)	700μA
Power output into 630Ω	0.5mW
Noise floor	40 dB below full output
Efficiency at full output	40%
Compression dynamic range	> 40 dB
Compression point adjustment range	20 dB
Compression attack time	2-5 mSec
Compression decay time range	20-300 mSec
Maximum input before "bleed-thru" over compression (at full gain)	10mV



78 db MAX GAIN FROM MIKE
90 db MAX GAIN FROM TELECOIL

FIGURE 11. SLIDING CLASS-A AID