The Transistor Amplifier

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Here is a basic circuit for a general purpose amplifier which can be made to deliver powers ranging from 100 mw up to 10w with minimum design effort

EVERY NOW AND AGAIN one seems to come across a really simple circuit which is easily designed and can be used over and over again in a variety of sizes. Sometimes, indeed, the circuit becomes so attractive to the designer's eye that he persists in using it even where it is completely unsuitable. I don't know whether I have reached this point of negative return yet with the transistor amplifier circuit I am describing here: I hope not, but at the moment it really looks like the answer to many problems that are around. That is why the title at the head of the page is so forthright.

I find that a basic two-stage transistor amplifier which can work efficiently when the second stage is delivering real power is an extremely useful standard part. Real power in this context has meant anything from 100 mw up to 10 w, depending on the scale in which the design has been planned, but in each application the design procedure has been exactly the same with only the numbers changing. What is more the design has been modified very easily to provide a high-power economy circuit which I will describe in a following article.

The output stage of a general purpose amplifier is most conveniently made a grounded emitter stage. It is very attractive at first to consider a ground collector stage with its very low output impedance but when you come to work out the drive circuit your enthusiasm is rapidly damped by the high voltage swing needed. I lost all my love for the grounded base circuit in the days of point contact transistors, when only too often there just was no choice but to accept the input transformer needed for the low emitter impedance. Split-load circuits have, on paper, considerable attractions and if I were designing an amplifier in which high quality and economy were to be wedded I should investigate them closely.

The other problem with the output stage is whether it should be class A or class B. When using transistors there is a whole bunch of factors to be taken into account which we never had with tubes. In general with class B the output transformer will be smaller, because there is no polarizing magnetic flux, or not much anyway, to make you use a big gap and more turns. The power consumption will be less, though in the following article I shall show you that for moderate quality this does not have to be true. Smaller transistors can be used. Against all these advantages we must consider that a class-B stage uses two transistors where a class-A stage needs to use only one, and this is not only an economy in itself but gets rid of all the phase-splitting circuit problems. When the bias goes a little wrong in a class-A stage it affects the quality at signal peaks, but with a class-B stage the low-level quality can get very bad indeed if the bias goes wrong and you get cross-over distortion. For some reason this kind of distortion sounds much worse, at a given percentage harmonic, than peak clipping. I would guess that this is because every cycle of a real signal must cross the base line but the high peaks are only a small fraction of the time.

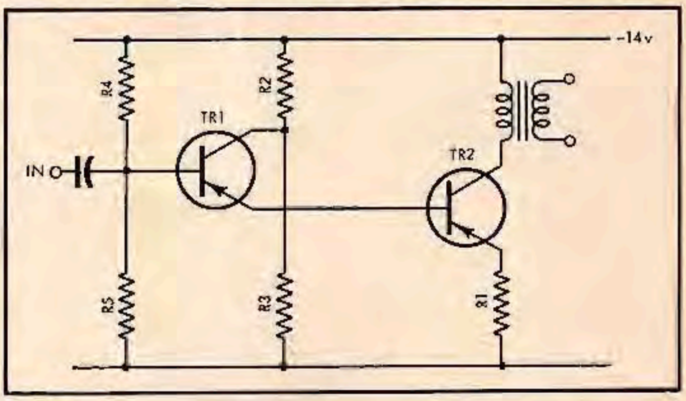


Fig. 1. The basic circuit.

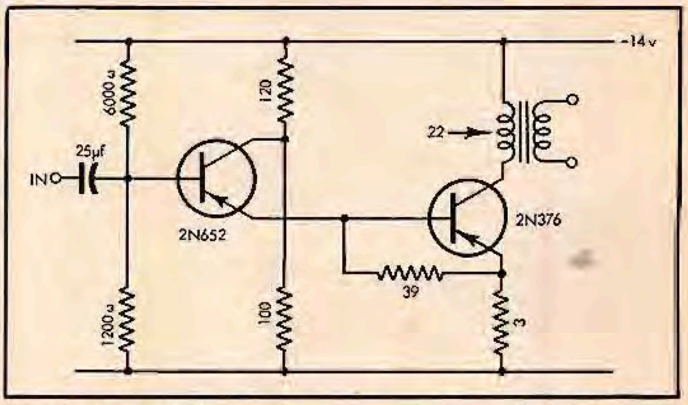


Fig. 2. Roehr's 2-watt high-quality amplifier.

I find that most amplifiers do not need to be power economizers. Either they are running off the power line and use transistors solely for reliability, or they run off rechargeable batteries (for example in an automobile) where current economy has not really very much justification. This affects the question of weight, too. If you want a pocket job or a ten-watt amplifier you can hide in your beard there is nothing in this article for you.

As you may have realized this preamble leads to the fact that the output stage is to be class A. This is a deliberate choice in which long-term economy in the first design and quality in the second is traded for simplicity. We now go on to consider the driver for a class-A grounded-emitter output stage.

Drivers for transistor power stages introduce far more problems than do their tube counterparts. The input impedance of the power stage is generally low and a substantial drive current is needed. This tends to settle the operating level of the driver at a higher level than we should expect from tube practice unless we choose to use a transformer. Without a transformer we take the drive current at the full supply voltage even though we really need only a fraction of it. The other problem is that of drive circuit impedance. In low-level transistor amplifier stages we try to use a high source impedance because of the nonlinearity of the input characteristic. This keeps the input current undistorted and as the transistor is a current amplifier this is what we need. You will remember that in tube circuits there is an upper limit to the grid circuit impedance above which grid current distortion becomes troublesome. When we come to use power transistors, however, we need to deal also with the way in which the current amplification factor, beta, falls as the current rises. The over-all result is that when the power transistor has this sort of characteristic it is profitable to use a low drive impedance and get a distortion balancing effect. At high base currents the base impedance is low, so that we get rather more base drive for our input volts than we should: this is the input circuit distortion. However, this high base current is not amplified as much as it should be so that the over-all effect is to give less distortion than either effect independently would prove. Like all distortion balancing schemes it is by no means perfect, but it does suggest that a low impedance driver is a good idea.

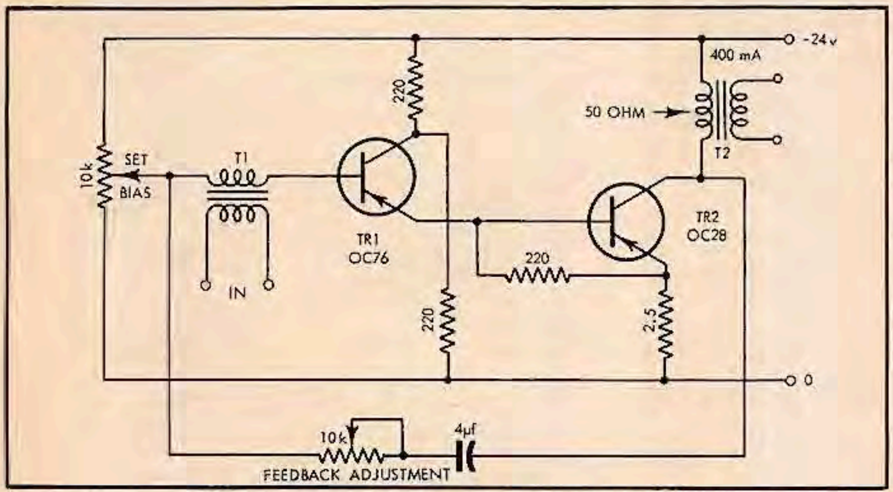


Fig. 3. This circuit provides more gain than *Fig.* 2 with good damping for the load. (T_1 secondary impedance = 10,000 ohms, secondary inductance = 5 h. T_2 primary impedance = 50 ohms, primary inductance = 33 mh. Apparent output impedance = 1/40 × load impedance. With 18-volt supply use CST1739 for Tr2.)

Here we want current drive, but not much in the way of voltage and an emitter follower or grounded collector stage will be exactly what is needed. We find that it has even more to commend it. The low impedances involved would make it necessary to use very large capacitances and rather low-resistance bias circuits. With the emitter follower it is perfectly practicable to use direct coupling between the two stages and eliminate these components entirely. The biasing of the driver stage then takes control of the whole amplifier.

It is perhaps time to draw the basic circuit diagram. *Figure* 1 shows the outline of the circuit which requires both discussion and development. The output transistor must first be selected. Let us assume that we are using a 14-volt supply and that for practical reasons to be considered later the peak collector swing will be 10 volts. If we now decide the output power we want all else will follow quite logically. To start with let us take an output power of 10 watts. At 10 volts peak we need a peak current swing of 2 amps (10 volts × 0.707 × 2 amps × 0.707 = 7 volts rms × 1.4 amps rms = 10 watts). The steady collector current of Tr_2 must be rather more than 2 amps so that it is not completely cut off on the down swing. The quiescent dissipation in T_2 is therefore 20 watts, and if the junction is not to rise more than 50 deg. C above the ambient temperature we need a thermal resistance, junction-to-ambient, of 2.5 deg. C/W. A good big transistor, say the Clevite 2N1147, has at worst 1 deg C/W internally, so the transistor must be mounted on a plate giving 1.5 deg. C/W. This is a sheet of painted aluminum, perhaps 50 sq. in. and .1-in. thick: it rather depends on whose curves you look at what size it comes out. You will need silicone grease to fill the space between transistor shell and cooling fin so that there is no air to impede the heat flow.

The choice of power has fixed transistor and also its cooling plate. The transformer, too, is pretty well fixed. The load impedance presented at the primary side must be 5 ohms (10 volts/2 amps), so that if the response is to be 3-db down at 80 cps the inductance must be $(5/2\pi \times 80)$h = 10 mh. Other frequencies, of course, and you alter the inductance in proportion. The core must be gapped and must have enough iron to remain below saturation even with the peak current of 4 amps flowing. And as you do not want to waste signal power in the winding resistance you will need enough copper to keep the resistance below, say, ¼ ohm. The secondary, naturally, depends on the load and is just the usual transformer problem.

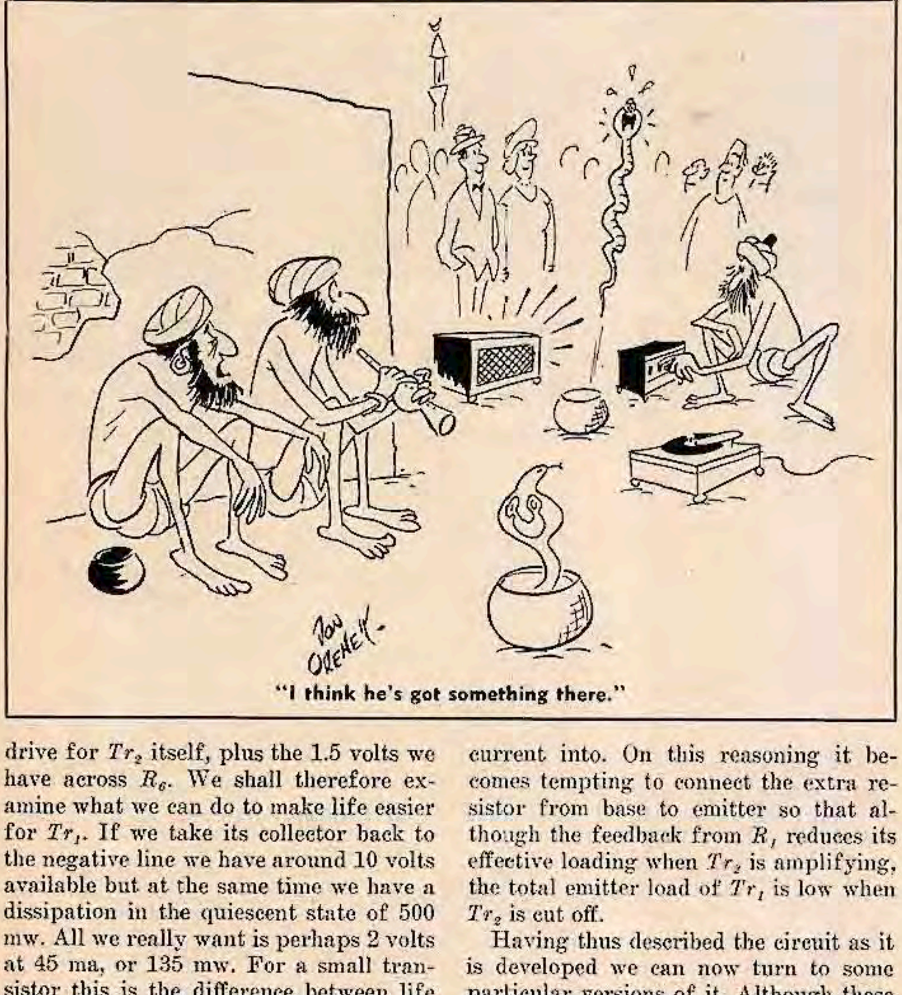
Now we turn to R_1. I have found two quite widely separated descriptions of this circuit which both come independently to the conclusion that across R_1 we should drop about 1.5 volts. For our 2 amp quiescent current this makes $R_1 =$ 0.75 ohms. This is the sort of resistance value you need to construct for yourself, remembering that it must dissipate 3 watts. Do not use ordinary resistance wire for this: most resistance wires have very low temperature coefficients and there is some advantage in making this resistance from copper or nickel wire with a good big structure to get rid of the heat. Then when the ambient temperature rises the resistance rises too, thus helping to counteract the increase in transistor cut-off current. This 1.5 volts in R_1, the half-volt in the transformer and the transistor saturation voltage account for much of the difference between the 14-volt supply and the limit of 10 volts peak.

For a 1-watt amplifier we should have proceeded in exactly the same way, to arrive at a current of 0.2 amp, a transistor dissipation of 2 watts, a load impedance of 50 ohms and an emitter resistance, R_1, of 7.5 ohms. The transformer primary inductance for an 80 cps 3-db point will be 100 mh, or for 40 cycles 200 mh. All these calculations you can do in your head as you go along.

Now you need to know the current gain of the output transistor. We have already decided this is not a constant, so we look at the characteristics to find what base current we need for our quiescent collector current and also what base current we need for the full drive current. Sometimes we can get this directly from the maker's data, sometimes we need a roundabout approach. Picking out another set of data since I don't have the 2N1147 data handy, I find that at 4 amps the current gain is 36 and at 2 amps it is 45. A driver must then provide a peak current of 4/36 = 110 ma and should run at a quiescent current of 2 amps/45 = 44 ma. It is advantageous to use transistors with higher current gains than this, but anyway, for our example, we find we need a driver which can go up to 110 ma. There is no difficulty in finding a suitable transistor.

The transistor characteristics also tell me that to get this base current into T_2 I shall need around 0.5 volts drop, base-emitter. For T_1 the base-emitter drop is only about 0.2 volts so that the base of T_1 is held at about $1.5+0.5+0.2=2.2$ volts. For this we use the voltage divider R_4, R_5. The thermal stability of the system will be good if the base source impedance, which is R_4 and R_5 in parallel, is not too large compared with the product of the two current gains and R_6. (R_6 is the base-emitter resistance of Tr_2 shown in *Fig.* 2.) We can easily have a total current gain of 2000 times, so that if R_6 is 0.75 ohms we are dealing with impedances of around 1500 ohms. As a lazy mathematician I shall make $R_4=2200$ ohms so that R_5 is around 10,000 ohms. This lifts the base of Tr_1 about 10 per cent above where it should be and will do the same to the current in Tr_2: in practice it is convenient to use a small potentiometer for trimming purposes.

Now we only need about one volt of drive for Tr_2 itself, plus the 1.5 volts we have across R_6. We shall therefore examine what we can do to make life easier for Tr_1. If we take its collector back to the negative line we have around 10 volts available but at the same time we have a dissipation in the quiescent state of 500 mw. All we really want is perhaps 2 volts at 45 ma, or 135 mw. For a small transistor this is the difference between life and death. Anyway Tr_1 must be kept cool, because changes in I_{co}' at Tr_1 are changes in the base drive to Tr_2 and are amplified again. The collector of T_1 is therefore fed from a fairly low impedance voltage divider R_2, R_3 which brings the collector to around 5–6 volts above ground. The parallel combination of R_2 and R_3 as a source impedance is added to the collector impedance of Tr_1 and thus reduces the effective transconductance, but with practical values this effect is too small to worry about.



"I think he's got something there."

We need to consider one more general aspect of the design. If Tr_1 is driven hard it will be cut off and this will leave the base of Tr_2 open-circuited. Under these conditions R_1 loses all its stabilizing effect since the voltage drop across it has no reference to the base conditions. An additional resistor must therefore be connected from the base of Tr_2 back either to ground or to the emitter. This resistor not only prevents the risk of thermal runaway in Tr_2 but it also provides a stabilizing effect for Tr_1 against changes which may take place in the V_{bc} of Tr_2. You will appreciate that if Tr_2 was in the cut-off state and passing only I_{co}', the emitter of Tr_1 would be in a pretty uncertain condition: with the additional resistor there is somewhere for the emitter of Tr_1 to continue to drive current into. On this reasoning it becomes tempting to connect the extra resistor from base to emitter so that although the feedback from R_1 reduces its effective loading when Tr_2 is amplifying, the total emitter load of Tr_1 is low when Tr_2 is cut off.

Having thus described the circuit as it is developed we can now turn to some particular versions of it. Although these are actual amplifier designs the important feature to notice is that they all have the same configuration, with the same voltages at the first base and the second emitter. I do not recommend any particular one of them. For your job there is yet another version which you can design to suit your needs.

The circuit shown in *Fig.* 2 is that given by Roehr in "IRE Trans. on Audio," Vol AU-7, No. 5, Sep–Oct 1959; pp. 125–128. It is a 2-watt amplifier using Motorola transistors and it gives only 1 per cent distortion at the 2-watt level. The current in the second transistor at 25 deg. C is around 550 ma, which is higher than we might have expected, but almost 2 watts is obtained at −25 deg C, when the current is down below 400 ma. This paper gives a very detailed study of the effects of I_{co}' on the performance of the amplifier and shows how important the base-emitter resistance in the second stage can be. The input impedance is almost entirely the impedance of the base-bias voltage divider, since with the high-gain transistors used by Mr. Roehr the rest of the circuit probably contributes only around 10–15,000 ohms in parallel with the net 1000 ohms.

The input level needed is around 1.2 volts, or, say 1.5 mw, giving a gain of just over 30 db. Much more gain is really available if you want it because an input transformer can be used with its secondary in series with the base of the first transistor. This transformer will provide a step up to match the 15,000 ohm input impedance and thus gives an extra 12 db of gain. In the circuit shown in *Fig.* 3 this extra gain has been obtained just so that it can be used up in negative feedback from the output collector. By this means the amplifier has an impedance of about 1/5 of the load impedance. For normal loudspeaker work this low source impedance is regarded as providing good damping but the particular application here was a three-wire multistation call intercom with private loud-to-loud working from any slave to the master. With a low source impedance there is no change of level when the system is switched over from the general call on four slaves to private speech on the wanted one.

There would seem to be a lower limit to the use of this amplifier circuit with germanium transistors. The base current of the second transistor is the emitter current of the first. It does not seem practicable to get this down below some hundreds of μa because of the leakage current. Thus we must expect that the second transistor will need to work up in the tens of ma region, which can be regarded roughly as implying hundreds of mw. To get round this difficulty it is necessary to go to a silicon transistor for the first stage and it is pleasant to notice that at present prices the saving in other components will almost make this a paying proposition. Indeed for manufacturers who must count the cost of every soldered joint, and it costs much more to get a resistor into a circuit than the price of the resistor, this circuit will probably pay off.

The reader will have noted that as we

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have described it the circuit suffers from the usual disadvantage of class-A circuits: a 2-watt amplifier draws some 8 watts from the battery the whole time it is switched on even though no signal is being amplified. There is, however, an interesting extension of the circuit, the floating-bias amplifier, which can be a real power economizer. I shall describe this in a second part to the article. This modified version of the amplifier is quite as efficient as a class-B amplifier and to my mind very much easier to build. Æ