CHAPTER

3 Linear power amplifiers

An amplifier is a circuit designed to impose a specified voltage waveform, $V(t)$, or, sometimes, a specified current waveform, $I(t)$, upon the terminals of a device known as the "load." The specified waveform is often supplied in the form of an analog "input signal" such as the millivolt-level signal from a dynamic microphone. In a public address system, an audio amplifier produces a scaled-up copy of the microphone voltage (the input signal) and this amplified voltage (the output signal) is connected to a loudspeaker (the load). An audio amplifier generally supplies more than a watt to the loudspeaker. The microphone cannot supply more than milliwatts, so the audio amplifier is a power amplifier as well as a voltage amplifier. The ability to amplify power is really the defining characteristic of an amplifier. Of course energy must be conserved; amplifiers contain or are connected to power supplies, usually batteries or power line-driven ac-to-dc converter circuits, originally known as "battery eliminators" but long since simply called "power supplies" (see Chapter 29). The amplifiers discussed in this chapter are the basic "resistance-controlled"[1] circuits in which transistors (or vacuum tubes) are used as electronically variable resistors to control the current through the load. Such circuits span the range from monolithic op-amps to the output amplifiers in high-power microwave transmitters.

3.1 Single-loop amplifier

Figure 3.1 shows the simplest resistance-controlled amplifier. This circuit is just a resistive voltage divider. The manually variable resistor (rheostat) in (a) represents the electronically variable resistor (transistor) in (b). Remember that the main current path through the transistor is between the emitter and the

[1] Resistance-controlled amplifier are also called *linear* amplifiers, to distinguish them from *switching* amplifiers, which are discussed in Chapters 9 and 29. Note, however, that *linear amplifier* is also used to denote amplifiers whose output waveform is a faithful (linearly proportional) copy of the input.

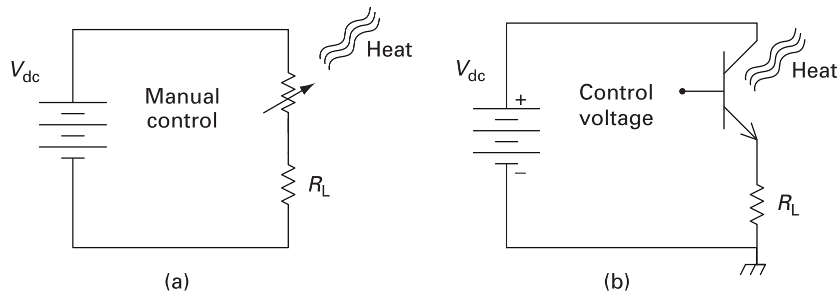

Figure 3.1. Basic single-loop amplifier.

collector; the current through the control terminal, the base, is typically less than 1% of the emitter-collector current. The base voltage can vary the transistor's resistance from infinity to almost zero so any arbitrary current waveform (within the range of zero to V_{dc}/R_L) can be obtained by using an appropriate corresponding control voltage waveform. The load, represented as a resistor, R_L, could be, for example a heating element, a loudspeaker, a servomotor, or a transmitting antenna.

3.2 Drive circuitry: common-collector, common-emitter, and common-base

We will concentrate on the topologies of the output circuit or "business end" of amplifiers, i.e., the high-current paths between the load and the power supply(s). But let us briefly discuss the drive circuitry that controls the resistance of the transistor(s). The discussion is illustrated with circuits using bipolar transistors, but the basic concepts apply also to FETs and tubes.

In Figure 3.1(b), only one terminal is shown for the control voltage (drive signal) input. When the return connection for the drive signal is made at the bottom of the load resistor, we get the amplifier shown in Figure 3.2. This circuit is called a *common-collector* amplifier because the collector, in common with the drive signal return, is a ground point with respect to *ac* signals, even though it does have a dc voltage.

This circuit is also called an *emitter follower*. The transistor will adjust its current flow to make the instantaneous emitter voltage almost equal to the instantaneous base voltage. Here "almost identical" means a small dc offset (the emitter voltage will be about 0.7 volts less than the base voltage) along with a one or two percent reduction in signal amplitude. The reason the emitter voltage closely follows the base voltage is that the emitter current is a rapidly increasing (exponential) function of the base-to-emitter voltage.

Figure 3.3 shows the *common-emitter* drive arrangement, in which the return for the drive signal is connected to the transistor's emitter. It is common to rearrange the circuit as in (b), so that the return connection for the drive signal and the negative terminal of the supply are at the same point (ground).

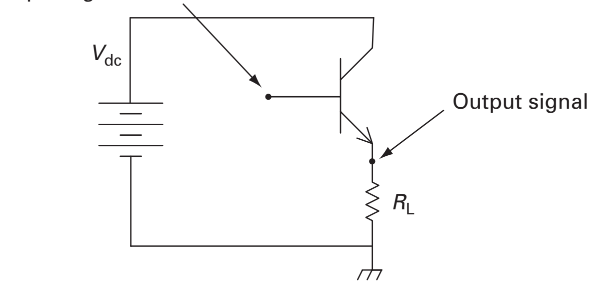

Figure 3.2. The emitter follower.

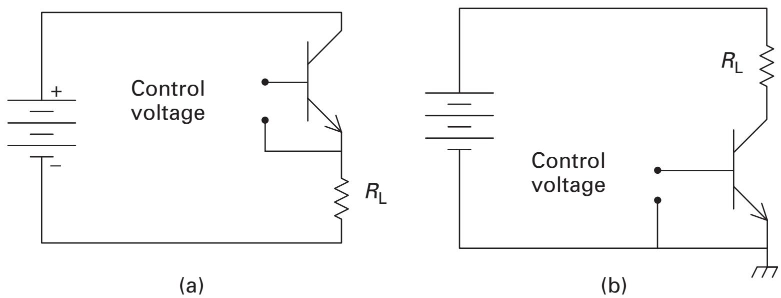

Figure 3.3. Common-emitter amplifier.

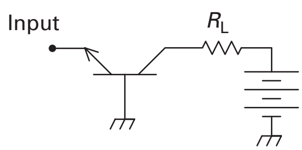

Figure 3.4. Common-base amplifier.

With the drive voltage placed directly across the base-emitter junction, the transistor current is a nonlinear (exponential) function of the drive voltage, and the output voltage (voltage across the load) will not be an accurate scaled version of the drive voltage. A special driver circuit can be used to generate an inverse exponential (logarithmic) drive signal to linearize the amplifier. This happens automatically if the base drive is a current waveform; the output current (and hence the voltage across the load) will have the same waveform shape as the base current. It is also common to use a negative feedback correction loop to force the output signal to follow the input signal. The common-emitter amplifier can supply voltage amplification as well as power amplification.

The third and final base drive arrangement, common-base, is shown in Figure 3.4. In this circuit the drive current flows through the main loop. Gain is obtained because, while the driver and load have essentially the same current (the base current might be only one percent as large as the collector-emitter current), the voltage swing at the collector, determined by the supply voltage, is much greater than the voltage swing at the emitter, determined by the near short-circuit base-emitter junction.

Note that, as in the common-emitter amplifier, the drive signal is applied across the transistor's base-to-emitter junction, so the signal developed across the load resistor will be a nonlinear function of the input voltage. But if the drive voltage is applied to the emitter through a series resistor, the drive current and, hence, the output current, will be essentially proportional to the drive voltage.

3.3 Shunt amplifier topology

In the amplifiers discussed above, the load current is controlled by a transistor in series with the load and the power supply. Another way to vary the current in the load is to divert current around it, as in the shunt circuit amplifier shown in Figure 3.5, where the supply and a series resistor form a (nonideal) current source.

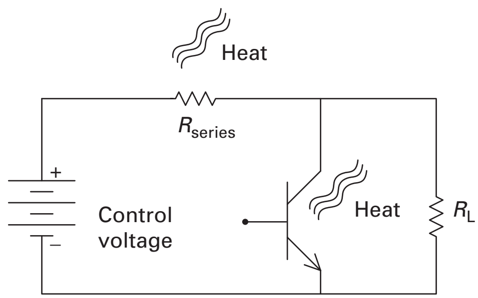

Figure 3.5. Shunt amplifier.

This shunt circuit appears inferior to the series circuit; power will be wasted in the series resistor and the full supply voltage is not available to the load. We will see later, however, that shunt circuits can be used to advantage in *ac* amplifiers which, unlike the general-purpose amplifiers above, are amplifiers designed for signals whose average dc value is zero, e.g., audio and RF signals.

3.4 Dual-polarity amplifiers

If the amplifier must supply output voltages of either polarity and also must handle arbitrary waveforms (as opposed to ac waveforms, whose average dc value is zero) it will require a circuit with two power supplies (or a single "floating" power supply, as we shall see later). The two-loop circuit shown in Figure 3.6 still uses only one transistor.

Here R_B pulls the output toward the negative supply as much as the transistor allows. The voltage on the load is determined by a tug of war between R_B and the transistor. Note that this circuit is a combination of the series and shunt amplifier arrangements. If we make $V_{NEG} = -2\ V_{POS}$ and $R_B = R_L$, you can see

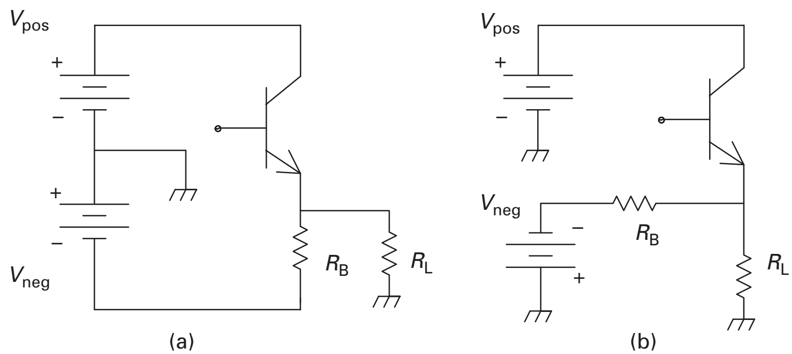

Figure 3.6. A dual-supply, single-transistor amplifier (drawn in two ways).

that the maximum negative swing will be equal to the maximum positive swing. A constant *bias* current is maintained in the transistor to set the output voltage at zero when the input signal is zero. The maximum efficiency is calculated in the next section, and is only $\frac{1}{12}$. Biased amplifiers (this one and everything discussed so far), which draw current from the supply(s) even when the input signal is zero, are known as *class-A* amplifiers. They are commonly used where their low efficiency is not a problem.

3.5 Push–pull amplifiers

The two-transistor *push–pull* configuration shown in Figure 3.7 provides output voltage of both polarities and has high efficiency compared to the single-transistor amplifiers. (Note: non-push–pull amplifiers are often called “single-ended” amplifiers.)

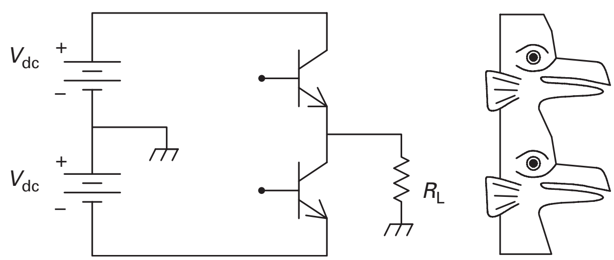

Figure 3.7. Totem pole push–pull amplifier.

The top transistor allows the top supply to “push” current into the load. The lower transistor lets the lower supply “pull” current from the load. The push–pull circuit is the circuit of choice for arbitrary waveforms. The efficiency, calculated in the next section, is $\pi/4$ (78%) for a sine wave of maximum amplitude. Since there are no series resistors, both positive and negative load currents are limited only by the size of the transistors and power supplies. By contrast, the single-transistor circuit of Figure 3.6 can deliver high positive

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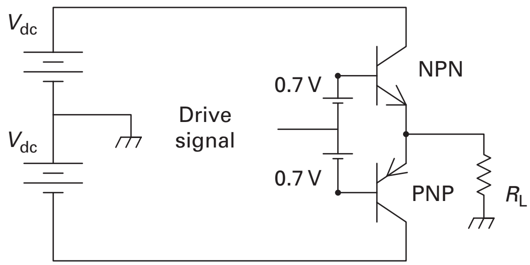

Figure 3.8. Complementary (PNP/NPN) push–pull amplifier.

current but the maximum negative current is limited by R_B.[2] Push–pull amplifiers are normally set up to run as *class-B* amplifiers, which means that, when the input voltage is zero, both transistors are just turned off and there is no power drawn from the supply(s). For low distortion, it is important that the crossover at $I=0$ be continuous, so sometimes push–pull amplifiers are run class-AB which means that each transistor is given some bias current. Note that the amplifier of Figure 3.7 uses two NPN transistors, placed one above the other like faces on a totem pole. The top transistor acts as an emitter follower; when it is conducting, the output voltage will be almost equal to that transistor's base voltage. The bottom transistor, however, is driven in the common-emitter mode. The two transistors need drive signals of opposite polarities and present different drive impedances, requiring separate and different drive circuits. This unappealing asymmetry is eliminated in the complementary push–pull amplifier shown in Figure 3.8.

The complementary push–pull amplifier uses an NPN and a complementary (identical, except for polarity) PNP transistor. Both operate as emitter followers. Except for the 0.7 V offsets, their bases could be tied together. This can be taken care of, as shown in the figure, by using a pair of 0.7 V batteries. (In practice, this is done with some diode circuitry, rather than batteries.) There is no vacuum tube analog to this circuit, because there are no PNP tubes.[3] For completeness, we note that a third type of push–pull amplifier is obtained by interchanging the transistors in the complementary push–pull amplifier. This circuit, in which both transistors are driven in the common-emitter mode, is found in some switching (one transistor full-on while the other is full-off) servo amplifiers.

So-called bridge amplifiers are shown in Figure 3.9(a). They use a single power supply, but can supply the load with either polarity.

[2] As long as the load is a pure resistor, the pull-down resistor, R_B, is not a problem; any waveform not exceeding the power supply voltage limits can be faithfully amplified. But if the load contains an unavoidable capacitance C_L in parallel with R_L, the amplifier must be able to deliver current $V_{out}/R_L + C_L\,\mathrm{d}/\mathrm{d}t\,(V_{out})$. See Problem 3.6.

[3] The charge carriers in semiconductors are both electrons (negative) and "holes" (positive). Vacuum tubes use only electrons as charge carriers, although unwanted positive ions are sometimes produced by electron impact.

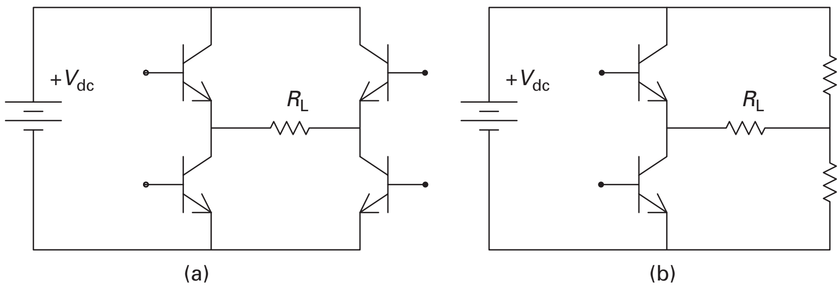

Figure 3.9. Bridge amplifiers: (a) full bridge (b) half bridge.

These circuits have no direct connection between the power supply and the load; either the supply or the load must "float," i.e., have no ground connection. In the circuit of Figure 3.9(a), the top pair or bottom pair of transistors can operate as on–off switches (fully conducting or fully turned off). This circuit is a true push–pull amplifier, while the half bridge of Figure 3.9(b) is equivalent to a push-pull amplifier that has resistors in series with the power supples. This reduces the maximum voltage swing as well as the efficiency.

3.6 Efficiency calculations

As we are assuming that the drive power is small compared to the output power, we will calculate efficiency as the ratio of the average output power to the dc input power. Depending on the devices used, this ratio is known as the *collector efficiency*, *drain efficiency*, or *plate efficiency*. Most often, we want to compute the efficiency for the situation in which the amplifier is producing a sinusoidal output at full power (the condition for which the efficiency is usually a maximum).

When calculating efficiency, it is important to remember that average power is the time average of instantaneous power, i.e., the time average of voltage × current. Consider, for example, a power supply of voltage V_{dc} that is furnishing a current $I = I_0 + I_1\cos(\omega t)$. The average power is $\langle V_{dc}(I_0 + I_1\cos(\omega t))\rangle$, where the brackets $\langle\ldots\rangle$ indicate averaging. Since the average of a sum is equal to the sum of the averages, we can expand this expression.

$$\langle V_{dc}(I_0 + I_1\cos(\omega t))\rangle = \langle V_{dc}I_0\rangle + \langle V_{dc}I_1\cos(\omega t)\rangle = V_{dc}I_0, \tag{3.1}$$

since the average value of $\cos(\omega t)$ is zero. When a sine wave $V_0\sin(\omega t)$ is applied to a resistor, the instantaneous power is $VI = [V_0 \sin(\omega t)]^2 / R$ and the average power is $V_0^2\langle\sin^2(\omega t)\rangle / R = V_0^2 / (2R)$.[4] It is also useful to remember that $\langle\sin(\theta)\cos(\theta)\rangle = 0$ and that the average value of $\sin(\theta)$ or $\cos(\theta)$ over one positive loop is equal to $2/\pi$.

[4] To see that $\langle\sin^2(\theta)\rangle = 1$, note that $\langle\sin^2(\theta)\rangle = \langle\cos^2(\theta)\rangle$, since the waveforms are identical, and use the identity $\sin^2(\theta) + \cos^2(\theta) = 1$.

We will first calculate the efficiency of the amplifier of Figure 3.6, under the conditions that $R_B = R_L$, $V_{pos} = V_{dc}$, and $V_{neg} = -2V_{dc}$. Let I_L denote the current downward into the load; I_B, the bias current leftward into R_B; and I_E, the current downward from the emitter. Note that $I_E = I_L + I_B$. Assume the maximum signal condition: $V_L = V_{dc}\cos(\omega t)$. This lets us write $I_B = (V_{dc}\cos(\omega t) + 2V_{dc})/R_B$. The power from the negative supply is therefore $P_{neg} = \langle I_B\ 2V_{dc}\rangle = 4{V_{dc}}^2/R_B$. The current into the load is just $I_L = V_{dc}\cos(\omega t)/R_L$. Adding I_L and I_B, we have $I_E = V_{dc}\cos(\omega t)/R_L + (V_{dc}\cos(\omega t) + 2V_{dc})/R_B$. Since this is the same as the current supplied by the positive supply (ignoring the transistor's small base current), we find that the power from the positive supply is given by $P_{pos} = 2{V_{dc}}^2/R_B$. The total dc power, P_{dc}, is the sum of P_{pos} and P_{neg}: $P_{dc} = 6{V_{dc}}^2/R_B$. The power into the load is ${V_0}^2/(2R_L)$, so the efficiency is given by

$$\eta = \frac{{V_{dc}}^2/(2R_L)}{6{V_{dc}}^2/R_B} \tag{3.2}$$

which reduces to $\eta = \frac{1}{12}$ when $R_B = R_L$.

Next we will find the efficiency of the push–pull amplifiers of Figures 3.7 and 3.8. Again, we assume the maximum signal condition, $V_L = V_{dc}\cos(\omega t)$. Consider the top transistor, which conducts during the positive half of the cycle. Assuming negligible base current, the current through this transistor will be the same as the current in the load, $I = (V_{dc}\cos(\omega t))/R_L$. During the positive half-cycle, the positive supply furnishes an average power given by $\langle V_{dc} \times (V_{dc}/R_L)\cos(\omega t)\rangle = ({V_{dc}}^2/R_L)\,2/\pi$, since here the average is just over the positive loop. The negative supply, during its half-cycle, furnishes the same average power, since the circuit is symmetric. Thus, the efficiency is given by

$$\eta = \frac{{V_{dc}}^2/(2R_L)}{({V_{dc}}^2/R_L)2/\pi} = \frac{\pi}{4} = 78\%. \tag{3.3}$$

3.7 AC amplifiers

All the amplifiers discussed above are known as *dc amplifiers* because they can handle signals of arbitrarily low frequency. (They might well be called universal amplifiers since they have no high-frequency limitations except those set by the transistors.) Audio and RF signals, however, are pure ac signals: their average value, i.e., their dc component, is zero. For these signals, special *ac amplifier* circuits provide simplicity and efficiency.

The circuit in Figure 3.10(a) is an ac version of the class-A amplifier of Figure 3.6. The drive signal at the base is given a positive offset (bias) which will create the same bias voltage at the emitter and a bias current through the pull-down resistor, R_E. The coupling capacitor (*dc blocking capacitor*) eliminates the dc bias from the load, and the output signal swings both positive and

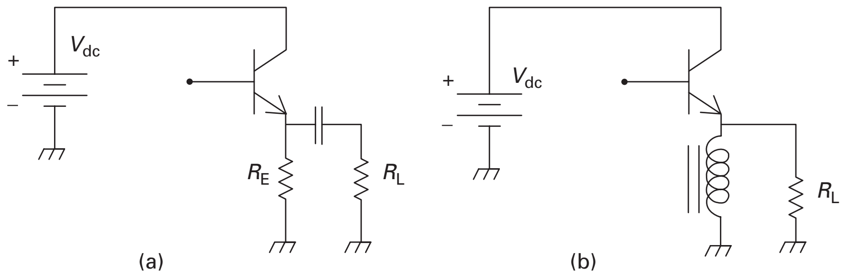

Figure 3.10. Common-collector single-ended ac amplifiers.

negative. The capacitance is chosen to be high enough that the full ac signal at the emitter will appear at the load. Only one power supply is required for this ac version. If $R_E = R_L$, the maximum peak-to-peak output swing is 2/3 V_{dc} and efficiency is again only $\frac{1}{12}$.

A major improvement is to replace the power-dissipating pull-down resistor with an inductor (ac *choke*) as shown in Figure 3.10(b). The inductor allows the output to go negative as well as positive[5] and makes possible a maximum output swing from $-V_{dc}$ to $+V_{dc}$. The inductance is chosen to be high enough to eliminate currents at the signal frequencies. No capacitor is needed; assuming the choke has negligible dc resistance, the average dc on the load will be zero. There must be sufficient bias current through the inductor to keep the transistor always on for the continuous control needed in linear operation. You can calculate (Problem 3.1) that the maximum efficiency of this circuit is 50%; the inductor improves the efficiency by a factor of 6 and the output swing by a factor of 3.

It might seem that the maximum efficiency of the class-B amplifier (78%) is only slightly better than the maximum efficiency of this class-A amplifier (50%). But these maximum efficiencies apply only when the amplifier is delivering a sine wave of maximum amplitude. For speech and music, the average power is much less than the maximum power. The class-B amplifier has little dissipation when the signal is low but a class-A amplifier, with its constant bias current, draws constant power equal to twice the maximum output power. A class-A audio amplifier rated for 25 watts output would consume a continuous 50 watts from its supply while a class-B amplifier of equal power rating would consume, on average, only a few watts, since the average power of audio signals is much lower than the peak power.

Common-emitter versions of this class-A amplifier are shown in Figure 3.11. The circuit of Figure 13.11(b) uses the shunt amplifier topology of Figure 3.5. Here, the inductor provides a wideband constant current source. (If the signal has a narrow bandwidth (RF), a parallel-resonant *LC* circuit will serve the same

[5] The bias current flowing downward in the inductor is essentially constant since the inductance is large. At the part(s) of the cycle when the current through the transistor becomes less than the inductor current, the inductor maintains its constant current by "sucking" current out of the load resistor and thus producing the negative output voltage.

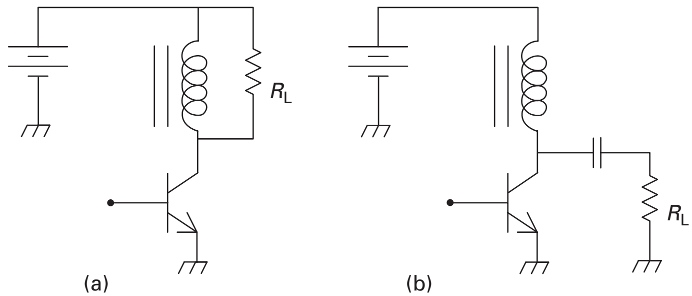

Figure 3.11. Common-emitter single-ended ac amplifiers.

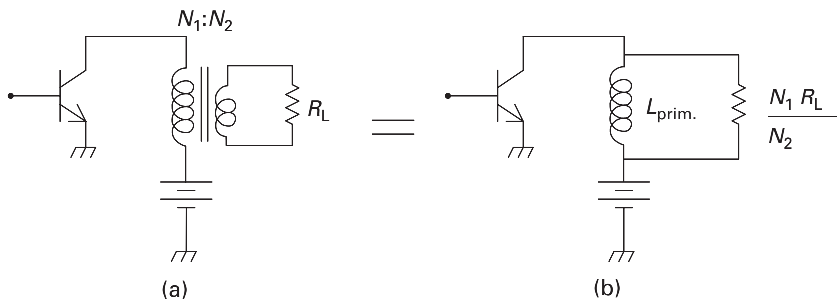

Figure 3.12. Transformer-coupled single-ended ac amplifier.

purpose.) A blocking capacitor allows one end of the load to be grounded, which is often a convenience. As we have seen, current drive is called for to achieve linearity if the emitter is tied directly to ground. At the expense of some efficiency, however, the emitter can be tied to ground through a resistor to allow the emitter voltage to follow the drive (base) voltage. Then the emitter current, collector current, and output voltage will all be linearly proportional to the input voltage. This technique of linearizing a common-emitter amplifier is known as "emitter degeneration" or "series feedback." To its credit, the common-emitter arrangement requires only a small and always positive drive signal, whereas the circuit of Figure 3.10(b) requires a drive voltage identical to the output signal, swinging both positive and negative.

Often the resistance of a given load is unsuitable for obtaining the desired power with the given power supply voltage. In this case, the choke and blocking capacitor can be replaced by a transformer as shown below in Figure 3.12.

This circuit is equivalent to that of Figure 13.11(a). The equivalence is shown in (b). Note how the load resistor is R_L, multiplied by the square of the transformer turns ratio. The transformer's primary winding provides the inductor. Again, these choke-coupled and transformer-coupled class-A amplifiers can provide a peak-to-peak collector swing of twice V_{dc}. Note that if we used only the simple "ideal transformer" model to replace the load resistor by its transformed value, we would have no inductance and would predict a maximum

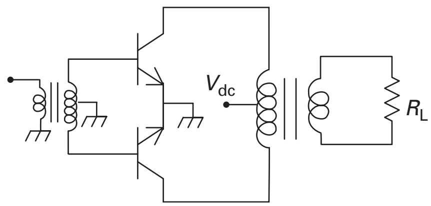

Figure 3.13. Symmetric transformer-coupled push–pull ac amplifier.

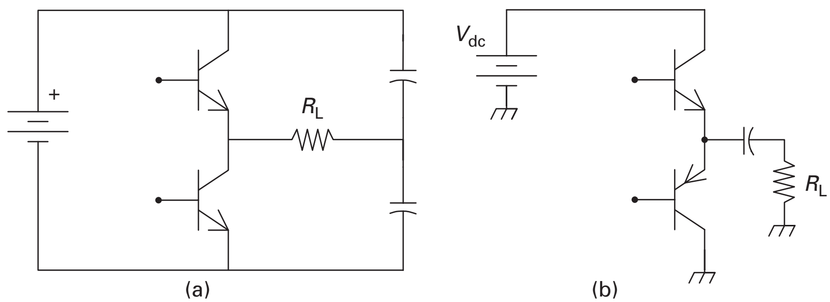

Figure 3.14. Half-bridge ac amplifier (a) and an equivalent version (b).

peak-to-peak swing of only V_{dc} (see Chapter 14). A center-tapped transformer can be used to make the symmetric push–pull amplifier shown in Figure 3.13.

This push–pull circuit, like the transformerless push–pull circuits, can be operated class B for high efficiency. Some high-power tube-type audio and RF amplifiers use this symmetric transformer circuit. Note the use of a center-tapped driver transformer – one way to supply the bases with the required opposite polarity signals.

Transistor audio amplifiers are usually push–pull and transformerless. They can be built with a single power supply by using capacitor coupling, as in the half-bridge circuit shown below in Figure 3.14(a). The circuit of Figure 3.14(b) is equivalent and uses only a single capacitor. The transistors can be in either the totem pole arrangement (a), or in the complementary NPN/PNP arrangement (b).

Since an audio or RF waveform has no dc component, the capacitors each charge to half the supply voltage and are equivalent to batteries. The capacitors thus form an artificial center tap for the power supply so this is an efficient push–pull amplifier, unlike the resistive half-bridge circuit of Figure 3.9(b).

3.8 RF amplifiers

RF amplifiers form a subset of ac amplifiers. RF signals are narrowband ac signals. Besides having no dc component, they have an almost constant waveform; while the amplitude and phase can vary, the shape remains sinusoidal.

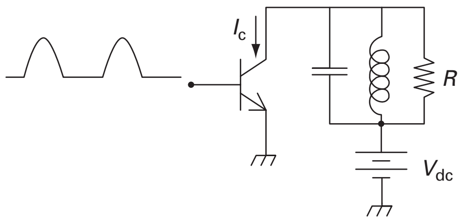

Figure 3.15. Single-ended class-B RF amplifier.

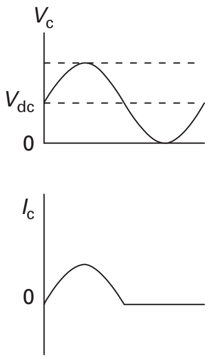

Figure 3.16. Collector voltage and current in the single-ended class-B RF amplifier.

This makes it possible to build a class-B RF amplifier with only a single transistor. The circuit (which looks no different from a class-A amplifier, except for the input waveform) is shown in Figure 3.15.

Here the transistor "pulls" current from the load, but there is no pusher transistor. Instead, a parallel resonant *LC* circuit provides a flywheel (energy storage) effect which maintains the sinusoidal waveform during the half-cycle in which the transistor is not conducting. The drive waveform consists only of positive loops. Between these loops, the transistor is nonconducting. This amplifier has the same 78% maximum efficiency of a push–pull class-B amplifier and also the class-B virtue of drawing no power when the signal level is zero. Let us analyze this circuit. Assume that, during the active half-cycle, the transistor current is $I_0 \sin(\theta)$, where $\theta = \omega t$ and I_0 is to be determined. Assume the resonant circuit provides enough energy storage (high enough Q) that the output voltage (the voltage across the load resistor) can be written as $A \sin(\theta)$. The output power is therefore $A^2/(2R)$. These voltage and current waveforms are shown in Figure 3.16.

During the active half-cycle, the power (*IV* product) into the *RCL* parallel circuit is $I_0 \sin(\theta) A \sin(\theta)$. Over a cycle, this averages to $I_0 A/4$, where one factor of $\frac{1}{2}$ is the time average of $\sin^2(\theta)$ and the other factor of $\frac{1}{2}$ comes from the transistor being turned off during half of every cycle. The power delivered to the parallel circuit must be equal to the power delivered to the load:

$$\frac{I_0 A}{4} = \frac{V_{dc}{}^2}{2R}. \tag{3.4}$$

From this we find $I_0 = 2A/R$. We can calculate the power delivered by the supply by noting that over the half-cycle, the instantaneous power is $V_{dc} I_0 \sin(\theta)$. The average over the half-cycle is $V_{dc}\, I_0\, 2/\pi$ and the average over the entire cycle is again half of this or $V_{dc}\, I_0/\pi = V_{dc}\, 2A/(\pi R)$. The efficiency, power out divided by power supplied by the supply, is therefore

$$\eta = \frac{A^2/(2R)}{V_{dc} 2A/(\pi R)} = \frac{A}{V_{dc}} \frac{\pi}{4}. \tag{3.5}$$

At the maximum output, where $A = V_{dc}$, the efficiency of this "single-ended" class-B amplifier is $\pi/4$, the same as the maximum efficiency for a push–pull class-B amplifier.

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The circuit of Figure 3.15, if made to conduct throughout the complete cycle, would be a class-A amplifier. The *LC* would not be needed as a flywheel, but it does act as a bandpass filter. Moreover, the inductance, or part of it, serves to cancel out the unavoidable collector-to-emitter parasitic capacitance inherent in the transistor.

3.9 Matching a power amplifier to its load

In Chapter 2 we saw that, for maximum power transfer, a load should have the same impedance as the source that drives it. However, the power amplifiers discussed in this chapter all have essentially zero output impedances. Their Thévenin equivalent circuits are almost perfect voltage generators. Do we therefore try to make the load resistances as low as possible? No. The amplifiers are designed to deliver a specified power to a specified load. This determines the power supply voltages and current capacities and the required current-handling capacity of the transistor(s). Therefore, power amplifiers are deliberately mismatched to their loads. But a power amplifier does still have some very small output impedance. Won't it therefore supply the most power to a load of that impedance? The answer is yes, as long as the amplitude is kept very low. If the amplitude is turned up, such a load will simply "short out" the amplifier.

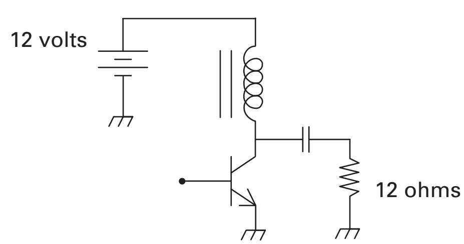
The output amplifier in a transmitter usually includes an impedance transforming network, often called an *antenna tuner*. The purpose of this network is *not* to make the antenna impedance equal to the amplifier's very low output impedance. Rather, the network transforms the antenna impedance to the impedance needed for the amplifier to produce its rated power.

Problems

Problem 3.1. Calculate efficiency of the class-A amplifier of Figure 3.10(b). Assume the output is a sine wave whose peak-to-peak amplitude is $2V_{dc}$, symmetric about $V = 0$.

Assume that the dc bias current in the inductor is just enough to allow the amplifier to produce the maximum signal.

Problem 3.2. The class-A amplifier shown below is operating at maximum power, applying a 24-volt peak-to-peak sine wave to the load resistor.



Assume the choke has zero dc resistance and enough inductance to block any ac current and that the capacitor has enough susceptance to prevent any ac voltage drop.

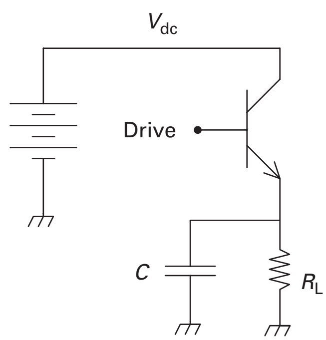
(a) Draw the waveform of the collector voltage. Hint: Remember that there can be no dc voltage drop across the choke.
(b) Draw the waveform of the collector current. Hint: Remember that there is no ac current through the choke.
(c) What power is drawn from the supply under the maximum signal sine wave condition?
(d) Show that the efficiency under this maximum signal sine wave condition is 50%.
(e) What power is drawn from the supply if the signal is zero?

Problem 3.3. An ideal push–pull amplifier does not have the current limitation of the emitter follower, so it can drive capacitive loads at high frequencies. But what about inductive loads? Suppose a load has an unavoidable series inductance but large voltages at high frequencies must be produced across the resistive part of the load. How does this impact the amplifier design?

Problem 3.4. Justify the statements made about the voltage gain (about 99%) and the offset (about 0.7 volts) of the emitter follower. Use the relation between the emitter current and base-to-emitter voltage of a (bipolar) transistor, $I \approx I_{sat}\exp([V_b - V_e]/0.026)$. To get a value for I_{sat}, assume that $I = 10$ ma when $V_b - V_e = 0.7$ volts. Remember that in the emitter follower, $V_e = I_e R$. Assume a reasonable value for R such as 1000 ohms and find V_e for several values of V_b.

Problem 3.5. Find the power gain of an emitter follower, i.e., the ratio of output signal power to input signal power. Use the fact that the input current (base current) is less than the emitter current by a factor $1/(\beta+1)$ where β is the transistor's current gain (typically on the order of 100). Remember that the output voltage is essentially the same (follows) the input voltage.

Problem 3.6. The emitter follower amplifier shown below has a load which includes an unavoidable parallel capacitance.



(a) What is the maximum peak-to-peak voltage that can be delivered to the load at low frequencies (where the capacitor can be neglected)?
(b) At what frequency will a sine-wave output signal of half the maximum amplitude become distorted? Hint: Express the emitter current as the sum of the resistor current

and capacitor current and note that distortion will occur if this current should ever be negative (the transistor can only supply positive current). Answer: $\omega = \sqrt{3(RC)}$.

Problem 3.7. Consider the push–pull amplifier of Figure 3.8 when it is being driven by a sine-wave signal, $V(t) = V_0 \sin(\omega t)$, and is connected to a load that is an inductor, L, rather than a resistor. Draw a graph showing the current flowing into the inductor and the individual emitter currents flowing in the direction of the load. Based on your graph, would you agree with the statement: The top transistor applies positive voltage to the load and the bottom transistor applies negative voltage to the load?

Problem 3.8. The maximum efficiency (the efficiency when the signal is a maximum-amplitude sine wave) of the amplifier in Figure 3.6 is $\frac{1}{12}$ when $R_B = R_L$ and $V_{NEG} = -2V_{POS}$.

(a) Calculate the maximum efficiency when $R_B = \sqrt{2} R_L$ and $V_{NEG} - (1 + \sqrt{2})\ V_{POS}$.

(b) Show that this combination of R_B and V_{NEG} yields the greatest maximum efficiency.

Problem 3.9. Draw a circuit for a "double push–pull" amplifier with four transistors. Two of the transistors connect the load to supply voltages $V_{dc}/2$ and $-V_{dc}/2$. The other two transistors connect the load to a second pair of supplies with voltages V_{dc} and $-V_{dc}$. The transistors connecting the smaller power supplies are turned off (nonconducting) when $|V_{out}| > V_{dc}/2$ and the transistors connecting the larger power supplies are turned off when $|V_{out}| < V_{dc}/2$. Calculate the efficiency when the output is a sine wave swinging from $-V_{dc}$ to $+V_{dc}$. This circuit is sometimes called a class-K amplifier.