x7

EXTRA TOPICS RELATED TO

Waverform Generation and Shaping

This supplement contains material removed from previous editions of the textbook. These topics continue to be relevant and for this reason will be of great value to many instructors and students.

The topics presented here build on and extend the material on nonlinear oscillators presened in Section 15.4 of the eighth edition.

x7.1 Generating a Standardized Pulse: The Monostable Multivibrator

In some applications the need arises for a pulse of known height and width generated in response to a trigger signal. Because the width of the pulse is predictable, its trailing edge can be used for timing purposes—that is, to initiate a particular task at a specified time. Such a standardized pulse can be generated by the third type of multivibrator, the **monostable multivibrator**.

The monostable multivibrator has one stable state in which it can remain indefinitely. It also has a quasi-stable state to which it can be triggered and in which it stays for a predetermined interval equal to the desired width of the output pulse. When this interval expires, the monostable multivibrator returns to its stable state and remains there, awaiting another triggering signal. The action of the monostable multivibrator has given rise to its alternative name, the *one-shot*.

Figure x7.1(a) shows an op-amp monostable circuit. We observe that this circuit is an augmented form of the astable circuit of Fig. 15.23(b) in the eighth edition of the textbook. Specifically, a clamping diode D_1 is added across the capacitor C_1, and a trigger circuit composed of capacitor C_2, resistor R_4, and diode D_2 is connected to the noninverting input terminal of the op amp. The circuit operates as follows: In the stable state, which prevails in the absence of the triggering signal, the output of the op amp is at

L_+ and diode D_1 is conducting through R_3 and thus clamping the voltage v_B to one diode drop above ground. We select R_4 much larger than R_1, so that diode D_2 will be conducting a very small current and the voltage v_C will be very closely determined by the voltage divider R_1, R_2. Thus $v_C = \beta L_+$, where $\beta = R_1/(R_1 + R_2)$. The stable state is maintained because βL_+ is greater than V_{D1}.

Now consider the application of a negative-going step at the trigger input and refer to the signal waveforms shown in Fig. x7.1(b). The negative triggering edge is coupled to the cathode of diode D_2 via capacitor C_2, and thus D_2 conducts heavily and pulls node C down. If the trigger signal is of sufficient height to cause v_C to go below v_B, the op amp will see a net negative input voltage and its output will switch to L_-. This in turn will cause v_C to go negative to βL_-, keeping the op amp in its newly acquired state. Note that D_2 will then cut off, thus isolating the circuit from any further changes at the trigger input terminal.

The negative voltage at A causes D_1 to cut off, and C_1 begins to discharge exponentially toward L_- with a time constant C_1R_3. The monostable multivibrator is now in its *quasi-stable state*, which will prevail until the declining v_B goes below the voltage at node C, which is βL_-. At this instant the op-amp output switches back to L_+ and the voltage at node C goes back to βL_+. Capacitor C_1 then charges toward L_+ until diode D_1 turns on and the circuit returns to its stable state.

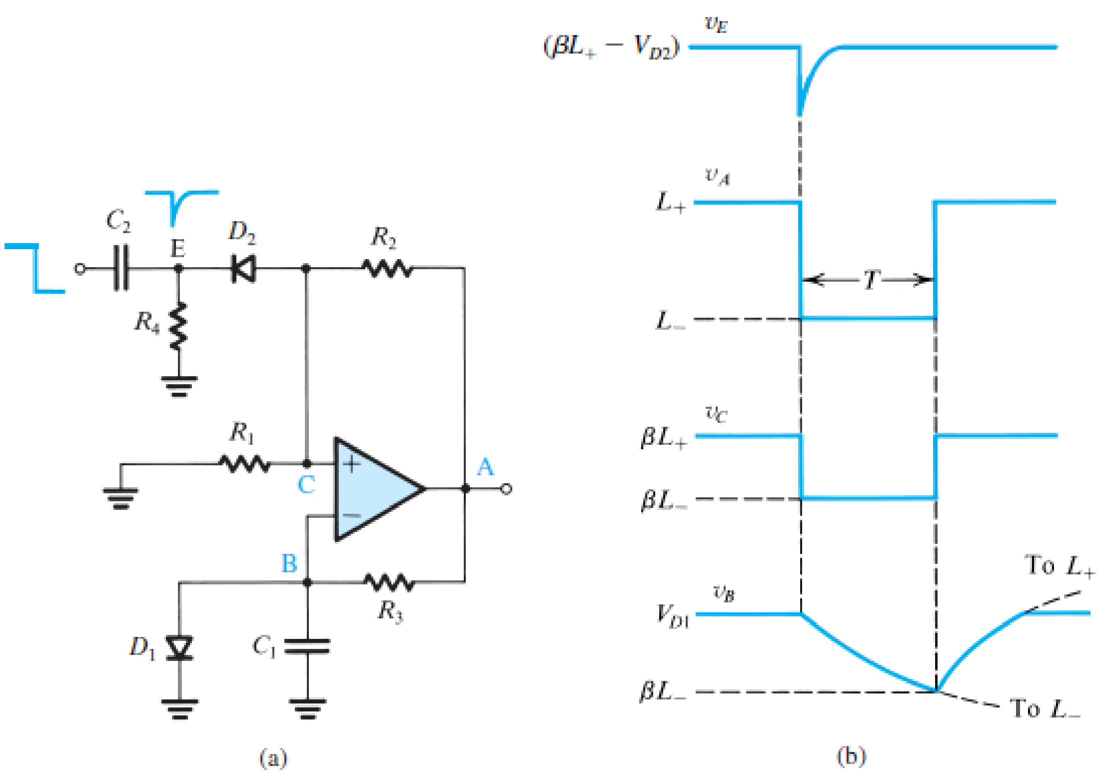

Figure x7.1 **(a)** An op-amp monostable circuit. **(b)** Signal waveforms in the circuit of (a).

From Fig. x7.1(b), we observe that a negative pulse is generated at the output during the quasi-stable state. The duration T of the output pulse is determined from the exponential waveform of v_B,

$$v_B(t) = L_- - (L_- - V_{D1})e^{-t/C_1R_3}$$

by substituting $v_B(T) = \beta L_-$,

$$\beta L_- = L_- - (L_- - V_{D1})e^{-T/C_1R_3}$$

which yields

$$T = C_1R_3 \ln\left(\frac{V_{D1} - L_-}{\beta L_- - L_-}\right) \qquad \text{(x7.1)}$$

For $V_{D1} \ll |L_-|$, this equation can be approximated by

$$T \simeq C_1R_1 \ln\left(\frac{1}{1-\beta}\right) \qquad \text{(x7.2)}$$

Finally, note that the monostable circuit should not be triggered again until capacitor C_1 has been recharged to V_{D1}; otherwise the resulting output pulse will be shorter than normal. This recharging time is known as the **recovery period**. Circuit techniques exist for shortening the recovery period.

EXERCISE

x7.1 For the monostable circuit of Fig. x7.1(a), find the value of R_3 that will result in a 100-μs output pulse for $C_1 = 0.1$ μF, $\beta = 0.1$, $V_D = 0.7$ V, and $L_+ = -L_- = 12$ V.

Ans. 6171 Ω

x7.2 Integrated-Circuit Timers

Commercially available integrated-circuit packages exist that contain the bulk of the circuitry needed to implement monostable and astable multivibrators with precise characteristics. In this section we discuss the most popular of such ICs, the **555 timer**. Introduced in 1972 by the Signetics Corporation as a bipolar integrated circuit, the 555 is also available in CMOS technology and from a number of manufacturers.

x7.2.1 The 555 Circuit

Figure x7.2 shows a block diagram representation of the 555 timer circuit (for the actual circuit, refer to Grebene, 1984). The circuit consists of two comparators, an SR flip-flop, and a transistor Q_1 that operates as a switch. One power supply (V_{CC}) is required for operation, with the supply voltage typically 5 V. A resistive voltage divider, consisting of the three equal-valued resistors labeled R_1, is connected across V_{CC} and establishes the

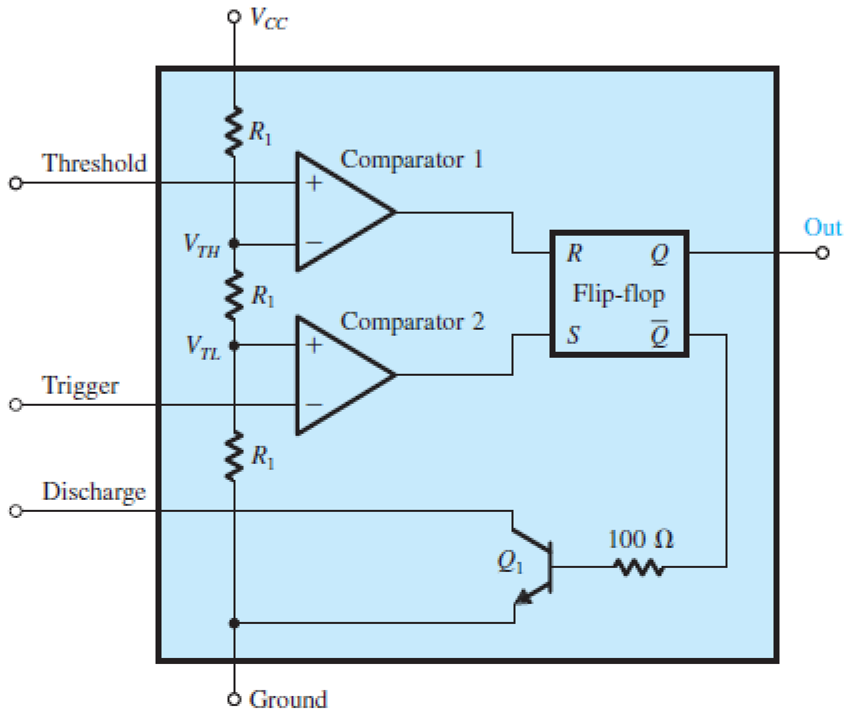

Figure x7.2 A block diagram representation of the internal circuit of the 555 integrated-circuit timer.

reference (threshold) voltages for the two comparators. These are $V_{TH} = \frac{2}{3}V_{CC}$ for comparator 1 and $V_{TL} = \frac{1}{3}V_{CC}$ for comparator 2.

SR flip-flops are studied in Chapter 18 of the textbook. For our purposes here we note that an SR flip-flop is a bistable circuit having complementary outputs, denoted Q and $\bar{Q}$. In the *set* state, the output at Q is "high" (approximately equal to V_{CC}) and that at $\bar{Q}$ is "low" (approximately equal to 0 V). In the other stable state, termed the *reset* state, the output at Q is low and that at $\bar{Q}$ is high. The flip-flop is set by applying a high level (V_{CC}) to its set input terminal, labeled S. To reset the flip-flop, a high level is applied to the reset input terminal, labeled R. Note that the reset and set input terminals of the flip-flop in the 555 circuit are connected to the outputs of comparator 1 and comparator 2, respectively.

The positive-input terminal of comparator 1 is brought out to an external terminal of the 555 package, labeled Threshold. Similarly, the negative-input terminal of comparator 2 is connected to an external terminal labeled Trigger, and the collector of transistor Q_1 is connected to a terminal labeled Discharge. Finally, the Q output of the flip-flop is connected to the output terminal of the timer package, labeled Out.

x7.2.2 Implementing a Monostable Multivibrator Using the 555 IC

Figure x7.3(a) shows a monostable multivibrator implemented using the 555 IC together with an external resistor R and an external capacitor C. In the stable state the flip-flop will be in the reset state, and thus its $\bar{Q}$ output will be high, turning on transistor Q_1. Transistor Q_1 will be saturated, and thus v_C will be close to 0 V, resulting in a low level at the output of comparator 1. The voltage at the trigger input terminal, labeled v_{trigger}, is kept high (greater than V_{TL}), and thus the output of comparator 2 also will be low. Finally, note that since the flip-flop is in the reset state, Q will be low and thus v_O will be close to 0 V.

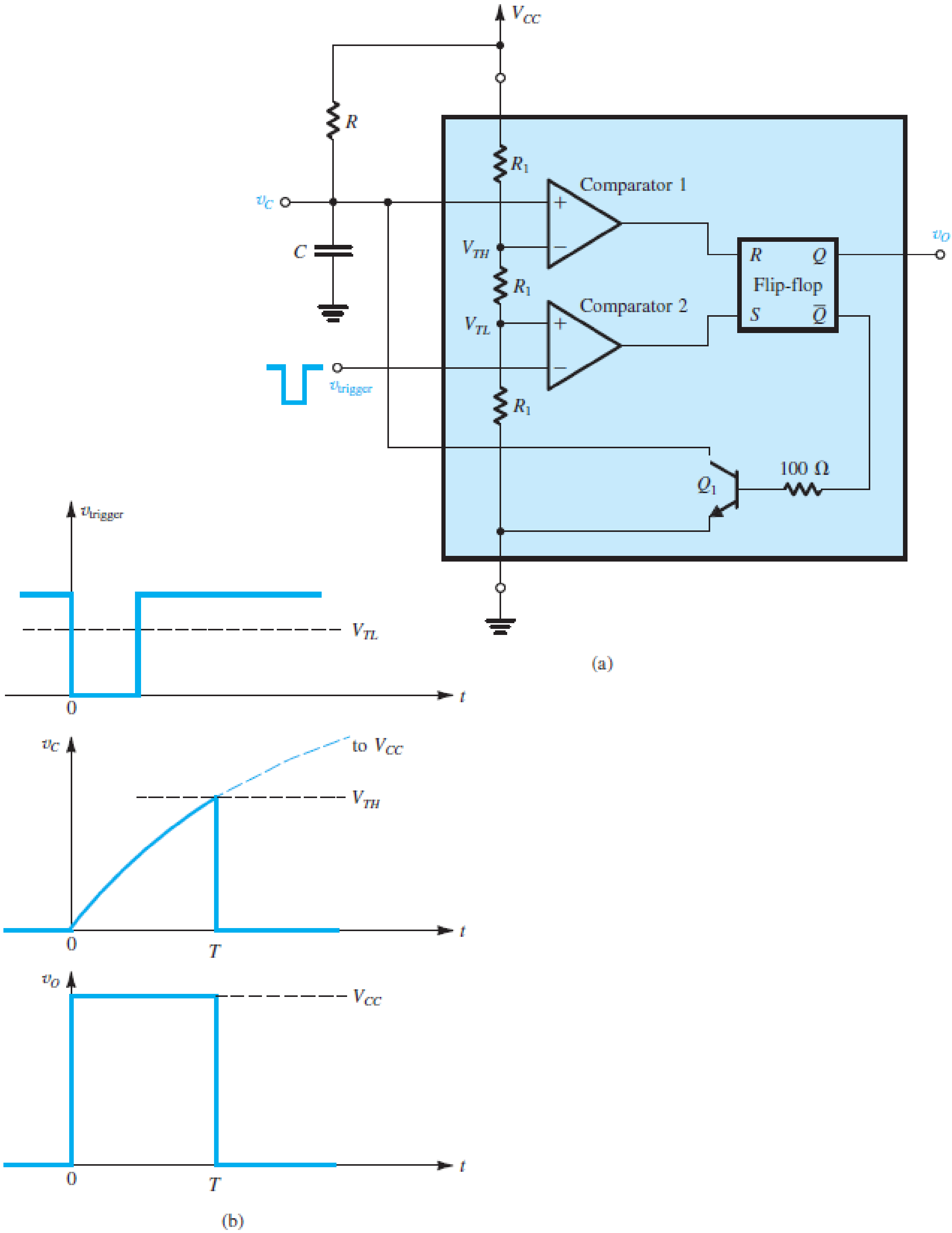

Figure x7.3 **(a)** The 555 timer connected to implement a monostable multivibrator. **(b)** Waveforms of the circuit in (a).

To trigger the monostable multivibrator, a negative input pulse is applied to the trigger input terminal. As v_{trigger} goes below V_{TL}, the output of comparator 2 goes to the high level, thus setting the flip-flop. Output Q of the flip-flop goes high, and thus v_O goes high, and output $\bar{Q}$ goes low, turning off transistor Q_1. Capacitor C now begins to charge up through resistor R, and its voltage v_C rises exponentially toward V_{CC}, as shown in Fig. x7.3(b). The monostable multivibrator is now in its quasi-stable state. This state prevails until v_C reaches and begins to exceed the threshold of comparator 1, V_{TH}, at which time the output of comparator 1 goes high, resetting the flip-flop. Output $\bar{Q}$ of the flip-flop now goes high and turns on transistor Q_1. In turn, transistor Q_1 rapidly discharges capacitor C, causing v_C to go to 0 V. Also, when the flip-flop is reset, its Q output goes low, and thus v_O goes back to 0 V. The monostable multivibrator is now back in its stable state and is ready to receive a new triggering pulse.

From the description above we see that the monostable multivibrator produces an output pulse v_O as indicated in Fig. x7.3(b). The width of the pulse, T, is the time interval that the monostable multivibrator spends in the quasi-stable state; it can be determined by reference to the waveforms in Fig. x7.3(b) as follows: Denoting the instant at which the trigger pulse is applied as $t = 0$, the exponential waveform of v_C can be expressed as

$$v_C = V_{CC}\left(1 - 3^{-t/CR}\right) \tag{x7.3}$$

Substituting $v_C = V_{TH} = \frac{2}{3}V_{CC}$ at $t = T$ gives

$$T = CR\ln 3 \simeq 1.1CR \tag{x7.4}$$

Thus the pulse width is determined by the external components C and R, which can be selected to have values as precise as desired.

x7.2.3 An Astable Multivibrator Using the 555 IC

Figure x7.4(a) shows the circuit of an astable multivibrator employing a 555 IC, two external resistors, R_A and R_B, and an external capacitor C. To see how the circuit operates, refer to the waveforms depicted in Fig. x7.4(b). Assume that initially C is discharged and the flip-flop is set. Thus v_O is high and Q_1 is off. Capacitor C will charge up through the series combination of R_A and R_B, and the voltage across it, v_C, will rise exponentially toward V_{CC}. As v_C crosses the level equal to V_{TL}, the output of comparator 2 goes low. This, however, has no effect on the circuit operation, and the flip-flop remains set. Indeed, this state continues until v_C reaches and begins to exceed the threshold of comparator 1, V_{TH}. At this instant of time, the output of comparator 1 goes high and resets the flip-flop. Thus v_O goes low, $\bar{Q}$ goes high, and transistor Q_1 is turned on. The saturated transistor Q_1 causes a voltage of approximately zero volts to appear at the common node of R_A and R_B. Thus C begins to discharge through R_B and the collector of Q_1. The voltage v_C decreases exponentially with a time constant CR_B toward 0 V. When v_C reaches the threshold of comparator 2, V_{TL}, the output of comparator 2, goes high and sets the flip-flop. The output v_O then goes high, and $\bar{Q}$ goes low, turning off Q_1. Capacitor C begins to charge through the series equivalent of R_A and R_B, and its voltage rises exponentially toward V_{CC} with a time constant $C(R_A + R_B)$. This rise continues until v_C reaches V_{TH}, at which time the output of comparator 1 goes high, resetting the flip-flop, and the cycle continues.

From this description we see that the circuit of Fig. x7.4(a) oscillates and produces a square waveform at the output. The frequency of oscillation can be determined as

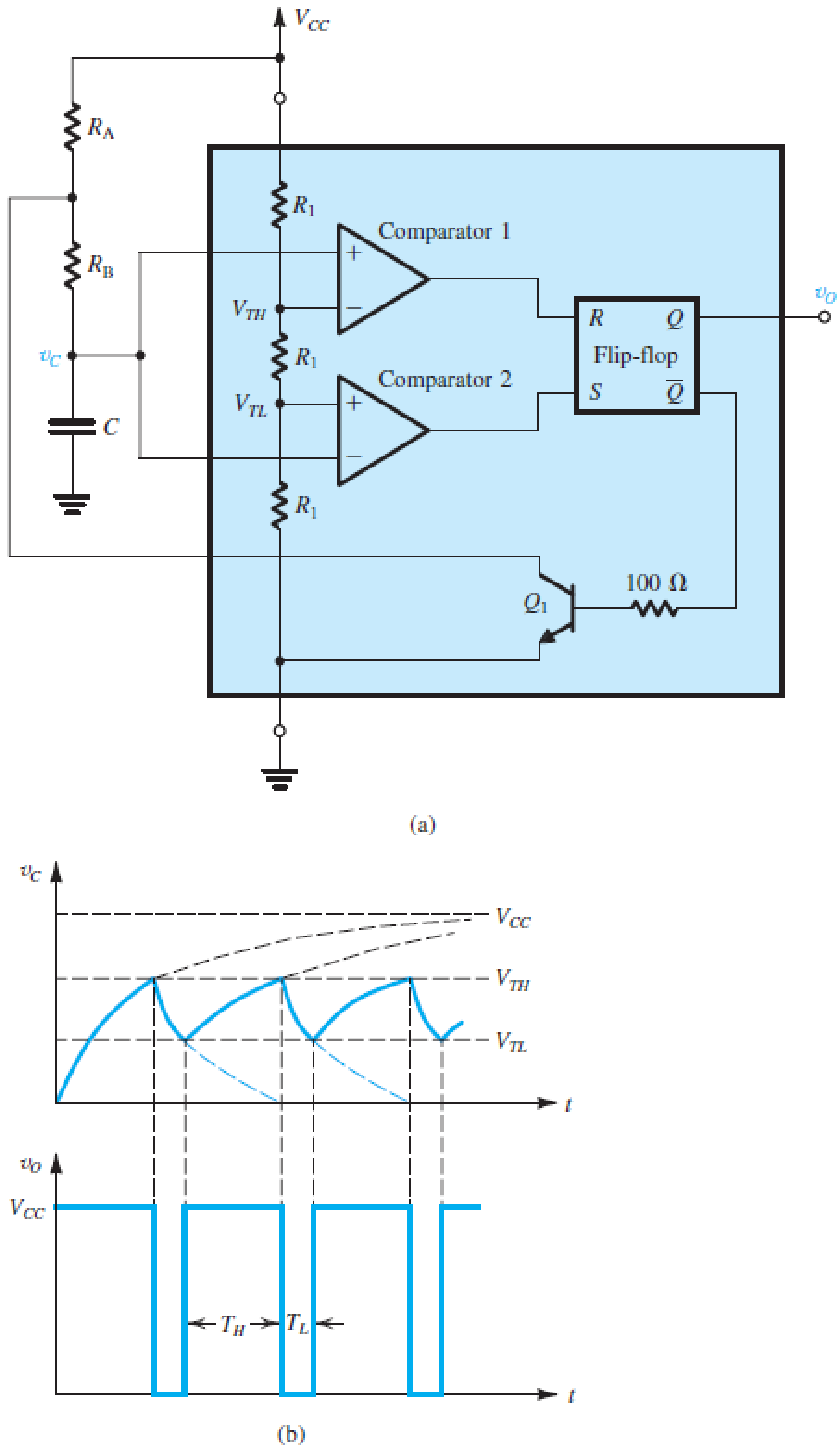

Figure x7.4 **(a)** The 555 timer connected to implement an astable multivibrator**. (b)** Waveforms of the circuit in (a).

follows. Figure. x7.4(b) shows that the output will be high during the interval T_H, where v_C rises from V_{TL} to V_{TH}. The exponential rise of v_C can be described by

$$v_C = V_{CC} - (V_{CC} - V_{TL})e^{-t/C(R_A+R_B)} \tag{x7.5}$$

where t = 0 is the instant at which the interval T_H begins. Substituteing $v_C = V_{TH} = ⅔V_{CC}$ at $t = T_H$ and $V_{TL} = ⅓V_{CC}$ results in

$$T_H = C(R_A + R_B)\ln 2 \simeq 0.69\,C(R_A + R_B) \tag{x7.6}$$

We also note from Fig. x7.4(b) that v_O will be low during the interval T_L, in which v_C falls toward zero, from V_{TH} to V_{TL}. The exponential fall of v_C can be described by

$$v_C = V_{TH}e^{-t/CR_B} \tag{x7.7}$$

where we have taken t = 0 as the beginning of the interval T_L. Substituting $v_C = V_{TL} = ⅓V_{CC}$ at $t = T_L$ and $V_{TH} = ⅔V_{CC}$ results in

$$T_L = CR_B \ln 2 \simeq 0.69\,CR_B \tag{x7.8}$$

Equations (x7.6) and (x7.8) can be combined to obtain the period T of the output square wave as

$$T = T_H + T_L = 0.69\,C(R_A + 2R_B) \tag{x7.9}$$

Also, the **duty cycle** of the output square wave can be found from Eqs. (x7.6) and (x7.8):

$$\text{Duty cycle} \equiv \frac{T_H}{T_H + T_L} = \frac{R_A + R_B}{R_A + 2R_B} \tag{x7.10}$$

Note that the duty cycle will always be greater than 0.5 (50%); it approaches 0.5 if R_A is selected to be much smaller than R_B (unfortunately, at the expense of increased supply current).

EXERCISES

xD7.2 Using a 10-nF capacitor C, find the value of R that yields an output pulse of 100 μs in the monostable circuit of Fig. x7.3(a).

Ans. 9.1 kΩ

xD7.3 For the circuit in Fig. x7.4(a), with a 1-nF capacitor, find the values of R_A and R_B that result in an oscillation frequency of 100 kHz and a duty cycle of 75%.

Ans. 7.2 kΩ, 3.6 kΩ

x7.3 Nonlinear Waveform-Shaping Circuits

Diodes or transistors can be combined with resistors to synthesize two-port networks having arbitrary nonlinear transfer characteristics. Such two-port networks can be employed in **waveform shaping**—that is, changing the waveform of an input signal in a prescribed manner to produce a waveform of a desired shape at the output. In this section we illustrate this application by a concrete example: the **sine-wave shaper**. This is a circuit whose purpose is to change the waveform of an input triangular-wave signal to a sine wave. Though simple, the sine-wave shaper is a practical building block used extensively in function generators. This method of generating sine waves should be contrasted to that using linear oscillators (Sections 15.1–15.3 of the textbook). Although linear oscillators produce sine waves of high purity, they are not convenient at very low frequencies. Also, linear oscillators are in general more difficult to tune over wide frequency ranges. In the following we discuss two distinctly different techniques for designing sine-wave shapers.

x7.3.1 The Breakpoint Method

In the breakpoint method the desired nonlinear transfer characteristic (in our case the sine function shown in Fig. x7.5) is implemented as a piecewise linear curve. Diodes are utilized as switches that turn on at the various breakpoints of the transfer characteristic, thus switching into the circuit additional resistors that cause the transfer characteristic to change slope.

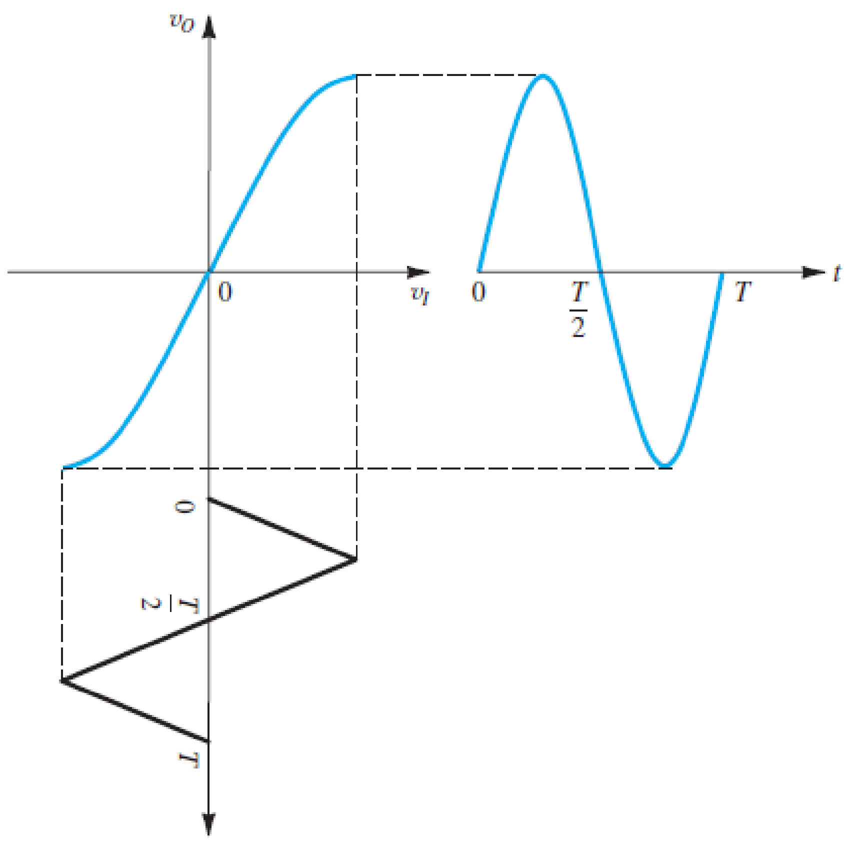

Figure x7.5 Using a nonlinear transfer characteristic to shape a triangular waveform into a sinusoid.

Consider the circuit shown in Fig. x7.6(a). It consists of a chain of resistors connected across the entire symmetrical voltage supply $+V$, $-V$. The purpose of this voltage divider is to generate reference voltages that will serve to determine the breakpoints in the transfer characteristic. In our example these reference voltages are denoted $+V_2$, $+V_1$, $-V_1$, $-V_2$. Note that the entire circuit is symmetrical, driven by a symmetrical triangular wave and generating a symmetrical sine-wave output. The circuit approximates each quarter-cycle of the sine wave by three straight-line segments; the breakpoints between these segments are determined by the reference voltages V_1 and V_2.

The circuit works as follows: Let the input be the triangular wave shown in Fig. x7.6(b), and consider first the quarter-cycle defined by the two points labeled 0 and 1. When the input signal is less in magnitude than V_1, none of the diodes conducts. Thus zero current flows through R_4, and the output voltage at B will be equal to the input voltage. But as the input rises to V_1 and above, D_2 (assumed ideal) begins to conduct. Assuming that the conducting D_2 behaves as a short circuit, we see that, for $v_I > V_1$,

$$v_O = V_1 + (v_I - V_1)\frac{R_5}{R_4 + R_5} \qquad \text{(x7.11)}$$

This implies that as the input continues to rise above V_1, the output follows, but with a reduced slope. This gives rise to the second segment in the output waveform, as shown in Fig. x7.6(b). Note that in developing the equation above we have assumed that the resistances in the voltage divider are low enough in value to cause the voltages V_1 and V_2 to be constant independent of the current coming from the input.

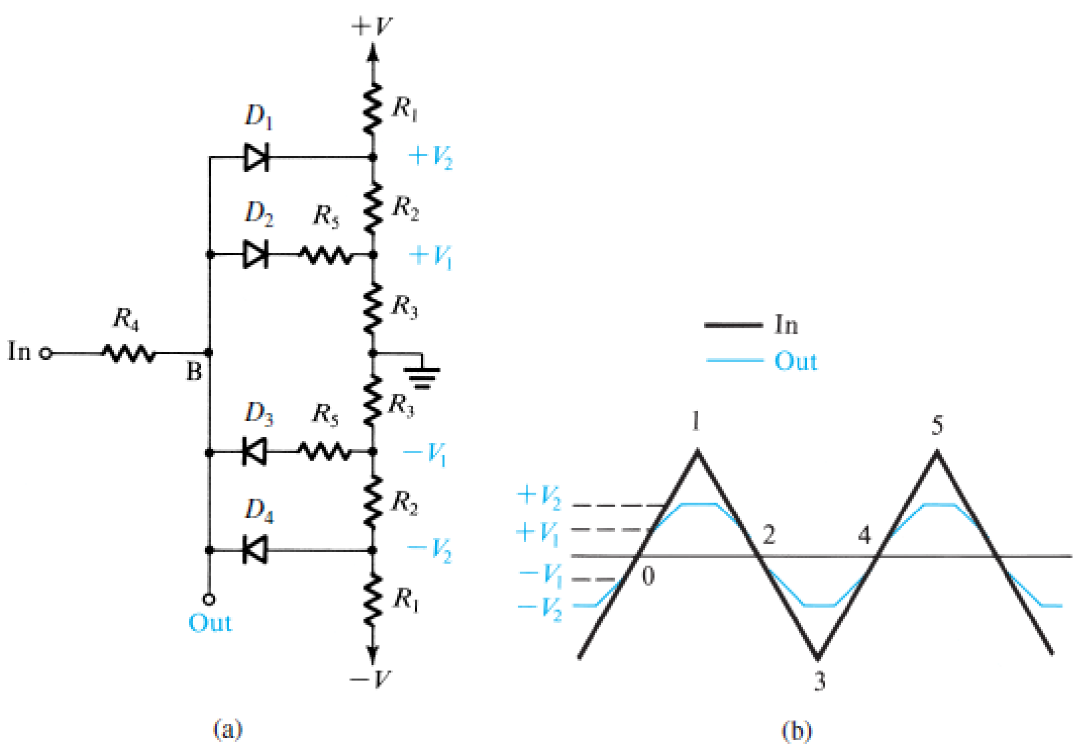

Figure x7.6 (a) A three-segment sine-wave shaper. **(b)** The input triangular waveform and the output approximately sinusoidal waveform.

Next consider what happens as the voltage at point B reaches the second breakpoint determined by V_2. Here, D_1 conducts, limiting the output v_O to V_2 (plus the voltage drop across D_1 if it is not assumed to be ideal). This gives rise to the third segment, which is flat, in the output waveform. The overall result is to "bend" the waveform and shape it into an approximation of the first quarter-cycle of a sine wave. Then, beyond the peak of the input triangular wave, as the input voltage decreases, the process unfolds, the output becoming progressively more like the input. Finally, when the input goes sufficiently negative, the process begins to repeat at $-V_1$ and $-V_2$ for the negative half-cycle.

Although the circuit is relatively simple, its performance is surprisingly good. A measure of goodness usually taken is to quantify the purity of the output sine wave by specifying the percentage **total harmonic distortion** (THD). This is the percentage ratio of the rms voltage of all harmonic components above the fundamental frequency (which is the frequency of the triangular wave) to the rms voltage of the fundamental (see also Chapter 12). Interestingly, one reason for the good performance of the diode shaper is the beneficial effects produced by the nonideal i–v characteristics of the diodes—that is, the exponential knee of the junction diode as it goes into forward conduction. The consequence is a relatively smooth transition from one line segment to the next.

Practical implementations of the breakpoint sine-wave shaper employ six to eight segments (compared with the three used in the example above). Also, transistors are usually employed to provide more versatility in the design, with the goal being increased precision and lower THD (see Grebene, 1984, pages 592–595).

x7.3.2 The Nonlinear-Amplification Method

The other method for converting a triangular wave into a sine wave is based on feeding the triangular wave to the input of an amplifier having a nonlinear transfer characteristic that approximates the sine function. One such amplifier circuit consists of a differential pair with a resistance connected between the two emitters, as shown in Fig. x7.7. With appropriate choice of the values of the bias current I and the resistance R, the differential amplifier can be made to have a transfer characteristic that closely approximates that

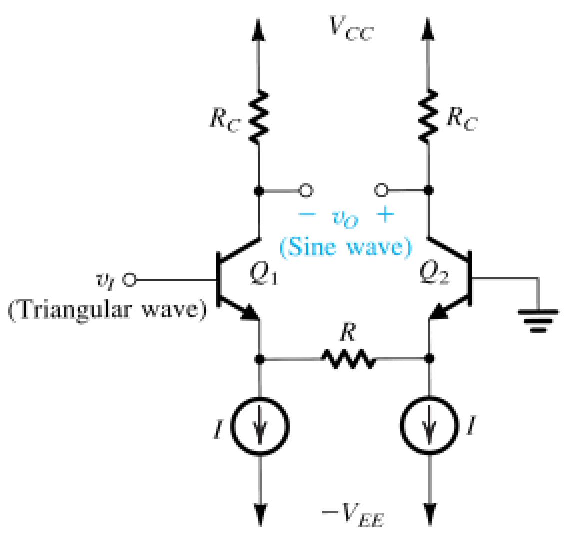

Figure x7.7 A differential pair with an emitter-degeneration resistance used to implement a triangular-wave to sine-wave converter. Operation of the circuit can be graphically described by Fig. x7.5.

shown in Fig. x7.5. Observe that for small v_I the transfer characteristic of the circuit of Fig. x7.7 is almost linear, as a sine waveform is near its zero crossings. At large values of v_I the nonlinear characteristics of the BJTs reduce the gain of the amplifier and cause the transfer characteristic to bend, approximating the sine wave as it approaches its peak. (More details on this circuit can be found in Grebene, 1984, pages 595–597.)

EXERCISES

xD7.4 The circuit in Fig. xE7.4 is required to provide a three-segment approximation to the nonlinear i–v characteristic, $i = 0.1v^2$, where v is the voltage in volts and i is the current in milliamperes. Find the values of R_1, R_2, and R_3 such that the approximation is perfect at v = 2 V, 4 V, and 8 V. Calculate the error in current value at v = 3 V, 5 V, 7 V, and 10 V. Assume ideal diodes.

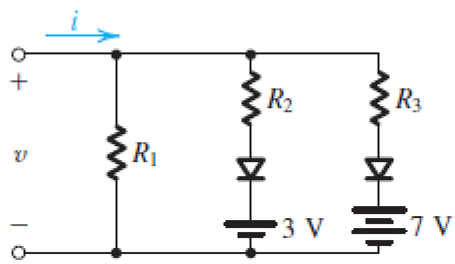

Figure xE7.4

Ans. 5 kΩ, 1.25 kΩ, 1.25 kΩ; −0.3 mA, +0.1 mA, −0.3 mA, 0

x7.5 A detailed analysis of the circuit in Fig. x7.7 shows that its optimum performance occurs when the values of I and R are selected so that $RI = 2.5V_T$, where V_T is the thermal voltage. For this design, the peak amplitude of the input triangular wave should be $6.6V_T$, and the corresponding sine wave across R has a peak value of $2.42V_T$. For I = 0.25mA and R_C = 10 kΩ, find the peak amplitude of the sine-wave output v_O. Assume $\alpha \simeq 1$.

Ans. 4.84 V

x7.4 Precision Rectifier Circuits

Rectifier circuits were studied in Chapter 4, where the emphasis was on their application in power-supply design. In such applications, the voltages being rectified are usually much greater than the diode voltage drop, rendering the exact value of the diode drop unimportant to the proper operation of the rectifier. Other applications exist, however, where this is not the case. For instance, in instrumentation applications, the signal to be rectified can be of a very small amplitude, say 0.1 V, making it impossible to employ the conventional rectifier circuits. Also, in instrumentation applications, the need arises for rectifier circuits with very precise transfer characteristics.

Here we study circuits that combine diodes and op amps to implement a variety of rectifier circuits with precise characteristics. Precision rectifiers, which can be considered a special class of wave-shaping circuits, find application in the design of instrumentation systems. An introduction to precision rectifiers is presented in Section 4.6.5 of the textbook. This material, however, is repeated here for the reader's convenience.

x7.4.1 Precision Half-Wave Rectifier: The "Superdiode"

Figure x7.8(a) shows a precision half-wave-rectifier circuit consisting of a diode placed in the negative-feedback path of an op amp, with R being the rectifier load resistance. The circuit works as follows: If v_I goes positive, the output voltage v_A of the op amp will go positive and the diode will conduct, thus establishing a closed feedback path between the op amp's output terminal and the negative input terminal. This negative-feedback path will cause a virtual short circuit to appear between the two input terminals of the op amp. Thus the voltage at the negative input terminal, which is also the output voltage v_O, will equal (to within a few millivolts) that at the positive input terminal, which is the input voltage v_I,

$$v_O = v_I \qquad v_I \geq 0$$

Note that the offset voltage ($\simeq$ 0.5 V) exhibited in the simple half-wave-rectifier circuit is no longer present. For the op-amp circuit to start operation, v_I has to exceed only a negligibly small voltage equal to the diode drop divided by the op amp's open-loop gain. In other words, the straight-line transfer characteristic v_O–v_I almost passes through the origin. This makes this circuit suitable for applications involving very small signals.

Consider now the case when v_I goes negative. The op amp's output voltage v_A will tend to follow and go negative. This will reverse-bias the diode, and no current will flow through resistance R, so that v_O remains equal to 0 V. Thus for $v_I < 0$, $v_O = 0$. Since in this case the diode is off, the op amp will be operating in an open-loop fashion and its output will be at the negative saturation level.

The transfer characteristic of this circuit will be that shown in Fig. x7.8(b), which is almost identical to the ideal characteristic of a half-wave rectifier. The nonideal diode characteristics have been almost completely masked by placing the diode in the negative-feedback path of an op amp. This is another dramatic application of negative feedback. The combination of diode and op amp, shown in the dashed box in Fig. x7.8(a), is appropriately referred to as a "superdiode."

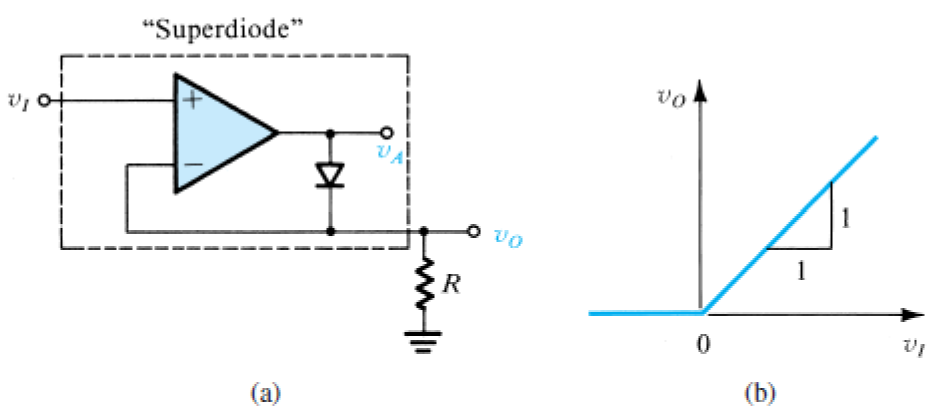

Figure x7.8 **(a)** The "superdiode" precision half-wave rectifier; **(b)** its almost ideal transfer characteristic. Note that when $v_I > 0$ and the diode conducts, the op amp supplies the load current, and the source is conveniently buffered, an added advantage.

As usual, though, not all is well. The circuit of Fig. x7.8 has some disadvantages: When v_I goes negative and $v_O = 0$, the entire magnitude of v_I appears between the two input terminals of the op amp. If this magnitude is greater than a few volts, the op amp may be damaged unless it is equipped with what is called "overvoltage protection" (a feature of most modern IC op amps). Another disadvantage is that when v_I is negative, the op amp will be saturated. Although not harmful to the op amp, saturation should be avoided, since getting the op amp out of the saturation region and back into its linear region of operation requires some time. The delay will slow down circuit operation and limit the frequency of operation of the superdiode half-wave-rectifier circuit.

x7.4.2 An Alternative Circuit

An alternative precision rectifier circuit that does not suffer from the disadvantages mentioned above is shown in Fig. x7.9. The circuit operates in the following manner: For positive v_I, diode D_2 conducts and closes the negative-feedback loop around the op amp. A virtual ground therefore will appear at the inverting input terminal, and the op amp's output will be *clamped* at one diode drop below ground. This negative voltage will keep diode D_1 off, and no current will flow in the feedback resistance R_2. It follows that the rectifier output voltage will be zero.

As v_I goes negative, the voltage at the inverting input terminal will tend to go negative, causing the voltage at the op amp's output terminal to go positive. This will cause D_2 to be reverse-biased and hence to be cut off. Diode D_1, however, will conduct through R_2, thus establishing a negative-feedback path around the op amp and forcing a virtual ground to appear at the inverting input terminal. The current through the feedback resistance R_2 will be equal to the current through the input resistance R_1. Thus for $R_1 = R_2$ the output voltage v_O will be

$$v_O = -v_I \qquad v_I \leq 0$$

The transfer characteristic of the circuit is shown in Fig. x7.9(b). Note that unlike the situation for the circuit shown in Fig. x7.8, here the slope of the characteristic can be set to any desired value, including unity, by selecting appropriate values for R_1 and R_2.

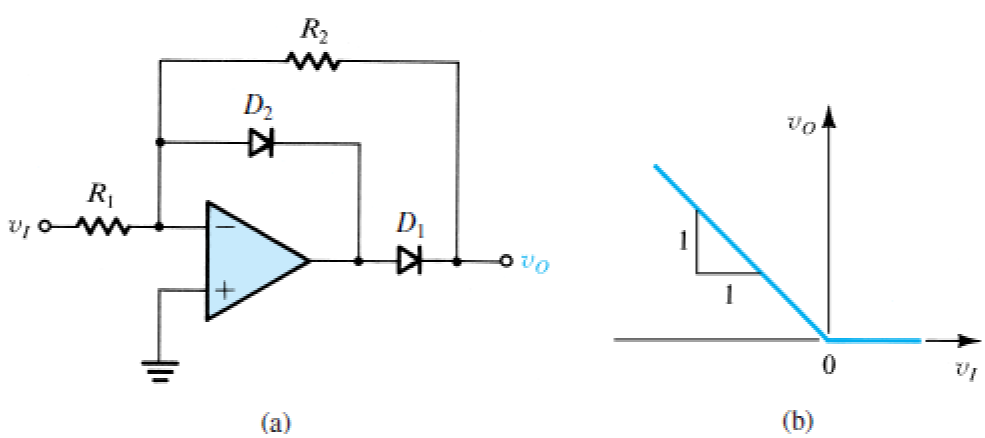

Figure x7.9 **(a)** An improved version of the precision half-wave rectifier: Diode D_2 is included to keep the feedback loop closed around the op amp during the off times of the rectifier diode D_1, thus preventing the op amp from saturating. **(b)** The transfer characteristic for $R_2 = R_1$.

As mentioned before, the major advantage of the improved half-wave-rectifier circuit is that the feedback loop around the op amp remains closed at all times. Hence the op amp remains in its linear operating region, avoiding the possibility of saturation and the associated time delay required to "get out" of saturation. Diode D_2 "catches" the op-amp output voltage as it goes negative and clamps it to one diode drop below ground; hence D_2 is called a "catching diode."

x7.4.3 An Application: Measuring AC Voltages

As one of the many possible applications of the precision rectifier circuits discussed in this section, consider the basic ac voltmeter circuit shown in Fig. x7.10. The circuit consists of a half-wave rectifier—formed by op amp A_1, diodes D_1 and D_2, and resistors R_1 and R_2—and a first-order low-pass filter—formed by op amp A_2, resistors R_3 and R_4, and capacitor C. For an input sinusoid having a peak amplitude V_p the output v_1 of the rectifier will consist of a half sine wave having a peak amplitude of V_pR_2/R_1. It can be shown using Fourier series analysis that the waveform of v_I has an average value of $(V_p/\pi)(R_2/R_1)$ in addition to harmonics of the frequency ω of the input signal. To reduce the amplitudes of all these harmonics to negligible levels, the corner frequency of the low-pass filter should be chosen to be much smaller than the lowest expected frequency $\omega_{\min}$ of the input sine wave. This leads to

$$\frac{1}{CR_4} \ll \omega_{\min}$$

Then the output voltage v_2 will be mostly dc, with a value

$$V_2 = -\frac{V_p}{\pi}\frac{R_2}{R_1}\frac{R_4}{R_3}$$

where R_4/R_3 is the dc gain of the low-pass filter. Note that this voltmeter essentially measures the average value of the negative parts of the input signal but can be calibrated to provide rms readings for input sinusoids.

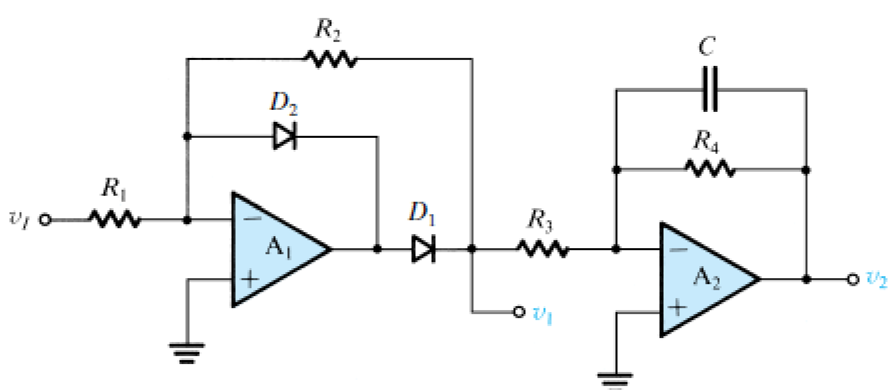

Figure x7.10 A simple ac voltmeter consisting of a precision half-wave rectifier followed by a first-order low-pass filter.

EXERCISES

x7.6 Consider the operational rectifier or superdiode circuit of Fig. x7.8(a), with R = 1 kΩ. For v_I = 10 mV, 1 V, and –1 V, what are the voltages that result at the rectifier output and at the output of the op amp? Assume that the op amp is ideal and that its output saturates at ±12 V. The diode has a 0.7-V drop at 1-mA current, and the voltage drop changes by 0.1 V per decade of current change.

Ans. 10 mV, 0.51 V; 1 V, 1.7 V; 0 V, –12 V

x7.7 If the diode in the circuit of Fig. x7.8(a) is reversed, what is the transfer characteristic v_O as a function of v_I?

Ans. $v_O = 0$ for $v_I \geq 0$; $v_O = v_I$ for $v_I \leq 0$

x7.8 Consider the circuit in Fig. x7.9(a) with R_1 = 1 kΩ and R_2 = 10 kΩ. Find v_O and the voltage at the amplifier output for v_I = +1 V, –10 mV, and –1 V. Assume the op amp to be ideal with saturation voltages of ±12 V. The diodes have 0.7-V voltage drops at 1 mA, and the voltage drop changes by 0.1 V per decade of current change.

Ans. 0 V, –0.7 V; 0.1 V, 0.6 V; 10 V, 10.7 V

x7.9 If the diodes in the circuit of Fig. x7.9(a) are reversed, what is the transfer characteristic v_O as a function of v_I?

Ans. $v_O = -(R_2/R_1)\, v_I$ for $v_I \geq 0$; $v_O = 0$ for $v_I \leq 0$

x7.10 Find the transfer characteristic for the circuit in Fig. xE7.10.

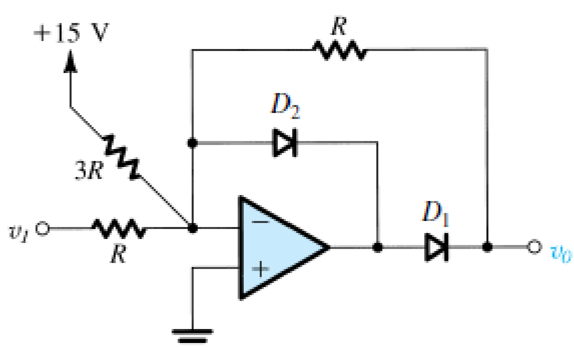

Figure xE7.10

Ans. $v_O = 0$ for $v_I \geq -5$V; $v_O = -v_I - 5$ for $v_I \leq -5$ V

x7.4.4 Precision Full-Wave Rectifier

We now derive a circuit for a precision full-wave rectifier. From Chapter 4 we know that full-wave rectification is achieved by inverting the negative halves of the input-signal waveform and applying the resulting signal to another diode rectifier. The outputs of the two rectifiers are then joined to a common load. Such an arrangement is depicted in Fig. x7.11, which also shows the waveforms at various nodes. Now replacing diode D_A with a superdiode, and replacing diode D_B and the inverting amplifier with the inverting precision half-wave rectifier of Fig. x7.9 but without the catching diode, we obtain the precision full-wave-rectifier circuit of Fig. x7.12(a).

To see how the circuit of Fig. x7.12(a) operates, consider first the case of positive input at A. The output of A_2 will go positive, turning D_2 on, which will conduct through R_L and thus close the feedback loop around A_2. A virtual short circuit will thus be established between the two input terminals of A_2, and the voltage at the negative-input terminal, which is the output voltage of the circuit, will become equal to the input. Thus no current will flow through R_1 and R_2, and the voltage at the inverting input of A_1 will be equal to the input and hence positive. Therefore the output terminal (F) of A_1 will go negative until A_1 saturates. This causes D_1 to be turned off.

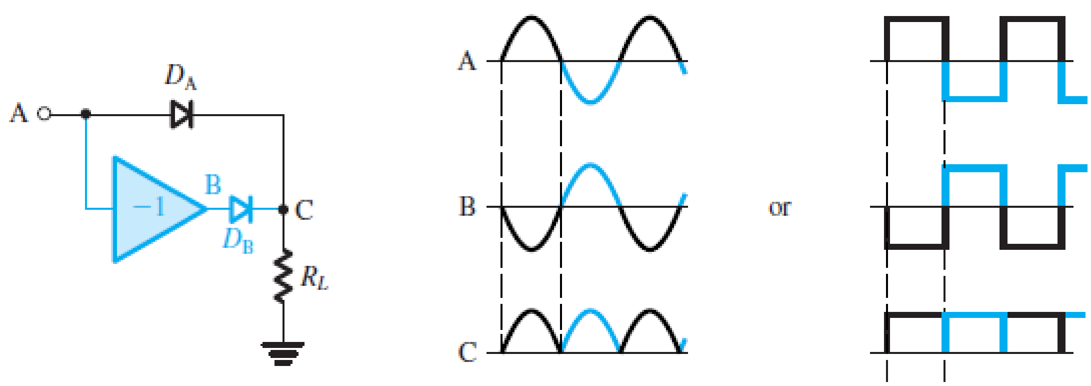

Figure x7.11 Principle of full-wave rectification.

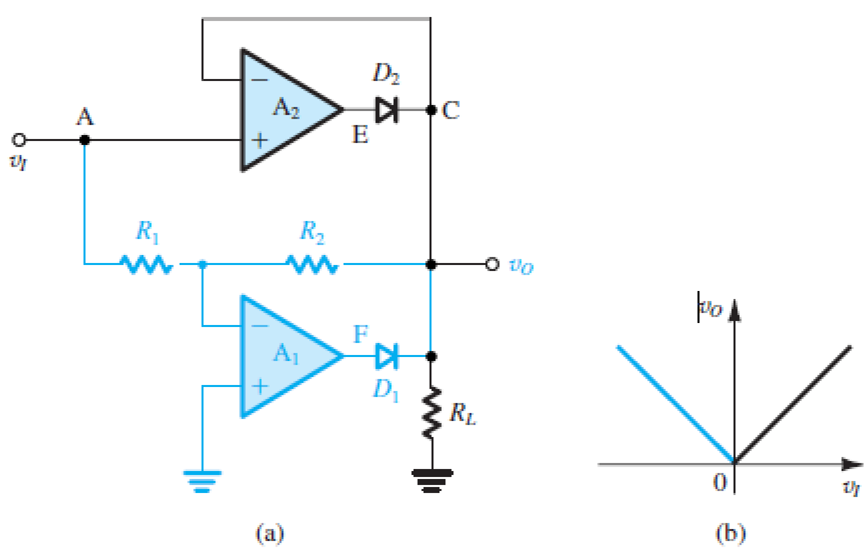

Figure x7.12 **(a)** Precision full-wave rectifier based on the conceptual circuit of Fig. x7.11. **(b)** Transfer characteristic of the circuit in (a).

Next consider what happens when A goes negative. The tendency for a negative voltage at the negative input of A_1 causes F to rise, making D_1 conduct to supply R_L and allowing the feedback loop around A_1 to be closed. Thus a virtual ground appears at the negative input of A_1, and the two equal resistances R_1 and R_2 force the voltage at C, which is the output voltage, to be equal to the negative of the input voltage at A and thus positive. The combination of positive voltage at C and negative voltage at A causes the output of A_2 to saturate in the negative direction, thus keeping D_2 off.

The overall result is perfect full-wave rectification, as represented by the transfer characteristic in Fig. x7.12(b). This precision is, of course, a result of placing the diodes in op-amp feedback loops, thus masking their nonidealities. This circuit is one of many possible precision full-wave-rectifier or **absolute-value circuits**. Another related implementation of this function is examined in Exercise x7.12.

EXERCISES

x7.11 In the full-wave rectifier circuit of Fig. x7.12(a), let $R_1 = R_2 = R_L = 10$ kΩ, and assume the op amps to be ideal except for output saturation at ±12 V. When conducting a current of 1 mA, each diode exhibits a voltage drop of 0.7 V, and this voltage changes by 0.1 V per decade of current change. Find v_O, v_E, and v_F corresponding to v_I = +0.1 V, +1 V, +10 V, −0.1 V, and −10 V.

Ans. + 0.1 V, + 0.6 V, −12 V; +1 V, +1.6 V, −12 V; +10 V, +10.7 V, −12 V; + 0.1 V, −12 V, + 0.63 V; +1 V, −12 V, +1.63 V; +10 V, −12 V, +10.73 V

xD7.12 The block diagram shown in Fig. xE7.12(a) gives another possible arrangement for implementing the absolute-value or full-wave-rectifier operation depicted symbolically in Fig. xE7.12(b). The block diagram consists of two boxes: a half-wave rectifier, which can be implemented by the circuit in Fig. x7.9(a) after reversing both diodes, and a weighted inverting summer. Convince yourself that this block diagram does in fact realize the absolute-value operation. Then draw a complete circuit diagram, giving reasonable values for all resistors.

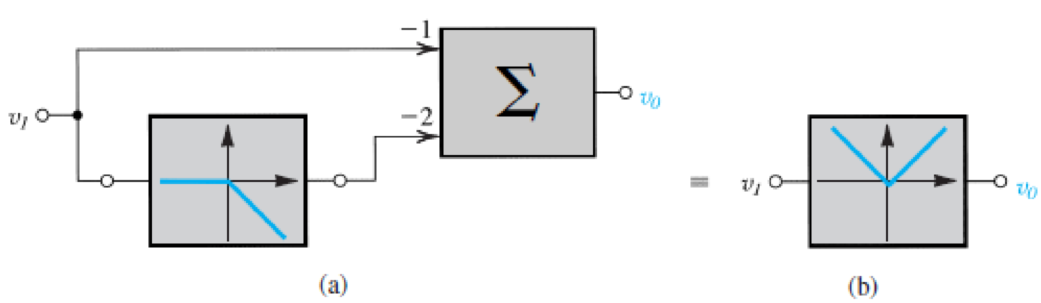

Figure xE7.12

x7.4.5 A Precision Bridge Rectifier for Instrumentation Applications

The bridge rectifier circuit studied in Section 4.6.3 of the textbook can be combined with an op amp to provide useful precision circuits. One such arrangement is shown in Fig. x7.13. This circuit causes a current equal to $|v_A|/R$ to flow through the moving-coil meter M. Thus the meter provides a reading that is proportional to the average of the absolute value of the input voltage v_A. All the nonidealities of the meter and of the diodes are masked by placing the bridge circuit in the negative-feedback loop of the op amp. Observe that when v_A is positive, current flows from the op-amp output through D_1, M, D_3, and R. When v_A is negative, current flows into the op-amp output through R, D_2, M, and D_4. Thus the feedback loop remains closed for both polarities of v_A. The resulting virtual short circuit at the input terminals of the op amp causes a replica of v_A to appear across R. The circuit of Fig. x7.13 provides a relatively accurate high-input-impedance ac voltmeter using an inexpensive moving-coil meter.

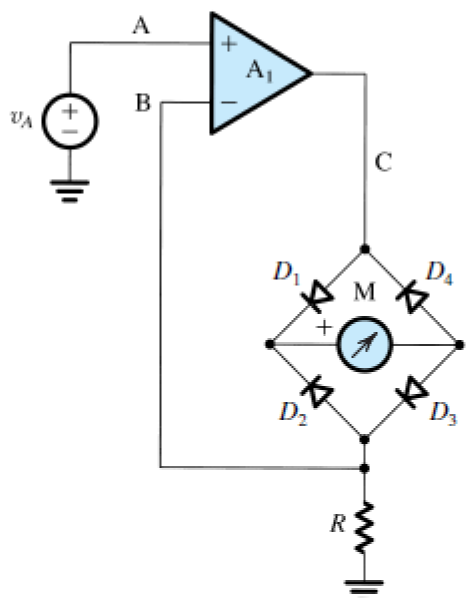

Figure x7.13 Use of the diode bridge in the design of an ac voltmeter.

EXERCISE

xD7.13 In the circuit of Fig. x7.13, find the value of R that would cause the meter to provide a full-scale reading when the input voltage is a sine wave of 5 V rms. Let meter M have a 1-mA, 50-Ω movement (i.e., its resistance is 50 Ω, and it provides full-scale deflection when the average current through it is 1 mA). What are the approximate maximum and minimum voltages at the op amp's output? Assume that the diodes have constant 0.7-V drops when conducting.

Ans. 4.5 kΩ; +8.55 V; −8.55 V

x7.4.6 Precision Peak Rectifiers

Including the diode of the peak rectifier studied in Section 4.6.4 of the textbook inside the negative-feedback loop of an op amp, as shown in Fig. x7.14, results in a precision peak rectifier. The diode–op-amp combination will be recognized as the superdiode of Fig. x7.8(a). Operation of the circuit in Fig. x7.14 is quite straightforward. For v_I greater than the output voltage, the op amp will drive the diode on, thus closing the negative-feedback path and causing the op amp to act as a follower. The output voltage will therefore follow that of the input, with the op amp supplying the capacitor-charging current. This process continues until the input reaches its peak value. Beyond the positive peak, the op amp will see a negative voltage between its input terminals. Thus its output will go negative to the saturation level and the diode will turn off. Except for possible discharge through the load resistance, the capacitor will retain a voltage equal to the positive peak of the input. Inclusion of a load resistance is essential if the circuit is required to detect reductions in the magnitude of the positive peak.

x7.4.7 A Buffered Precision Peak Detector

When the peak detector is required to hold the value of the peak for a long time, the capacitor should be buffered, as shown in the circuit of Fig. x7.15. Here op amp A_2, which should have high input impedance and low input bias current, is connected as a voltage follower. The remainder of the circuit is quite similar to the half-wave-rectifier circuit of Fig. x7.9. While diode D_1 is the essential diode for the peak-rectification operation, diode D_2 acts as a catching diode to prevent negative saturation, and the associated delays, of op amp A_1. During the holding state, followerA_2 supplies D_2 with a small current through R. The output of op amp A_1 will then be clamped at one diode drop below the input voltage. Now if the input v_I increases above the value stored on C, which

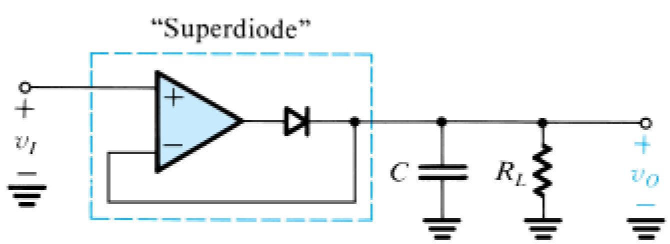

Figure x7.14 A precision peak rectifier obtained by placing the diode in the feedback loop of an op amp.

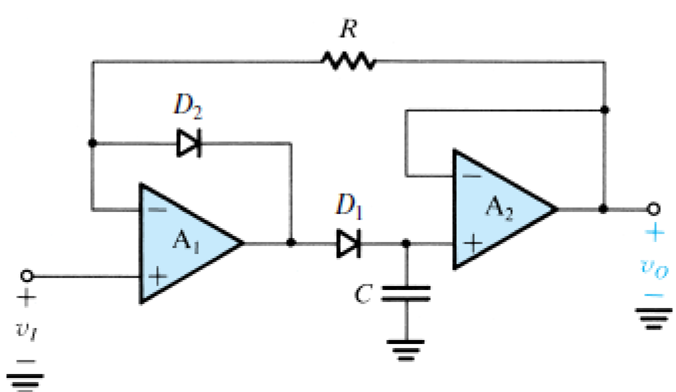

Figure x7.15 A buffered precision peak rectifier.

is equal to the output voltage v_O, op amp A_1 sees a net positive input that drives its output toward the positive saturation level, turning off diode D_2. Diode D_1 is then turned on and capacitor C is charged to the new positive peak of the input, after which time the circuit returns to the holding state. Finally, note that this circuit has a low-impedance output.

x7.4.8 A Precision Clamping Circuit

By replacing the diode in the clamping circuit studied in Section 4.7.1 of the textbook with a "superdiode," we obtain the precision clamp shown in Fig. x7.16. This circuit's operation should be self-explanatory.

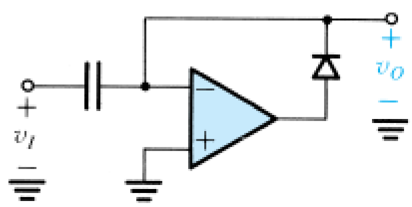

Figure x7.16 A precision clamping circuit.