

CHAPTER 12 SIGNAL GENERATORS AND WAVEFORM-SHAPING CIRCUITS

Chapter Outline

- 12.1 Basic Principles of Sinusoidal Oscillators
- 12.2 Op Amp-RC Oscillators
- 12.3 LC and Crystal Oscillators
- 12.4 Bistable Multivibrators
- 12.5 Generation of Square and Triangular Waveforms using Astable Multivibrators
- 12.6 Generation of a Standardized Pulse-The Monostable Multivibrators
- 12.7 Integrated-Circuit Timers
- 12.8 Nonlinear Waveform-Shaping Circuits
- 12.9 Precision Rectifier Circuits

12.1 BASIC PRINCIPLES OF SINUSOIDAL OSCILLATORS

Types of Oscillators

- ❑ Linear oscillator:
 - Employs a positive feedback loop consisting of an amplifier and a frequency-selective network.
 - Some form of nonlinearity has to be employed to provide control of the amplitude of the output.
- ❑ Nonlinear oscillator:
 - Generates square, triangular, pulse waveforms.
 - Employs multivibrators: bistable, astable and monostable.

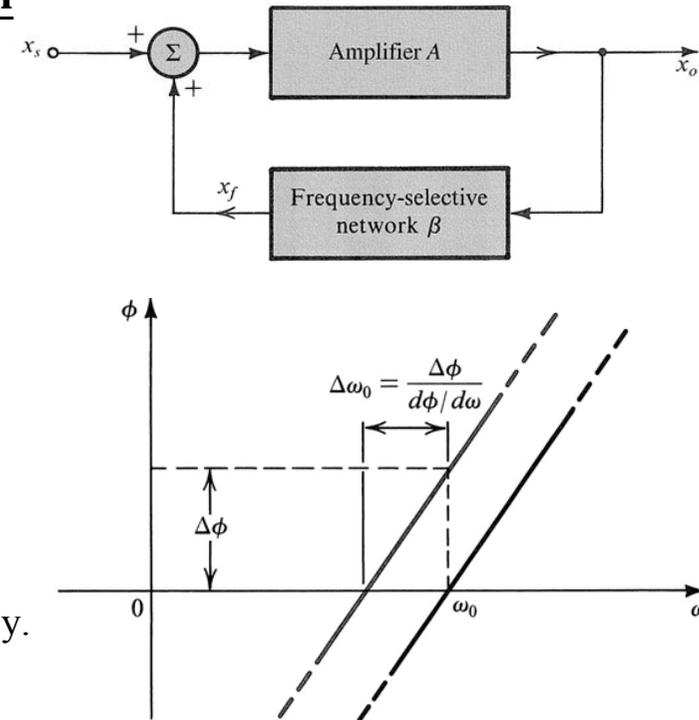
The Oscillator Feedback Loop and Oscillation Criterion

- ❑ Positive feedback loop analysis:

$$A_f(s) \equiv \frac{x_o}{x_i} = \frac{A(s)}{1 - A(s)\beta(s)} \quad \text{loop gain : } L(s) \equiv A(s)\beta(s)$$

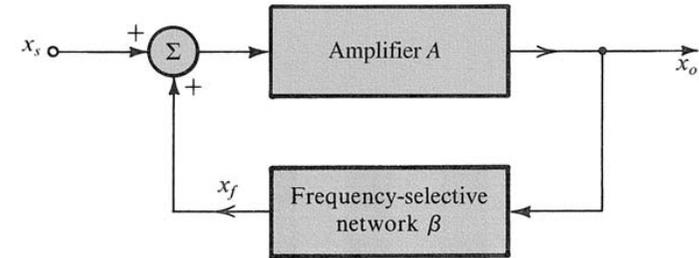
$$L(j\omega_0) \equiv A(j\omega_0)\beta(j\omega_0) = 1$$

- ❑ Barkhausen criterion:
 - The phase of loop gain should be zero at ω_0 .
 - The magnitude of the loop gain should be unity at ω_0 .
 - The characteristic equation has roots at $s = \pm j\omega_0$.
- ❑ Stability of oscillation frequency:
 - ω_0 is determined solely by the phase characteristics.
 - A “steep” function $\phi(\omega)$ results in a more stable frequency.



Nonlinear Amplitude Control

- ❑ Oscillation: loop gain $A\beta = 1$
- ❑ Growing output: loop gain $A\beta > 1$
- ❑ Decaying output: loop gain $A\beta < 1$
- ❑ Oscillation mechanism:
 - Initiating oscillation: loop gain slightly larger than unity (poles in RHP).
 - Gain control: nonlinear network reduces loop gain to unity (poles on $j\omega$ -axis).



Limiter Circuits for Amplitude Control

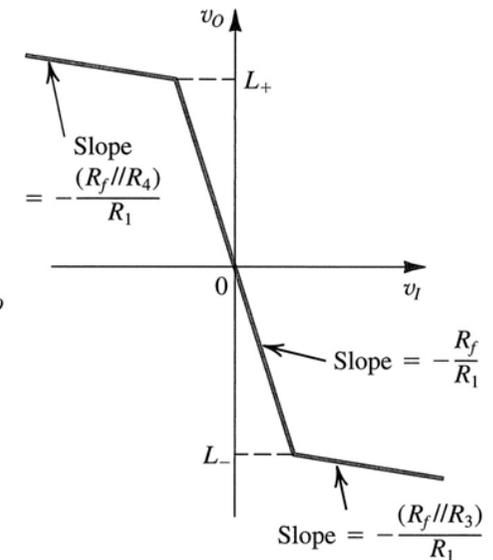
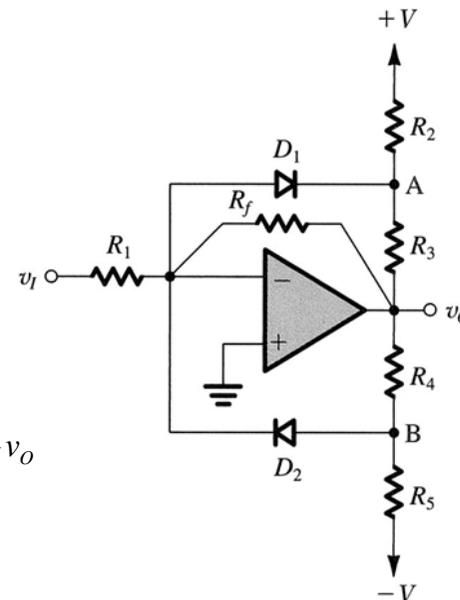
- ❑ For small amplitude (D_1 off, D_2 off)
 - incremental gain (slope) = $-R_f/R_1$
- ❑ For large negative swing (D_1 on, D_2 off)
 - incremental gain (slope) = $-(R_f \parallel R_4)/R_1$
- ❑ For large positive swing (D_1 off, D_2 on)
 - incremental gain (slope) = $-(R_f \parallel R_3)/R_1$

$$v_A = \frac{R_3}{R_2 + R_3} V + \frac{R_2}{R_2 + R_3} v_O$$

$$v_B = -\frac{R_4}{R_4 + R_5} V + \frac{R_5}{R_4 + R_5} v_O$$

$$L_+ = \frac{R_4}{R_5} V + \frac{R_4 + R_5}{R_5} V_D$$

$$L_- = -\frac{R_3}{R_2} V - \frac{R_2 + R_3}{R_2} V_D$$



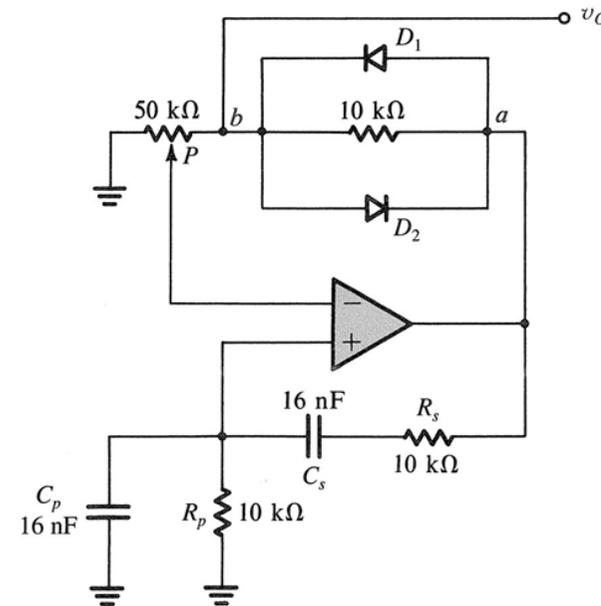
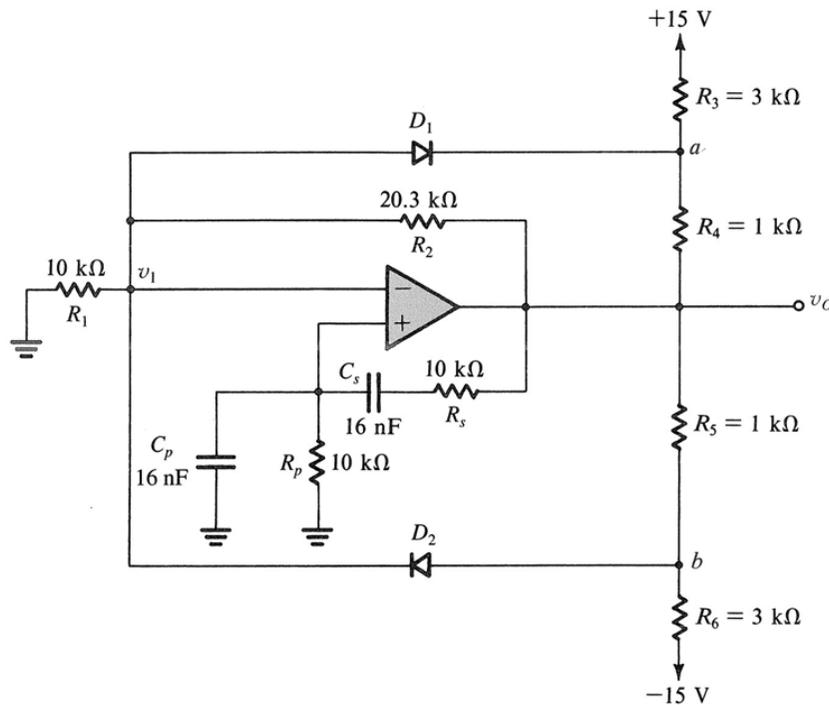
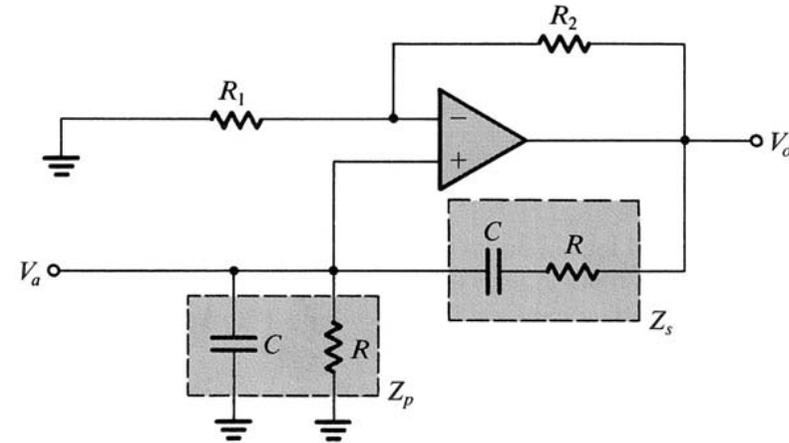
12.2 OP AMP-RC OSCILLATOR CIRCUITS

Wien-Bridge Oscillator

$$L(s) = \left[1 + \frac{R_2}{R_1} \right] \frac{Z_p}{Z_p + Z_s} \rightarrow L(s) = \frac{1 + R_2/R_1}{3 + sRC + 1/sRC}$$

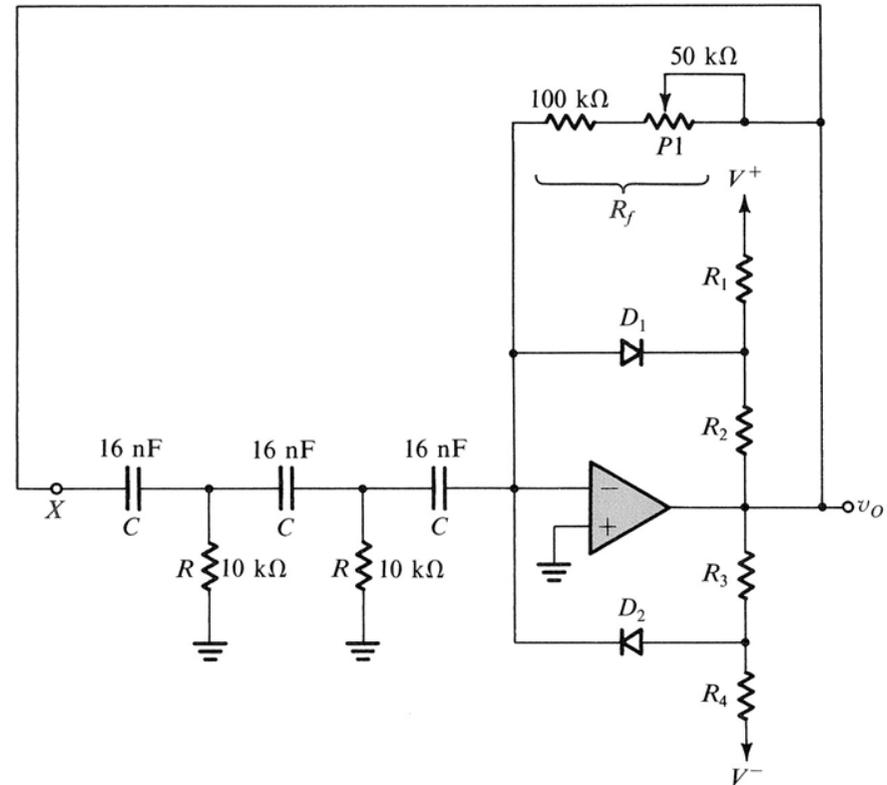
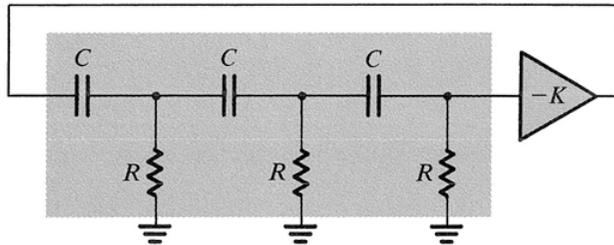
$$L(j\omega) = \frac{1 + R_2/R_1}{3 + j(\omega RC - 1/\omega RC)}$$

- ❑ For $L = 1 \rightarrow \omega_0 = 1/RC$ and $R_2/R_1 = 2$.
- ❑ To initiate oscillation $\rightarrow R_2/R_1 = 2 + \delta$.
- ❑ Limiter is used for amplitude control.



Phase-Shift Oscillator

- ❑ The circuit oscillates at the frequency for which the phase shift of the RC network is 180° .
- ❑ Only at this frequency will the total phase shift around the loop be 0° or 360° .
- ❑ The minimum number of RC sections is three.
- ❑ K should be equal to the inverse of the magnitude of the RC network at oscillation frequency.
- ❑ Slightly higher K is used to ensure that the oscillation starts.
- ❑ Limiter is used for amplitude control.



Quadrature Oscillator

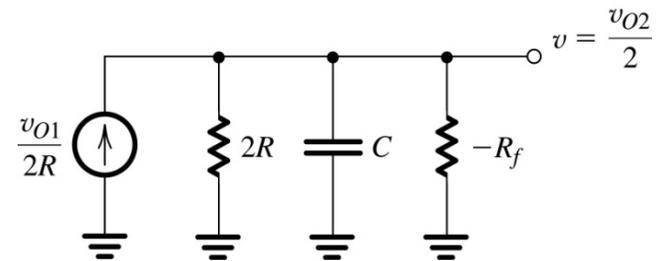
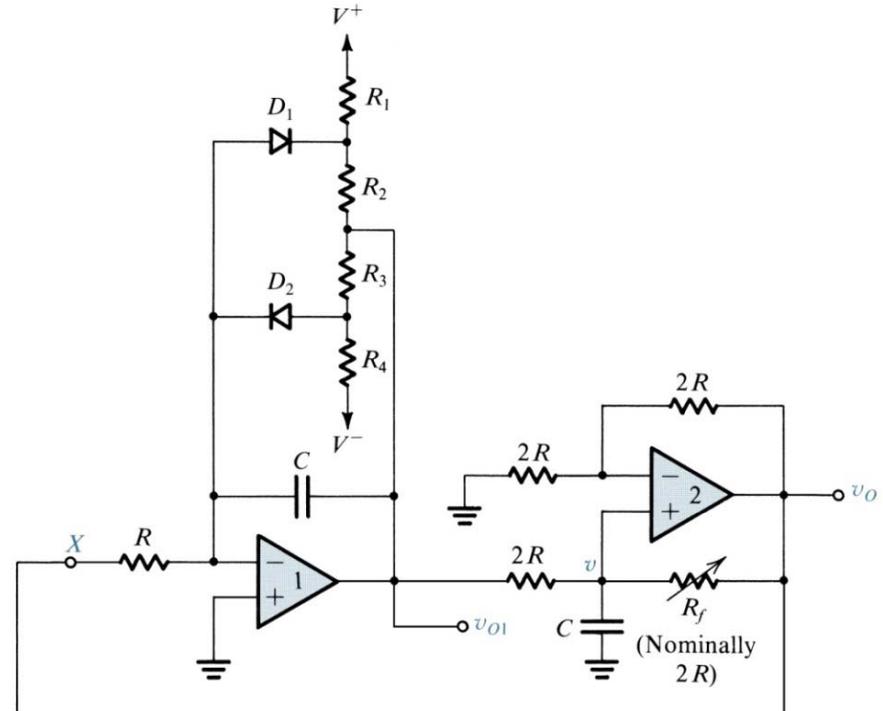
- ❑ Based on the two-integrator loop without damping.
- ❑ R_1, R_2, R_3, R_4, D_1 and D_2 are used as limiter.
- ❑ Loop gain:

$$v_{o2} = 2v = \frac{2}{C} \int_0^t \frac{v_{o1}}{2R} dt \rightarrow \frac{V_{o2}}{V_{o1}} = \frac{1}{sRC}$$

$$v_{o1} = \frac{1}{C} \int_0^t \frac{v_x}{R} dt \rightarrow \frac{V_{o1}}{V_x} = \frac{1}{sRC}$$

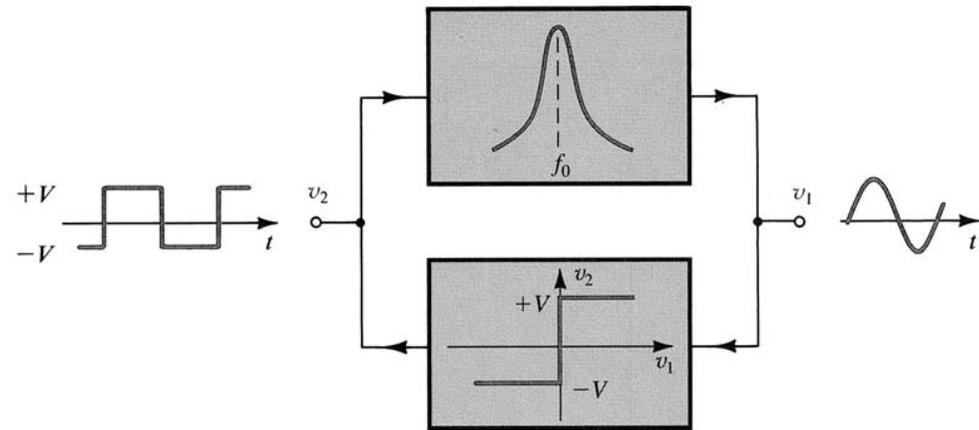
$$L(s) \equiv \frac{V_{o2}}{V_x} = -\frac{1}{s^2 R^2 C^2}$$

- ❑ Poles are initially located in RHP (decreasing R_f) to ensure that oscillation starts.
- ❑ Too much positive feedback results in higher output distortion.
- ❑ v_{o2} is purer than v_{o1} because of the filtering action provided by the second integrator on the peak-limited output of the first integrator.



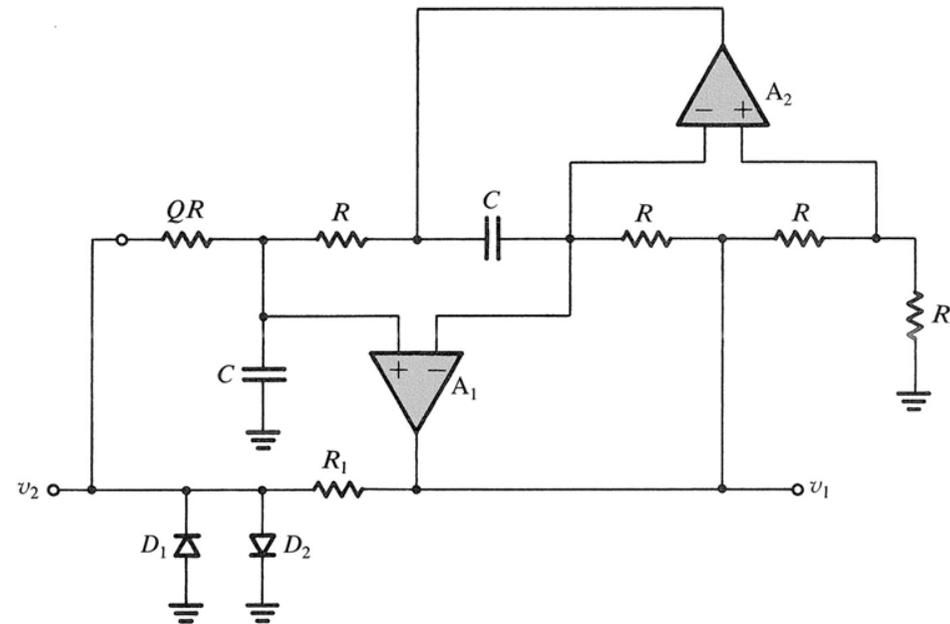
Active-Filter Tuned Oscillator

- ❑ The circuit consists of a high- Q bandpass filter connected in a positive-feedback loop with a hard limiter.
- ❑ Any filter circuit with positive gain can be used to implement the bandpass filter.
- ❑ Can generate high-quality output sine waves.
- ❑ Have independent control of frequency, amplitude and distortion of the output sinusoid.



Final Remark

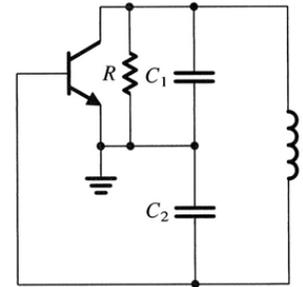
- ❑ Op amp-RF oscillators ~ 10 to 100kHz .
- ❑ Lower limit: passive components.
- ❑ Upper limit: frequency response and slew rate of op amp.



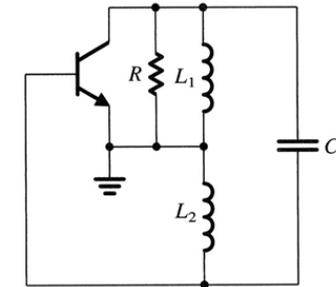
12.3 LC AND CRYSTAL OSCILLATORS

LC Tuned Oscillators

- ❑ Colpitts oscillator: capacitive divider.
- ❑ Hartley oscillator: inductive divider.
- ❑ Utilize a parallel LC circuit between base and collector.
- ❑ R models the overall losses.

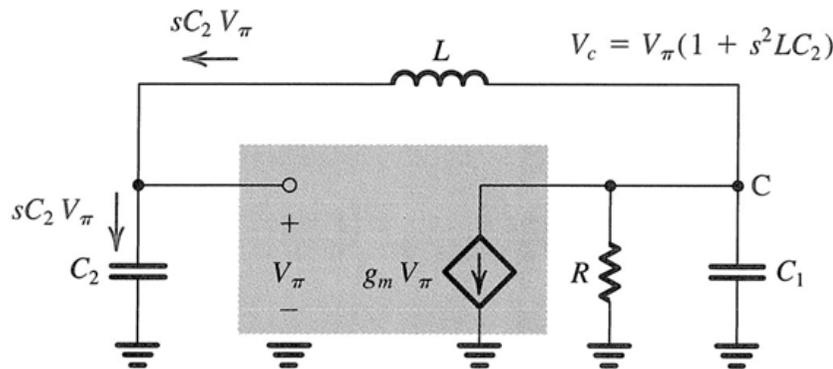


$$\omega_0 = 1/\sqrt{L(1/C_1 + 1/C_2)^{-1}}$$



$$\omega_0 = 1/\sqrt{(L_1 + L_2)C}$$

Analysis of Colpitts Oscillators



$$sC_2V_\pi + g_mV_\pi + (sC_1 + 1/R)(1 + s^2LC_2)V_\pi = 0$$

$$s^3LC_1C_2 + s^2LC_2/R + s(C_1 + C_2) + (g_m + 1/R) = 0$$

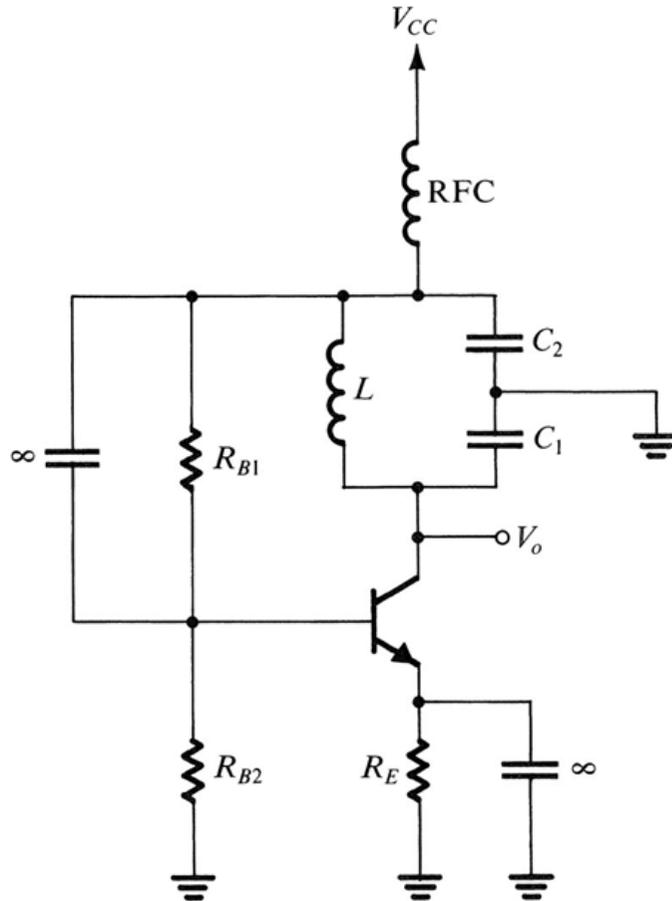
$$(g_m + \frac{1}{R} - \frac{\omega^2LC_2}{R}) + j[\omega(C_1 + C_2) - \omega^3LC_1C_2] = 0$$

$$\rightarrow \omega_0 = 1/\sqrt{L(1/C_1 + 1/C_2)^{-1}}$$

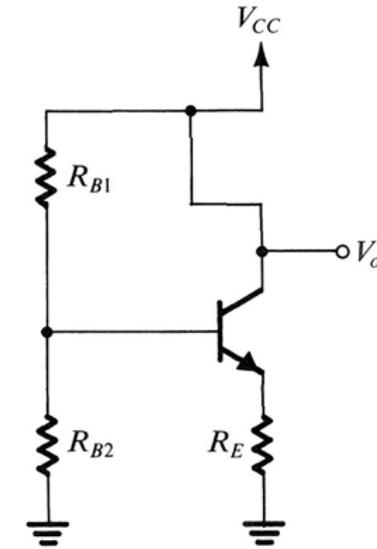
$$\rightarrow g_mR = C_2/C_1$$

- ❑ LC -tuned oscillators utilize the nonlinear transistor I - V characteristics for amplitude control (self-limiting).
- ❑ Collector (drain) current waveforms are distorted due to the nonlinear characteristics.
- ❑ Output voltage is a sinusoid with high purity because of the filtering action of the LC tuned circuit.

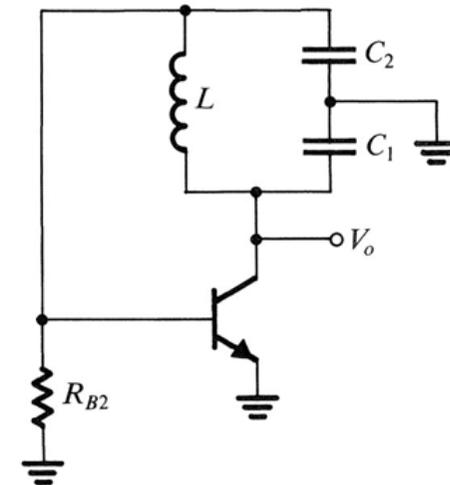
Complete Circuit for a Colpitts Oscillator



DC Analysis



AC Analysis



Crystal Oscillators

- Crystal impedance:

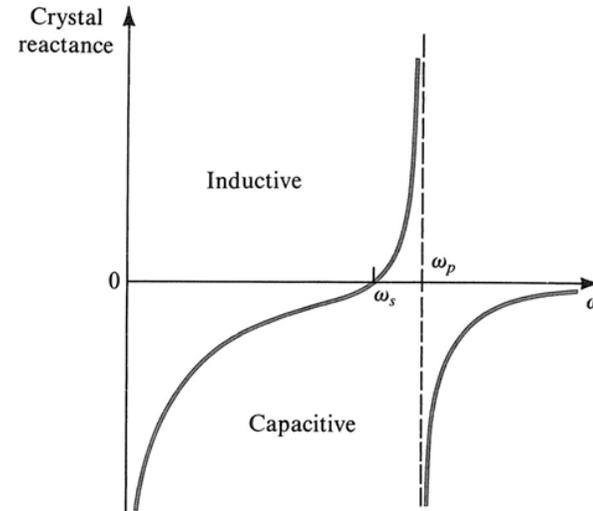
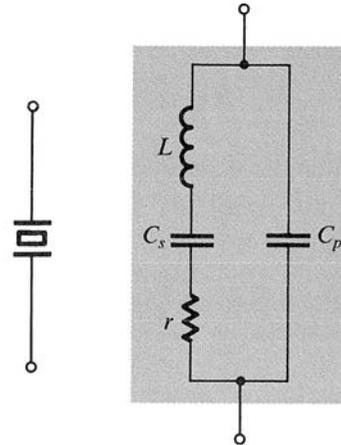
$$Z(s) = 1 / \left[sC_p + \frac{1}{sL + 1/sC_s} \right]$$

$$Z(s) = \frac{1}{sC_p} \frac{s^2 + 1/LC_s}{s^2 + [(C_p + C_s)/LC_p C_s]}$$

$$\omega_s = 1 / \sqrt{LC_s}$$

$$\omega_p = 1 / \sqrt{L(1/C_s + 1/C_p)^{-1}}$$

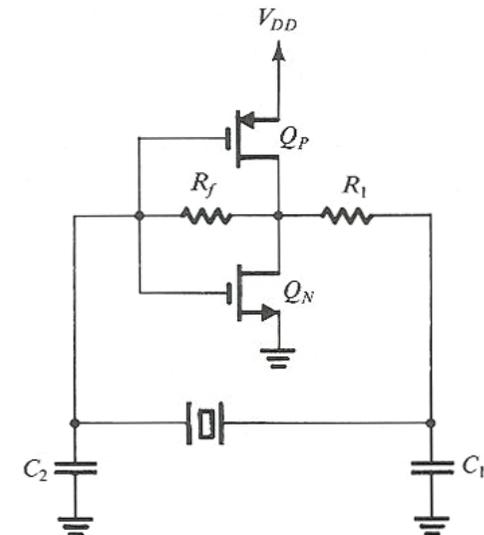
$$Z(j\omega) = -j \frac{1}{\omega C_p} \left(\frac{\omega^2 - \omega_s^2}{\omega^2 - \omega_p^2} \right)$$



- Crystal reactance is inductive over very narrow frequency (ω_s to ω_p).
- The frequency band is well defined for a given crystal.
- Use the crystal to replace the inductor of the Colpitts oscillators.
- Oscillation frequency is dominated by C_s (much smaller than other C 's).

$$\omega_0 \approx 1 / \sqrt{LC_s} = \omega_s$$

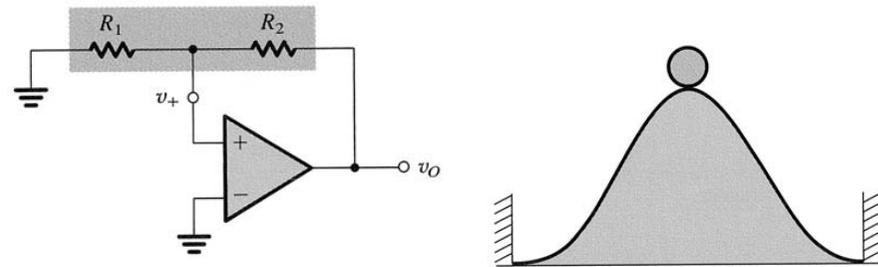
- Crystals are available with resonance frequencies KHz ~ hundred MHz.
- The oscillation frequency is fixed (tuning is not possible).



12.4 BISTABLE MULTIVIBRATORS

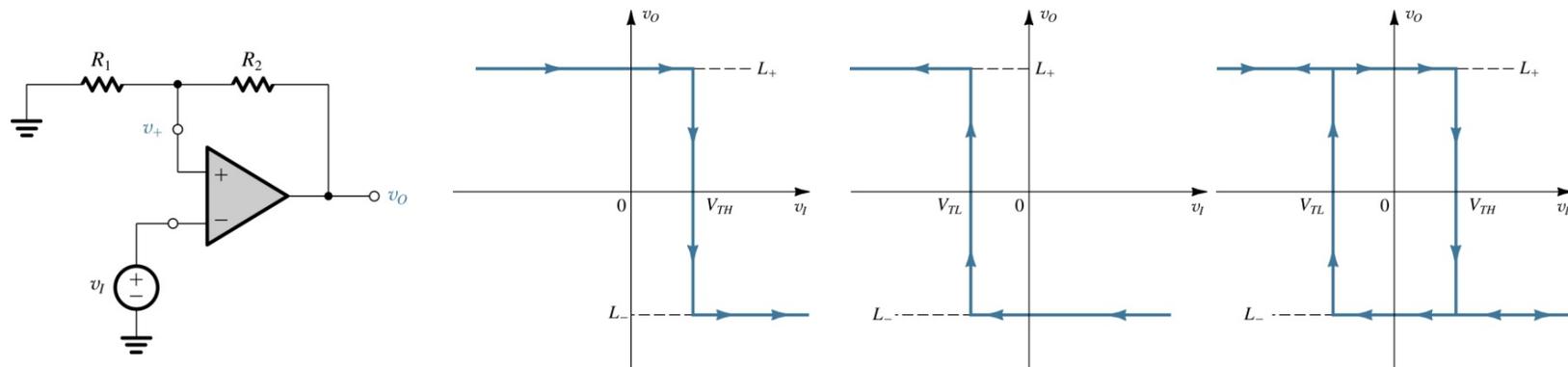
Bistable Characteristics

- ❑ Positive feedback is used for bistable multivibrator.
- ❑ Stable states:
 - (1) $v_O = L_+$ and $v_+ = L_+R_1/(R_1+R_2)$.
 - (2) $v_O = L_-$ and $v_+ = L_-R_1/(R_1+R_2)$.
- ❑ Metastable state: $v_O = 0$ and $v_+ = 0$.



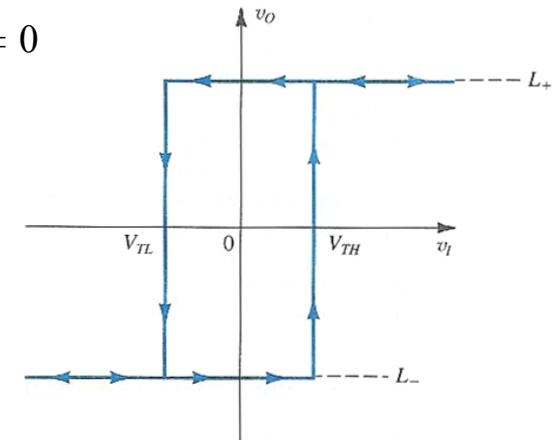
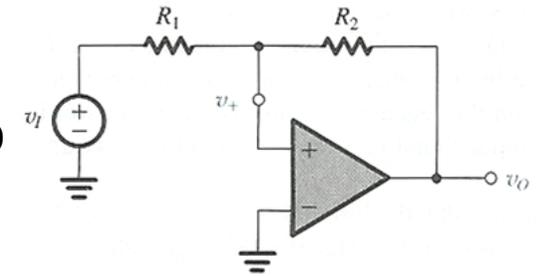
Transfer Characteristics of the Inverting Bistable Circuit

- ❑ Initially $v_O = L_+$ and $v_+ = L_+R_1/(R_1+R_2) \rightarrow v_O$ change stage to L_- when v_I increases to a value of $L_+R_1/(R_1+R_2)$.
- ❑ Initially $v_O = L_-$ and $v_+ = L_-R_1/(R_1+R_2) \rightarrow v_O$ change stage to L_+ when v_I decreases to a value of $L_-R_1/(R_1+R_2)$.
- ❑ The circuit exhibits hysteresis with a width of $(V_{TH} - V_{TL})$.
- ❑ Input v_I is referred to as a trigger signal which merely initiates or triggers regeneration.

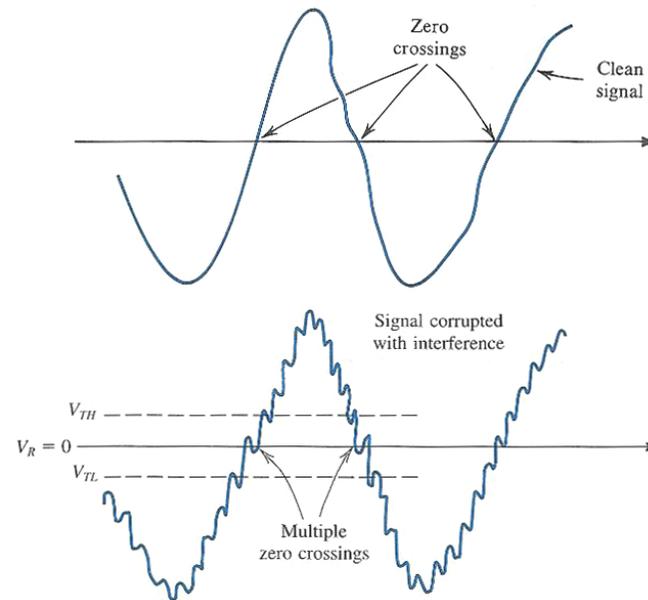
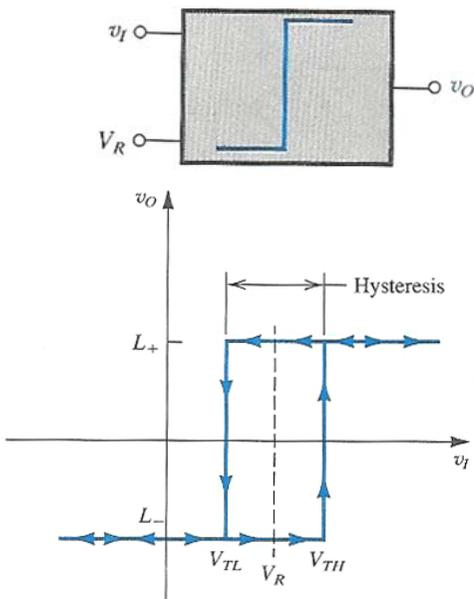


Transfer Characteristics of the Noninverting Bistable Circuit

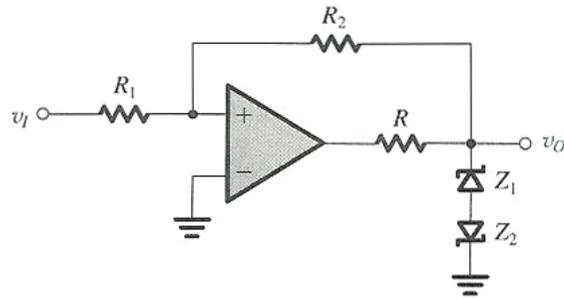
- Initially $v_O = L_+$ and $v_+ = v_1 R_2 / (R_1 + R_2) + L_+ R_1 / (R_1 + R_2) > 0$
 - v_O change stage to L_- when v_1 decreases to a value (V_{TL}) that causes $v_+ = 0$
 - $V_{TL} = -L_+(R_1/R_2)$
- Initially $v_O = L_-$ and $v_+ = v_1 R_2 / (R_1 + R_2) + L_- R_1 / (R_1 + R_2) < 0$
 - v_O change stage to L_+ when v_1 increases to a value (V_{TH}) that causes $v_+ = 0$
 - $V_{TH} = -L_-(R_1/R_2)$



Application of the Bistable Circuit as a Comparator

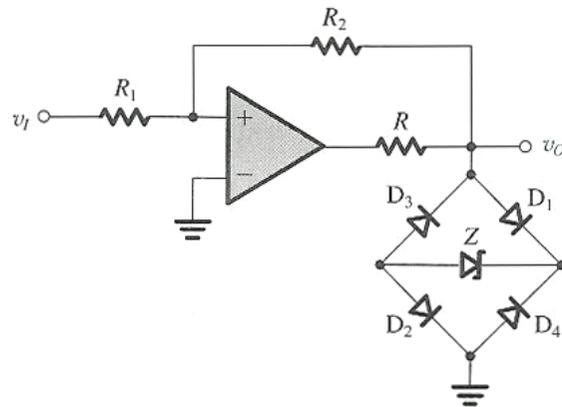


Limiter Circuits for Precise Output Levels



$$L_+ = V_{Z1} + V_D$$

$$L_- = -(V_{Z1} + V_D)$$

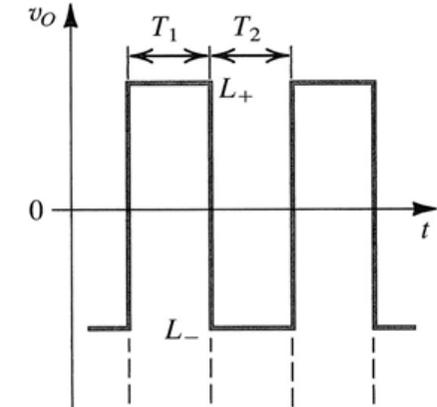
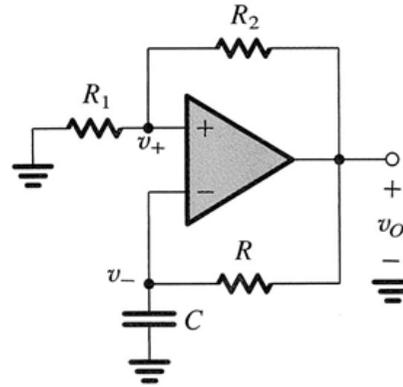
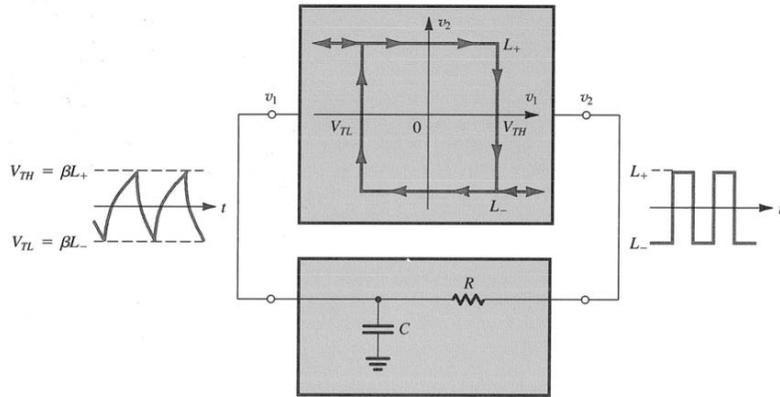


$$L_+ = V_Z + V_{D1} + V_{D2}$$

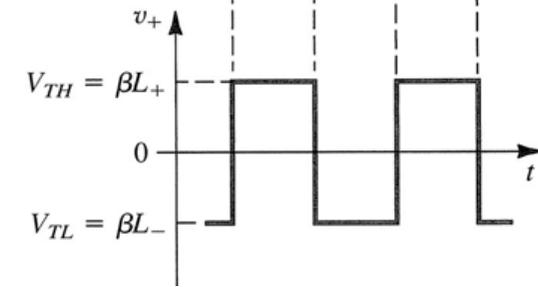
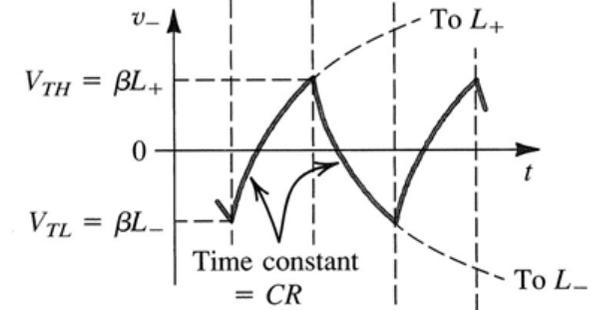
$$L_- = -(V_Z + V_{D3} + V_{D4})$$

12.5 GENERATION OF SQUARE AND TRIANGULAR WAVEFORMS USING ASTABLE MULTIVIBRATORS

Operation of the Astable Multivibrator



- For $v_O = L_+$ and $v_+ = v_O R_1 / (R_1 + R_2) > 0$
 $\rightarrow v_-$ is charged toward L_+ through RC
 $\rightarrow v_O$ change stage to L_- when $v_- = v_+$
- For $v_O = L_-$ and $v_+ = v_O R_1 / (R_1 + R_2) < 0$
 $\rightarrow v_-$ is discharged toward L_- through RC
 $\rightarrow v_O$ change stage to L_+ when $v_- = v_+$



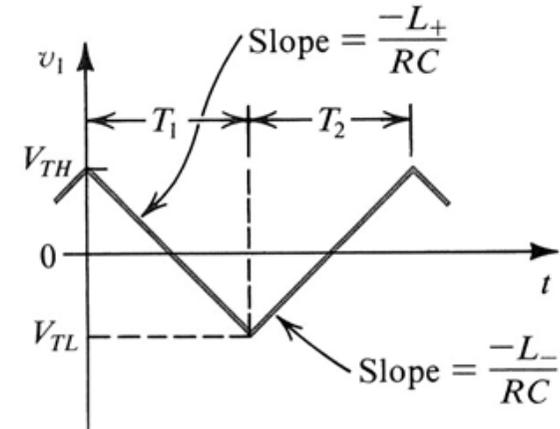
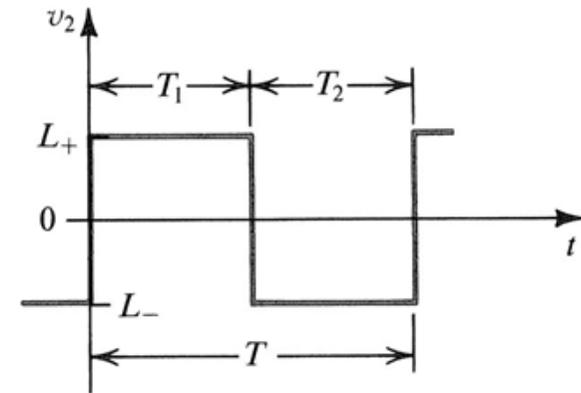
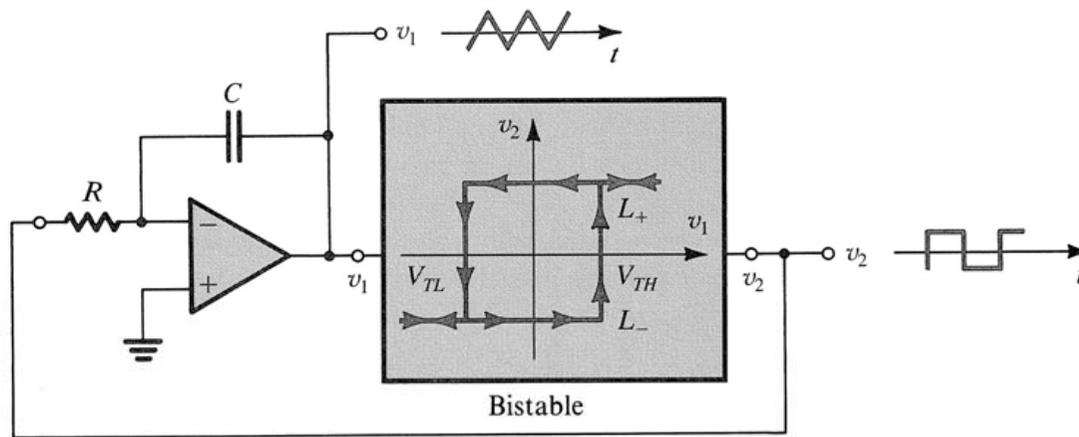
$$v_- = L_+ - (L_+ - \beta \cdot L_-) e^{-t/RC} = L_+ - (L_+ - \beta \cdot L_-) e^{-t/\tau} \rightarrow T_1 = \tau \ln \frac{1 - \beta(L_- / L_+)}{1 - \beta}$$

$$v_- = L_- - (L_- - \beta \cdot L_+) e^{-t/RC} = L_- - (L_- - \beta \cdot L_+) e^{-t/\tau} \rightarrow T_2 = \tau \ln \frac{1 - \beta(L_+ / L_-)}{1 - \beta}$$

$$T \approx 2\tau \ln \frac{1 + \beta}{1 - \beta}$$

Generation of Triangular Waveforms

- ❑ Triangular can be obtained by replacing the low-pass RC circuit with an integrator.
- ❑ The bistable circuit required is of the noninverting type.



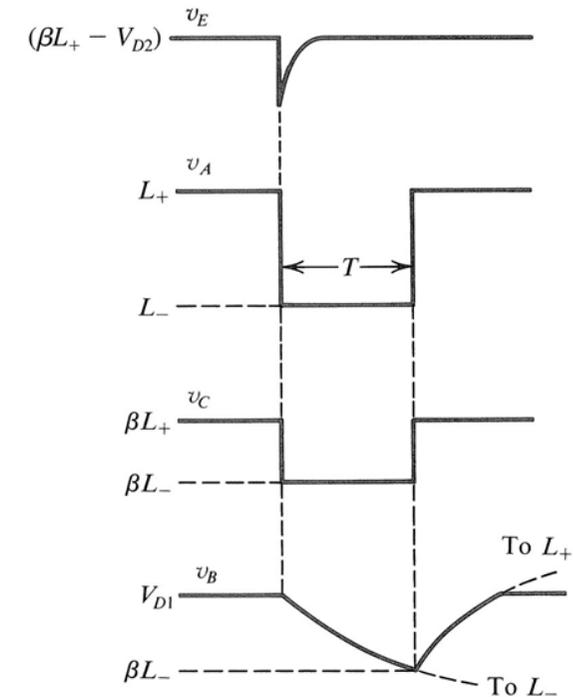
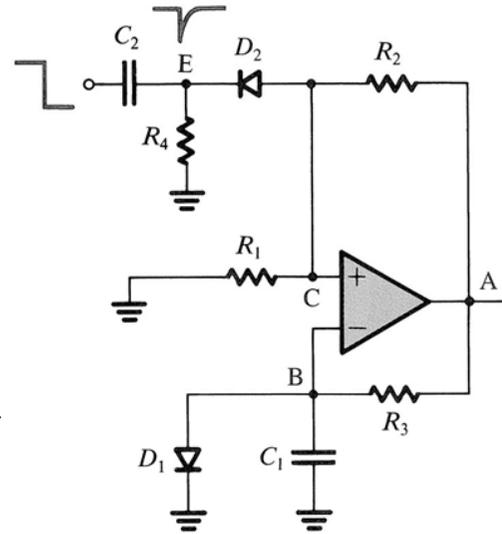
$$\frac{V_{TH} - V_{TL}}{T_1} = \frac{L_+}{RC} \rightarrow T_1 = RC \frac{V_{TH} - V_{TL}}{L_+}$$

$$\frac{V_{TH} - V_{TL}}{T_2} = \frac{-L_-}{RC} \rightarrow T_2 = RC \frac{V_{TH} - V_{TL}}{-L_-}$$

12.6 GENERATION OF A STANDARDIZED PULSE – THE MONOSTABLE MULTIVIBRATORS

Op-Amp Monostable Multivibrators

- ❑ Circuit components:
 - Trigger: C_2 , R_4 and D_2
 - Clamping diode: D_1
 - $R_4 \gg R_1 \rightarrow i_{D4} \approx 0$
- ❑ The circuit has one stable state:
 - $v_O = L_+$
 - $v_B = V_{D1} \approx 0$
 - D_1 and D_2 on
- ❑ Operation of monostable multivibrator
 - Negative step as the trigger input
 - D_2 conducts heavily
 - v_C is pulled below v_B
 - v_O changes state to L_- and v_C becomes negative
 - D_1 and D_2 off and C_1 is discharged toward L_-
 - v_O changes state to L_+ as $v_B = v_C$
 - Stays in the stable state
 - Positive trigger step turns off D_2 (invalid trigger)



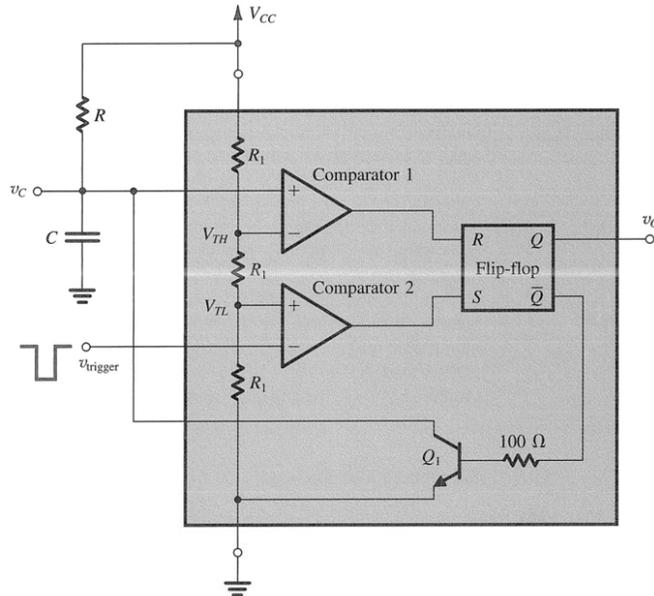
$$v_B(t) = L_- - (L_+ - V_{D1})e^{-t/R_3C_1}$$

$$v_B(T) = L_- - (L_+ - V_{D1})e^{-T/R_3C_1} = \beta \cdot L_-$$

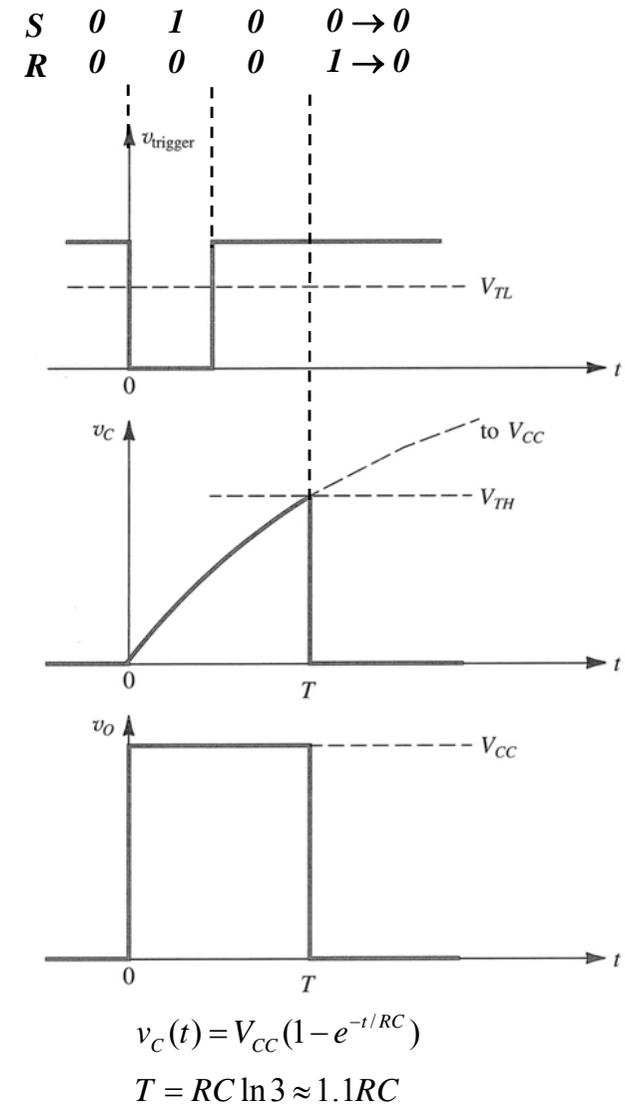
$$\rightarrow T \approx C_1 R_3 \ln \left(\frac{V_{D1} - L_-}{\beta \cdot L_- - L_-} \right) \approx C_1 R_3 \ln \left(\frac{1}{1 - \beta} \right)$$

12.7 INTEGRATED-CIRCUIT TIMERS

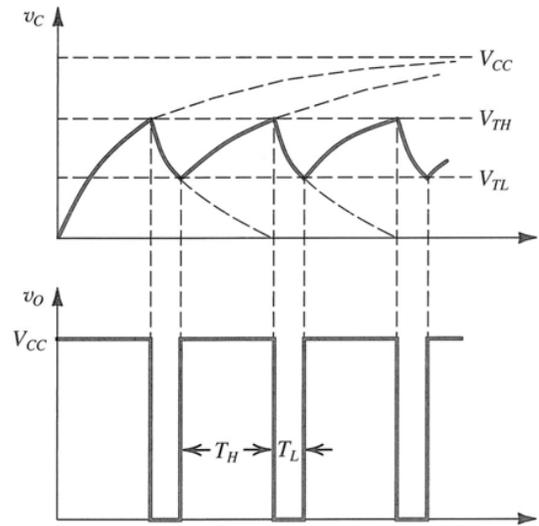
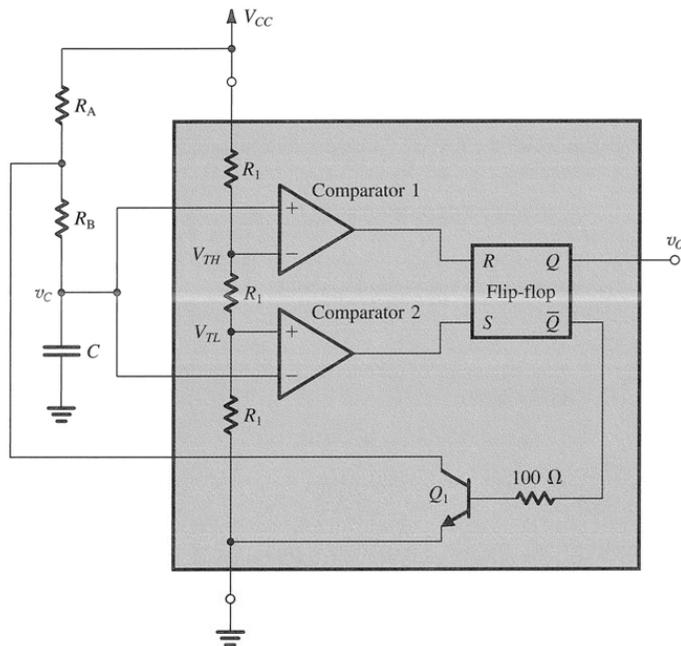
Monostable Multivibrator using 555 Timer Circuit



- ❑ Stable state: $S = R = 0$ and $Q = 0$
 $\rightarrow Q_1$ on and $v_C = 0$
- ❑ Trigger ($v_{\text{trigger}} < V_{TL}$): $S = 1$ and $Q = 1$
 $\rightarrow Q_1$ off and v_C is charged toward V_{CC}
- ❑ Trigger pulse removal ($v_{\text{trigger}} > V_{TL}$): $S = R = 0$ and $Q = 1$
 $\rightarrow Q_1$ off and v_C is charged toward V_{CC}
- ❑ End of recovery period ($v_C = V_{TH}$): $R = 1$ and $Q = 0$
 $\rightarrow Q_1$ on and v_C is discharged toward GND
- ❑ Stable state: v_C drops to 0 and $S = R = 0$ and $Q = 0$



Astable Multivibrator using 555 Timer Circuit



$$v_C(t) = V_{CC} - (V_{CC} - V_{TL})e^{-t/C(R_A + R_B)}$$

$$T_H = C(R_A + R_B) \ln 2 \approx 0.69C(R_A + R_B)$$

$$v_C = V_{TH}e^{-t/CR_B}$$

$$T_L = CR_B \ln 3 \approx 0.69CR_B$$

$$T = T_H + T_L = 0.69CR_B$$

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

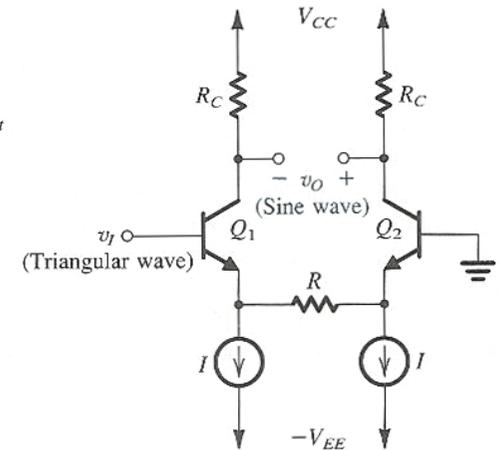
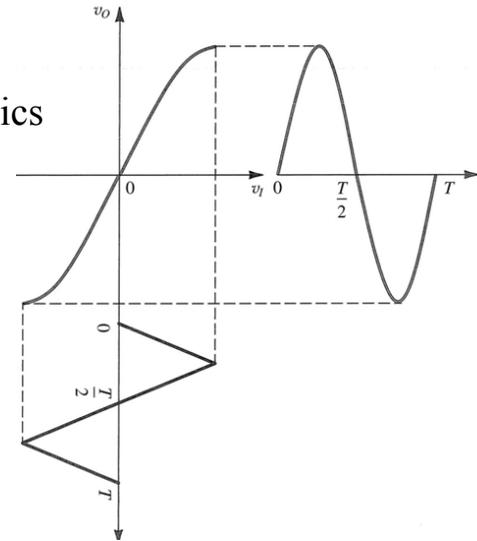
□ Operation of astable multivibrator

- Initially $v_C = 0$: $S/R = 1/0$ and $Q = 1 \rightarrow Q_1$ off and v_C is charged toward V_{CC} thru R_A and R_B
- v_C reaches V_{TH} : $S/R = 0/1$ and $Q = 0 \rightarrow Q_1$ on and v_C is discharged toward GND thru R_B
- v_C reaches V_{TL} : $S/R = 1/0$ and $Q = 1 \rightarrow Q_1$ off and v_C is charged toward V_{CC} thru R_A and R_B

12.8 NONLINEAR WAVEFORM-SHAPING CIRCUITS

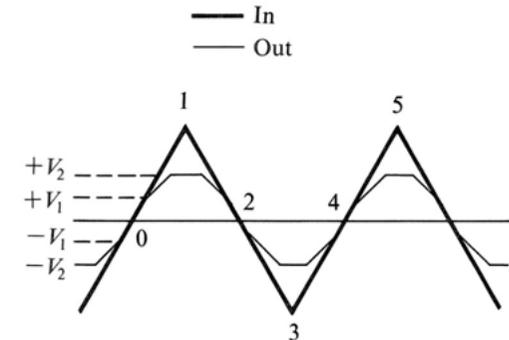
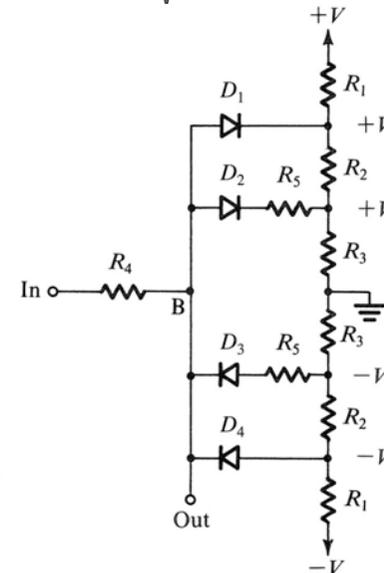
Nonlinear Amplification Method

- ❑ Use amplifiers with nonlinear transfer characteristics to convert triangular wave to sine wave.
- ❑ Differential pair with an emitter degeneration resistance can be used as sine-wave shaper.



Breakpoint Method

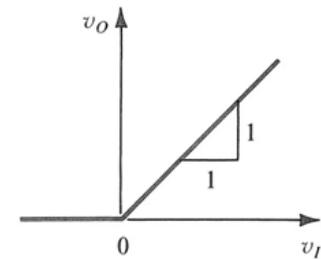
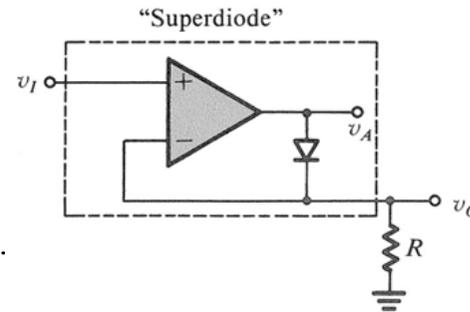
- ❑ $R_4, R_5 \gg R_1, R_2$ and R_3 to avoid loading effect
 - $-V_1 < v_{IN} < V_1$:
 $\rightarrow v_O = v_{IN}$
 - $-V_2 < v_{IN} < -V_1$ or $V_1 < v_{IN} < V_2$
 $\rightarrow v_O = V_1 + (v_{IN} - V_1) R_5 / (R_4 + R_5)$
 - $v_{IN} < -V_2$ or $V_2 < v_{IN}$
 $\rightarrow v_O = V_2$



12.9 PRECISION RECTIFIER CIRCUITS

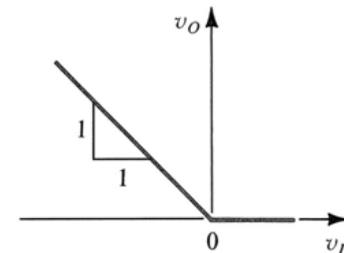
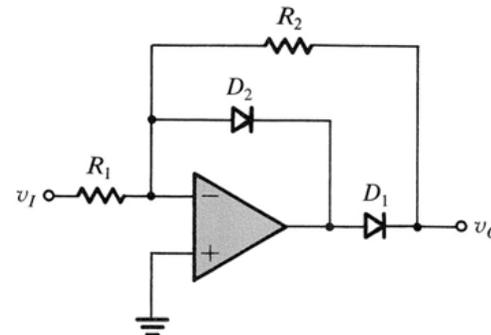
Precision Half-Wave Rectifier (Superdiode)

- ❑ Operation of super diode:
 - $v_O = v_I$ for $v_I > 0$
 - $v_O = 0$ for $v_I < 0$
- ❑ The offset voltage ($\sim 0.5V$) can be eliminated.
- ❑ Nonideal characteristics are masked by the loop gain.
- ❑ Disadvantages:
 - Reverse bias may damage the input terminals.
 - Op saturation (open loop) degrades the speed.



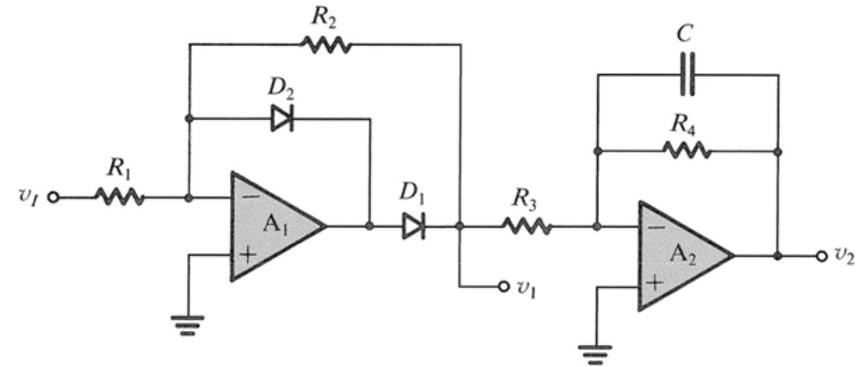
Improved Precision Half-Wave Rectifier

- ❑ Rectifier operation:
 - $v_I > 0$: D_1 off, D_2 on $\rightarrow v_O = 0$
 - $v_I < 0$: D_1 on, D_2 off $\rightarrow v_O = -(R_2 / R_1) v_I$
- ❑ The feedback loop remains closed at all times.
- ❑ The op amp remains in its linear operation region.
- ❑ Can prevent the delay due to saturated op amp.



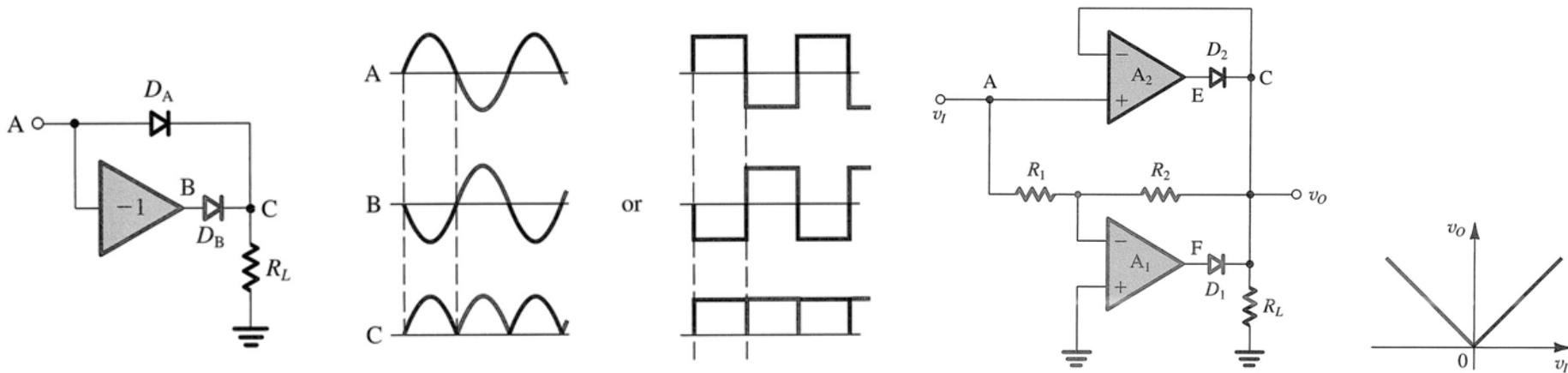
AC Voltage Measurement

- ❑ The circuit consists of a half-wave rectifier and a first-order low-pass filter.
- ❑ Dc component of v_1 is $(V_p/\pi)(R_2/R_1)$.
- ❑ The LPF corner frequency should be much smaller than the input sine wave to reduce error by the harmonics.

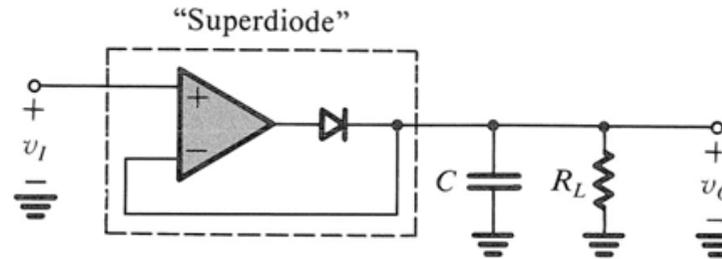


Precision Full-Wave Rectifier

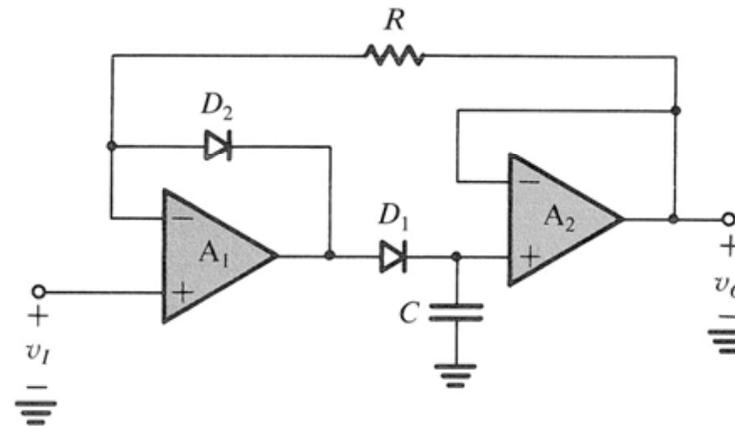
- ❑ Full-wave rectifier is implemented by combining two rectifiers with a common load.
- ❑ Diode A is replaced by a superdiode.
- ❑ Diode B is replaced by the inverting precision half-wave rectifier.



Precision Peak Rectifiers



Buffered Precision Peak Detector



Precision Clamping Circuit

