Dr. Nguyen Anh Quang

Electronic Circuits and Applications

Lesson 12. Op-Amp Application (II)

Learning Contents

1. Active Filters
2. Precision Amplifier
3. Practical Amplifiers using Op-Amp

Learning Goals

1. Understand and design the active filter by using op-amp.
2. Design the precision rectifier for small signals
3. Understand and explain other practical amplifiers using Op-Amp

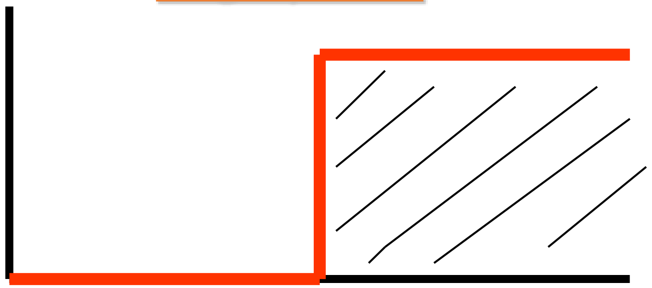
1. Active Filters

1.1. Basic Filter Response

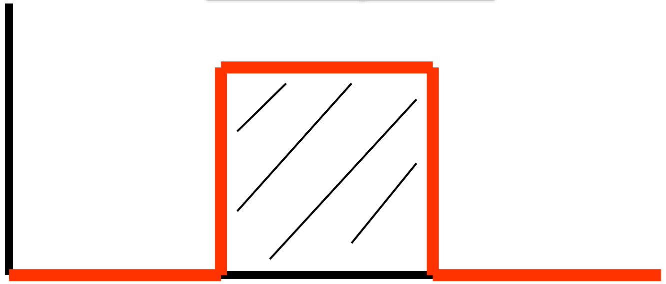
Passive Filters: Ideal

lowpass

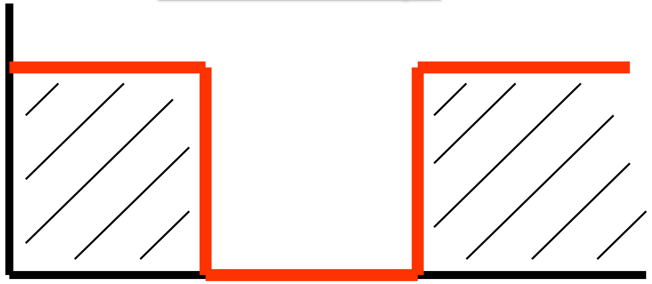
highpass



bandpass



bandstop



1. Active Filters

1.1. Basic Filter Response

1.2. Low-Pass Filter

1.3. High-Pass Filter

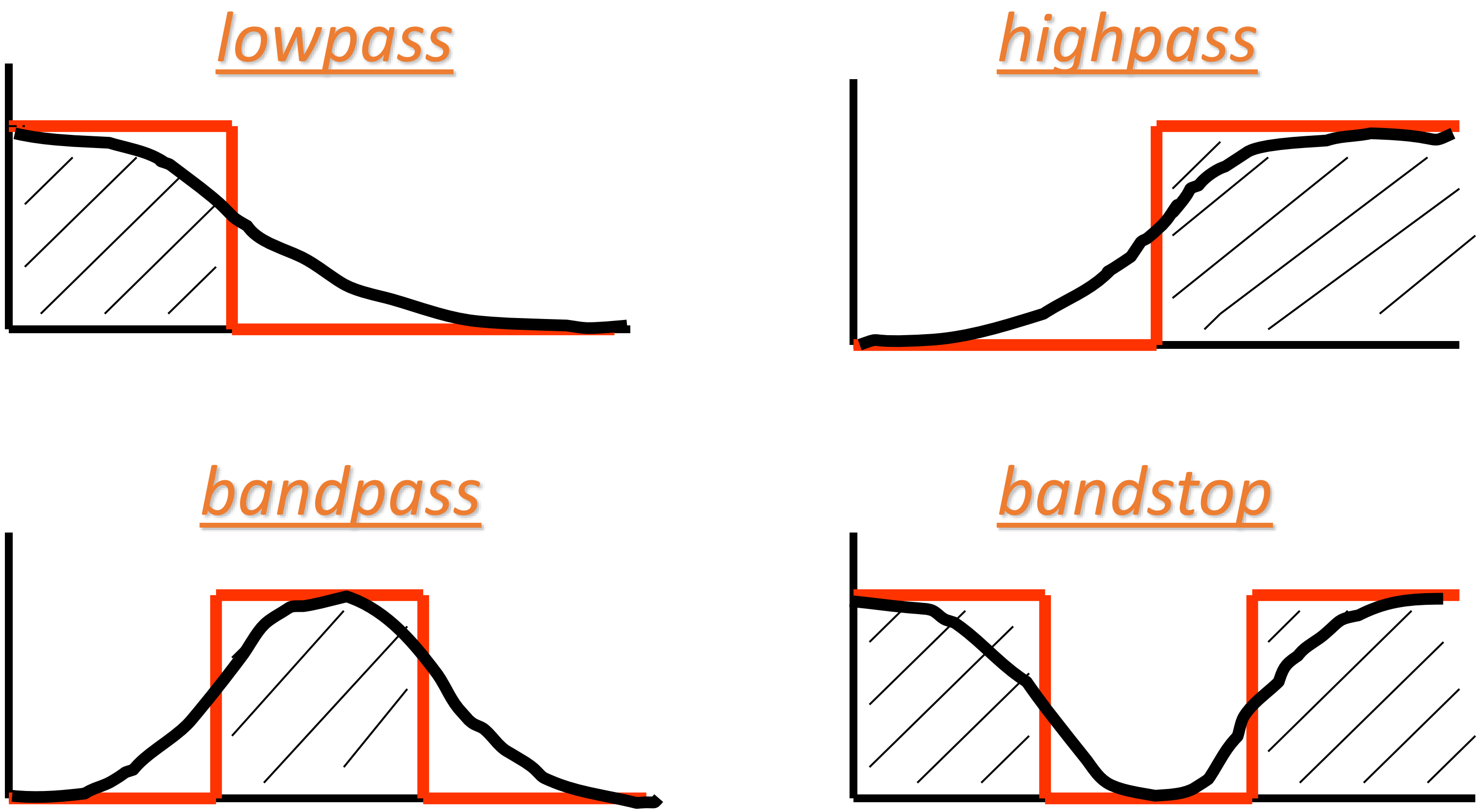
1.4. Band-Pass Filter

1.5. Band-Stop Filter

1. Active Filters

1.1. Basic Filter Response

Passive Filters: Realistic

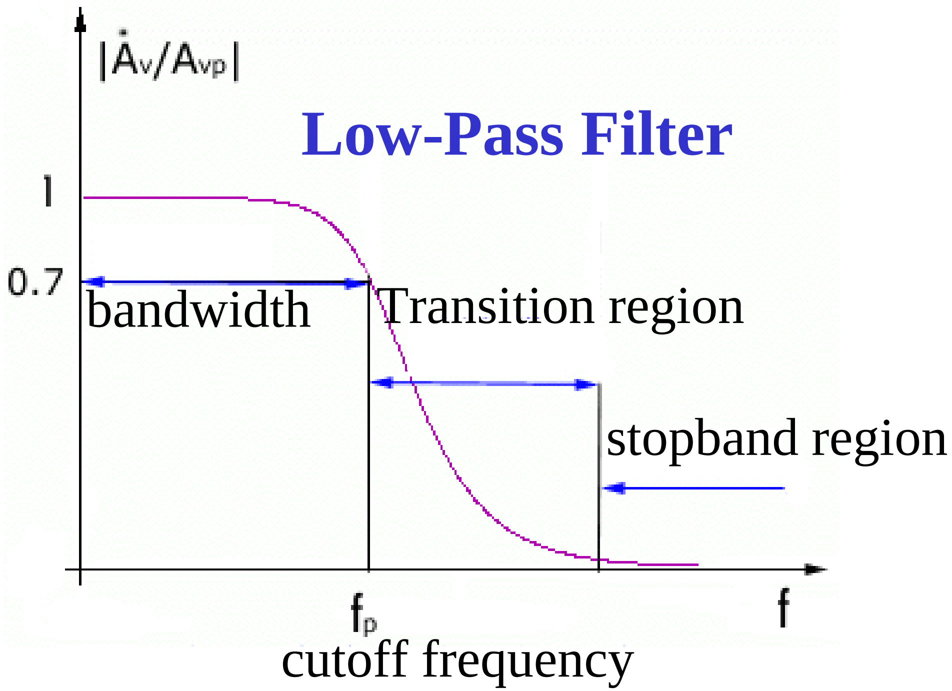


1. Active Filters

1.1. Basic Filter Response

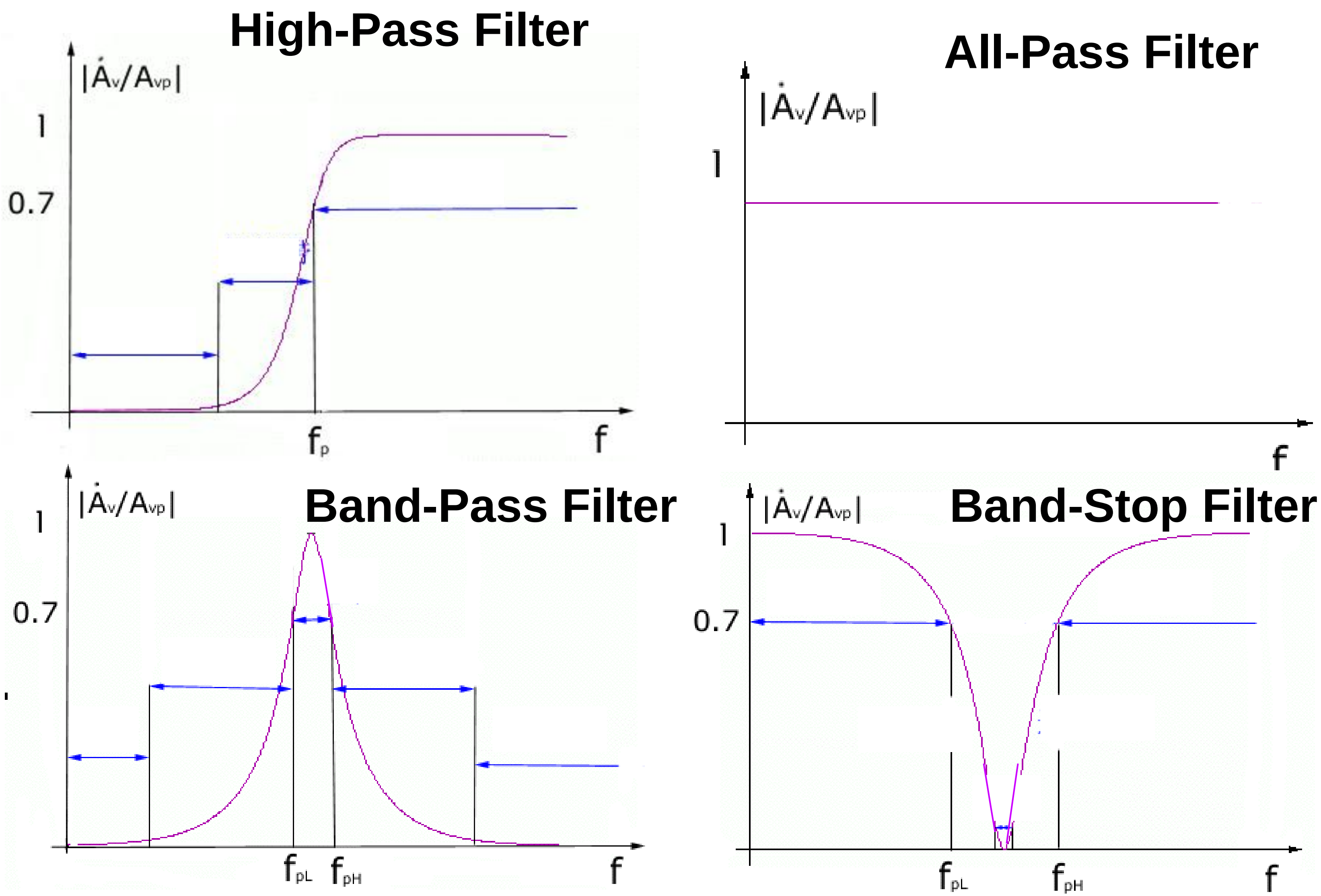
Voltage gain $A(s) = \frac{v_O(s)}{v_i(s)}$

$$S = j\omega \qquad \dot{A}(j\omega) = \frac{\dot{V}_o(j\omega)}{\dot{V}_i(j\omega)} = |A(j\omega)| \angle \varphi(j\omega)$$



1. Active Filters

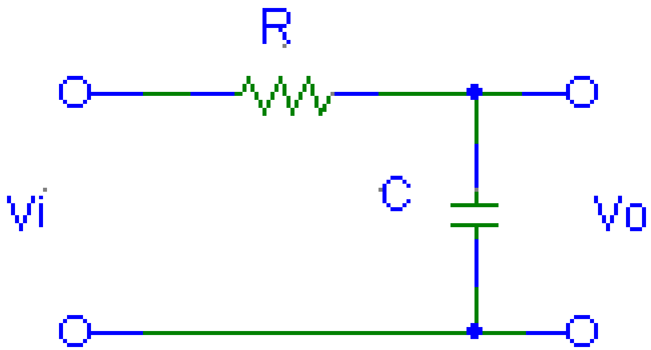
1.1. Basic Filter Response



1. Active Filters

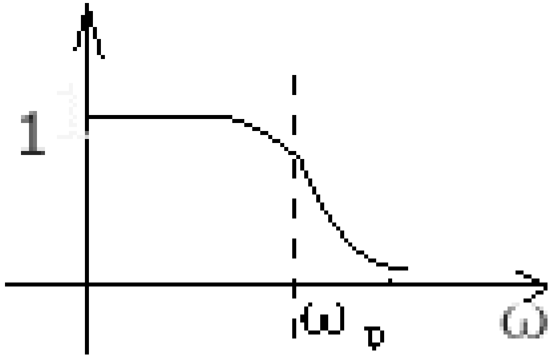
1.1. Basic Filter Response

Low-Pass Filter



$$\dot{A} = \frac{\dot{V}_O}{\dot{V}_i} = \frac{1/\,j\omega c}{R + \frac{1}{j\omega c}} = \frac{1}{1 + j\frac{\omega}{\omega_0}} = \frac{1 - j\frac{\omega}{\omega_0}}{1 + \left(\frac{\omega}{\omega_0}\right)^2}$$

$$(\omega_O = \frac{1}{RC})$$

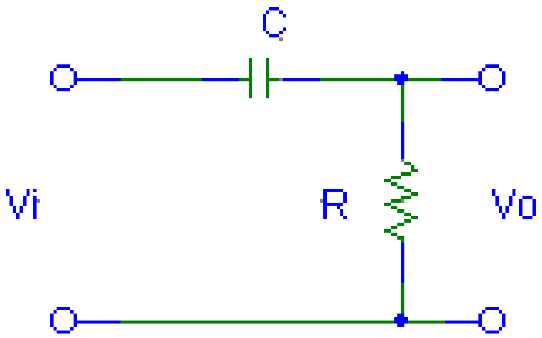


$$\varphi = -tg^{-1}\frac{\omega}{\omega_0} \xrightarrow{\omega=\omega_0} -45°$$

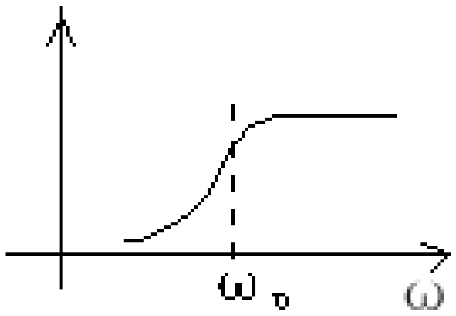
1. Active Filters

1.1. Basic Filter Response

High-Pass Filter

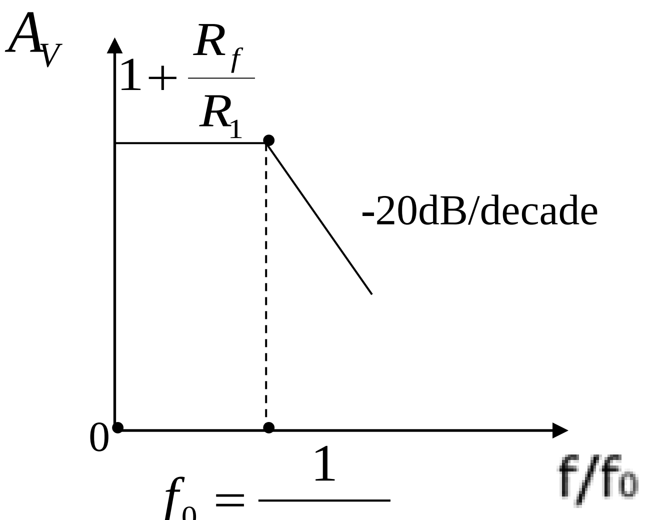


$$\dot{A} = \frac{\dot{V}_O}{\dot{V}_i} = \frac{R}{R+\frac{1}{j\omega c}} = \frac{1}{1+\frac{1}{j\omega Rc}} = \frac{1}{1-j\frac{\omega_o}{\omega}}$$



1. Active Filters

1.2. Low-Pass Filter



$$f_0 = \frac{1}{2\pi RC}$$

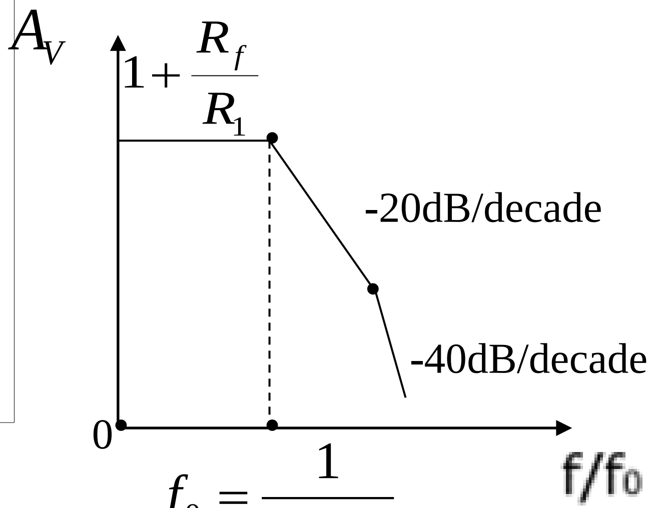
$$V_0 = V_+ \cdot \left(1+\frac{R_f}{R_1}\right) = \left(1+\frac{R_f}{R_1}\right)\frac{V_i \cdot \frac{1}{j\omega c}}{R+\frac{1}{j\omega c}}$$

$$A(j\omega) = \frac{V_O(j\omega)}{V_i(j\omega)} = \frac{1+\frac{R_f}{R_1}}{1+j\omega cR} = \frac{A_{VF}}{1+j\frac{\omega}{\omega_O}}$$

First-order (one-pole) Filter

1. Active Filters

1.2. Low-Pass Filter



$$f_0 = \frac{1}{2\pi RC}$$

$$V_0 = V_+ \cdot \left(1+\frac{R_f}{R_1}\right)$$

$$= \left(1+\frac{R_f}{R_1}\right)\frac{V_i \cdot \frac{1}{j\omega c}}{\left(R+\frac{1}{j\omega c}\right) // \left(R+\frac{1}{j\omega c}\right)}$$

$$A(j\omega) = \frac{V_O(j\omega)}{V_i(j\omega)} = A_{VF} \times \frac{1}{1+3j\omega RC+(j\omega RC)^2}$$

Second-order (two-pole) Filter

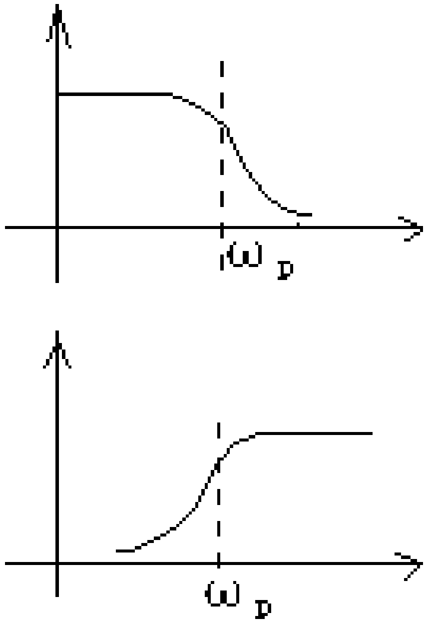
1. Active Filters

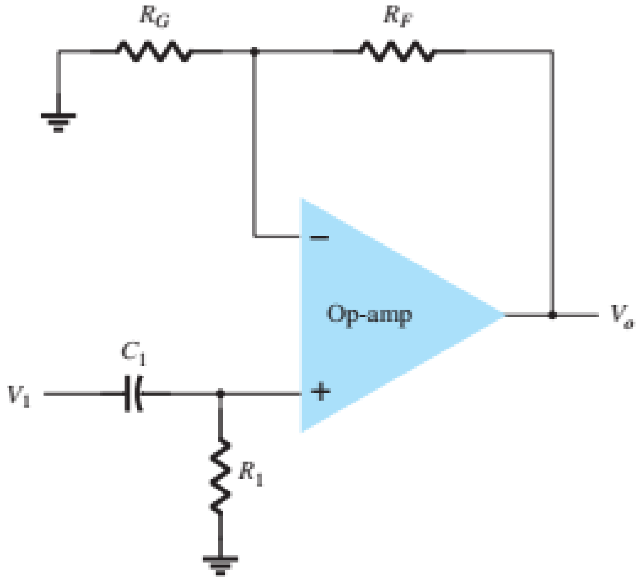
1.3. High-Pass Filter

- Transfer functions: $$A_L = \frac{1}{1 + j\omega RC} \xrightarrow{SRC \to \frac{1}{SRC}} \frac{1}{1 + \frac{1}{SRC}} = A_H$$

- Circuit: $R \leftrightarrow C$

- Frequency domain





The Non-Inverting First-order High-Pass Filter

1. Active Filters

1.3. High-Pass Filter

$$-\frac{v_o}{R_f}=\frac{v_i}{R_1+Z_C}$$

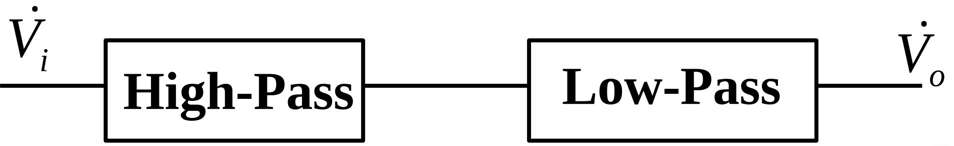
$$\dot{A}=\frac{\dot{V}_o}{\dot{V}_i}=\frac{-V_i\cdot\dfrac{R_f}{R_1+Z_C}}{V_i}=-R_f\cdot\frac{1}{R_1+\dfrac{1}{j\omega c}}$$

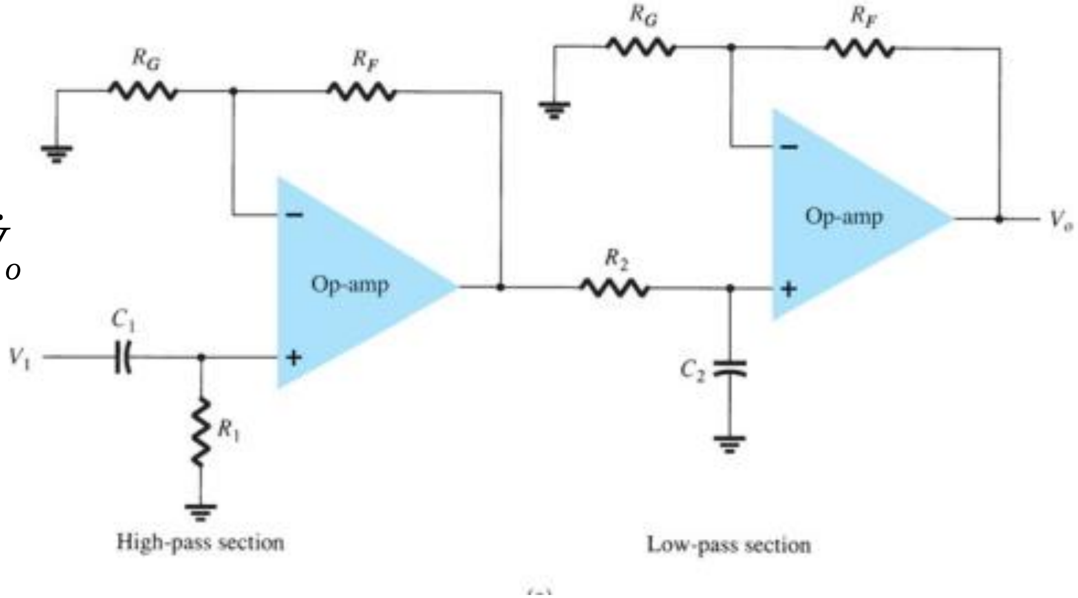
$$=-\frac{R_f}{R_1}\cdot\frac{1}{1+1/\,j\omega R_1 C}=A_{VF}\cdot\frac{1}{1-j\dfrac{\omega_o}{\omega}}$$

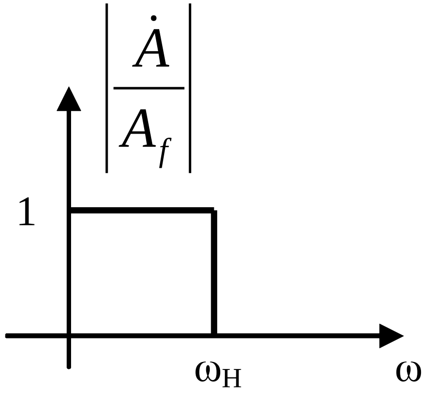
The Inverting First-order High-Pass Filter

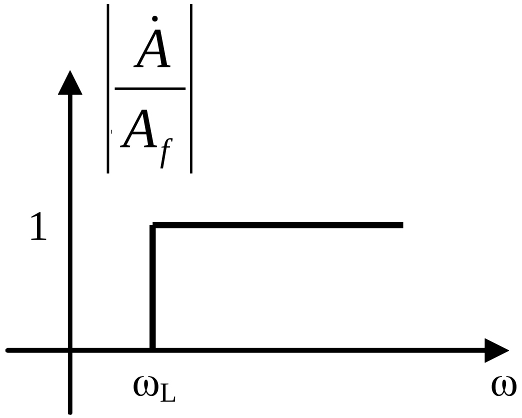
1. Active Filters

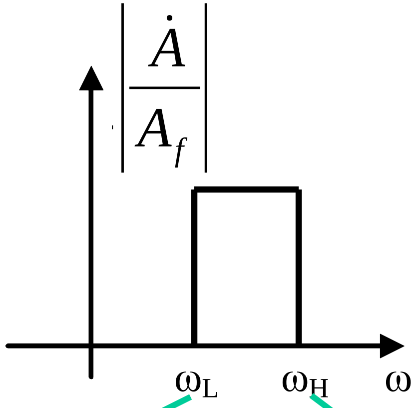
1.4. Band-Pass Filter







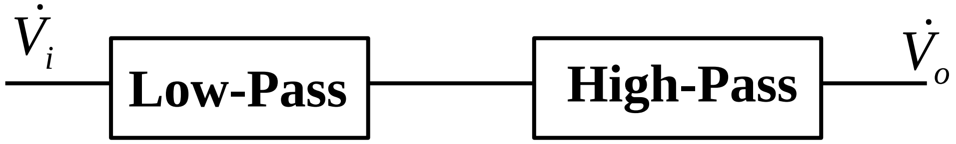


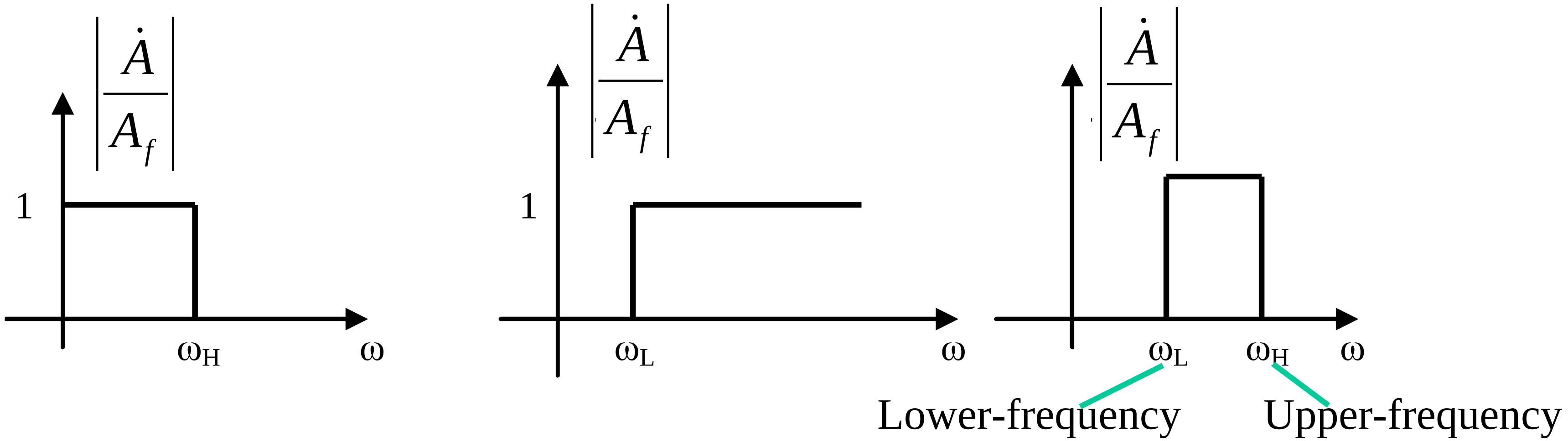


Lower-frequency Upper-frequency

1. Active Filters

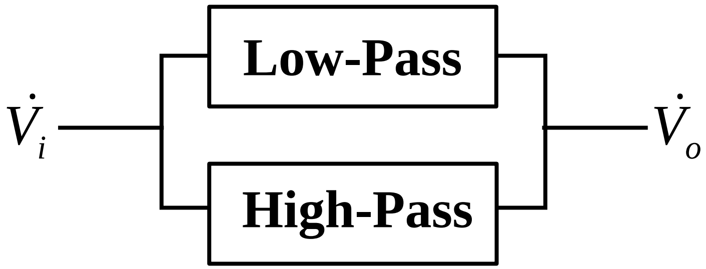
1.4. Band-Pass Filter

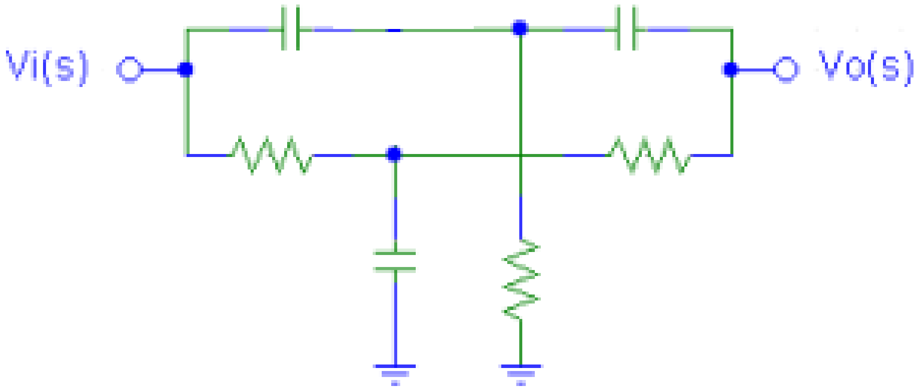


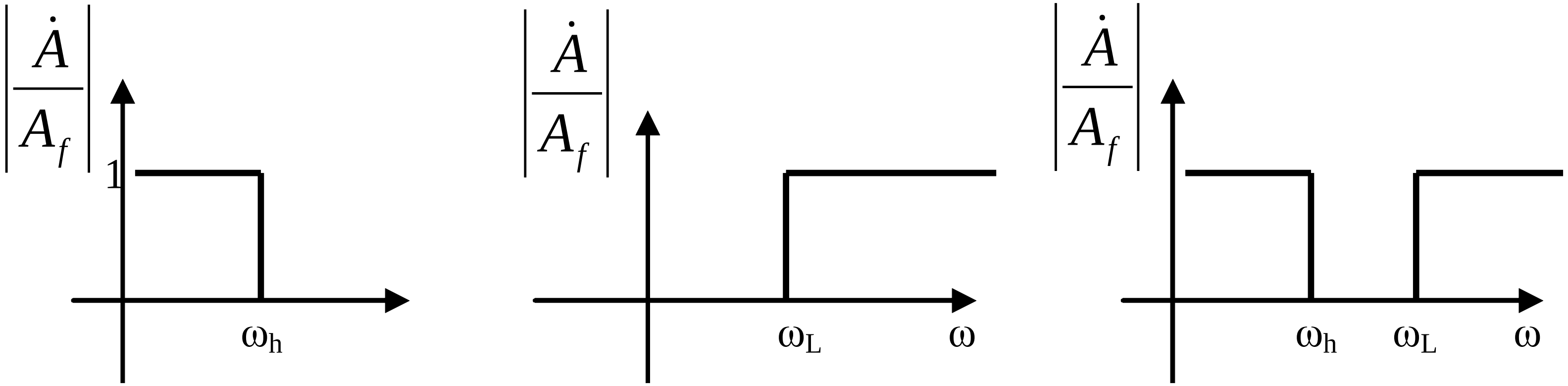


1. Active Filters

1.5. Band-Stop Filter







1. Active Filters

1.5. Band-Stop Filter

The Non-Inverting Band-Stop Filter

2. Precision Rectifier

2.1. Rectifier using Diodes

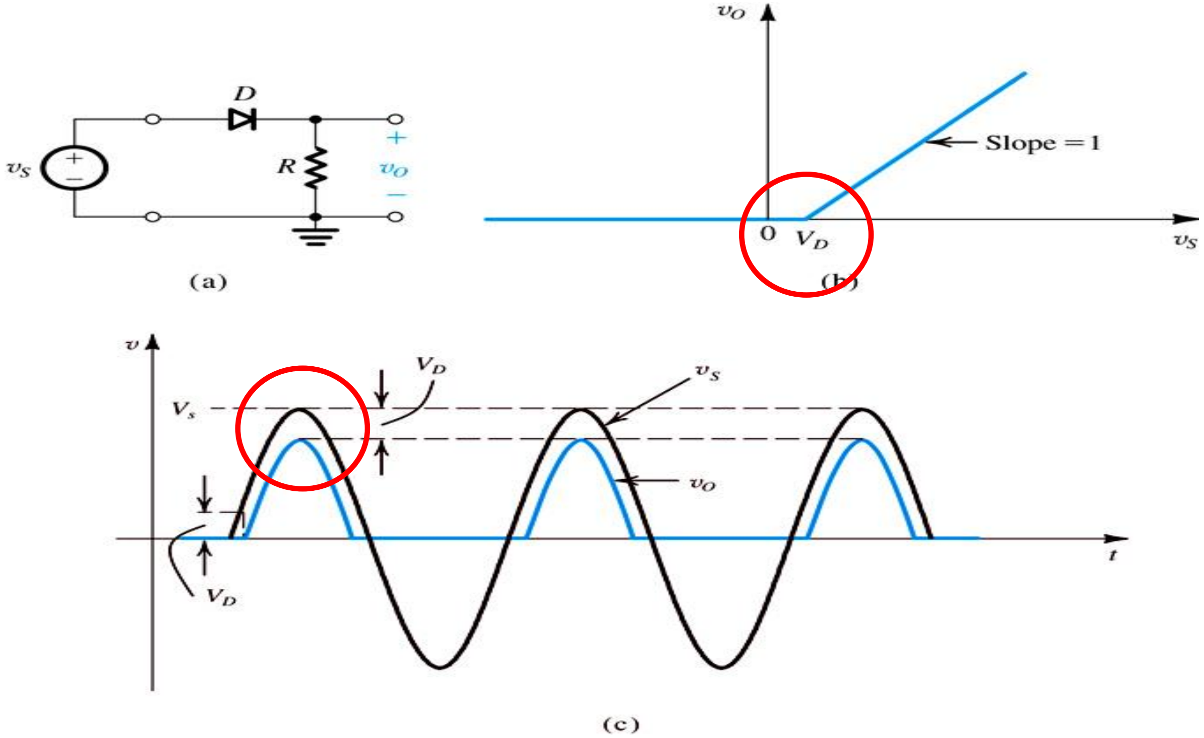
2.2. Precision Half-Wave Rectifier

2.3. Precision Full-Wave Rectifier

2. Precision Rectifier

2.1. Rectifier using Diodes

- Rectifier circuits are used in the design of power supply circuits.
- In such applications, the voltage 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.

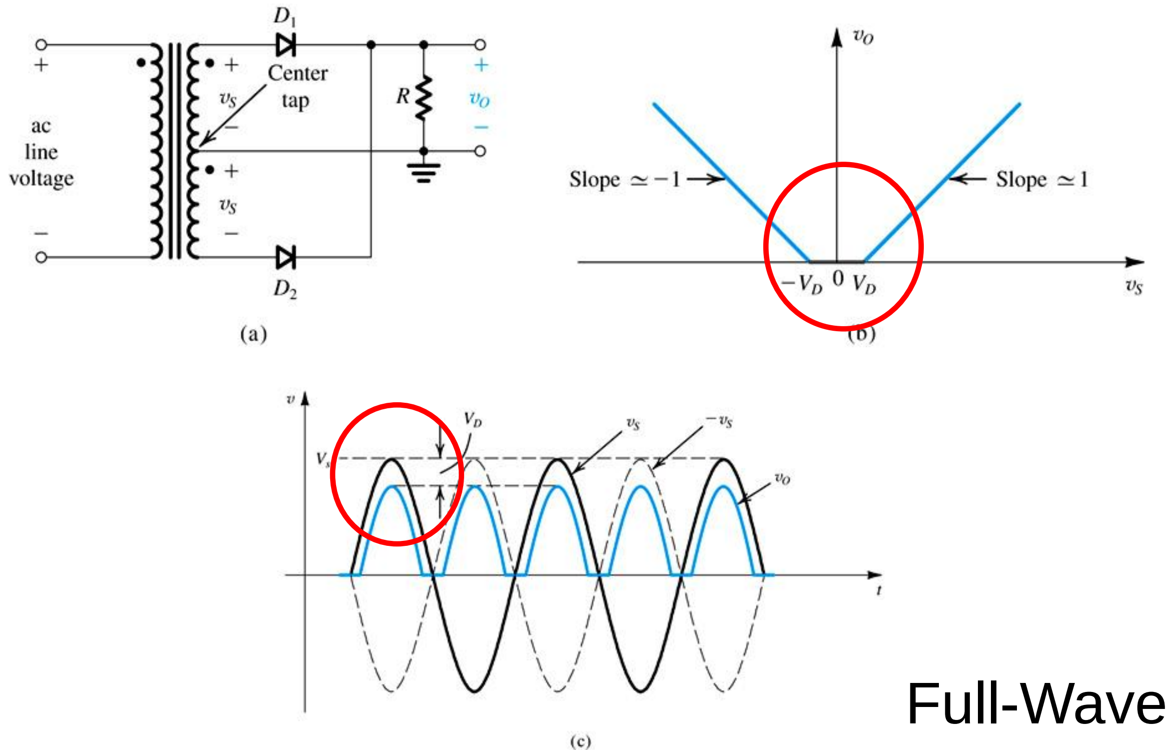


Half-Wave Rectifier

2. Precision Rectifier

2.1. Rectifier using Diodes

In some applications, the signal to be rectified can be of very small amplitude, say 0.1 V, making it impossible to employ the conventional rectifier circuits. Also the need arises for very precise transfer characteristics.

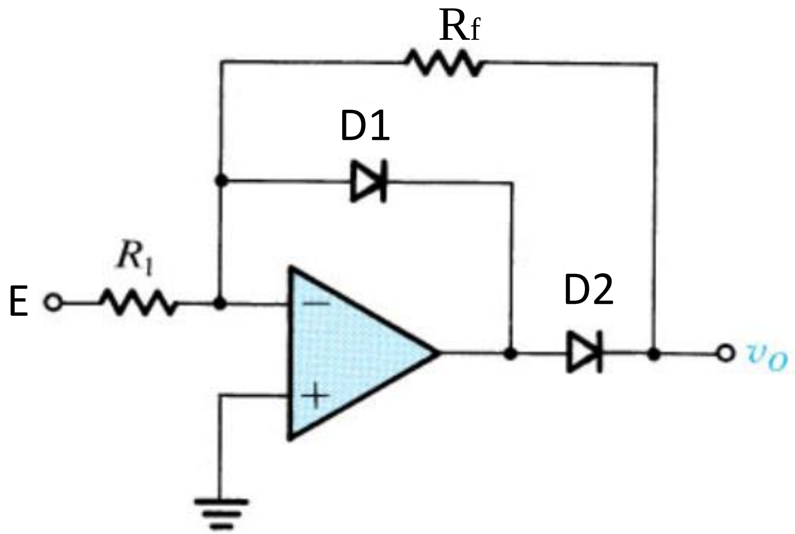


Full-Wave Rectifier

2. Precision Rectifier

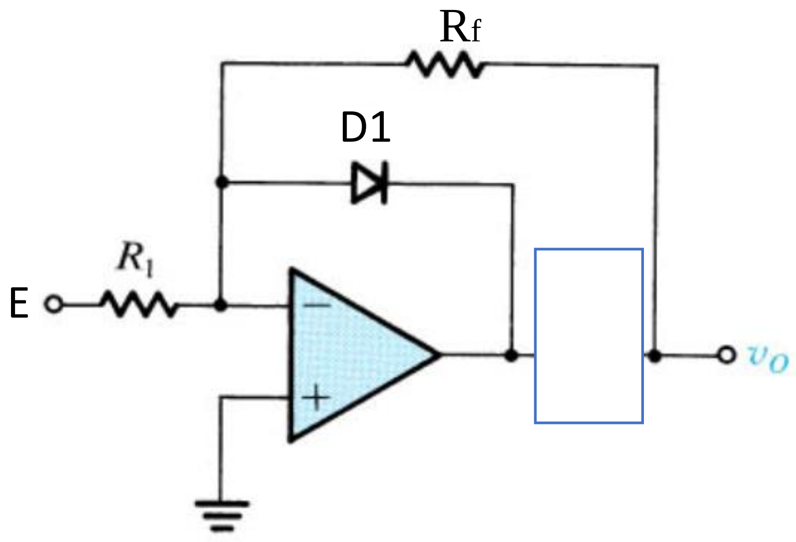
2.2. Precision Half-Wave Rectifier

- The inverting amplifier is converted into an ideal (linear precision) half-wave rectifier by adding two diodes.



2. Precision Rectifier

2.2. Precision Half-Wave Rectifier



- When *E,* is positive, diode *D1* conducts,

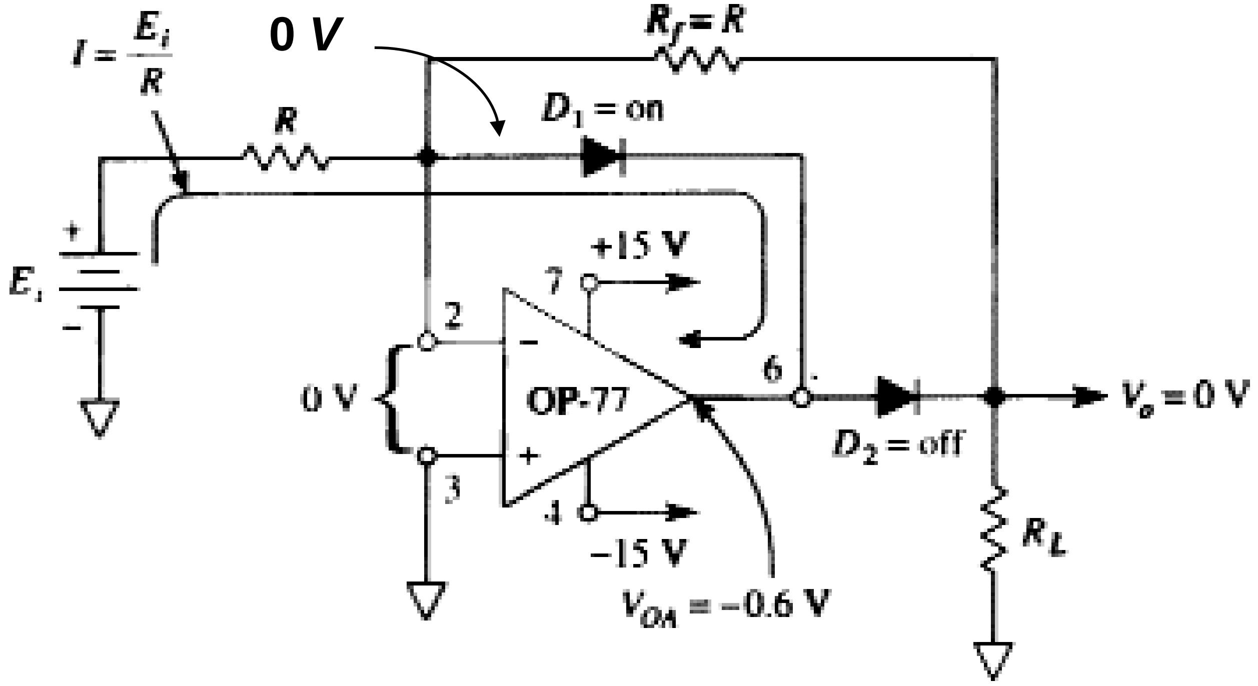
=> op amp's output voltage, V_{OA}, to go negative.

- This forces diode *D2* to be reverse biased.
  - *Vo* equals zero because input current *I* flows through *D1*.
  - No current flows through *Rf* and therefore *Vo = 0.*

2. Precision Rectifier

2.2. Precision Half-Wave Rectifier

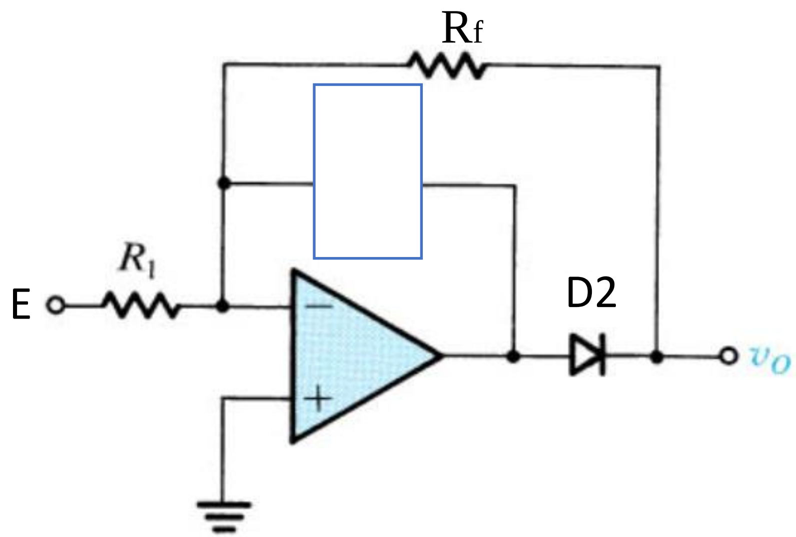
Positive Input: D1 on; D2 off



2. Precision Rectifier

2.2. Precision Half-Wave Rectifier

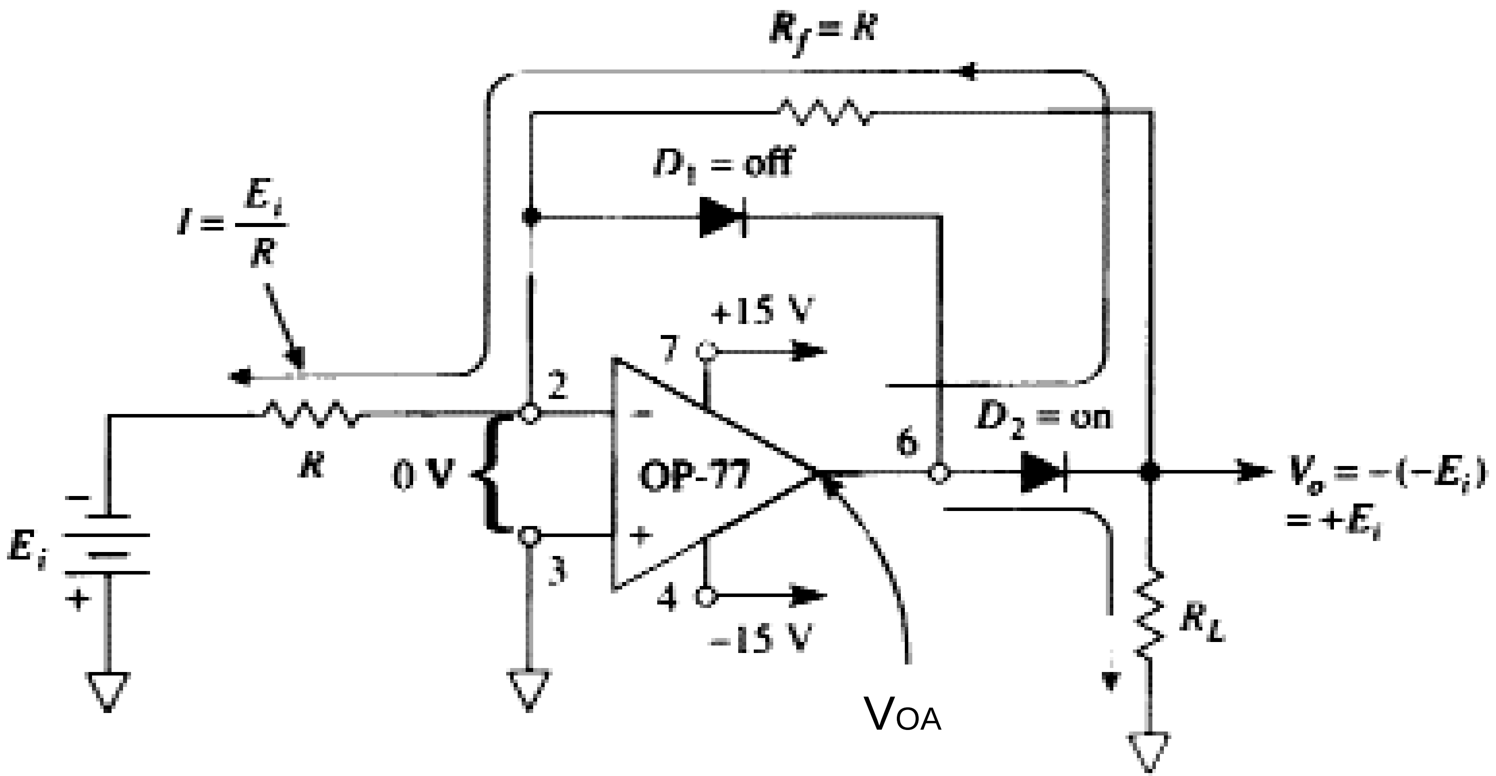
- The negative input *E*, forces the op amp output ***VOA*** to go positive.
- This causes D2 to conduct. Since the (—) input is at ground potential, diode *D1* is reverse biased.
- The circuit then acts like an inverter, since Rf = Ri, and Vo =-E >0.



2. Precision Rectifier

2.2. Precision Half-Wave Rectifier

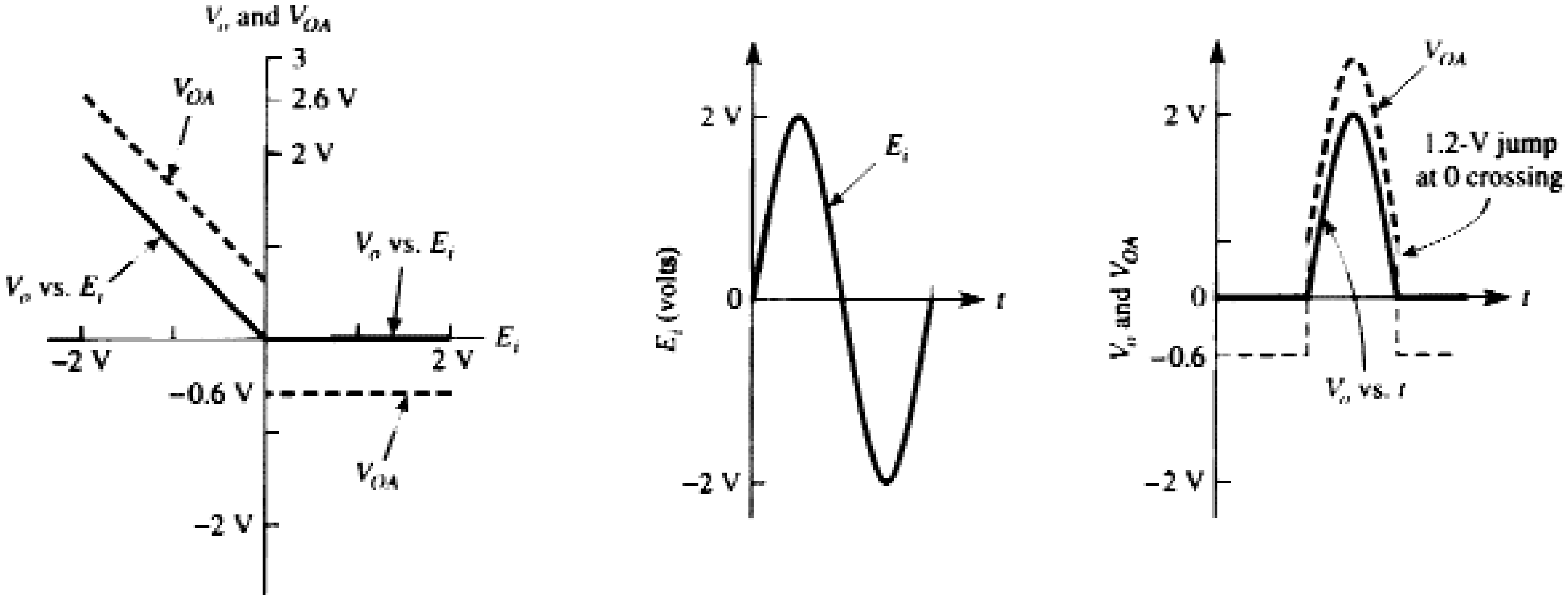
Negative Input: D1 off; D2 on



2. Precision Rectifier

2.2. Precision Half-Wave Rectifier

- Circuit operation is summarized by the following waveshapes.
- *Vo* can only go positive in a linear response to negative inputs.

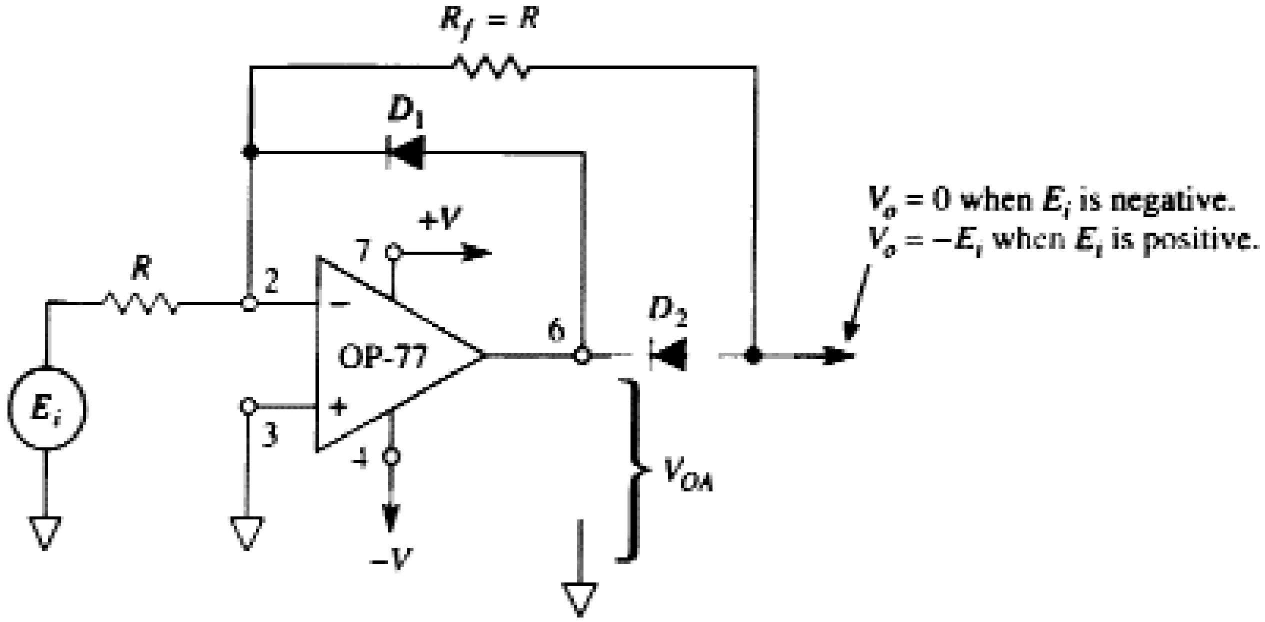


2. Precision Rectifier

2.2. Precision Half-Wave Rectifier

- Positive input signal rectifier ?

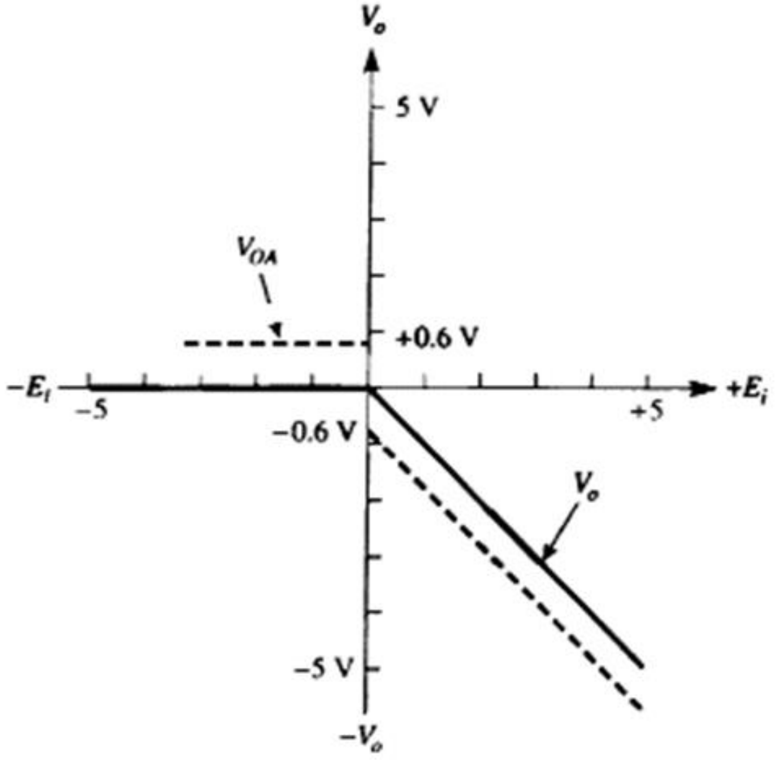
The diodes can be reversed. Now only positive input signals are transmitted and inverted.



2. Precision Rectifier

2.2. Precision Half-Wave Rectifier

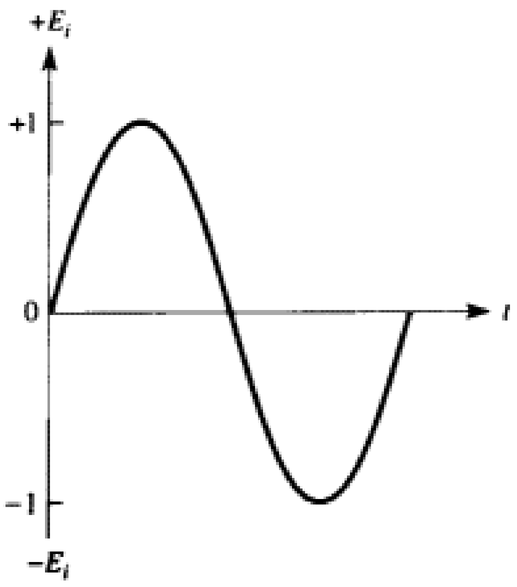
- The output voltage *Vo* equals 0 V for all negative inputs.
    - Circuit operation is summarized by the plot of *V~* and ***VOA*** versus *E.*

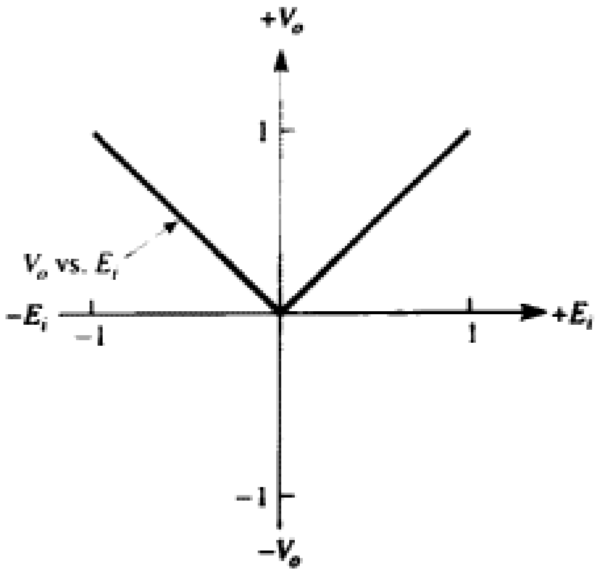


2. Precision Rectifier

2.3. Precision Full-Wave Rectifier

- The precision full-wave rectifier (PFWR) *transmits one polarity of the input signal and inverts the othe*r.
- Both half-cycles of an alternating voltage are transmitted but are converted to a *single polarity of the circuits output*.

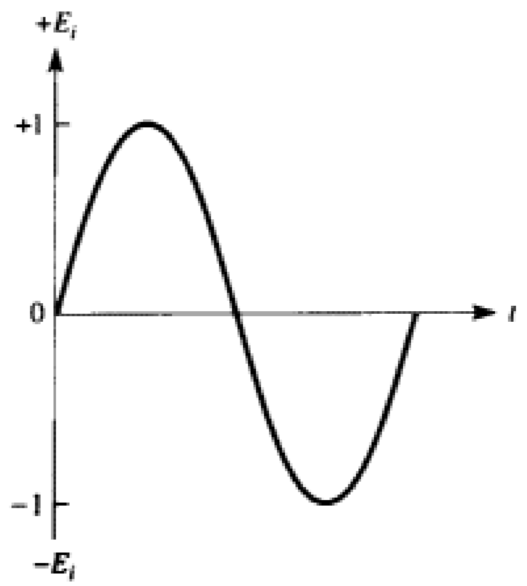


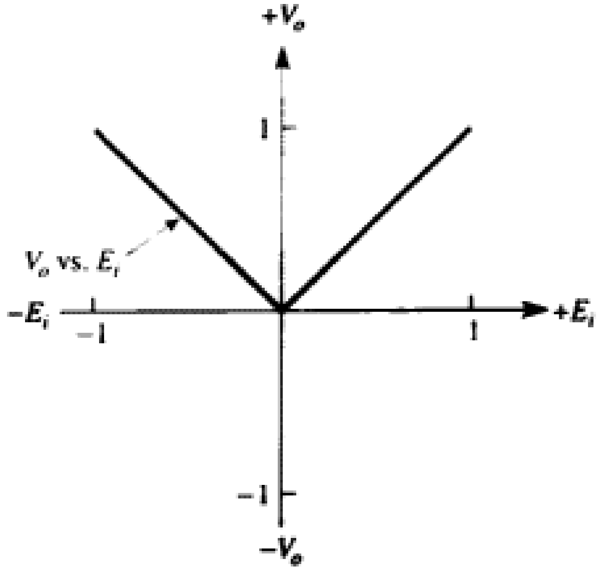


2. Precision Rectifier

2.3. Precision Full-Wave Rectifier

- The PFWR can rectify input voltages *with millivolt amplitudes*
- => useful to *prepare signals* for multiplication, averaging, or demodulation
- The precision rectifier is also called an ***absolute-value*** circuit.
- The absolute value of a number (or voltage) is equal to its magnitude regardless of sign.



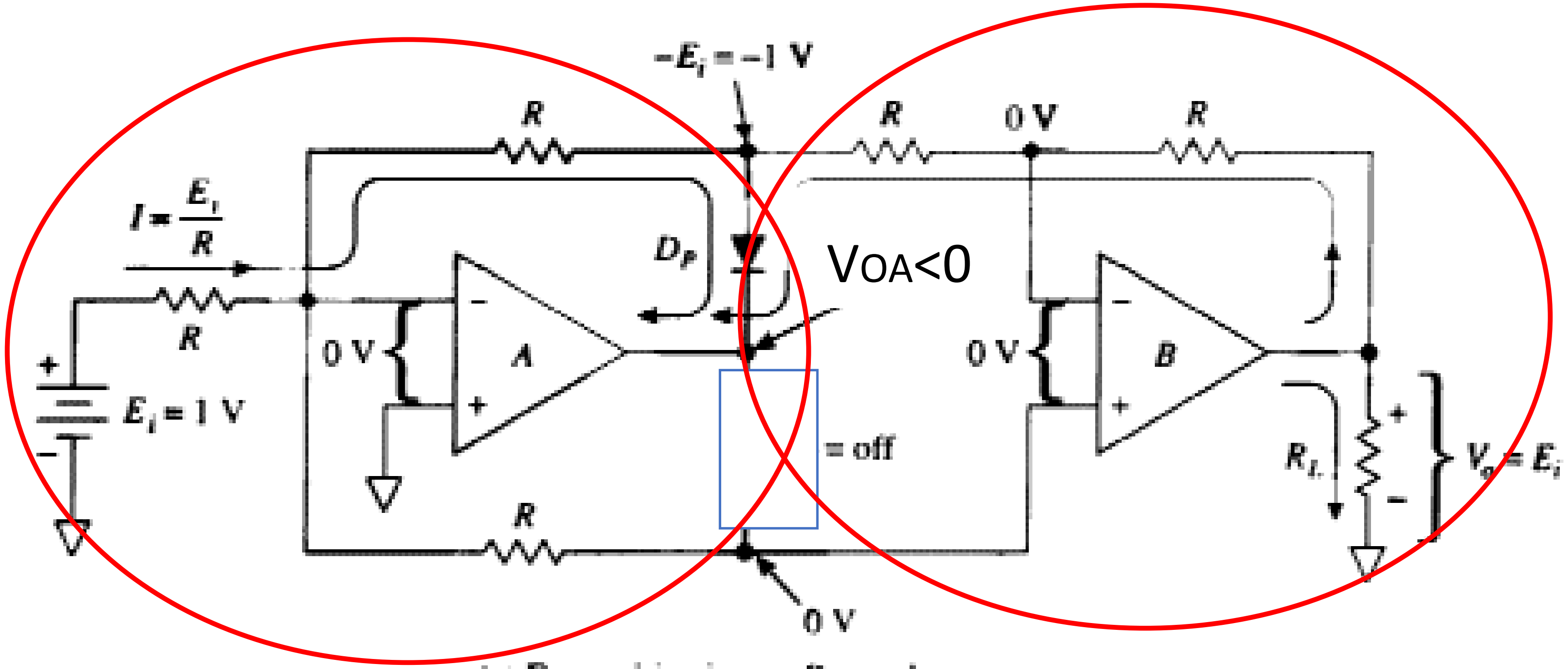


2. Precision Rectifier

2.3. Precision Full-Wave Rectifier

- Uses <u>*two op amps*</u>, <u>*two diodes*</u>, and <u>*five equal resistors*</u>.
- This circuit has an input resistance equal to *R*. (Disadvantage)

Positive Input : D_P on; D_N off

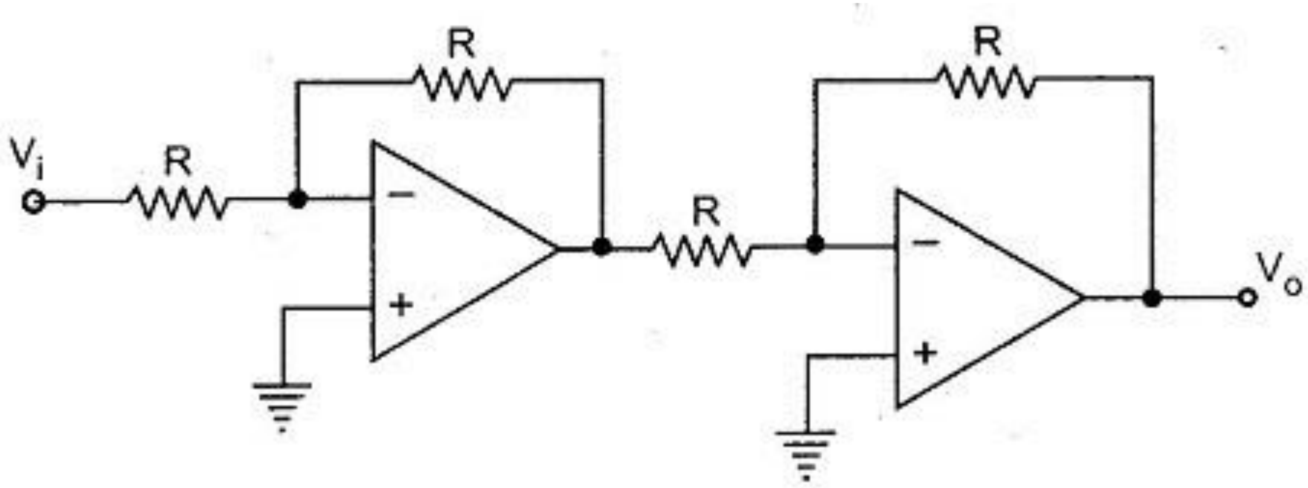


(a) For positive inputs D_P conducts; op amps *A* and *B* act as inverting amplifiers.

2. Precision Rectifier

2.3. Precision Full-Wave Rectifier

Two consecutive inverting op-amp

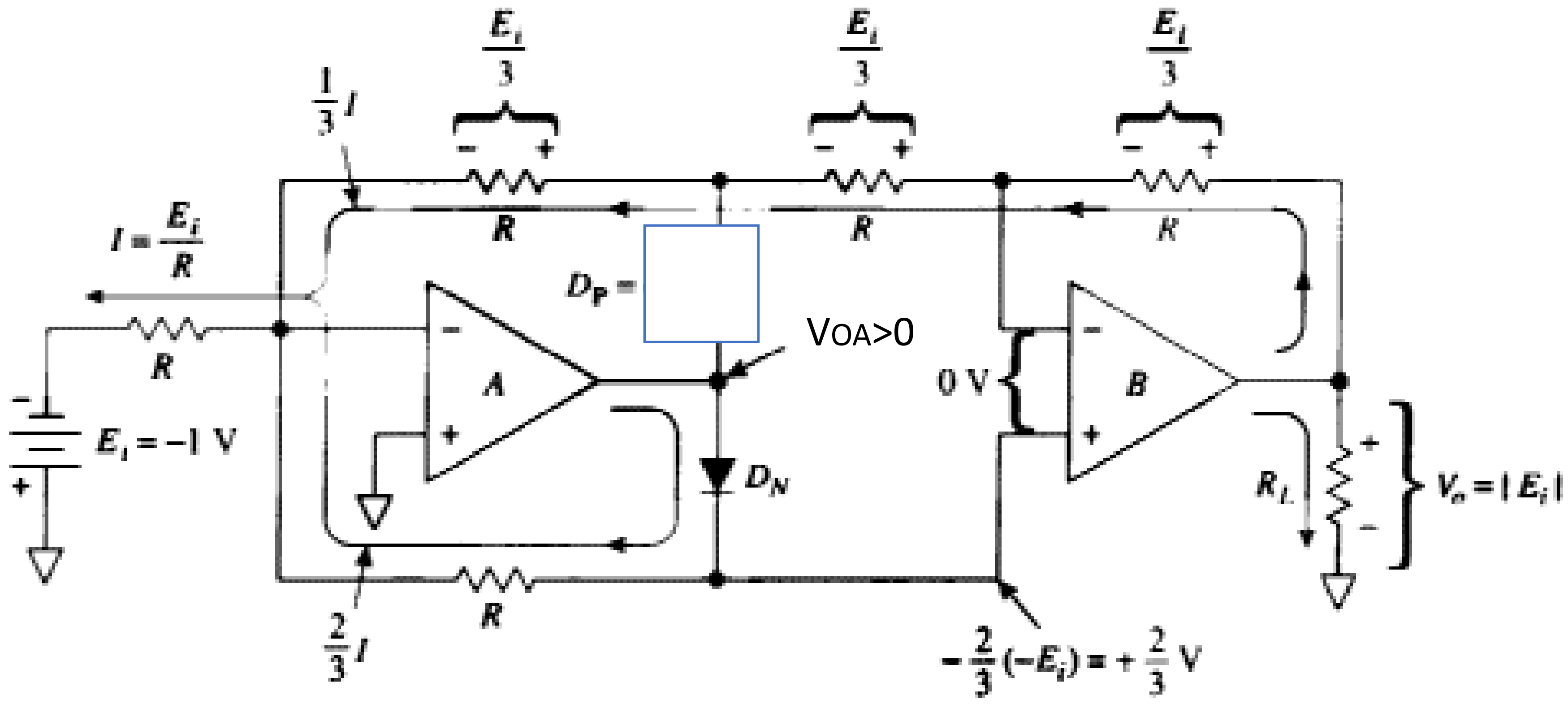


Vo = Vi =+E

2. Precision Rectifier

2.3. Precision Full-Wave Rectifier

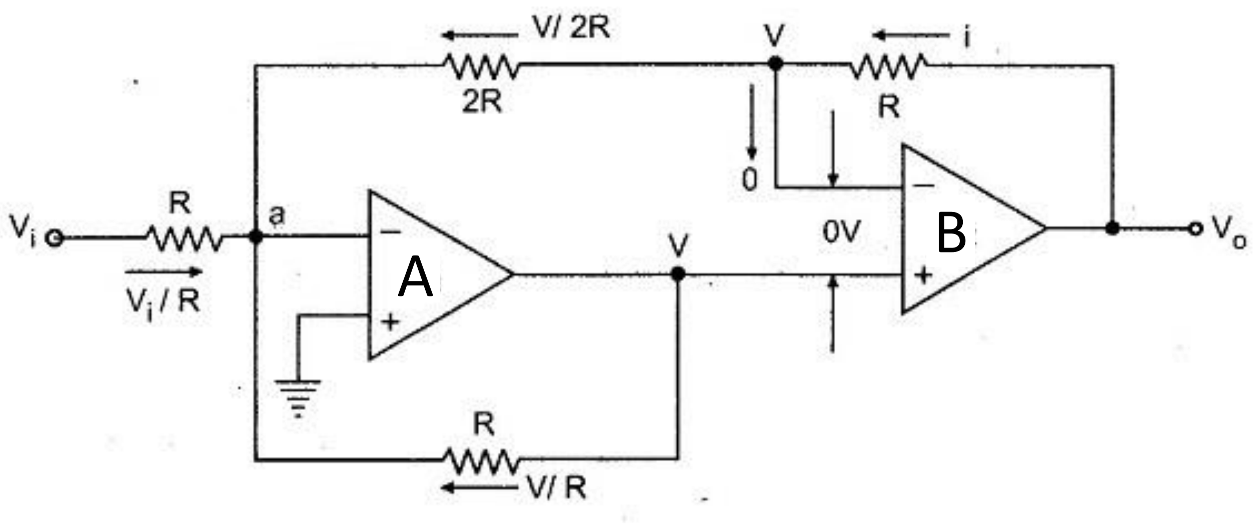
Negative Input : D_P on; D_N off



(b) For negative inputs, D_N conducts.

2. Precision Rectifier

2.3. Precision Full-Wave Rectifier



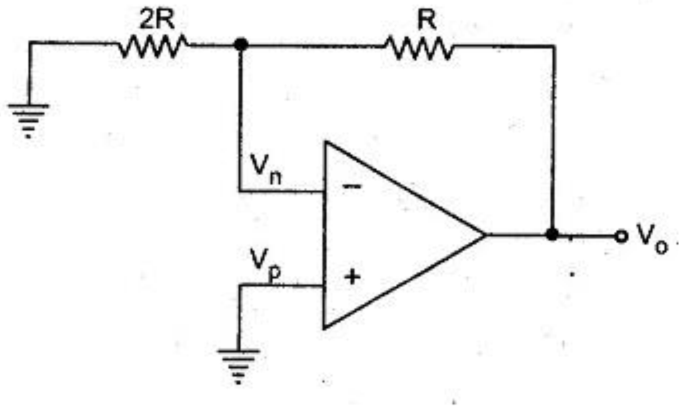
$$\frac{V_i}{R} + \frac{V}{2R} + \frac{V}{R} = 0$$

$$\frac{3V}{2R} = -\frac{V_i}{R}$$

$$V = -\frac{2V_i}{3}$$

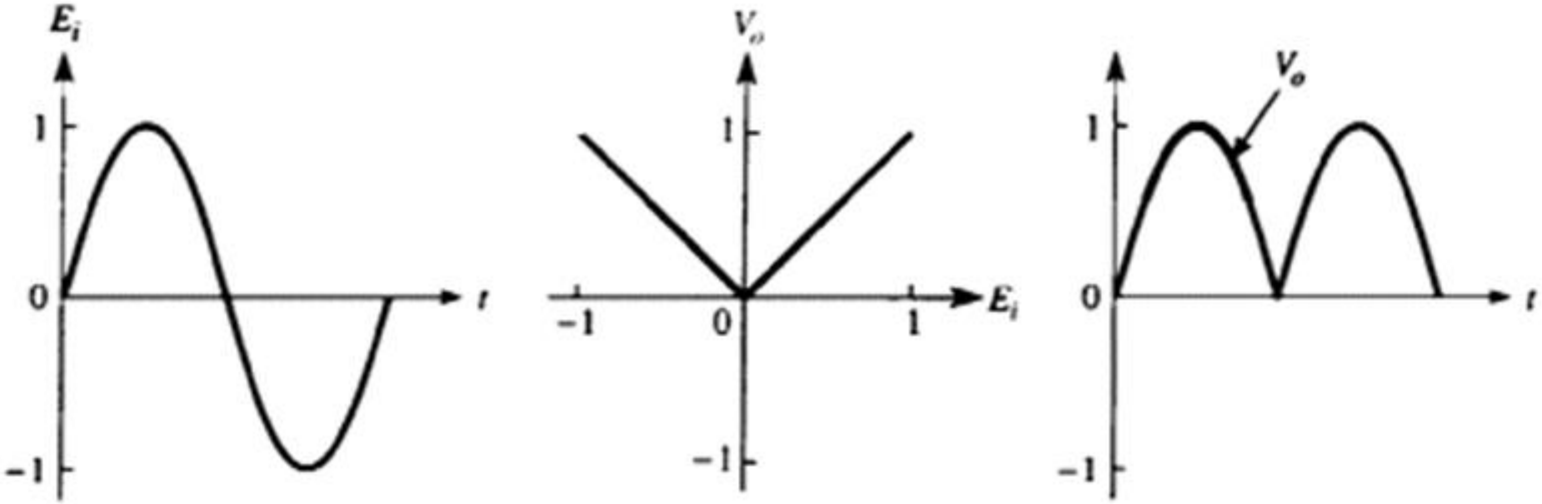
2. Precision Rectifier

2.3. Precision Full-Wave Rectifier



$$V_P = V_N = V = -\frac{2V_i}{3}$$

$$V_o = \left(1 + \frac{R}{2R}\right) V_p = -V_i = |\mathrm{E}|$$



3. Practical Amplifiers using Op-Amp

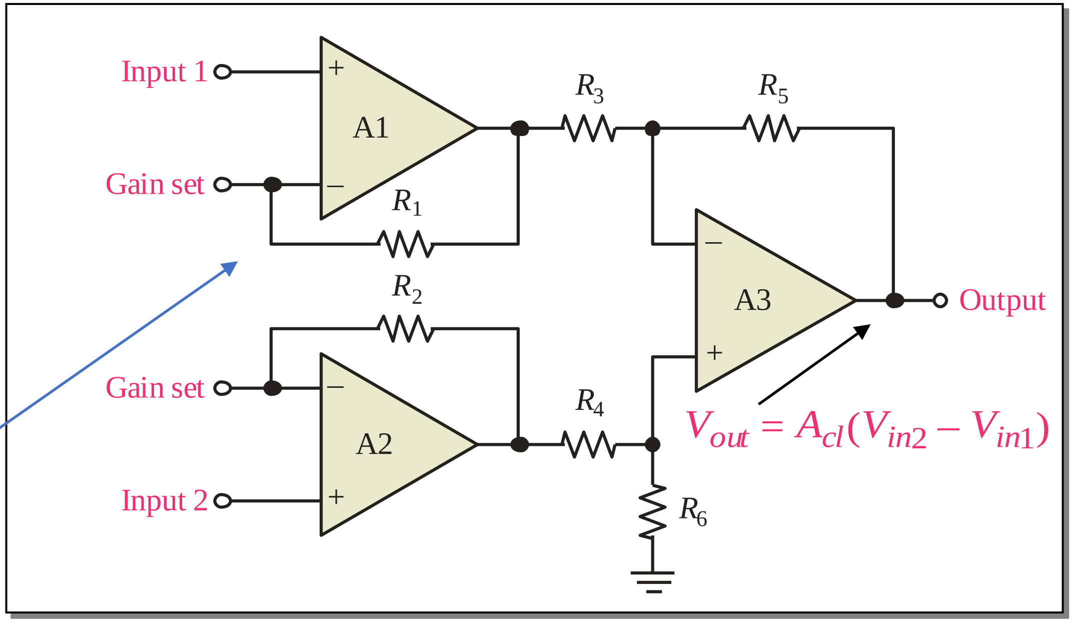
3.1. Instrumentation Amplifier

3.2. Operational Transconductance Amplifier (OTA)

3. Practical Amplifiers using Op-Amp

3.1. Instrumentation Amplifier

- An **instrumentation amplifier** (IA) amplifies the voltage difference between its terminals. It is optimized for small differential signals that may be riding on a large common mode voltages.

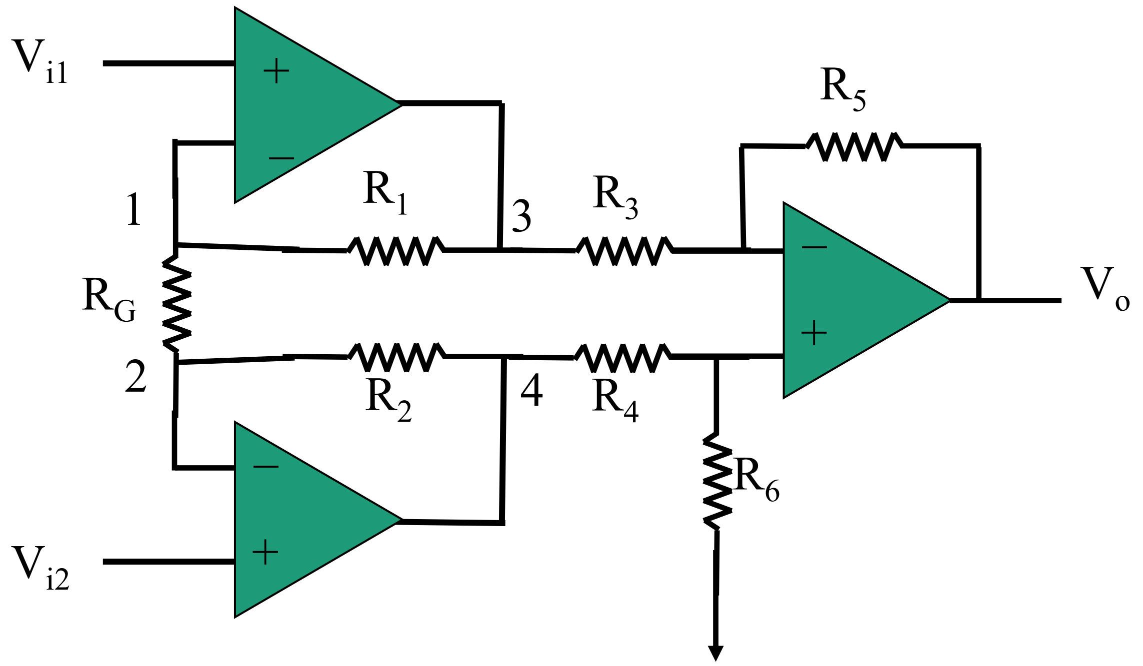


- The gain is set by a single resistor that is supplied by the user .

3. Practical Amplifiers using Op-Amp

3.1. Instrumentation Amplifier

- Very high CMRR
- Fixed, precision, internal gain
- Always used as difference amp



We have

$$V_{out} = (V_4 - V_3)$$

Current between point 3 and 4

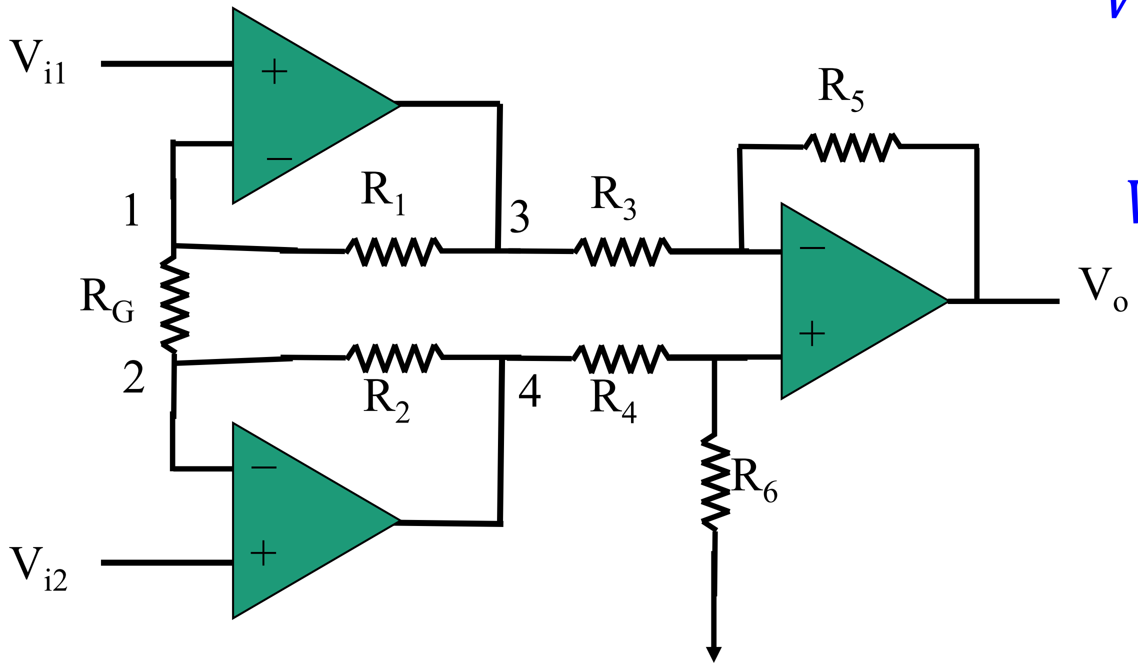
$$I = \frac{(V_3 - V_4)}{2R + R_G}$$

In other hand,

$$I = \frac{V_1 - V_2}{R_G}$$

3. Practical Amplifiers using Op-Amp

3.1. Instrumentation Amplifier



$$V_3 - V_4 = (V_1 - V_2)\,\left(\frac{2R}{R_G} + 1\right)$$

$$V_{out} = (V_2 - V_1)\,\left(\frac{2R}{R_G} + 1\right)$$

Note that $V_1 = V_{i1}$, $V_2 = V_{i2}$

$$A_v = \frac{2R}{R_G} + 1$$

$$R_G = \frac{2R}{A_v - 1}$$

3. Practical Amplifiers using Op-Amp

3.1. Instrumentation Amplifier

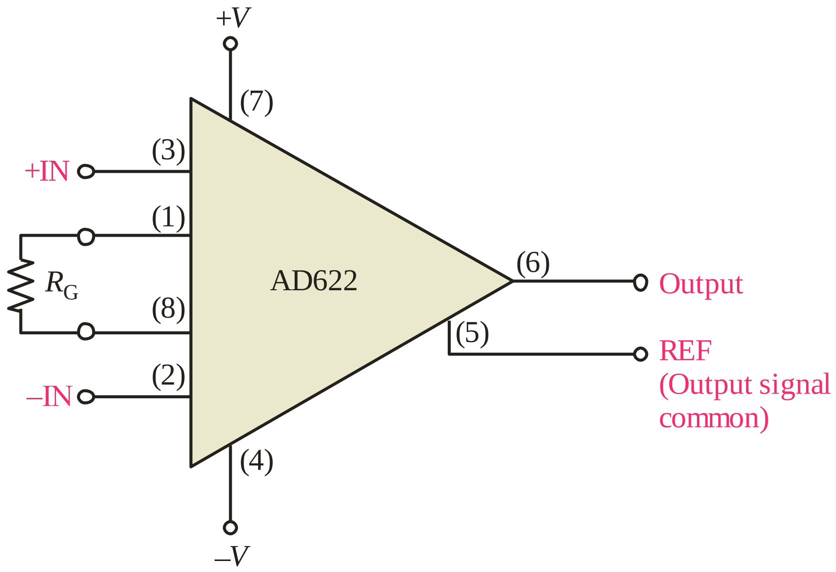
- An IA that is based on the three op-amp design is the AD622. The formula for choosing R_G is:

$$R_G = \frac{50.5\ \text{k}\Omega}{A_v - 1}$$

- Example: What value of R_G will set the gain to 35?
- Solution:

$$R_G = \frac{50.5\ \text{k}\Omega}{A_v - 1} = \frac{50.5\ \text{k}\Omega}{35 - 1}$$

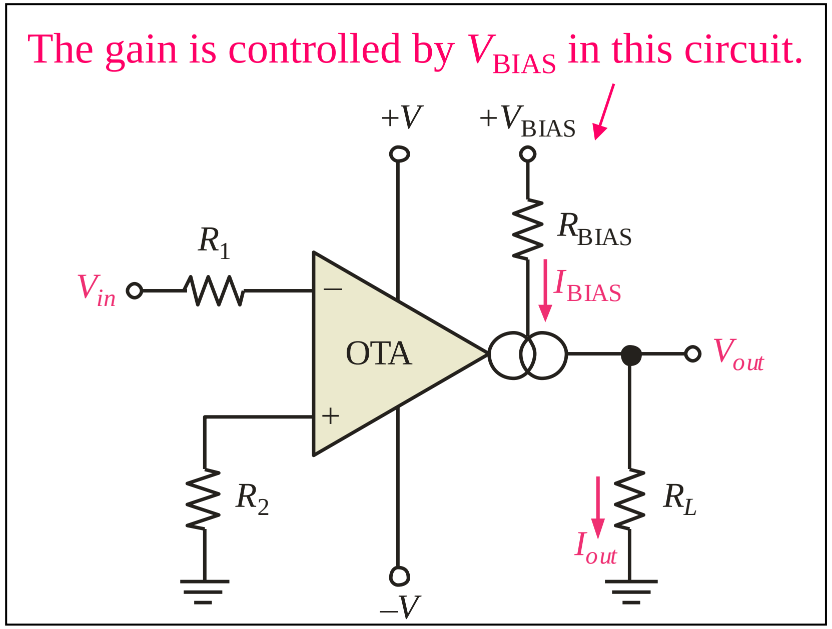
$$= 1.5\ \text{k}\Omega$$



3. Practical Amplifiers using Op-Amp

3.2. Operational Transconductance Amplifier

- The **operational transconductance amplifier** (OTA) is a *voltage-to-current amplifier*.
- As in the case of FETs, the conductance and the gain of an amplifier are: $g_m = \dfrac{I_{out}}{V_{in}}$ $A_v = g_m R_L$

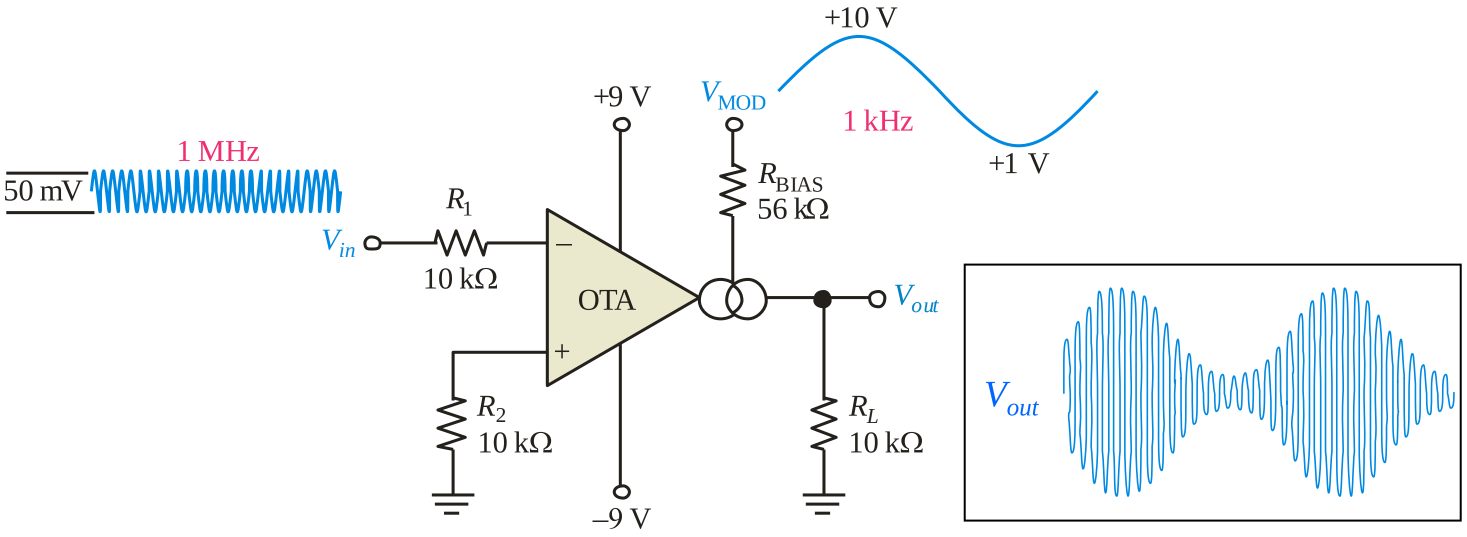


- Unlike FETs, the OTA has a g_m that can be "programmed" by the amount of bias current.
- Variable Gain Amplifier (changed electronically by varying a dc voltage)

3. Practical Amplifiers using Op-Amp

3.2. Operational Transconductance Amplifier

- Applications for OTAs include voltage controlled low-pass or high-pass filters, voltage-controlled waveform generators and amplifiers, modulators, comparators, and Schmitt triggers.
- In this example from the text, an amplitude modulator is shown.



Quiz 1.

<table>
<tr><td rowspan="2">Quiz Number</td><td rowspan="2">1</td><td rowspan="2">Quiz Type</td><td>OX</td><td>Example Select</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Question</td><td colspan="4">An application where an isolation amplifier is particularly useful is when</td></tr>
<tr><td>Example</td><td colspan="4">A. the input signal has very large dynamic range
B. control of the frequency response is necessary
C. voltages could present a hazard
D. all of the above</td></tr>
<tr><td>Answer</td><td colspan="4">C</td></tr>
<tr><td>Feedback</td><td colspan="4"></td></tr>
</table>

Quiz 2.

Quiz Number	2	Quiz Type	OX	Example Select
Question	A circuit that is useful for signal compression is a			
Example	A. instrumentation amplifier B. OTA C. logarithmic amplifier D. antilog amplifier			
Answer	C			
Feedback				

Summary

1. **Active Filter**: An amplifier used for amplifying small signals riding on large common-mode voltages.
2. **Precision Half-Wave Rectifier**: An inverting amplifier adding two diodes in both path.
3. **Precision Full-Wave Rectifier**: Uses two op amps, two diodes, and five equal resistors, can rectify input voltages with millivolt amplitudes.
4. **Instrumentation amplifier**: An amplifier used for amplifying small signals riding on large common-mode voltages.
5. **Isolation amplifier**: An amplifier with electrically isolated internal stages.
6. **Transconductance**: In an electronic device, the ratio of the output current to the input voltage.
7. **Operational transconductance Amplifier**: A voltage-to-current amplifier.

Next lesson guide...

Lesson 13: Linear Source

Reference

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[4] http://en.wikipedia.org/wiki/Instrumentation_amplifier
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[6] https://ti.com