Op Amp Circuits

Precision Rectifiers

Introduction

Fig. 1 (a) shows a half-wave rectifier using a diode. The V_o versus V_i relationship for this circuit is shown in Fig. 1 (b). If $V_i < V_{\text{on}}$, the turn-on voltage of the diode, the diode does not conduct, and V_o is zero. If $V_i > V_{\text{on}}$, the diode conducts, and $V_o = V_i - V_{\text{on}}$, which appears as a straight line in the V_i-V_o plane with a slope of 1. Ideally, we would like to have $V_{\text{on}} = 0\,\text{V}$, which will give us the V_o versus V_i relationship shown in Fig. 1 (c). Unfortunately, there is no diode with $V_{\text{on}} = 0\,\text{V}$, but an op amp, with its large gain, allows us to obtain the ideal relationship of Fig. 1 (c) while still using any commonly available silicon diode.

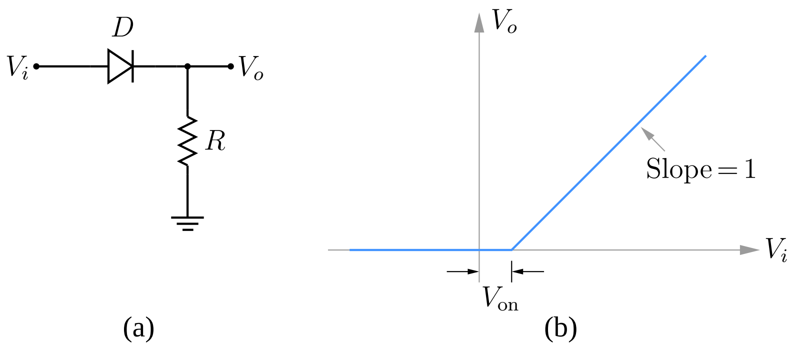


Figure 1: (a) Simple half-wave rectifier circuit, (b) V_o versus V_i relationship for the circuit in (a), (c) Ideal V_o versus V_i relationship for a half-wave rectifier.

Precision half-wave rectifier

Fig. 2 (a) shows an improved half-wave rectifier, also known as the "super diode" since it behaves like an ideal diode with $V_{\text{on}} = 0\,\text{V}$. Let us see the operation of this circuit when positive and negative values of V_i.

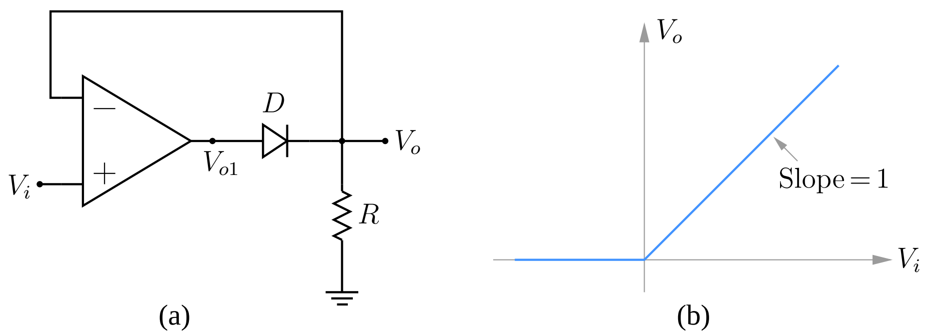


Figure 2: (a) Improved half-wave rectifier ("super diode"), (b) V_o versus V_i relationship for the super diode, (c) Sinusoidal input $V_i(t)$ with the corresponding $V_o(t)$ and $V_{o1}(t)$.

(a) Consider $V_i < 0\,\text{V}$. In this case, is it possible for the diode to conduct? Let us suppose that the diode conducts, implying that $V_i = V_o$ is positive (since the diode current must go through R_L, from V_o to ground). Since $V_o = A_V(V_+ - V_-)$ for the op amp and $V_o > 0$, we must have $(V_+ - V_-) > 0$, i.e., $V_+ > V_-$, or $V_+ > 0$ (since V_- is positive). Clearly, this clashes with our starting point, $V_i = V_+ < 0$. In short, D must be off when $V_i < 0$.

If D is off, there is no current through R_L, and therefore $V_o = 0\,\text{V}$. Note that there is no feedback loop in this case, and the op amp operates in the open-loop configuration which will drive it to saturation.

(b) Consider $V_i > 0\,\text{V}$. The diode now turns on and completes a (negative) feedback loop, and the op amp operates in the linear region. The condition $V_i \approx V_+$ is now valid, and we have $V_o = V_- = V_+ = V_i \quad \rightarrow \quad V_o = V_i$.

What happened to the turn-on voltage V_{on} of the diode? Let us look at the output of the op amp $V_{o1} = V_o + V_{\text{on}}$. Since $V_{o1} = A_V(V_+ - V_-)$, A_V being the gain of the op amp, we have Since $(V_+ - V_-) = \dfrac{V_{o1}}{A_V} = \dfrac{V_o + V_{\text{on}}}{A_V}$. We can see that V_{on} has got divided by a very large number A_V (about 10^5 for Op Amp 741), and it has therefore become inconsequential.

Putting the above two cases together, we get the V_o versus V_i relationship shown in Fig. 2 (b).

Improved precision half-wave rectifier-A

While the precision rectifier circuit of Fig. 2 (a) does get rid of the diode voltage drop V_{on}, it has the op amp operating in the saturation region for $V_i < 0$. When V_i changes from negative to positive values, the op amp needs to come out of saturation, which is a relatively slow process. For this reason, the high-frequency performance of this circuit is limited. A circuit in which the operates in the linear region for both positive and negative values of V_i is therefore desirable.

Fig. 3 (a) shows an improved precision half-wave rectifier circuit which addresses the above issue. As shown in Figs. 3 (a) and 3 (b), there is a feedback path for both positive and negative values of V_i in this circuit, and the op amp always operates in the linear region.

(a) Consider $V_i > 0\,\text{V}$. In this case, D_1 conducts. Suppose that D_2 is also on. Then, we would have $V_o = V_- V_{\text{on}}^{D1} - V_{\text{on}}^{D2}$. Since V_- is $0\,\text{V}$, V_o is -1.4 V, assuming V_{on} to be 0.7 V. This value of V_o is however not possible since it would mean that all three currents entering node V_o are positive, thus violating KCL at that node.

Hence, diode D_2 cannot be conducting, no current can flow through R_2 and R_L, giving $V_o = 0\,\text{V}$.

(b) Consider $V_i < 0\,\text{V}$. In this case, D_2 conducts, and the circuit behaves like an inverting amplifier. $V_- = V_+$ is at virtual ground, and $V_o = V_- - R_2\,\dfrac{V_i}{R_1} = -\,\dfrac{R_2}{R_1}\,V_i$. Since $V_i < 0$, we

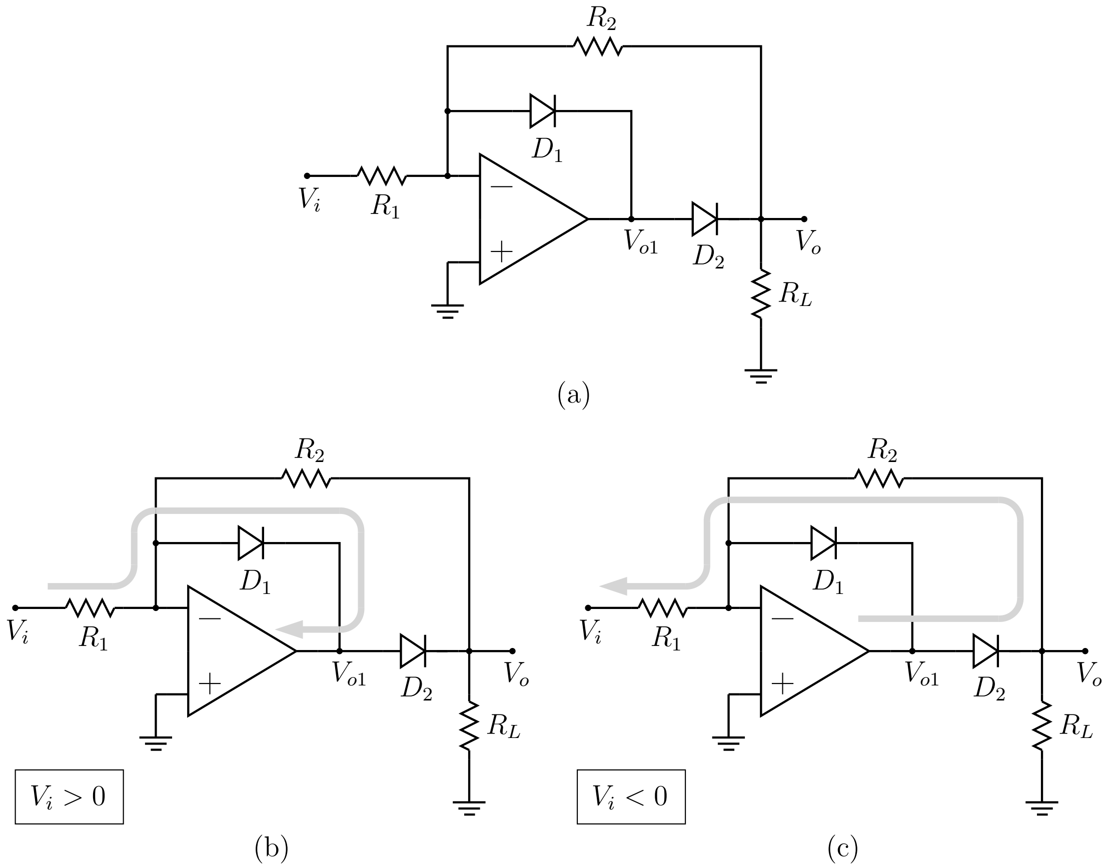


Figure 3: (a) Improved precision half-wave rectifier-A, (b) current path for $V_i > 0$, (c) current path for $V_i < 0$.

have $V_o > 0$, which means $V_{o1} = V_o + V_{\text{on}}$ is also positive. The diode D_1 therefore finds itself under reverse bias (since $V_{D1} = V_- - V_{o1} = 0 - V_{o1}$ is negative) and does not conduct.

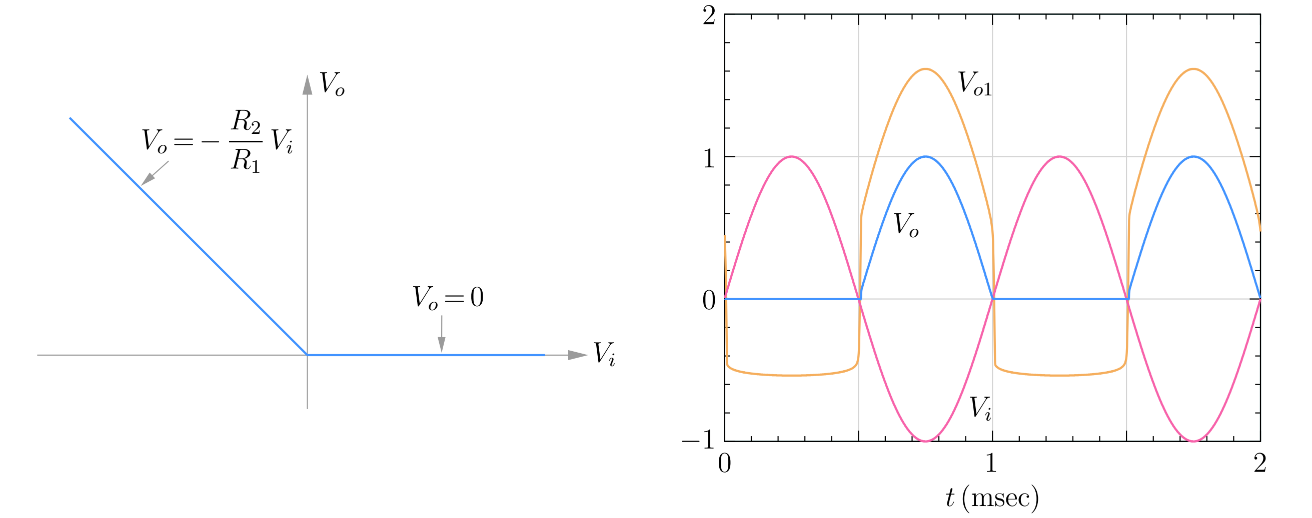
Putting these two cases together, we get the overall V_o versus V_i relationship for the circuit (see Fig. 4 (a)). The time-domain relationship between V_i and V_o is shown in Fig. 4 (b). Also shown in the figure is V_{o1}, the op amp output, which clearly shows that the op amp does not enter saturation, thus making the circuit faster than the super diode.

Improved precision half-wave rectifier-B

Another version of the precision half-wave rectifier is shown in Fig. 5 (a). When $V_i < 0$, D_1 conducts, D_2 is off, and $V_o = 0\,\text{V}$. When $V_i > 0$, D_2 conducts, D_1 is off, and the circuit behaves like an inverting amplifier, with $V_o = -\dfrac{R_2}{R_1} V_i$. In either case, there is a feedback path, and the op amp operates in the linear region. The overall V_o versus relationship is shown in Fig. 5 (b).

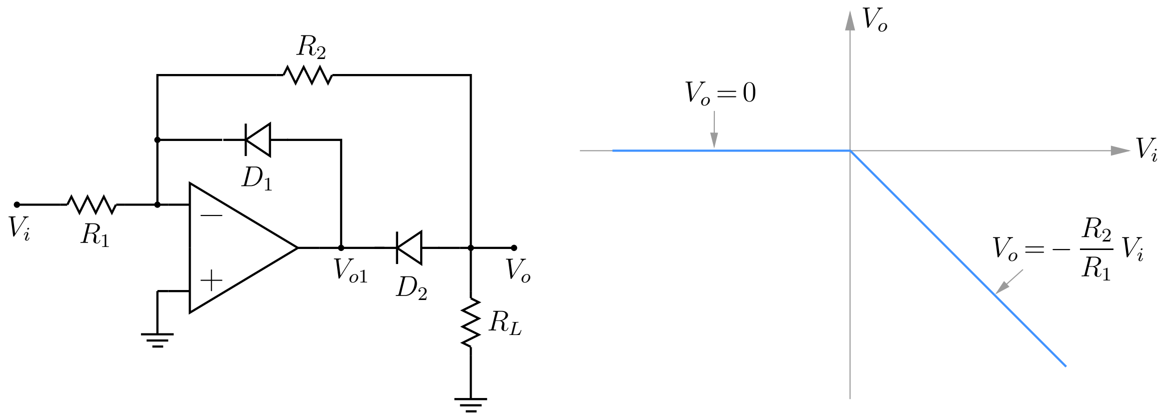
Precision full-wave rectifier

It is possible to implement a precision full-wave rectifier by suitably combining the circuits we have discussed earlier. Fig. 6 shows the block diagram for this approach, and Fig. 7 shows



(a) (b)

Figure 4: (a) V_o versus V_i relationship for the circuit of Fig. 3 (a) with $R_1 = R_2 = 1\,\text{k}\Omega$, (b) Sinusoidal input $V_i(t)$ with the corresponding $V_o(t)$ and $V_{o1}(t)$.



(a) (b)

Figure 5: (a) Improved precision half-wave rectifier-B, (b) V_o versus V_i relationship.

its implementation using a precision half-wave rectifier and a weighted summer. The output voltage is given by

$$V_o = -\left(\frac{R}{R} V_i + \frac{R}{R/2} V_{o1}\right) = -\left(V_i + 2V_{o1}\right) , \tag{1}$$

as required.

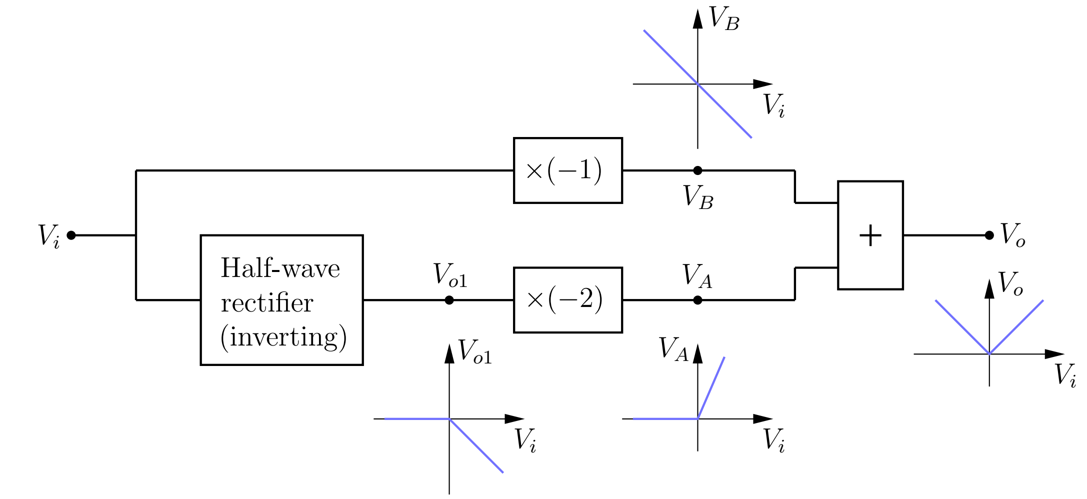


Figure 6: Block diagram showing use of precision half-wave rectifier to implement a precision full-wave rectifier.

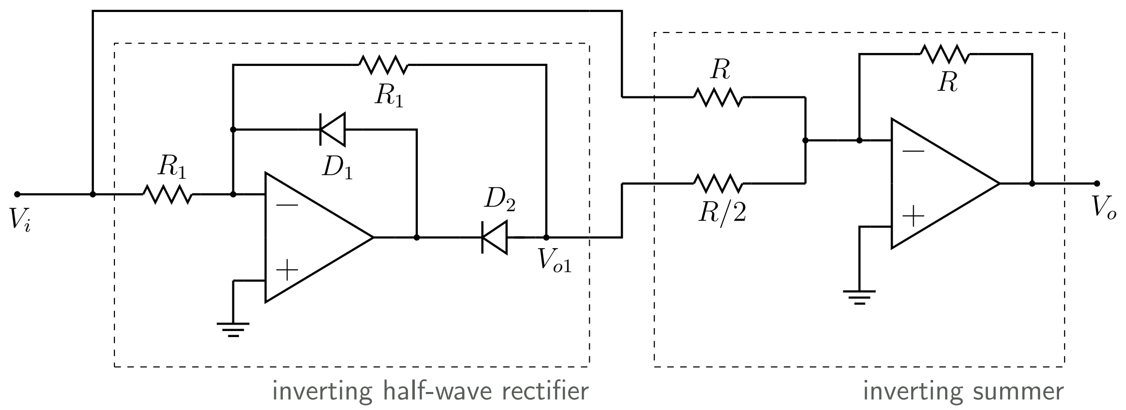


Figure 7: Implementation of the block diagram of Fig. 6.