Basic Electronics
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Lecture - 46
Precision rectifiers

Welcome back to Basic Electronics. Earlier in this course we have seen diode circuits of various functions, such as peak detection, clipping, and clamping. We have seen that because of finite turn on voltage of a diode the waveforms for these circuits are not quite ideal. We will now look at a combination of a diode and op-amp for accurate peak detection. We will see how the circuit can be used for AM demodulation. So, let us begin.

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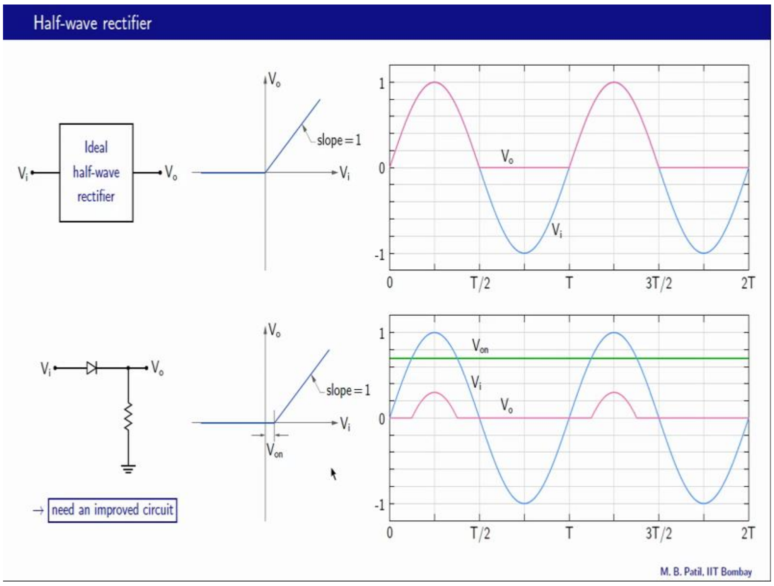

Half-wave rectifier

We will now discuss how op-amps can be used for the purpose of rectification along with diodes. Let us start with the half-wave rectifier, here is an ideal of a rectifier black box input V i output V o; V on the output voltage to be 0 if V i is negative and if V i is positive if we want V o to be equal to be V i. It is a straight line going through the origin with a slope of 1. These are the time domain wave forms, that is V i and V o would be equal to V i when v i is positive and V o is 0 if V i is negative.

We have seen this diode circuit which was used for half-wave rectification, but this had this diode voltage drop V on here and therefore the V o V i relationship is not quite what we want. And this can become an issue if our amplitude of the input voltage is not large enough. For example here; this is our input voltage this is our V on the voltage drop across the diode when it conducts. And now conduction is possible only if V i exceed V on; that means up to this point no conduction is no possible V o is 0. And then the diodes starts conducting and then V o is equal to V i minus V on.

So, clearly this V o is not what we would like, and therefore we need an improved circuit.

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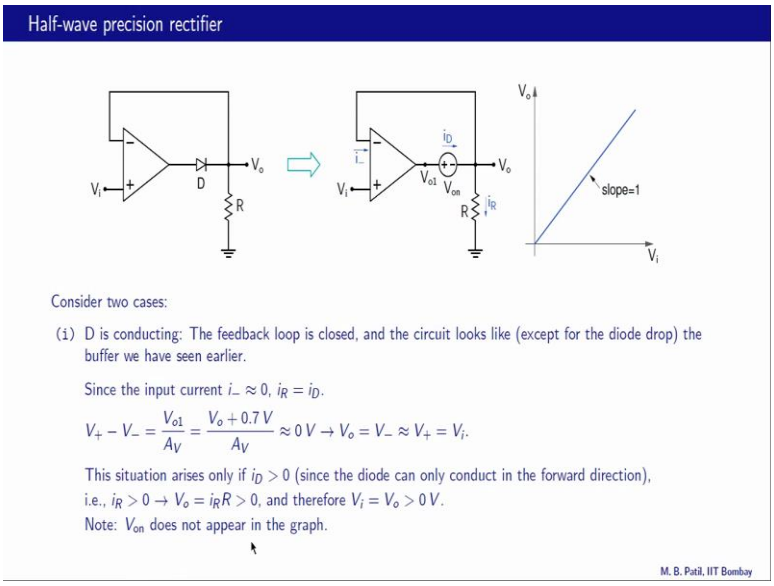

Half-wave precision rectifier

Consider two cases:

(i) D is conducting: The feedback loop is closed, and the circuit looks like (except for the diode drop) the buffer we have seen earlier.

Since the input current $i_- \approx 0$, $i_R = i_D$.

$$V_+ - V_- = \frac{V_{o1}}{A_V} = \frac{V_o + 0.7\,V}{A_V} \approx 0\,V \rightarrow V_o = V_- \approx V_+ = V_i.$$

This situation arises only if $i_D > 0$ (since the diode can only conduct in the forward direction),
i.e., $i_R > 0 \rightarrow V_o = i_R R > 0$, and therefore $V_i = V_o > 0\,V$.
Note: V_{on} does not appear in the graph.

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Here is an op-amp circuit and it works as half-wave precision rectifier. And we will see that the voltage drop V on of the diode does not appear in the V o versus V i relationship for this circuit; we will figure out why. So, let us take two cases: one, D is conducting and when the diode is conducting we will replace that with the battery say 0.7 volts for a silicon diode. And in that case this feedback loop is closed, the op-amp operates in the linear region and the circuit looks very much like the op-amp buffer circuit that we have seen except for this voltage drop there.

Now, since the input current i minus is 0 this current i R is equal to i D, so the current pass is like that. And what is p plus minus V minus then it is equal to V o 1 divided by A v the voltage gain of the op-amp which is a large number something like 100000 for the (Refer Time: 04:01) for 1 op-amp. What is V o 1? Remember the diode is conducting so therefore V o 1 is V o plus this diode voltage drop which is say 0.7 volts. Therefore, V plus minus V minus is V o plus 0.7 divided by A v. Now since A v is such a large number this quantity is nearly 0 volts, and therefore V plus and V minus are nearly equal.

What is V o now? V o is the same as V minus, and therefore V o is nearly equal to V plus which is this same as V i. So, when the diode is conducting we have V o equal to V i. Now let us figure out when this situation happens; that is when does D conduct? This situation arises only if i D is greater than 0, because that is the only way the diode can conduct it cannot conduct in the reverse direction. And therefore, since i D and i R are equal that is our current path i R is also positive and therefore V o which is r times i R is positive.

So, this situation namely diode conducting happens if V o is positive, and since V o and V i are equal that means V i is also positive. So, in short if V i is positive V o is equal to V i that is the straight line passing through the origin with the slope of 1. And the most important point to be noted is that V on the diode drop does not appear in the graph. What happen to V on? It got divided by this very large voltage gain of the op-amp.

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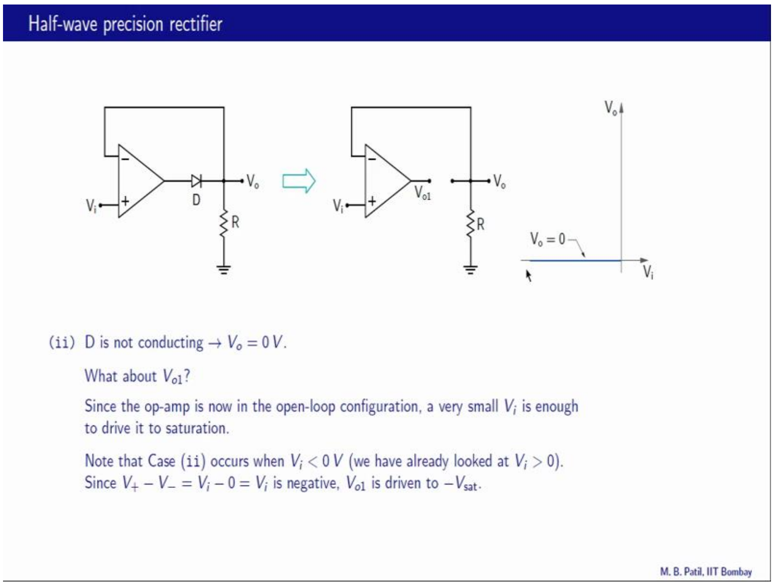

Half-wave precision rectifier

(ii) D is not conducting $\rightarrow V_o = 0\,V$.

What about V_{o1}?

Since the op-amp is now in the open-loop configuration, a very small V_i is enough to drive it to saturation.

Note that Case (ii) occurs when $V_i < 0\,V$ (we have already looked at $V_i > 0$).
Since $V_+ - V_- = V_i - 0 = V_i$ is negative, V_{o1} is driven to $-V_{sat}$.

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Let us now consider the second case that is D not conducting. So, we replace D with an open circuit, and now there is no possibility of any current here because there is no current going in or out to the op-amp. So therefore, V o is equal to 0. What about V o 1 this op-amp output? Since the op-amp is now in the open loop configuration there is no feedback path because this loop is broken here. A very small V i is enough to drive it to saturation.

Note that V minus is the same as V o which is 0 volts. So therefore, all it requires now to drive the op-amp in to saturation is the small value of V i. And that V i has to be negative because we have already consider the other case when V i was positive, the last slide. That means, V plus is negative V minus is 0. So therefore, the op-amp is going to get driven to minus V sat. And that is what V o versus V i would look like in this case: V o is simply 0 when V i is negative.

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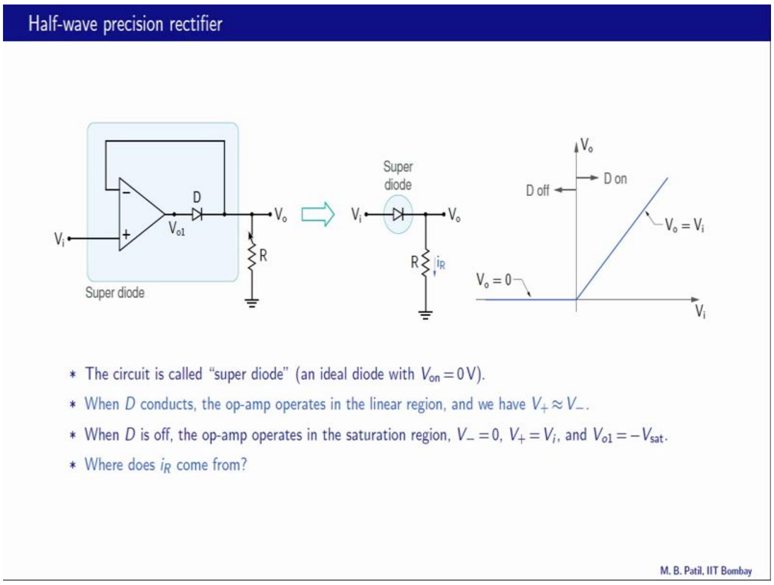

Half-wave precision rectifier

- The circuit is called "super diode" (an ideal diode with $V_{on} = 0\,V$).
- When D conducts, the op-amp operates in the linear region, and we have $V_+ \approx V_-$.
- When D is off, the op-amp operates in the saturation region, $V_- = 0$, $V_+ = V_i$, and $V_{o1} = -V_{sat}$.
- Where does i_R come from?

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This plot summarizes the operation of the half-wave precision rectifier; when V i is positive V o is equal to V i, the diode conducts, when V i is negative V o is 0 and the diode does not conduct. This circuit, this blocks here is called the super diode; why is it called super diode? Because it behaves like an ideal diode with V on equal to 0 volts, and it is represented by this symbols sometimes. When the diode conducts the op-amp operates in the linear region and we have V plus nearly equal to V minus.

Just summarizing the important points that we have already looked at; when the diode is off the op-amp operates in the saturation region V minus is 0 the same as V o which is 0 when the diode does not conduct V plus is v i and therefore V o 1 is equal to minus V sat.

One question that arises is where does i R come from in this figure. Does it come from V i? The answer is no, it actually comes from the op-amp so it is supplied by the op-amp power supply; there is something we should remember.

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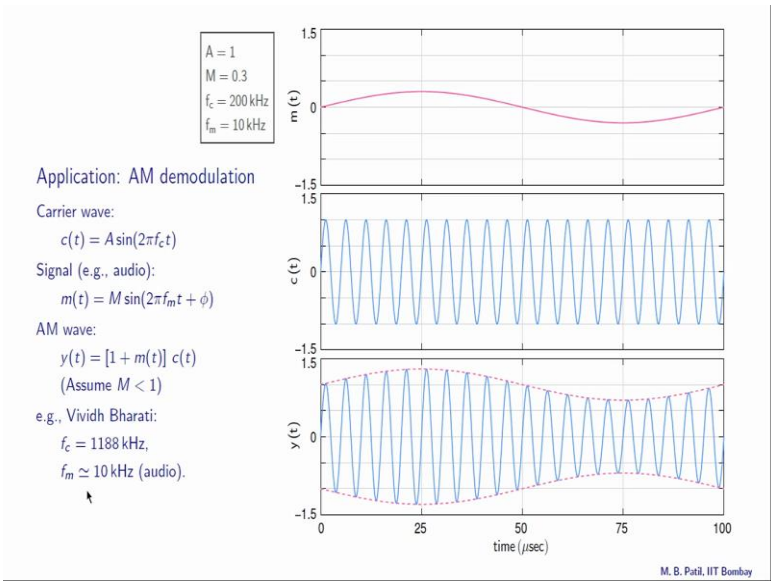

$A = 1$
$M = 0.3$
$f_c = 200$ kHz
$f_m = 10$ kHz

Application: AM demodulation

Carrier wave:
$c(t) = A \sin(2\pi f_c t)$
Signal (e.g., audio):
$m(t) = M \sin(2\pi f_m t + \phi)$
AM wave:
$y(t) = [1 + m(t)]\ c(t)$
(Assume $M < 1$)
e.g., Vividh Bharati:
$f_c = 1188$ kHz,
$f_m \simeq 10$ kHz (audio).

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Let us now look at an application of the super diode or the half-wave precision rectifier. And that is AM demodulation; AM signals are amplitude modulated signals and let us see what those are first. There are three components in amplitude modulation: one is the carrier wave c of t which is a sin 2 pi f c times t and f c is called the Carrier Frequency. Now this is a relatively high frequency and here is an example of c of t. Then there is the signal itself for example, an audio signal and it could be of the form small m of t equal to capital M sin 2 pi f m t plus some phase angle.

Now, this f m is a frequency which is must smaller than the carrier frequency and here is an example of small m of t. Clearly this frequency is much smaller than this frequency. And in real life of course this modulating signal is not generally just a simple single sinusoid it could be much more complex. But, all the frequency components of the model to signal are much slower than the carrier frequency. And from the carrier wave and the signal we derive the AM or amplitude modulated wave; y of t equal to 1 plus m of t times c of t. And we will assume that this capital M is less than 1.

So, here are the waveforms: we have A equal to 1 the amplitude of the carrier, M equal to 0.3 this number, f c is 200 kilo hertz the frequency of the carrier, f m is 10 kilo hertz the frequency of the signal. And clearly this f m is much smaller than f c. This is our y of t, and what do we notice? We notice that the frequency is the same as the carrier signal, but its amplitude goes on changing. And that dash line shows the amplitude of this y of t, and that is of course because we have this 1 plus m of t here as a pre factor in y of t.

Now, this is called the envelope because if we see carefully this signal waveform is enveloping the carrier in y of t. And the goal of AM demodulation is to detect this envelope which is the same as our signal. Now this numbers are representative in real life if we are talking about audio signals then the numbers can be somewhat different. For example, with the Vividh Bharati channel the carrier frequency is 1188 kilo hertz and f m is the audio frequencies which can range say from few hertz to like 12 or 15 kilo hertz.

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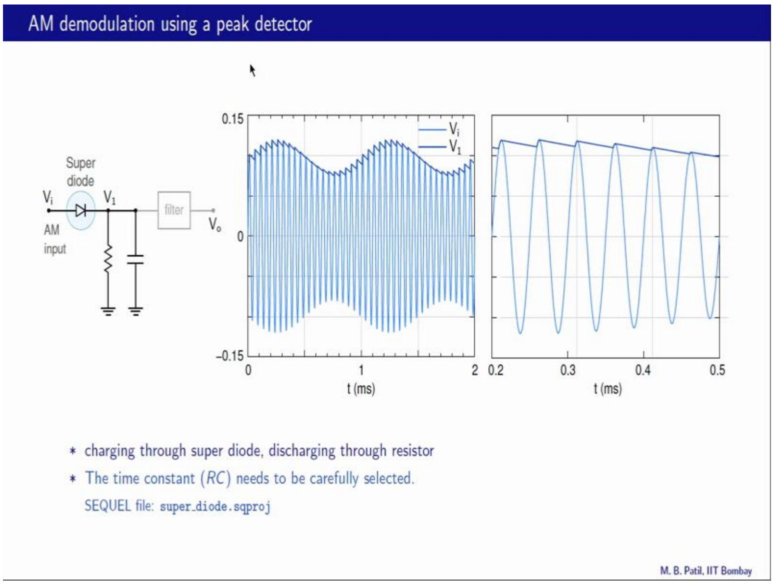

AM demodulation using a peak detector

- charging through super diode, discharging through resistor
- The time constant (RC) needs to be carefully selected.

SEQUEL file: `super_diode.sqproj`

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Here is a circuit using the super diode which can be used for demodulation of AM signals. It is essentially a peak detector and we have looked at this circuit earlier when we will talk about diodes. The only difference is that it has a super diode here with V on equal to 0 volts. So therefore, it can go up with small input voltages; for example here the input voltage is only 150 millivolts or less. The input voltage is shown by the light blue waveform that is our amplitude modulated signal, and the purpose of the circuit is to detect this envelope that is our signal.

When V i is larger than V 1 the capacitor gets charged, otherwise it discharges through this resistor. So, the charging happens through the super diode and discharging through the resistor. And here is an expanded view of these waveforms which shows discharging and discharging process more clearly. So, here we have charging then discharging then charging then discharging and so on. And this V 1 is almost what we want, but not quite because it has got this little ripple riding on it. So, it is not this envelope that we are seeking, but the envelope with some ripple voltage on top of it.

And we of course, want to remove that ripple voltage; and that is done with this filter here which we are not shown in detail. So, the final output is the output of this filter which is indicated here by V o. Now the time constant RC here, has to be very carefully selected and let us demonstrate that with this circuit file.

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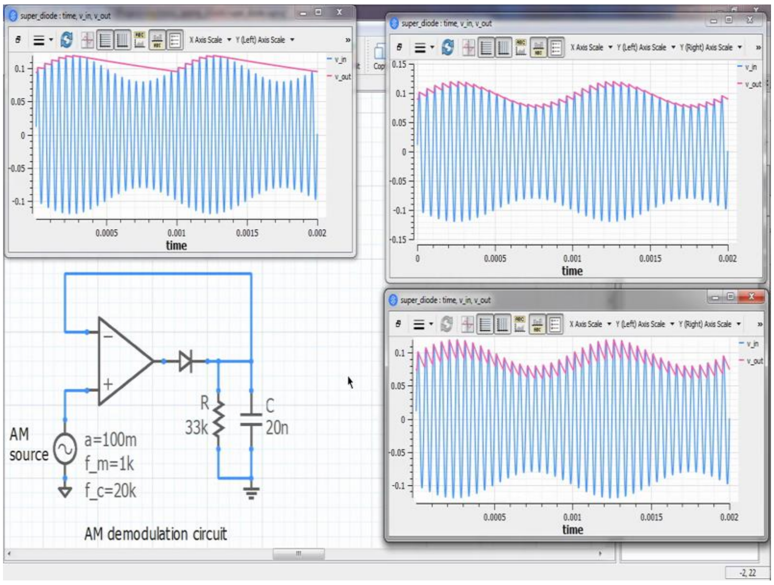

Here are some simulation results with R equal to 33 k and C equal to 20 nanofarads and carrier frequency of 20 kilo hertz and the signal frequency of 1 kilo hertz, we get this result. And here the output is that we would like, this is the envelope which is detected as the output voltage and it has got small ripple riding on it which we can filter out. Now if we increase the capacitance from 20 nano to 100 nano then this is what we get and this definitely has a problem, because we are missing out on some peaks here. And definitely this output voltage is not a faithful reproduction of the signal voltage.

But if we make a the capacitance too small; for example, this plot corresponds to c equal to 5 nano ohm and in this case the output does follow the envelope, but then the ripple voltage is a little too large which again is not desirable. So, that indicates that this RC time constant must be carefully selected, and that would depend on all of these parameters.

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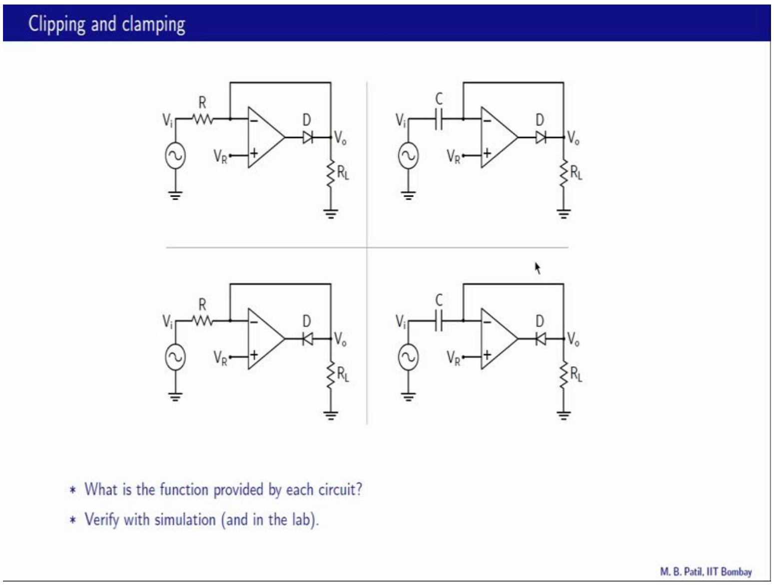

Clipping and clamping

- What is the function provided by each circuit?
- Verify with simulation (and in the lab).

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Here are some more circuits in which an op-amp is used to eliminate the voltage drop across the diode when it conducts that is V on. So for these circuits we will also these following questions in the subsequent slides. Question one: what is the function provided by each of these circuits? We will analyze the circuits and look at the functionality that each circuit provides. Second: we will verify that functionality with simulation. In addition of course, you are encourage to go to your electronics lab look up this circuits and look at it function as well.

Although there are four circuits here, essentially we need to look at two different circuits this one and this one and the other circuits operate in a very similar manner. For example this circuit here is derived from the upper circuit simply by changing the direction of the diode; similarly this circuit here is derived from this circuit by simply changing the direction of the diode.

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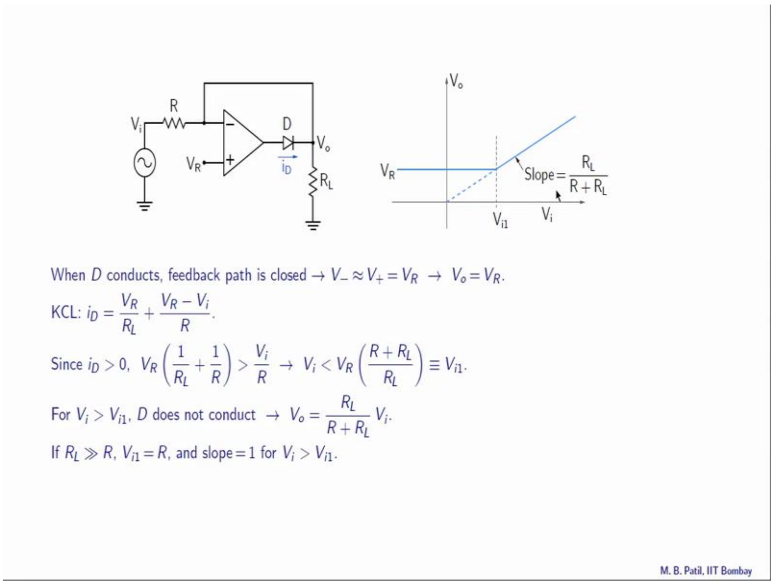

When D conducts, feedback path is closed $\rightarrow V_- \approx V_+ = V_R \rightarrow V_o = V_R$.

KCL: $i_D = \frac{V_R}{R_L} + \frac{V_R - V_i}{R}$.

Since $i_D > 0$, $V_R\left(\frac{1}{R_L}+\frac{1}{R}\right) > \frac{V_i}{R} \rightarrow V_i < V_R\left(\frac{R+R_L}{R_L}\right) \equiv V_{i1}$.

For $V_i > V_{i1}$, D does not conduct $\rightarrow V_o = \frac{R_L}{R+R_L} V_i$.

If $R_L \gg R$, $V_{i1} = R$, and slope$=1$ for $V_i > V_{i1}$.

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Here is our first circuit. We have an op-amp here with the non-inverting input conducted to a reference voltage V R. This reference voltage could be adjusted using a part which we have not shown in this figure. So, as far as V R concerned this V R is simply a constant. This is our input voltage and we will take an example of a sinusoidal voltage applied as V i and this is the output voltage.

Let us see what this circuit is doing. Let us first consider the case where the diode d is conducting. And when D conducts their feedback path is closed this path here, and we can expect V minus to be then equal to V plus these two voltages and V plus of course is equal to V R. So therefore, V minus is equal to V R; V minus is in fact the same as V o, so therefore V o is equal to V R. So, that is the situation when the diode D conducts. Now when does that happen? To see that let us write the KCL equation at this node we have three currents here; one is i D, so that i D is equal to this current plus this current. This current is simply V o by R L and V o is the same as V R as we saw. So therefore, this current is v r divided by R L. What about this current? This current must be the same as this current here, because the input current for the op-amp is 0 and therefore we have V R minus V i divided by R. So, that is our KCL equation.

Now, the diode current i D then only be positive, because the diode cannot conduct in the reverse direction. So therefore, this quantity must be positive. And what that means is V R times 1 over R L plus 1 over r must be greater than V i by r. In other words V i must be less than V R times R plus R L divided by R L. This factor is always greater than 1 and we will define this entire quantity as V i 1.

When V i is less than V i 1 the diode conducts and we have V o equal to V R which is a constant and that happens irrespective of V i as long as V i is less than V i 1. So, that is one situation that we have. And in the other case that is when V i is greater than V i 1 the diode does not conduct. And what do we have then? Then this current is 0 and we have V i dividing between R and R L. So, then V o is given simply by voltage division V o is then R L divided by R plus R L times V i like that.

And here is the plot of V o versus V i; this axis is V o, this axis is V i and this value here is V i 1. When V i is less than V i 1; that means, this region V o is constant and equal to V R like that. Otherwise V o is given by R L by R plus R L times V i which is the straight line passing through the origin this line with the slope equal to R L divided by r plus R L. So this circuit is essentially a clipper circuit. Let us now take a special case in which R L is much larger than R, when that happens this factor becomes equal to 1; and our V i 1 this boundary here becomes equal to V R and the slope here becomes equal to 1.

To summarize we have looked at the super diode the combination of a diode and an op-amp which behaves like an ideal diode with a turn on voltage of 0 volts. We then looked at an interesting application of the super diode namely; AM demodulation. After that we have started looking at precision clipping and clamping circuits. We will continue this discussion in the next class, until then goodbye.