Basic Electronics
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Lecture – 30
BJT amplifier (continued)

Welcome back to Basic Electronics. In this lecture we will use the complete AC equivalent circuit for the common emitter amplifier to find the amplifier gain. Combining the DC and the AC solutions for the amplifier we will obtain the complete solution and compare it with stimulation results. We will then look at the frequency response of the common emitter amplifier in qualitative manner and explain why the amplifier gain varies with frequency. Let us start.

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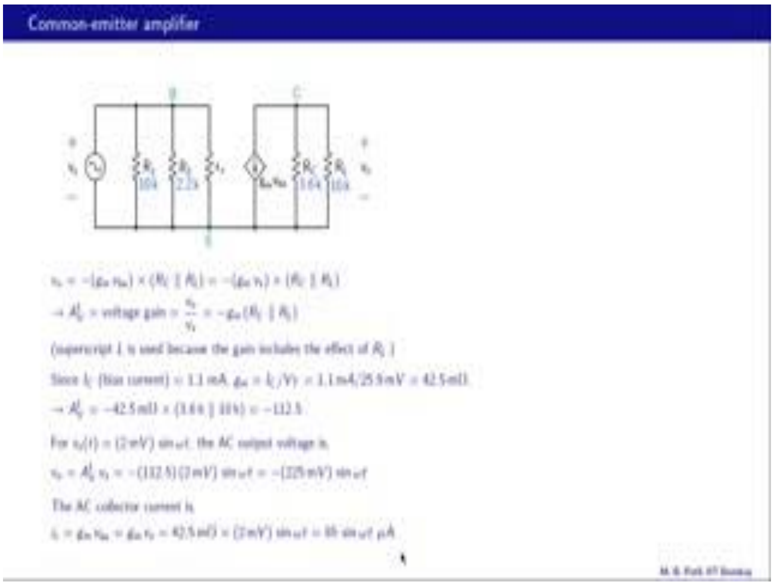

Common-emitter amplifier

$v_o = -(g_m v_{be}) \times (R_C \parallel R_L) = -(g_m v_s) \times (R_C \parallel R_L)$

$\rightarrow A_V^L$ = voltage gain = $\dfrac{v_o}{v_s} = -g_m (R_C \parallel R_L)$

(superscript L is used because the gain includes the effect of R_L.)

Since I_C (bias current) = 1.1 mA, $g_m = I_C/V_T$ = 1.1 mA/25.9 mV = 42.5 m℧

$\rightarrow A_V^L = -42.5$ m℧ × (3.6k ∥ 10k) = −112.5

For $v_s(t)$ = (2 mV) sin ωt, the AC output voltage is,

$v_o = A_V^L v_s = -(112.5)(2\,\text{mV}) \sin \omega t = -(225\,\text{mV}) \sin \omega t$

The AC collector current is,

$i_c = g_m v_{be} = g_m v_s$ = 42.5 m℧ × (2 mV) sin ωt = 85 sin ωt μA

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Here is the AC circuit again and we have added the component values. What we want to do first is to obtain the gain for this amplifier that is v o divided by v s. And let us remember that all of these quantities v s, v o, v v etcetera are signal quantities all right. So, let us look at v o. What is v o is equal to? This current going through this parallel combination of R C and R L and causing a voltage drop. So, it is gm times V BE times R C parallel R L, but that voltage drop is positive in that direction and our v o is marked the other way. So therefore, v o is negative of that quantity. So, that is minus gm V BE times R C parallel R L. And what is V BE? V BE is the voltage between the base and the emitter and this particular circuit it is the same as v s. Because the base is connected there the emitter is connected there. So, the V BE is the same as v s, and therefore v o is minus gm multiplied by R C parallel R L.

We now calculate the voltage gain denoted by a/ with a subscript b which stands for voltage. Since we have an input voltage and an output voltage this A is a ratio of voltages and that is why the subscript V and there is a superscript L which is used, because the gain includes the effect of the load resister R L as we will see. So, what is the voltage gain it is v o by v s and we already have v o here in terms of v s. So, all we need to do is to take v s on the other side and then we get this expression for A V L. So, that is minus gm times R C parallel R L. And as we can see from this expression A V L does include the effect of R L here if we change R L to some other value this is going to change and therefore, A V L is going to change.

Now the next step is to evaluate this trans conductance parameter. And as we have seen it is related to the collector bias current. Since I C is 1.1 mill ampere with DC or bias current gm is equal to I C by V T 1.1 milliamps divided by 25.9 millivolts and that turns out to be 42.5 milliseimens or milliohms. And now all we have to do is to substitute that in this expression I will get a number for the gain. So, A V L is then minus 42.5 milliohms times 3.6 k in parallel with 10 k and that turns out to be minus 112.5.

There is significance to this negative sign here, and what it says is that if this v s is increasing then the v o will decrease. So, they are out of phase with each other. Let us now calculate the output voltage, for an input voltage of 2 milli volts sin omega t. So, this 2 milli volts is the amplitude of the sinusoidal input voltage, v o is A V L times v s. A V L we already know minus 112.5 times v s which is right here. So, that turns out to be minus 225 milli volts times sin omega t. So, the input amplitude is 2 milli volts the output amplitude is 225 milli volts; so definitely much larger than the input voltage.

What about the collector current? We are talking about the signal current now that is gm times V BE that is the collector current we already have gm 42.5 milliohms and v s is 2 milli volts times sin omega t. So, if we evaluate that this milli times milli is micro 42.5 times 2 is 85. So, 85 times sin omega t that many microamperes.

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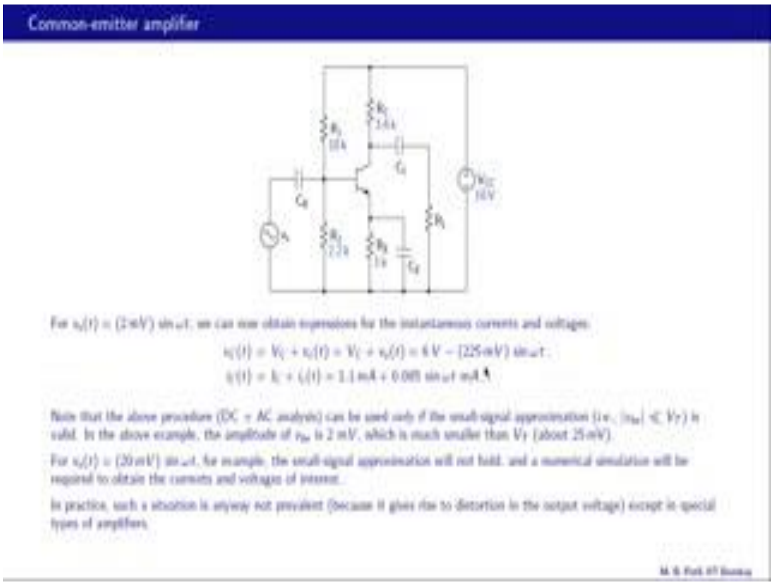

Common-emitter amplifier

For $v_s(t) = (2\,mV)\,\sin\omega t$, we can now obtain expressions for the instantaneous currents and voltages:

$$v_C(t) = V_C + v_c(t) = V_C + v_o(t) = 6\,V - (225\,mV)\,\sin\omega t\,,$$
$$i_C(t) = I_C + i_c(t) = 1.1\,mA + 0.085\,\sin\omega t\ mA.$$

Note that the above procedure (DC + AC analysis) can be used only if the small-signal approximation (i.e., $|v_{be}| \ll V_T$) is valid. In the above example, the amplitude of v_{be} is 2 mV, which is much smaller than V_T (about 25 mV).

For $v_s(t) = (20\,mV)\,\sin\omega t$, for example, the small-signal approximation will not hold, and a numerical simulation will be required to obtain the currents and voltages of interest.

In practice, such a situation is anyway not prevalent (because it gives rise to distortion in the output voltage) except in special types of amplifiers.

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We can now obtain the expressions for the instantaneous currents and voltages in particular, we are interested in the output voltage or the voltage at the collector. And that would be the DC value plus the AC VC of t and VC capital bs of capital C the bias value we have already seen earlier for this example is 6 volts and the signal value we have calculated to be minus 25 milli volts times sin omega t. So, that is the total instantaneous voltage at the collector. And if we look at the total instantaneous voltage at this node, we are not going to see the DC part because the capacitor is going to block the DC that DC voltage is going to appear across the capacitor. And here we are only going to see the small the signal part 225 milli volts times sin omega t.

What about the total instantaneous collector current? Bias current plus signal current bias current as we have seen earlier is 1.1 milliamps the signal current as we saw on the last slide is 85 micro amps which is the same as 0.085 milliamps times sin omega t. So, if we plot this voltage the instantaneous collector voltage we are going to see 6 volts and around 6 volts we are going to see a variation which has amplitude of225 milli volts. Similarly, if we plot the instantaneous collective current we are going to see 1.1 milliamps as the base level around that we are going to see amplitude a variation with amplitude 0.085 mill amperes. Let us make a few comments now.

The procedure that we have followed that is treating the DC and AC circuits separately and then adding the results that procedure can be used only if the small signal approximation is valid. That is the magnitude of the v e should be small compared to V T. In our example if you recall the last slide the amplitude of V BE was the same as the amplitude of v s. And that was surely much smaller than V T. And therefore, the results we have obtained here are valid. If v s was made larger let us say an amplitude of 20 milli volts which means the amplitude of V BE also would be 20 milli volts in our circuit. Then the small signal approximation will not hold and our procedure of separate DC and AC analysis then is not valid anymore. And in that case a numerical simulation will be required to obtain the currents and voltages of interest. And in this kind of simulation what is done is the transistor model is considered for example, the ebers moll model or more advanced model like the gammar por model and the circuit equations for the entire circuit are then solved simultaneously to obtain the solution.

In practice such a situation with large V BE compared to V T e is anyway not prevalent not very common. And that is because as we have seen earlier that will give distortion in the output voltage. So, even for a sinusoidal input voltage, the output voltage will not be sinusoidal anymore and that is certainly a situation which we do not desire. So, in practice generally this small signal approximation will be valid especially for circuits of this type and therefore, we can use DC and AC analysis separately like we have done here.

There are some amplifiers like the so, called class c amplifier in which the transistor. In fact, is not operating in the linear region it is made to operate in the cut off and linear region, and in that case all of these cannot be used because the small signal approximation certainly goes for a toss in that case, and then we require numerical simulation of the circuit or some other approximate way of analyzing it.

We will now look at some simulation results to check whether these waveforms are indeed what we expect them to be. So, let us quickly go through these equations VC of t should have a DC value of 6 volts. And it should go around that is 6 volts with an amplitude of 225 millivolts. Which means peak to peak voltage of 225 times 2 that is 450 millivolts or 0.45 volts. So, let us remember that number when we look at the simulation reasons we will verify whether that is what we see. The collector current has a DC component of 1 mill ampere and it is peak to peak variation is 0.085 times 2 or 0.17 mill ampere.

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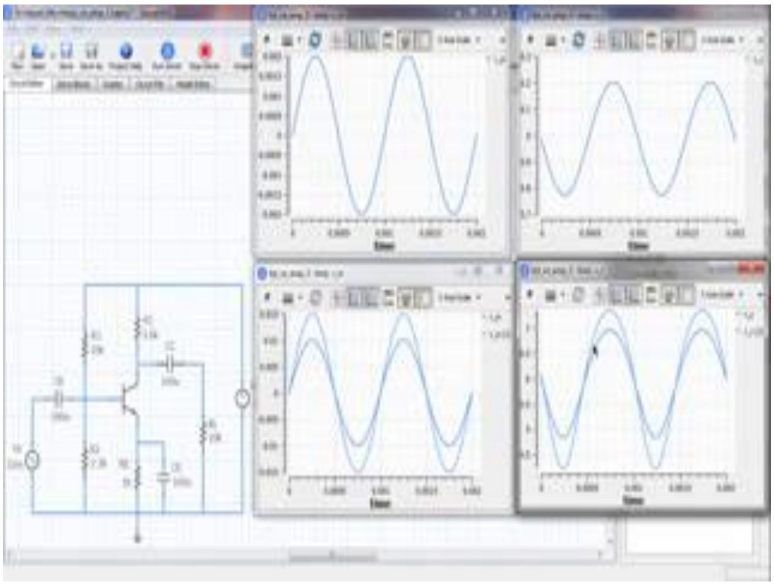

Here are the simulation results. This graph is the input voltage v s here. Which has an amplitude of 2 millivolts as mentioned here. And we are showing 2 cycles which means 2 milliseconds since our frequency is 1 kilohertz. So, that is 1 millisecond. And that is 2 milliseconds this time is in seconds. So, that is 2 milliseconds and the input voltage is going from 0 to 0.002 that is 2 millivolts and then going down to minus 0.002. So, it is varying between minus 2 millivolts and plus 2 millivolts. As the input voltage varies the collector current also varies that is the collector current.

And as we notice it is DC value it is something like 1.1 milliamp, the current here is in milliamps. So, it is DC value is around 1.1 milliamp and it varies around that. And we expect the amplitude or the peak to peak variation to be 0.17 milliamp if you remember. So, let us take whether that is happening. This is 0.05 milliamp 1.2 minus 1.15. So, we have 0.05 another 0.05 another 0.05, so 0.15 and a little bit. So, it does indeed look like 0.17 milliamp as we would expect.

And this is the BC the collector voltage at that node. And what do we expect that to be we expect it to be centered around 6 volts that is the bias value of VC. And we expect the peak to peak voltage to be 0.45 from the last slide. Also we expect the gain to be negative that is this voltage divided by this voltage the signal part is negative; that means, we expect VC to be out of phase bits the input voltage. And that is indeed what we see this is the input voltage and that is the collector voltage. So, definitely they are out of phase when this increases that decreases and so, on it is base value or the DC value is indeed 6 volts very close and the peak to peak variation here let us see how much, that is this one division is 0.1 volt. So, we have 0.1, 0.1, 0.1 and may be 0.02 or something like or something like that.

So, it is 0.42 or 0.43 and we expect 0.45. So, it is reasonably close. So, our calculations are fairly accurate and little bit of difference of course, expected because their model used here, may not be exactly the same as what we did in our calculations. So, that is encouraging our calculations seem to work and; that means, we can use the methods that we discussed. Now apart from simulation if you go to the lab and hook up the circuit you should definitely expect to see the same results. So, you can apply an input voltage of 2 millivolts amplitude and see whether output voltage does indeed look like this. In the lab you may not easily be able to apply amplitude an input voltage with amplitude 2 milivolts and you may need to use potential divider regiment over here but that is fairly straight forward and hope you will be able to do that.

What happens if we increase the input voltage amplitude? 2 things: one the output voltage amplitude or the collector voltage amplitude will increase. Second if the input amplitude is too large, then our small signal approximation may not hold any more, and that will lead to some distortion in the output voltage or the voltage at the collector. So, let us look at these points now. Here is our original input voltage, amplitude 2 millivolts and that is our original collector voltage and that is sinusoidal without any distortion. Here are 2 more cases. This case corresponds to an input amplitude of 10 millivolts and this case to 15 millivolts.

Now the corresponding collector voltage waveforms are shown here. When the input amplitude is 10 millivolts we start seeing some distortion; the positive half that one is looking now different than the negative half. If we increase the input amplitude to 15 millivolts, then we have this output waveform. And now the distortion is more obvious this positive half definitely looks broader in a way than the negative half.

So, these are things we need to keep in mind when we use an amplifier. We should be aware that there is a limit on the input voltage amplitude, beyond which there may be some distortion in the output voltage.

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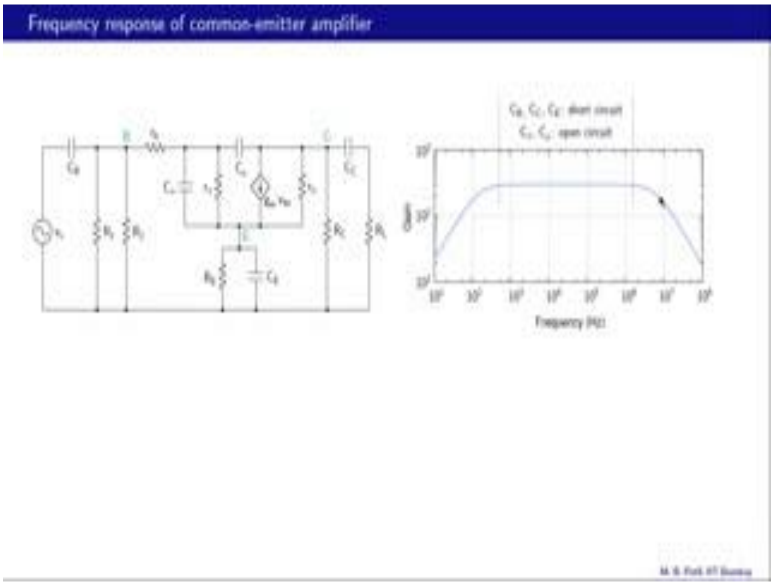

Frequency response of common-emitter amplifier

Let us now take a brief look at the frequency response of a common emitter amplifier and example is shown in this plot. How do we measure the frequency response? Here is what we do we apply an input voltage, with a certain amplitude and a certain frequency. We measure the output voltage. Then we take the ratio of the output amplitude and the input amplitude. And that gives us the gain for that particular frequency. Then we go to the next frequency and so on. And when we have all of these data points then we plot the gain as a function of frequency. That is one is this example. And we should remember of course, that the amplitude of the input voltage is always kept sufficiently small. So, that there is no distortion in the output voltage.

Now, as we see in this plot the gain is not quite a constant, but there is a frequency dependence of the gain. It drops when the frequency is low, then it is constant for this particular circuit in some range and then again when the frequency is high, then the gain drops. Now where does the frequency dependence come from, is easy to see let us take a resistor the relationship for resistor v equals to I times r. And there is no omega in the relationship. So, the frequency dependence surely cannot come from resistors. Similarly, this voltage controlled current source does not have any omega and it is relationship. So, what does have omega is the capacitor.

So, all of these capacitors CB C phi CE etcetera present an impedance which depends on the frequency. So, the circuit becomes frequency dependent and therefore, the gain becomes frequency dependent. And once we understand this point then it should be easy to see why in the common emitter amplifier we have this kind of behavior.

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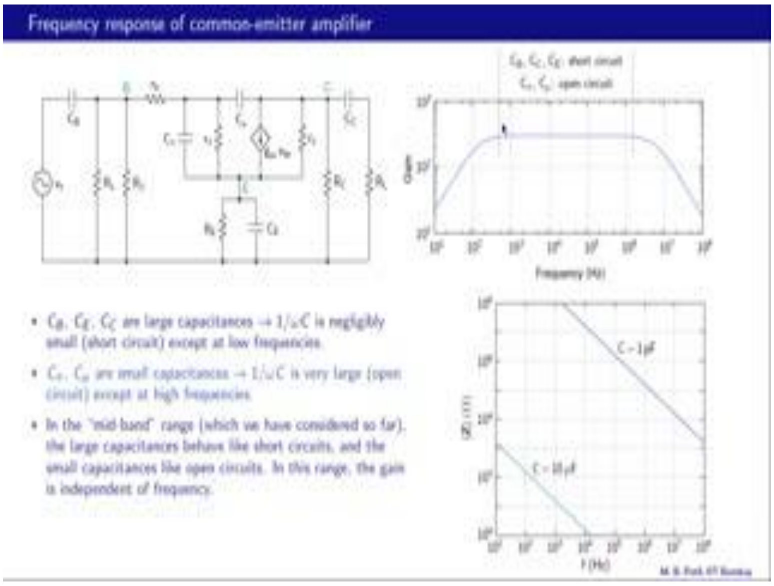

Frequency response of common-emitter amplifier

- C_B, C_E, C_C are large capacitances → $1/\omega C$ is negligibly small (short circuit) except at low frequencies.
- C_π, C_μ are small capacitances → $1/\omega C$ is very large (open circuit) except at high frequencies.
- In the "mid-band" range (which we have considered so far), the large capacitances behave like short circuits, and the small capacitances like open circuits. In this range, the gain is independent of frequency.

The capacitances CB CE and CC are large, in the tense of microfarad range or even larger. And for these capacitances one over omega C the impedance presented by them is negligibly small. That is they are like short circuits except at low frequencies. Now this can be seen in this plot here where we are plotting the impedance presented by the capacitor as a function of frequency. Essentially this one over omega C, and because it is a log plot both of these axis are log axis this quantity looks like a straight line. So, as we see one over omega C for this case is very small. This is 1 ohm this is 100 ohms. So, it is 1 ohm or smaller in this frequency range.

And it starts becoming appreciable only when frequencies are low. Let us say 1 kilo hertz or lower. What happens then is the following for example, let us consider CB. In this range when the frequency is high enough CB is like a short circuit and therefore, this v s appears across the amplifier as such. Now when the frequency is low for example, if we are in this region the frequency could be hundred hertz or 10 hertz, and the impedance presented by CB may then be in the kilo ohms range. Now that becomes comparable to the impedance that is seen from this port. And now there is a voltage division of v s between CB and rest of the circuits and therefore, the circuit sees a smaller voltage than v s. And because of these reasons there is a drop in the gain at low frequencies.

On the other hand, the capacitances C phi and C mu the device capacitances are small they are in the peak farad range and for these 1 over omega C is very large that is they are like open circuits except at high frequencies. And we can see that also in this plot here. This is 100 mega ohms this is 1 mega ohm. So, the impedance presented by a capacitance of 1 peak farad is small enough only in this range here. And otherwise it is very high certainly much higher than the other resistances in this circuit like R1, R2, RE, R C, R L.

When the frequency is sufficiently low, that is in this region the impedance presented by C phi and C mu is very high. Let us say 1 weak or a 1 larger. And then these could be considered as open circuits. And then all of this current passes through R pi and that produces some output voltage at the collector. Now imagine that the frequency has increased say we are somewhere here so; that means, the impedance presented by C pi and C mu, has now become smaller. And now this current is going to split into different branches and that is going to reduce the current through this R pi causing a reduction in the output voltage. So, that is what is happening roughly in this region.

In summary there are 3 regions in the common emitter amplifier frequency response. There is a mid-band region this region here. In this region the large capacitances behave like short circuits, and the small capacitances behave like open circuits. So, CB, CC, CE behave like short circuits, C pi and C mu behave like open circuits. And this is the range that we have considered in our analysis if we remember, that is what we have considered in deriving the gain expression. Then there is low frequency region in which the large capacitors the coupling capacitors and bypass capacitors.

They start presenting a sufficiently large impedance and therefore, causing a reduction in the gain. Then there is a high frequency region, in which the impedance because of C phi and C mu becomes small enough and that causes a reduction in the gain in this region. So, this is a typical frequency response of an amplifier and depending on what our signal is we need to make sure that we are operating in the mid band region where we expect the gain that the amplifier is designed for.

In summary, we have completed gain calculation for the common emitter amplifier. Also for a given input signal we worked out the complete solution that is DC plus AC and compared it with simulation results. We have taken a qualitative look at the variation of the amplifier gain with frequency and pointed out the factors responsible for this behavior. In the next class, we will look at the general representation of an amplifier. So, see you next time.