# Analog ICs

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## Lecture - 03
## Translinear Networks (Currentmode Circuits)

It is a kind of multiplier, a current multiplier. There are two cells that we talked about, and one such cell is an important cell that is depicted here.

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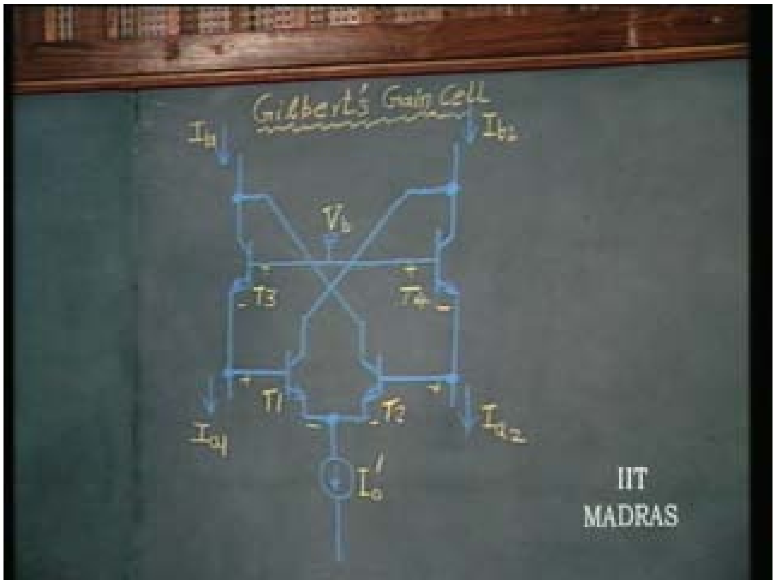

We can see how this forms the translinear loop minus T3, T4, T1, T2 form the translinear loop - type A and type B cell, we had drawn last time. This is the type B cell, where now we are trying to input signals and see what happens to this cell in terms of the signals that are inputted. The common base point is connected to an arbitrary base potential. This $V_b$ is an arbitrary base potential with this put to ground. Now let us see how this circuit behaves. This is called Gilbert's Gain Cell. This concept is important in VLSI design, analog VLSI design, particularly.

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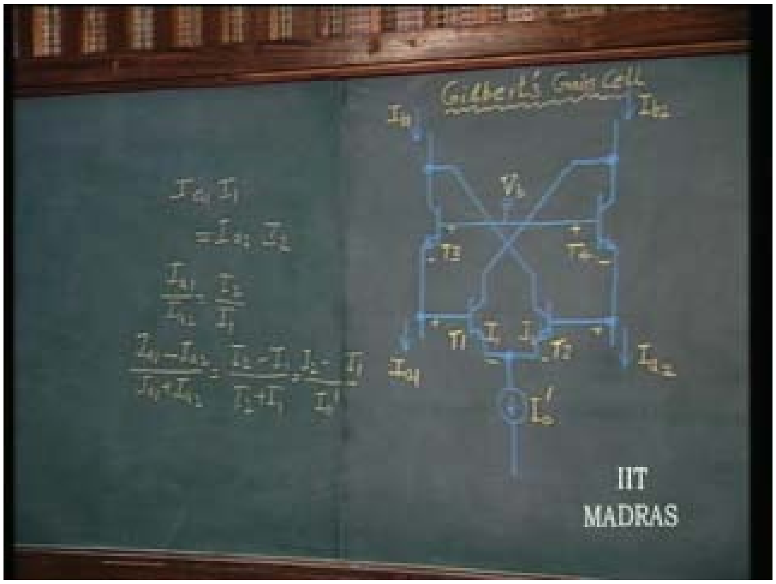

The cell should be always something that can be used to build as a superstructure. It should be such that it should be identical in its nature when we build a superstructure with this kind of cell. Let us see whether that characteristic is present in this particular cell. Let us now see the relationship. Let us see how the current relationship is there. $I_{a1}$ is the current flowing in this, into, let us call the current flowing in this as $I_1$, the current flowing through this as $I_2$. So, $I_{a1}$ into $I_{a1}$ into 1 $I_1$ is equal to, again $I_{a2}$ is flowing through this into $I_2$.

Based on translinear principle current flowing through the counter clockwise diode will be product of those will be equal to the current flowing through the diodes which are clockwise. So $I_{a1}$ into $I_1$ is equal to $I_{a2}$ into I. This is the basic current multiplication relationship. In this context, let us see how this can be used for current amplifier. So, $I_{a1}$ by $I_{a2}$, therefore, is equal to $I_2$ by $I_1$. The ratio relationship is clear from this. $I_{a1}$ by $I_{a2}$, we will call this as input current. The ratio of the input current, $I_{a1}$ by $I_{a2}$ is equal to $I_2$ by $I_1$ $I_2$ by $I_1$. $I_2$ and $I_1$ will form the part of output current.

So, the ratio of input current, is it exactly equal to ratio of the output current? This relationship is valid, as I told you, over a large magnitude of variation of current. It is not a small signal relationship. So, from maybe microamperes to hundreds of mA, this relationship is valid. Now, suppose we write it as $I_{a1}$ minus $I_{a2}$ by $I_{a1}$ plus $I_{a2}$, what is it going to be equal to? It is $I_2$ minus $I_1$ by $I_2$ plus $I_1$, the ratio relationship. And we have $I_2$ plus $I_1$ always equal to a constant current minus dc current minus $I_0$. So, if we say that $I_{a1}$ minus $I_{a2}$ is the differential input current, $I_{a1}$ and $I_{a2}$ are two input currents.

Whenever we have two input currents, like in the case of two input voltages, we can have a differential input voltage. Then, we have two input currents. We can talk of differential input current and a common mode input current, any current. Therefore, $I_{a1}$ can be split up as a current common to both. What is that? $I_{a1}$ plus $I_{a2}$ by 2 plus $I_{a1}$ minus $I_{a2}$ by 2.

This is the differential part. So, any current, $I_{a1}$, can be split up as a common current, current common to both, plus half of differential path. Similarly, $I_{a2}$ can be written as same common current $I_{a1}$ plus $I_{a2}$ by 2, minus $I_{a1}$ minus $I_{a2}$ by 2. This aspect of common mode, and differential mode current, or common mode and differential mode voltage, has already been exposed to as far as you are concerned. In differential amplifier, same thing can be thought of in terms of current. So, what does it mean?
I have a common current here which can be made a DC, and differential current can only be kept as signal current.

Suppose this common current, $I_{a1}$ plus $I_{a2}$ by 2 is a DC, let us call that as, let us say $I_0$ prime, $I_0$, say, $I_0$, because $I_0$ prime we have called this current, so, we will call this as $I_0$, a common current, the common current $I_1$ plus $I_2$ by 2. And $I_1$ plus $I_2$, we are calling it as $I_0$ prime. So, if I say $I_{a1}$ plus $I_{a2}$ is equal to, let us call it as $I_0$ common current, then we will, for that, in order to keep it in line with this, it is $I_1$ plus $I_2$ is equal to $I_0$ prime.

Similarly, $I_{a1}$ plus I $I_{a2}$, we will call it as $I_0$, thereby, this is $I_0$ by 2, we will call it. But common current is a single value, whether you call it $I_0$ or $I_0$ by 2, it does not really matter. It is a single current. So it is $I_0$ by 2 plus the differential current $I_0$ by 2 minus the differential current. What happens to this relationship now? $I_{a1}$ minus $I_{a2}$ that is, the differential current by $I_{a1}$ plus $I_{a2}$ is nothing but $I_0$. This is equal to $I_2$ minus $I_1$ by $I_0$ prime.

This is an important relationship. If you notice this relationship, we will see something very nice emerging out of it; $I_2$ minus I by $I_0$ prime. Therefore, $I_2$ minus $I_1$ equals, what is it? It is $I_0$ prime by $I_0$ which is nothing but the ratio of two currents minus the ratio of two DC currents. What happens? It is a constant; it can be controlled by us. Ratio of two currents into $I_{a1}$ minus $I_{a2}$ in differential input current. So, this is an important relationship in what is called as current mode amplifier.

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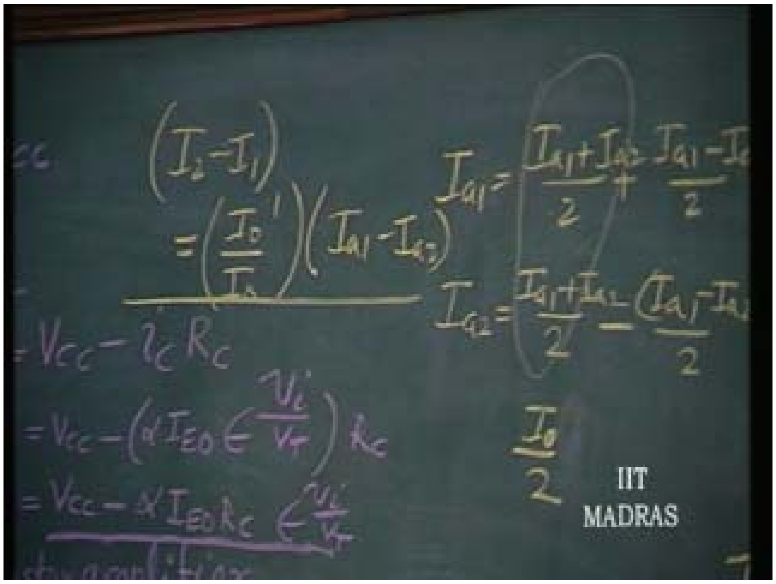

So far you have been exposed to voltage mode amplifiers. Why cannot we think amplifiers as current mode amplifiers? That is, that seems to more basic, and that kind of amplification can be done easily compared to voltage mode amplification. Look at the way we have obtained it: differential input current times a gain factor is equal to output current.

Now, this gain factor is not something very simple. In fact, this gain factor is absolutely constant, because we have already known that we can obtain a current ratio by area ratio. I can obtain a current mirror; I can generate a current reference, and I can obtain any current ratio by area ratio. So, I can see to it that this ratio of current is going to be same as the ratio of areas. It means it is just geometry-dependent. That is absolutely constant, independent of temperature, supply voltage, everything. This is what you have been trying best to achieve in the case of voltage amplifiers which you have failed to achieve in a simple manner; which you could achieve only by using feedback, etc.

Here there is no feedback at all adopted. Without using negative feedback, I have been able to demonstrate to you that we can get an amplifier minus current amplifier minus whose amplification factor is absolutely constant. This Gilbert's Gain Cell, even though it was proposed way back in 1970s, its prominence was never understood at that time. But in a VLSI context, analog VLSI context, you see that this gain cell is the most important concept ever to be given to analog circuitry. Why?

First of all, its dynamic range is fantastic. There is no other amplifier whose dynamic range can be as high as this. Then, it is independent of device property like beta, etc. device parameters, and that you are achieving without negative feedback. If you do not do it without forgetting to feedback, what will happen?

If you do not adopt negative feedback, then all the problems associated with negative feedback, like need for frequency, compensation, all these things, do not exist. Therefore, this concept can be adopted for designing what are called as wide-band amplifiers, or video amplifiers. This basic concept is the concept that can be straightaway adopted for video amplifiers, or wide-band amplifiers, because, there is no need for negative feedback, and if there is no need for negative feedback, there is no need for negative feedback because of the fact that amplifier gain is independent of device parameters.

And if you do not have negative feedback, then the consequent problem of frequency compensation being needed, and oscillation to be prevented, all these things are avoided. Now, apart from that, look at this structure. This is the input current. What will be the output current? Differential output current.

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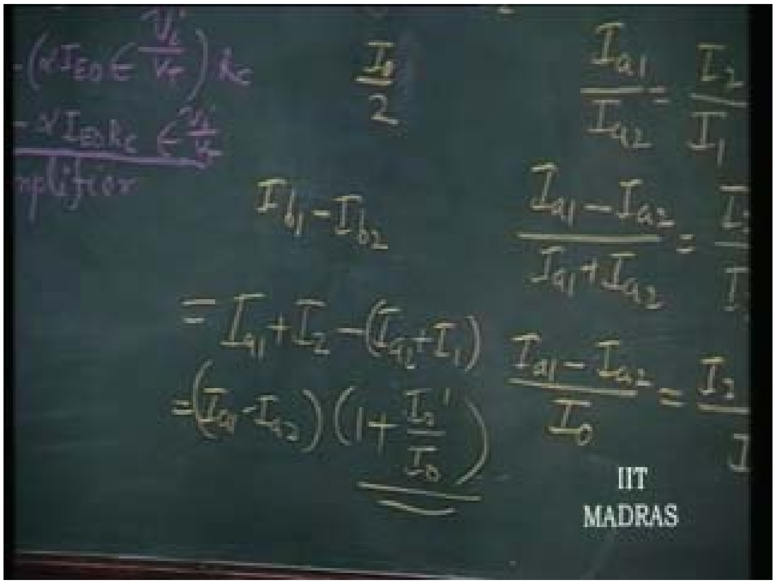

$-(\alpha I_{E0} \epsilon^{V_i/V_T}) R_C$

$-\alpha I_{E0} R_C \epsilon^{V_i/V_T}$

$\frac{I_0}{2}$

$I_{b1}-I_{b2}$

$= I_{a1}+I_2-(I_{a2}+I_1)$

$=(I_{a1}-I_{a2})\left(1+\frac{I_0'}{I_0}\right)$

$\frac{I_{a1}}{I_{a2}} = \frac{I_2}{I_1}$

$\frac{I_{a1}-I_{a2}}{I_{a1}+I_{a2}} =$

$\frac{I_{a1}-I_{a2}}{I_0} =$

$I_{b1}$ minus $I_{b2}$ is the differential output current, $I_{b1}$ is equal to $I_{a1}$ plus $I_2$; $I_{b1}$ $I_{b2}$ is equal to $I_{a2}$ plus $I_1$. What does it mean? This is equal to $I_{a1}$ minus $I_{a2}$ into 1 plus $I_0$ prime. This is like your non-inverting amplifier. So, differential output current is equal to 1 plus $I_0$ prime by $I_0$ into $I_{a1}$ minus $I_{a2}$, and this can now become $I_{a1}$ and $I_{a2}$ for the next stage which is exactly identical to this, only that we should be operating at $I_0$ double prime which is higher than $I_0$ prime in order to get a gain factor.

Now this can become the input current to another identical stage which will come here and the output of that will be again this as the input current into 1 plus $I_0$ double prime by $I_0$ prime. So now you can put this cell over another cell and keep on building your structure of current amplifier until you reach the power level of current that you desire. You can go on doing it. So this is truly a self-structure needed for VLSI design because this structure looks exactly identical, and it can be put one over the other, and you can build a superstructure. So you go on doing this, and then where do you stop?

Suppose you will reach the current level that you desire, then you cannot convert this into a voltage simply by putting two resistors to the final supply voltage and take the differential output. So, converting a differential output current into voltage is simply by putting resistors. So, that is not a problem at all.

This is what is done here, and it is truly wide-band, primarily because you are at all times dealing with only currents, and the voltages involved are only diode voltages, and therefore, the capacitors to be charged will be those capacitors across the diodes, and therefore, they are to be charged by a very small magnitude of voltage, and therefore, it is going to be very fast. So, that is the current mode of operation; is always fast because in the case of voltage mode of operation the capacitors have to be charged up to a certain value of voltage. In this case, since we are operating in current mode and the voltage is always equal to the diode voltage you do not have to spend time in charging the capacitor. That is why, please remember the current integrated circuit design is primarily with current mode of operation. That is quite suitable for all designs of circuits of analog VLSI systems. That is why we are calling it Gilbert's Gain Cell.

Like we do namaskaram to Vinayaga before proceeding with any work, when I started discussing about amplifier, I had to bring about this important concept of current amplifier by Gilbert, that is, Gilbert cell, as that pride of place. We have to preserve that pride of place for the Gilbert cell as a current amplifier. Remember, this has not yet become popular in design of ICs. It is going to become popular in a very short time. Now we will go back to the conventional amplifier which is always treated as a voltage amplifier. This we had discussed earlier as an inverter in our digital circuit.

We said the bipolar inverter, or mass inverter, is the basic stage which can also be used as an amplifier. Let us see how this inverter is suitable as an amplifier. This is a basic transistor amplifier which is called common emitter amplifier, all of us know about it.

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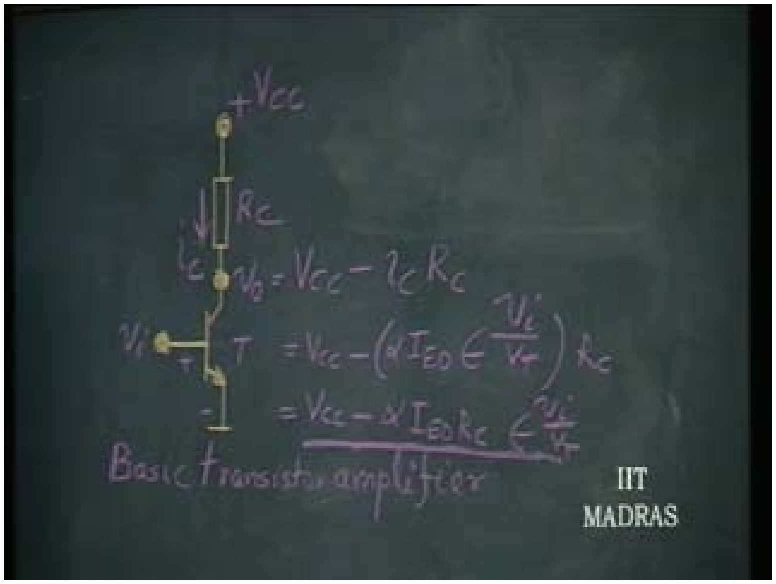

Vi is the input signal and $V_0$ is equal to $V_{cc}$ minus $I_c(R_C)$; and that is equal to $V_{cc}$ minus alpha times $I_E$, and $I_E$ is, in turn, equal to $I_{E0}$ exponent $V_i$ by $V_T$ into $R_C$. So, $V_{cc}$ minus alpha $I_{E0,}$ $R_C$ into exponent $V_i$ by $V_T$. So, this we already know. This is an exponential, therefore, relationship between output and input of a transistor stage, basic transistor stage, if you plot this, how will we see this? This, we had already seen in our discussion about digital inverter.

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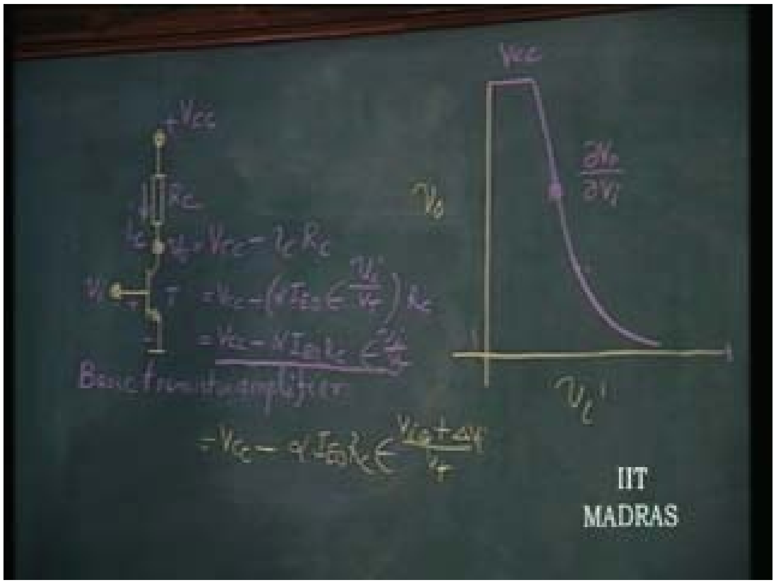

Now, let us see how it looks like when we discuss its characteristic in the case of amplifier. When Ic is, when $V_i$ is very small, this is equal to $V_{cc}$, and therefore, it will start with $V_{cc}$, then as Vi keeps on increasing, current will keep on increasing, and therefore, this is the kind of characteristic, this is the exponential characteristic: as current keeps on increasing, the output voltage here keeps on decreasing. Finally, the transistor will enter the saturation reached where it is absolutely useless. That is, the moment this voltage reaches about this, $V_i$ plus V gamma, or $V_i$, $V_i$ plus 0, that is, $V_{CT}$ is equal to 0 is the point where it is entering the saturation region.

So, this collector base potential should be reaching 0, or $V_{CE}$ should be reaching V gamma. So that is when it is entering the saturation. When it is getting forward biased, both the junctions will be getting forwards bias. So, the voltage will be of the order of 0.1 to 0.2V. So this is the state of affairs as far as this amplifier is concerned. Now, we are interested in operating this in this region. So far, in the digital circuitry, we were interested in operating it either here or here in the steady state. It was only transiting from here to here when it was going from high to low, or low to high, whereas, in the case of amplifier design we are going to operate it in this region. So, somewhere here, let us say, where the gain is going to be, the gain is nothing but the slope, $\Delta V_0$ by $\Delta V_i$. So, gain is nothing but the slope, that is, nothing but $\Delta V_0$ by $\Delta V_i$. Let us see this. As far as this is concerned, we have this as $V_{cc}$ minus $\alpha$ ($IE_0$).

Now, $R_C$ exponent $V_i$ by $V_T$, in order to make this get located somewhere here, so that it can act as a good amplifier. I have to apply what is called a bias voltage, so that if I do in terms of voltage, it will be $V_{iq}$ from bias and voltage, plus the signal voltage which is $\Delta V$ by $V_T$. What happens here? This is $V_{cc}$ minus alpha $I_{E0}$, then exponent $V_{iQ}$ by $V_T$ into $R_C$ exponent $\Delta V_i$ by $V_T$. So what is alpha $I_{E0}$ exponent $V_{iQ}$ by $V_T$? What is this value? $I_{E0}$ exponent $V_{iQ}$ by $V_T$ is equal to $I_{EQ}$. $I_{E0}$ exponent $V_{iQ}$ by $V_T$ is equal to $I_{EQ}$ cohescent operating current and alpha times $I_{EQ}$ is nothing but $I_{CQ}$. So, this entire thing is nothing but $I_{CQ}$. This is, therefore, $V_{cc}$ minus $I_{CQ}$ into exponent $\Delta V_i$ by $V_T$ into $R_C$.

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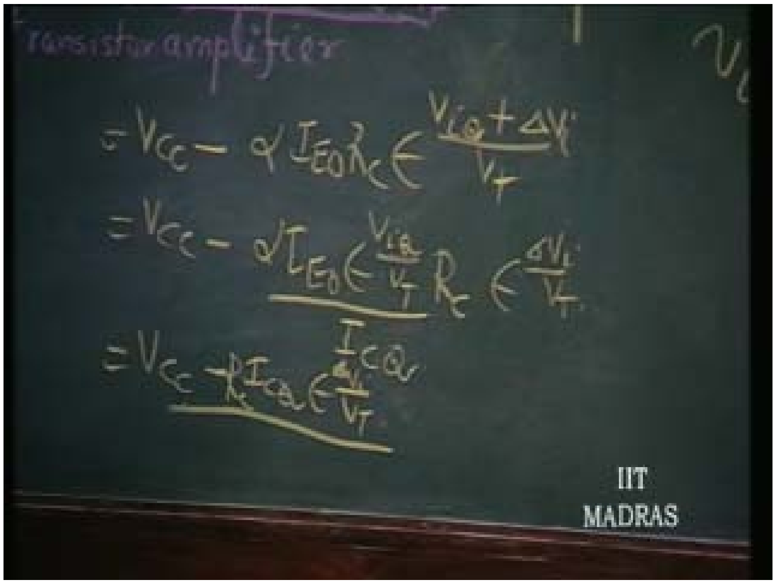

So we see here that this is $V_{cc}$ minus $I_{CQ}$ $R_C$. What is exponent $\Delta$? $V_i$ by $V_{T1}$ plus $\Delta V_i$ by $V_{T1}$ plus X plus X power 2 by 2 factorial and so on. So, in an amplifier, which is supposed to be linear the $\Delta V_i$ when it varies the output should also vary according to $\Delta V_i$. That means all the other terms should become very small. These are the nonlinear terms. So what is the condition for this to be a linear amplifier? We can see that $\Delta V_i$ by $V_T$ has to be much less than 1. This is an important relationship. In the case of a bipolar transistor that $\Delta V_i$ by $V_T$ should be much less than 1 irrespective of the operating points. That means if $\Delta V_i$ by $V_T$ is very small, then the nonlinearity resulting in the exponent is going to be minimal. It does not mean saturation, as well as cutoff nonlinearity will not come into picture. Those things are to be separately taken into account.

If saturation and cutoff nonlinearity does not come into the picture, then the nonlinearity resulting due to the exponential relationship is going to depend upon only $\Delta V_i$ by $V_T$ magnitude. Then $\Delta V_i$ by $V_T$ should be made very small compared to work. That was the assumption that, if $\Delta V_i$ is a sine wave, then immediately we know that there is predominant second harmonic distortion in this because of this square term. This also is to be noted clearly.

The predominant second harmonic distortion is responsible for the first instance to cause final distortion. Therefore what is this equal to now? $V_{cc}$ minus $I_{CQ}$. $R_C$ is nothing but $V_{CQ}$. $V_{cc}$ minus $I_{CQ}$ $R_C$ is nothing but $V_{CQ}$ minus $I_{CQ}$, $R_C$ into $\Delta$, $V_i$ by $V_T$ that is the wanted term that into 1 plus rest of the term is the nonlinear term which has to be made very small, which is nothing but $\Delta V_i$ by $V_{T2}$. So we want this factor to be very small compared to 1, strictly speaking, is $\Delta V_i$ by $2V_T$ which should be made very small compared to 1.

So what is this, $I_{CQ}$ $R_C$ by $V_T$? Nothing but the gain which we have been calling as $V_{CQ}$ minus gm the transconductance of the transistor into $R_C$ into $\Delta V_i$.

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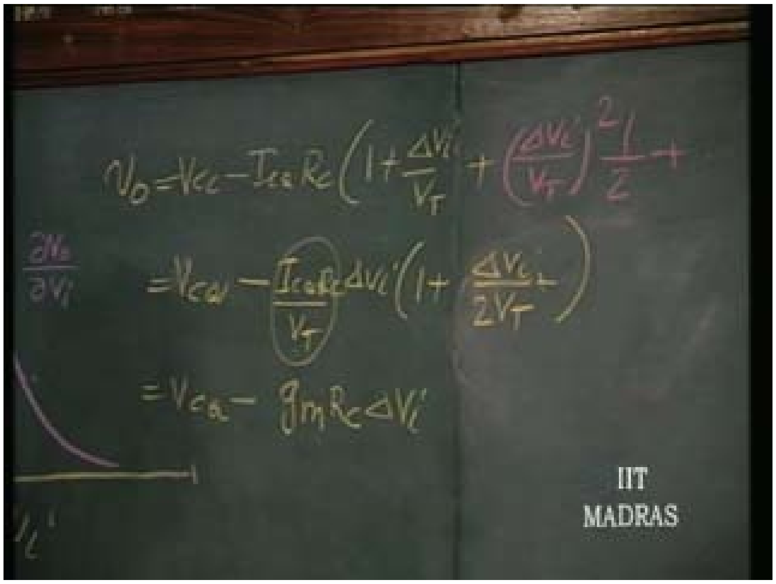

So you can see that phase shift coming about, that when $V_i$ increases the collector voltage is decreasing. So you see the phase shift of 180 degree, and also the gain of gm $R_C$ coming to picture. This is clear. So this amplifier is not good enough for us.

Look at the problem associated with this amplifier. First of all, I have to bias it at a voltage which is $V_{iQ}$, then superimpose over that the required signal set of a pair, that $V_{iQ}$ should be of the order of 0.5 to 0.6, and that itself should not change.

Suppose I am able to get a voltage source of that type, I can bias it, but, even if I bias it, you know that this voltage itself is going to keep changing with respect to temperature. What is the coefficient of this voltage, $\Delta V_{BE}$? $V_{BE}$ changes with respect to temperature in a manner which is minus 2 mV by degree C rise in temperature. You know all this. A diode which is forward biased has a temperature coefficient of minus 2 mV by degree C rise in temperature.

That is, $\Delta V_{BE}$ by $\Delta T$, that is the temperature coefficient of a diode which is going to result in minus even if the signal is not varying, if the temperature is varying, what will happen? This collector voltage is going to drift. That is the problem of drift. So, because $V_{BE}$ is changing with respect to temperature, the output voltage is changing even though input has remained constant. Input has not changed. So, output changes with respect to temperature, and consequently, with respect to time. So, it is drifting with respect to time because of its dependence on temperature. This is the major disadvantage of this amplifier. Particularly for low-frequency signal this is going to be nuisance.

For high-frequency signal at least I can decouple this and only extract the high-frequency path and couple it on another stage. So, it is not going to be a problem. But for low-frequency signal, this is going to be a problem. That is the reason that this stage is not preferred in integrated circuits. In integrated circuits, you would like to exploit the property of the device to compensate for this. Straightaway I would say that one technique is to see to it that this is modified somehow, and in an amplifier, when I have given an input signal, I would like to give it straight to the input of the input terminal of the amplifier. I do not want to couple it again through capacitor, etc. That means preferably I would like the amplifier input voltage to be 0 when the output voltage is also 0.

If the input voltage, when it is non-zero, output voltage is also finite for some reason, because of operation, etc. There is one more thing called the Offset. The only way I can make the input 0 when the output is 0 and to become the operating point is just to see that the device works with both positive as well as negative supply. Otherwise, I cannot say with the single supply you can see that output has to be always somewhere in between, which means it has to have an offset etc. That means, when the input is 0, output is not going to be 0. So, in a true amplifier, I would like the output to be 0 when the input is 0. Or I should be capable of connecting the input directly to the ground when there is no input. So what do I do? I use another supply. So the dual supply concept comes if you want to get rid of coupling the whole circuit by means of a capacitor.

In capacitor of things which have to be avoided in integrated circuit we are not developed even though they are available with very small values. They have to be cautious. They take up a lot of area, and therefore, this concept of biasing it by means of another supply. How do I bias it? No, I can put a negative supply, but I just told you that it is easier to supply a current into it and force the voltage. So I would rather apply a current here.

So using a current source what happens? Automatically, I can make sure that this can be grounded. Now, when the signal is there not there, this can be grounded simply and automatically. It gets biased by the required voltage in order to carry this current, $I_E$. In order minus this is the emitter current minus in order to, sort of, say that this current is something that we are obtaining from another current source, we will call this as $I_0$. Now, I have biased it by means of a current, whereas biasing it by means of a voltage is a very troublesome effect.

First of all, I have to get the exact voltage, which is very difficult, and even if I get the voltage, it is going to drift because of temperature variation, whereas here, the current emitter current is fixed, and even if the transistor based emitter voltage drift nothing happens, as far as output current is concerned, cohescent current is concerned. So, biasing by a transistor, by means of a current, is preferred to biasing the transistor by means of a voltage. So, I would rather bias it by means of a current in this following manner. Next, you will see that obviously the emitter has to be grounded, otherwise, it cannot be common emitter amplifier.

How do I ground this?

For AC it should be a ground, or for signal it should be a ground. So normally, in a discrete circuit, I would have put a capacitor, which is called a bypass capacitor. But, this capacitor, for low-frequency operation, has to be very high in order to act as a short circuit at that frequency. But in an integrated circuit, what should I do? So, in an integrated circuit I should not use a capacitor, but I should use dynamic impedance which will act as a short circuit for signal but it will not disturb my biasing current. I still know what devising current it is, as long as I know what the biasing current is, that is called stable biasing. If I am not able to tell you what the biasing current is, that is called unstable biasing.

Suppose I ask you: Please tell me the beta of the transistor, only then I will come up with the biasing current. Then it is unstable biasing. If I say, I know what the biasing current is going to be irrespective of the transistor parameter. Then it is called stable biasing. In this case, therefore, I have to put a device here. What will be the device that I will put? Automatically, I will put a forward biased diode here. Please understand this, because a forward biased diode is a short circuit for signal. But what will we do for this current? Because of the IC property, the $I_0$ is going to be split equally because bases are connected, emitters are connected. So, these are identical transistors, and therefore, the currents have to be equal.

The principle is that we depend upon so much in integrated circuits, that when the transistors are equal, and if the base emitters are at the same potential then the current should be equal, this is what is used for biasing it in a stable fashion. That means, the biasing is not going to be disturbed, it is going to be $I_0$ by 2, I am able to tell without any hesitation. That means, it is a stable biasing. And apart from that, what have I achieved? As far as the signal is concerned it is going to act as a near-short, not exactly a short.

What is the impedance from that emitter to ground? Incremental diode impedance which is small $R_E$ itself and therefore this is going to still act as an amplifier which is very similar to common emitter amplifier, with the gain now being reduced to half, because instead of being a short circuit, it is also $R_E$.

So this $R_E$ of a common emitter amplifier, and $R_E$ of this diode, will share the input voltage. Earlier, input voltage was totally coming across based emitter junction of the amplifier. Now, based emitter junction of the amplifier gets only half the input voltage, because $R_E$ of this amplifier, as well as the diode, will be sharing the input voltage. When the input voltage is fed here, $V_i$ by 2 you can see here that the operating current is going to be $I_0$ by 2, $I_0$ by 2. Then I say, in order to have the early effect also the same, if the early effect … what is the early effect? Collector base voltage is going to still determine the collector current.

Therefore, if collector base voltage also happens to be the same, then I make sure that the current deviation is equal, and therefore, what do I do?
I also connect this so that it also has the same collector, because otherwise I will have to leave the collector hanging; instead, I will as well connect the collector resistance through the same value with the resistance RC to the supply. What is this? This is nothing but the

difference. This is one way of presenting differential. It is not how this has developed. This is one way of presenting the differential amplifier as something that has originated out of necessity of getting rid of the disadvantages of discrete common emitter amplifier when it is being adopted for IC version.

When you are adopting a common emitter amplifier for IC version we can say that we want to get rid of the bypass capacitor. We do not want coupling capacitor, and this is one way you can get rid of coupling capacitor, as well as bypass capacitor, in any discrete circuit. This is one important powerful technique converting every discrete circuit into integrated version.

Any discrete version of a circuit that you have can be easily converted getting rid of all the bypass capacitors simply by making it differential. This is a powerful technique. So you have to understand this technique, therefore, I brought it out. Now, once you say that this is going to be differential, what happens here? This current is going to remain constant $I_0$.

If signal voltage gets dropped here as $V_i$ by 2, and this will be minus $V_i$ by 2 superimposed over the Iq, this will be plus minus, minus Vi by 2, and therefore, it will develop a voltage which will be in phase opposition to this, but of the same magnitude, when therefore, if this is minus $gmR_C$, this will be plus $gmR_C$. The gm in this case is 1 by $2R_E$ and not 1 by $R_E$ because the input voltage is divided between two diodes. So, $V_i$ by $2R_E$ into $R_C$ is the single stage gain with the minus for the first stage, and for the other stage it is plus $R_C$ by $2R_E$. Therefore if you take the differential output here as the output, what will we get? One is going to be minus $R_C$ by $2R_E$, another is plus $R_C$ by $2R_E$.

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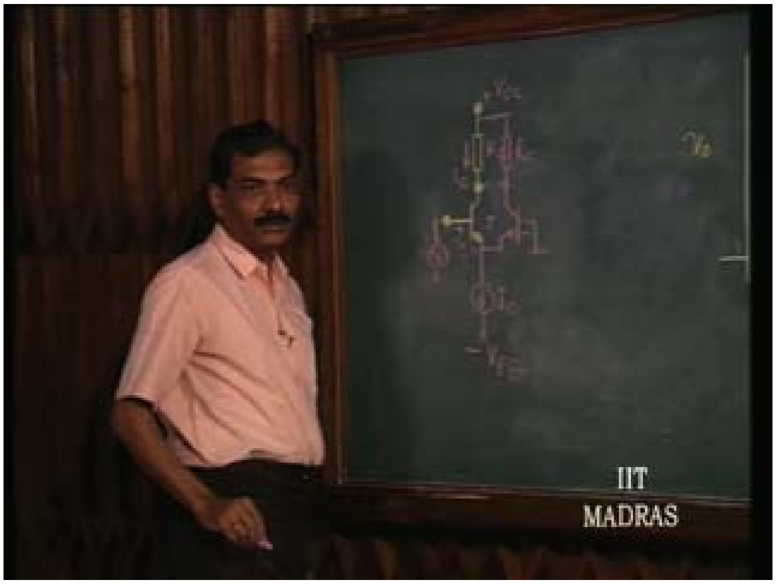

If we take the differential output, it is $R_C$ by $R_E$, or gm into $R_C$. That means, you are getting back the common emitter gain which you had thought you have lost because of converting this stage into a differential stage. So you have not lost anything at all by converting this single stage into a differential stage. It retains all the small signal properties associated with the common emitter amplifier. The gain remains the same, but it has advantages now. The output voltage can be made equal to 0 when input voltage is 0. That is because of the fact that we are using the dual supply. That is what brings in dual supply in all analog circuits, and then we have got rid of the bypass capacitor and the coupling capacitor.

We will discuss further about this important building block. This is the most important building block again in analog integrated circuits next to current mirrors, next to translinear principle. It is part of the translinear principle.