Electronics for Analog Signal Processing - II
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Lecture - 31
Log - Antilog Multipliers

In the last class, we discussed log-antilog amplifiers. Let us now consider how a multiplier can be built using log-antilog operation. This, I had illustrated in the end of the last class. Suppose we develop a voltage which is summation of log of voltages, V T log. These are all diode voltages. V T log V x by I E naught Rx this is one log amplifier voltage, plus V T log V y by R y I E naught minus V T log V R by R R I E naught. Then, that voltage will be looking as V T log V x V y; these will be getting multiplied, divided by I E naught squared R x R y, multiplied by I E naught. So, I E naught gets cancelled. R, R, divided by V r.

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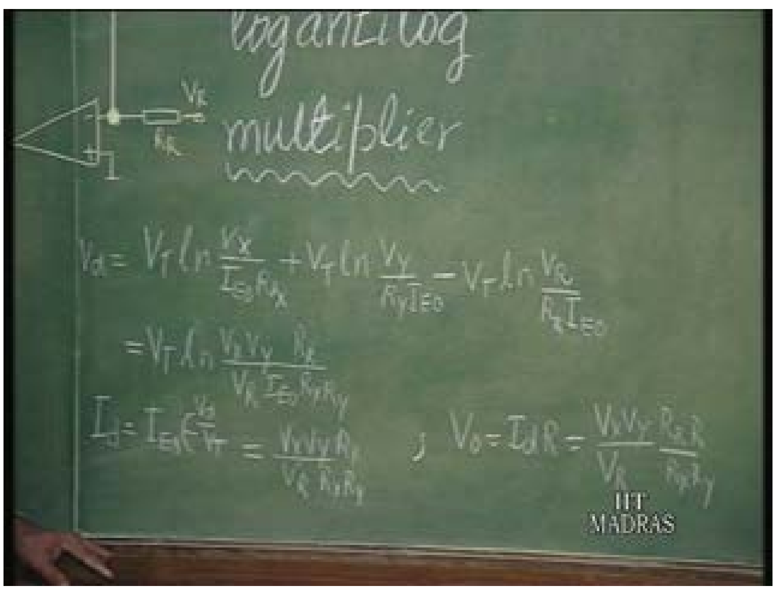

So, that is the voltage that you develop and that voltage, if it becomes the forward biasing voltage of another diode, then you take a...antilog of that voltage. That means that will be I E naught exponent V diode divided by V T. So, this V T, V T gets cancelled. It is exponent log of this value which is that value itself; V x V y by V R, R x R y R R; I E naught getting cancelled.

So, that I illustrated as a sort of place where it is not necessary to use compensated amplifiers because when you take log and antilog, both effect of V T and I E naught get cancelled. So, this current is got. This is a very accurate method of getting this multiplier and this current when it is made to pass through a resistance, develops a voltage which is V x V y by V R.

If I make R R, R, R x, R y all equal resistors, then we know that this becomes V x V y by V R and V R can be made equal to 10 volts and we have the multiplier. But this is one quadrant multiplier because you please note that all these diode voltages are valid for one polarity of the current.

So, this is called a single quadrant multiplier. Single quadrant multiplier because V x V y and V R can only take one polarity; in this case, let us say plus. How to implement this scheme using, let us say op-amps and transistors is what we are going to now see.

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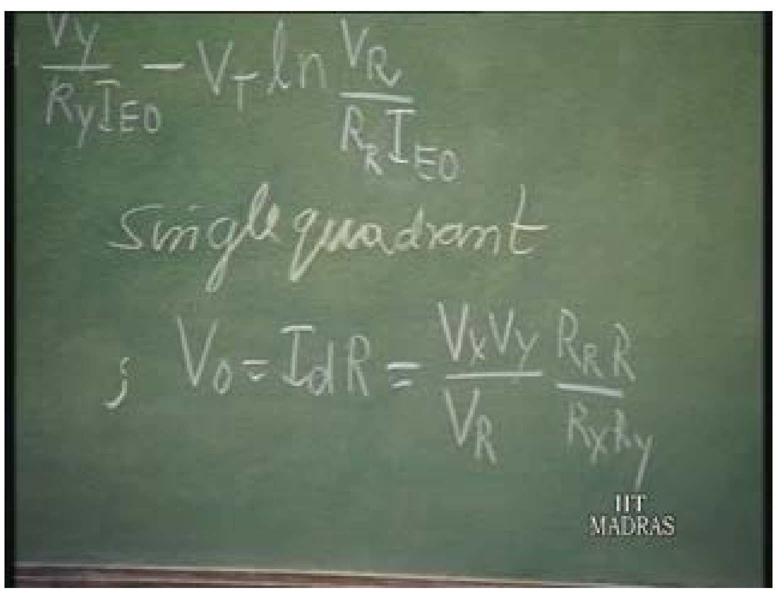

This is the circuit of a log-antilog multiplier. Let us see what it is. I have the op-amp here and V x is connected and R x is connected like that, so that current in this is V x divided by R x. So, this converts this voltage into current. This current is now made to flow through the collector of a transistor which means that is done by the op-amp's negative feedback.

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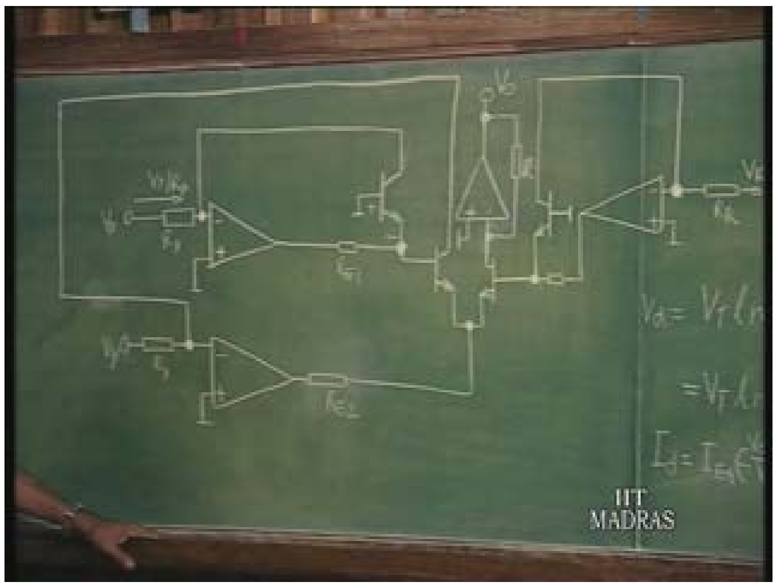

So, this op-amp has a negative feedback arrangement such that this current is forced to flow through this. If that current flows, then the voltage here is going to be V B E corresponding to that current, which corresponds to nothing but minus V T log V x by I E naught R x. So, this voltage here is nothing but minus V T log V x by I E naught R x. So, we get here this voltage straightaway; but the thing is, I can, for negative feedback, keep this connected to this output.

Now I just want to digress a little bit and say why this is not connected here. This particular thing is not connected here because look at this log amplifier of ours.

If this is like this, this is what we discussed as a log amplifier. If you consider this as a feedback circuit, the original amplifier was getting fed back from this point - unity gain feedback.

Now you are putting output of this to an amplifier here. This is nothing but a common base amplifier. This is fed to the emitter and at the collector load you are taking the output. So, it is not a simple op-amp. It is an op-amp with active feedback. In that, there is normally passive feedback is used. Here, in this case, it is a thing with active feedback because feedback factor can be more than one.

So, this feedback factor in this case is nothing but g m into R where g m is 1 over R e of this transistor. This is the gain of this. There is no phase shift between this voltage and this voltage which is common base. Therefore, this is a negative feedback with feedback factor itself equal to g m into R.

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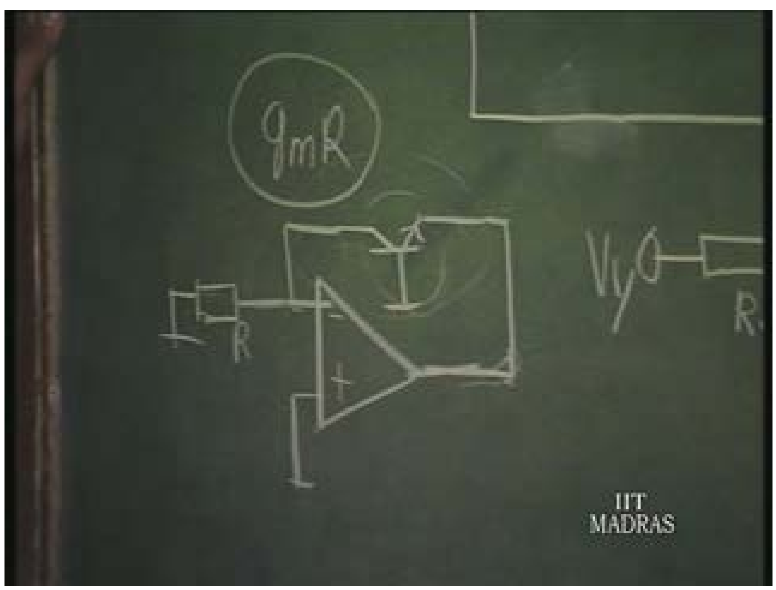

If the amplifier gain is A naught, A, then A into g m into R should be less than 1, when the phase shift of A is equal to 180 degree. That is the condition for frequency compensation; otherwise, it will go into oscillation.

Normally, what is done for making these op-amps work is when the phase shift of A is equal to 180 degrees, magnitude of A is made less than 1.

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But that will be violated here, when the phase shift of A equal to 180 degree occurs at the same frequency as the other one. But the magnitude of the whole thing, loop gain, even if A is less than 1, is not going to be less than 1 because g m into R may be greater than 1.

So, this might go into oscillation even if the op-amp is compensated for unity gain. So, this will go into oscillation. How to prevent this or how to use compensated op-amp here and not cause any oscillation in this circuit? That can be done by reducing the gain here. So, that means g m has to be reduced. g m is reduced by putting a resistance in series with R E, let us say, R E 1. So, this g m, instead of small r e, 1 over small r e, it will be 1 over small r e plus R E 1, so that R over R E 1 is less than 1.

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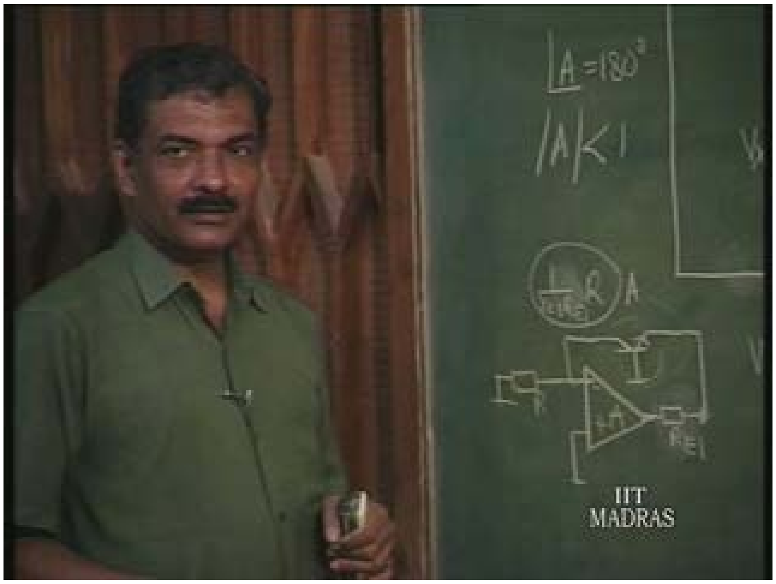

So, that is the idea for putting a resistance in series here. Now, whether you put a resistance or not, the voltage developed is going to be always the same in order to make this current flow.

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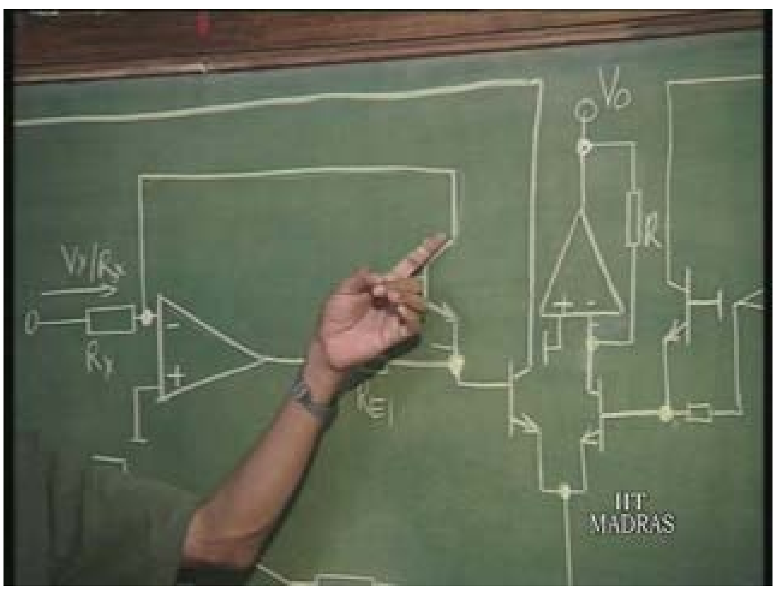

So, this is something that you have to see that in all log amplifiers, they will put a resistance in series in order to make it work for the same frequency compensation arrangement as before. Now, what happens to the output voltage? Obviously, R E 1 can be made very large so that this can...gain can be reduced considerably. That is not the point. As R E 1 is increased, the voltage which is necessary to sort of for...a certain current is going to increase, because suppose 1 milliampere flows through this.

Normally, if you have not put a resistance here, the voltage would have been the diode voltage. But now that you have put a resistance, this voltage has to rise up to 1 milliampere into R E 1. That should not go up to the supply voltage. That means R E 1 cannot be increased so much that it goes up to supply voltage. So, this is the limitation of this circuit.

Now that we have understood the presence of R e, how to select it, we can further discuss about the circuit for multiplier.

So, we have already developed a voltage. This corresponds to minus V T log V x by R x I E naught with respect to ground. Now, to this voltage, we have to add minus V T log V y by R y I E naught. So, that we can add by putting a...another diode, whose current is forced to be equal to V y by R y. So, that can come in series; addition of...so, base emitter junction.

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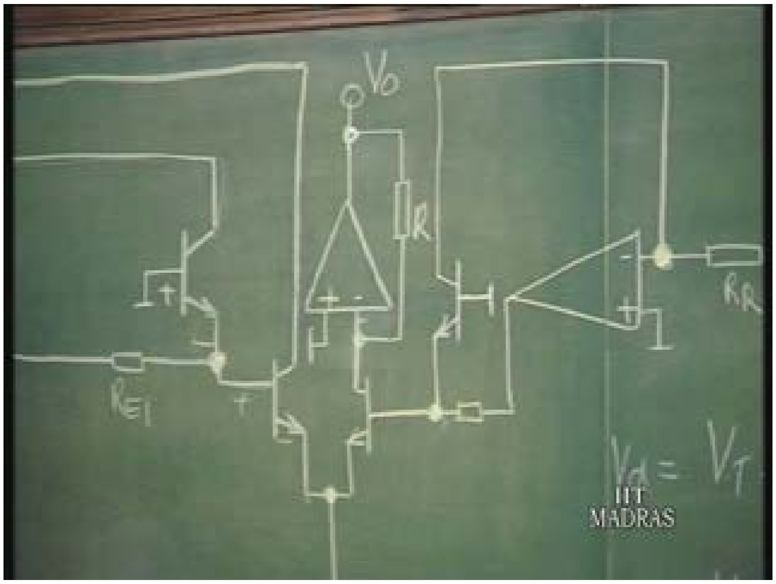

The collector of this should be all the way connected to this point so that the current is V y by R y. In order that the feedback is effective, obviously, the emitter of this is connected through another R E 2 to the output. So, you can see that this transistor, base to emitter junction voltage is decided by the negative feedback arrangement of this...

So, V y by R y is the current here and this collector current is forced to be the same as this. So, emitter base voltage is going to be that minus V T log V y by R y I E naught; and that gets added automatically here. If I connect the negative feedback, R E 2 has the same property that I mentioned about R E 1, in order to make the frequency compensation become valid; and also, in order to prevent the op-amp from going to saturation in that attempt.

Now that we have got here a voltage which is summation of minus V T log V x R x...by R x into I E naught minus V T log V y by R y into I E naught here, this is what we have got. Of course, only negative sign. So, this is a negative voltage. This is a negative voltage comprising of sum of these. Then I had to subtract from this another voltage which is minus V T log V R by R R I E naught, I had to subtract; or, what I can do is I can again for these two voltages to be the difference voltages, both are negative; and apply that as the diode voltage. So, this also I generate with respect to ground. What is the voltage that we want to generate?

Corresponding to minus V T log V R by R R I E naught; you can see V R by R R is the current here and this collector current is forced to be the same as that. If the emitter resistance, let us say R E 3 is properly chosen so that it is connected to the op-amp output automatically, this voltage is developed. So, this voltage minus this voltage is going to be the voltage...that is going to be the voltage between these two terminals of another base emitter junction, which will convert the voltage into antilog current.

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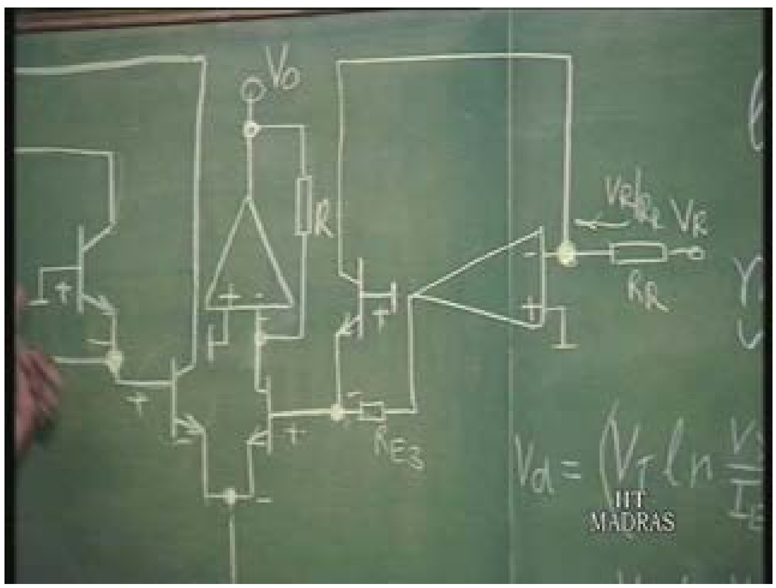

So, this voltage now is nothing but this negative voltage minus another negative voltage and that is more negative on this side and more positive on this side. So, this is forward bias by a voltage which is equal to this, exactly. So, this generates then a current which is I diode which is going to pass through a resistance R and therefore that will be developing voltage like this. So, V naught is going to be nothing but I d into R. This is at zero volts.

So, this amplifier converts that current into a voltage I d into R and as you can see here this, if you have 4 op-amps and 2 pairs of transistors match, you yourself can build a very accurate log-antilog multiplier.

These matching pairs of transistors are available very readily as transistor. You can build a multiplier very easily and this will be very accurate as long as they are perfectly matched. What you have to remember is this is only a single quadrant multiplier, because the current can only flow in this direction in all these things. So, V x, V y, V R, have to be all positive in this case.

So, it is going to work only in one quadrant. So, only in this quadrant it is going to work; but that is not a very serious limitation because by properly selecting this operating point of this, I can make it work for signal which is going both positive and negative. That means I can put V x as equal to V x dash plus 10 volts, V y as V y dash plus 10 volts.

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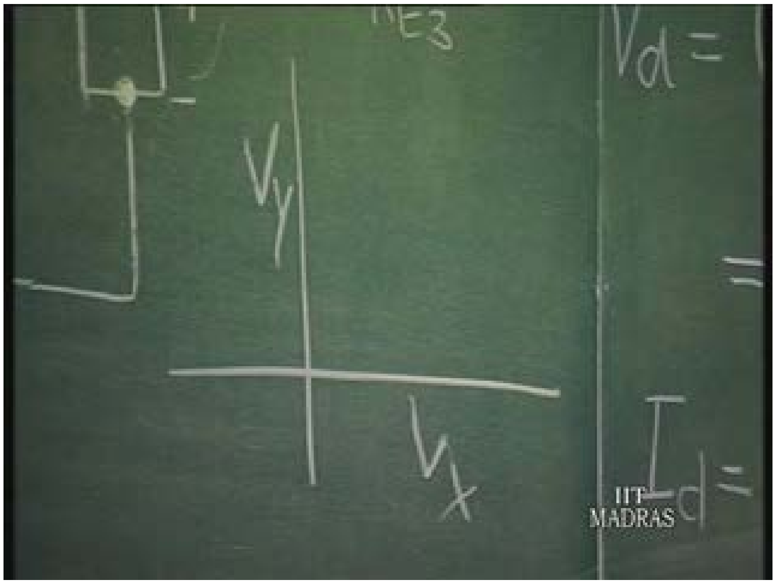

So, what I can do is V x can be put as V x dash plus 10 volts. V y is V y dash plus 10 volts. Both V x dash and V y dash have to go 2 plus minus 10 volts. That means effectively, V x and V y will have to go up to 20 volts in this case. Therefore, if V x and

V y limits are made equal to 20 volts, zero to 20 volts, then V x dash and V y dash can be made plus minus 10 volts. Then, we will do the multiplication using this.

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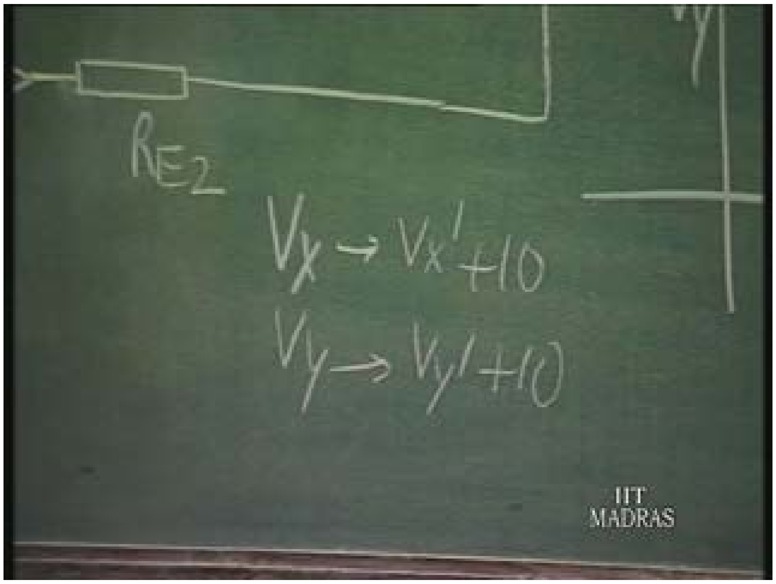

This will be V x V y by V R which is V x V y by 10 volts. V R can be made equal to this 10 volts. So, V x V y by V R.

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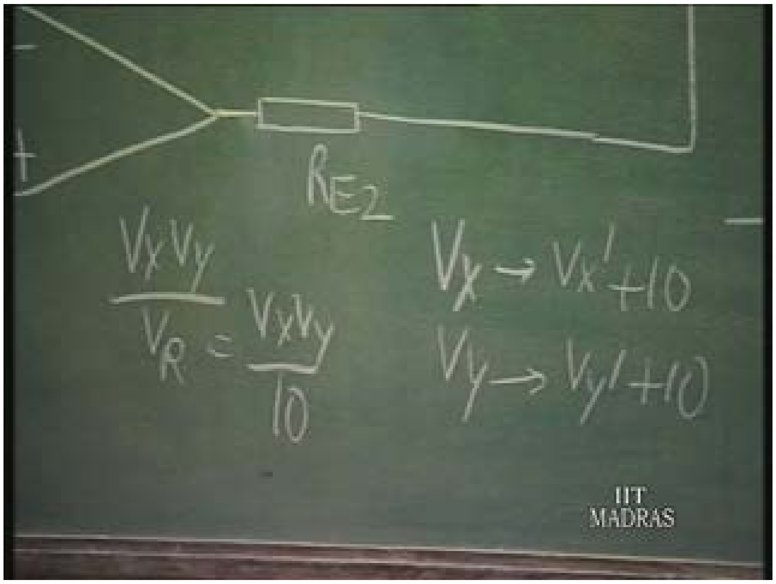

So, what it will become is V x dash plus 10, V y dash plus 10 divided by 10. So, this is going to be equal to V x dash V y dash by 10 which is what we want here, plus...now, you will have error components in this. V x dash into 10 by 10. That means this will have V x dash along with it. Then V y dash into 10 by 10. That is, plus V y dash, plus 10 into 10 by 10. That is the offset.

So, this as the x feed through y feed through and the offset which can be subtracted because we have already V x dash and V y dash as input to the multiplier. So, you subtract V x dash V y dash and the D C of that 10 volts. Then you will get at the output of this which is V x dash V y dash by 10 volts as the apparent multiplier.

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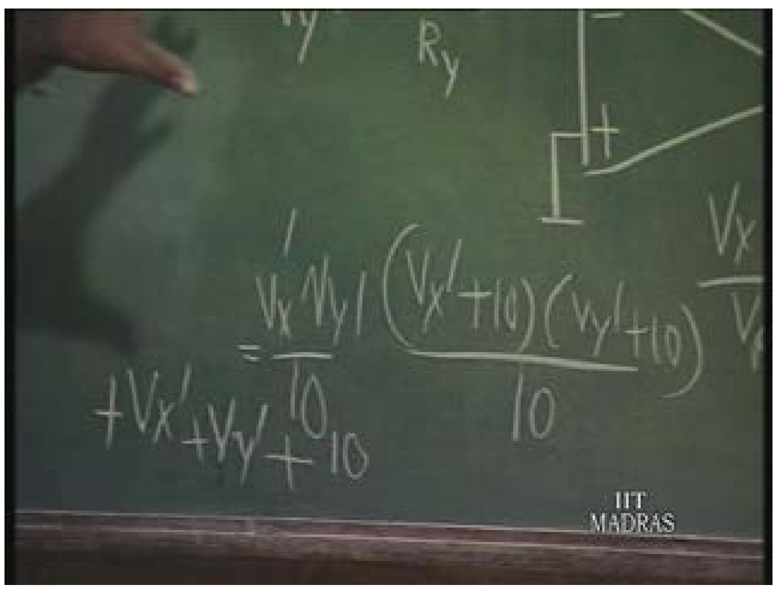

So, any single quadrant multiplier can be converted to four quadrant by means of the pre bias arrangement. Once again, we made V x is equal to V x dash plus 10 volts so that V x dash can vary from plus 10 to minus volts as desired by us, when V x is going on varying only from zero to 20 volts, because it is single quadrant.

Similarly V y, when it varies from zero to 20 volts, this V y dash can vary from plus 10 volts to minus 10 volts. Then we get the multiplied output of this multiplier, single quadrant multiplier, as V x dash plus 10, V y dash plus 10, divided by 10 which will give us the wanted output which is V x dash V y dash by 10 plus V x dash plus V y dash plus 10 volts. This can be deducted from the total output of the multiplier by using another operational amplifier which we know how to design, because in our earlier discussion we have discussed how to design an amplifier which will subtract whatever voltage you want to from the output.

So, the offset can be removed, the x feed through can be removed and y feed through can be removed, so that output of that op-amp which is subtracting all these things will be giving you the four quadrant output, V x dash V y dash by 10. So this particular thing, we will work out as an example so that we can design a four quadrant multiplier out of a single quadrant one.

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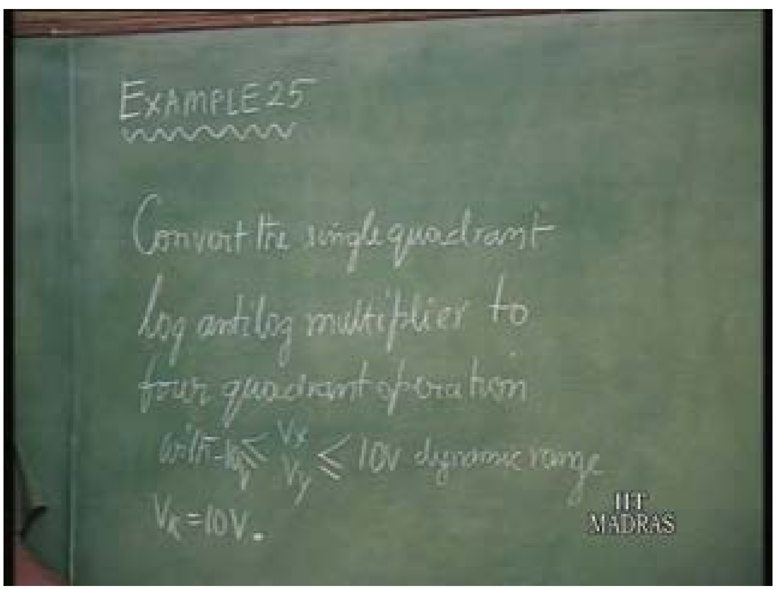

Consider this example in order to illustrate how to convert any four quad...single quadrant multiplier into four quadrant. Example 25. Convert the single quadrant log-antilog multiplier to four quadrant operation with 10, minus 10 volts less than or equal to V x V y less than or equal to 10 volts dynamic range. V R equal to 10 volts.

So, let us assume that this is my...the block that we have already discussed log-antilog multiplier with single quadrant operation. So, we want to give this, let us say input V x and V y; output, we will get as V x V y by 10 volts by making V R equal to 10 volts. Only thing is how to select V x and V y such that it is operated in single quadrant even though our actual input is plus minus 10 volts, dynamic range.

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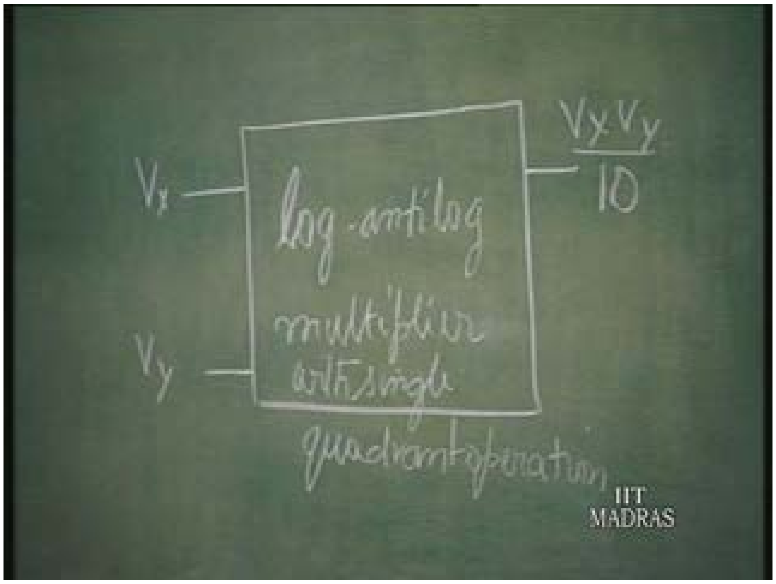

So, we have to assume that we will give this V x dash and V y dash. So, this is going to become V x dash and V y dash into 10 volts. So basically, we have to have now V x dash and V y dash as nothing but V x... This is V x dash and V y dash. V x plus 10 volts is V x dash; V y plus 10 volts is V y dash.

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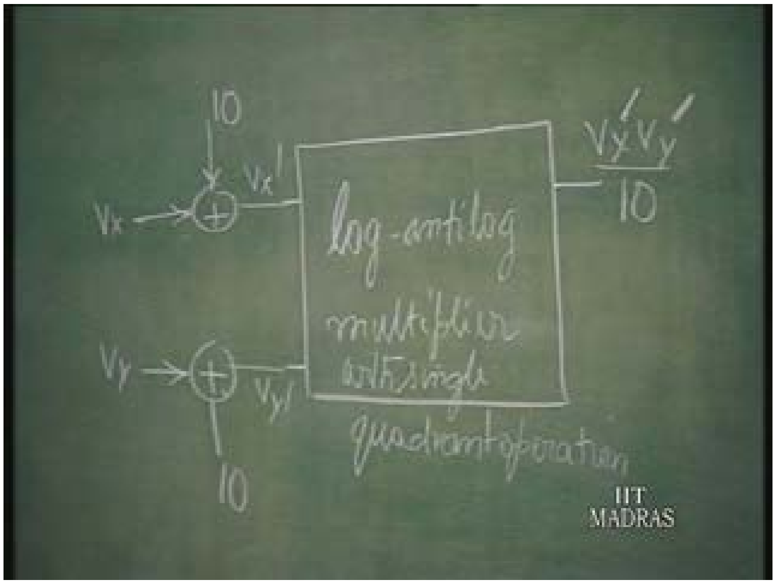

So, this can be easily done with the help of an op-amp. This op-amp I do not have to really draw because all of you are knowing how to do it. So, one simple way is... So, you have here, let us say...V x let us say; and this is 10 volts. This is R, R, R.

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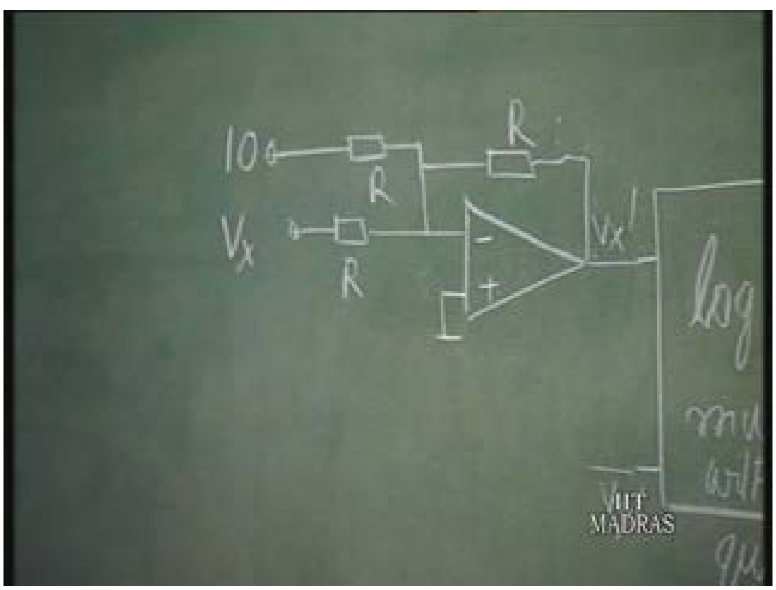

So, what will appear at V x dash is minus V x minus 10 volts; minus V x minus 10 volts...so, if this is operating only in one quadrant corresponding to only negative voltages. If it is operating with only positive voltages, then what we have to do is apply minus x, V x and minus 10 volts here. Then, this will be plus V x and plus 10 volts; or use a summing amplifier which will not give a phase inversion of 180 degree. That also can be done.

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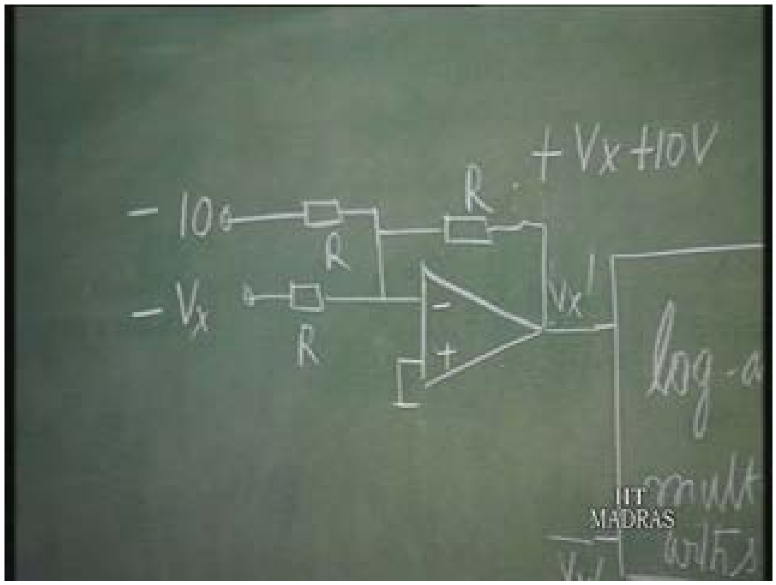

I just want to illustrate the point. Now another one, where we will give minus 10 volts and V y, minus V y. So, V y dash now becomes plus 10 volts plus V y. So now, output is V x dash V y dash by 10 volts, which is essentially speaking, equal to V x plus 10 into V y plus 10 divided by 10, which as I told you earlier, has the wanted component of V x V y by 10 and x feed through of V x and y feed through of V y and an off...D C offset of 10 volts, which has to be deducted from this.

So, let us assume that this is going to be another amplifier that I am going to use for the purpose of subtraction and all that. How to do that? So, we have from this, 10 volts to be subtracted.

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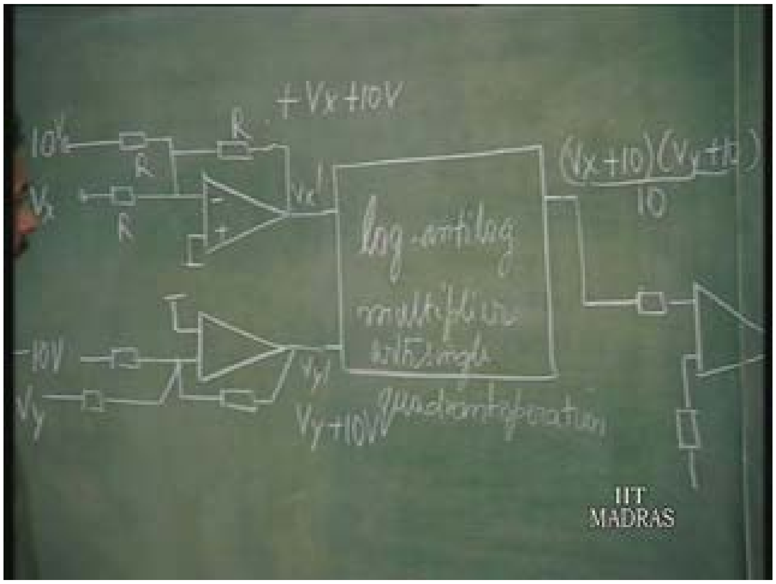

This particular thing let us say, is going to be there such that it is going to simply invert this.

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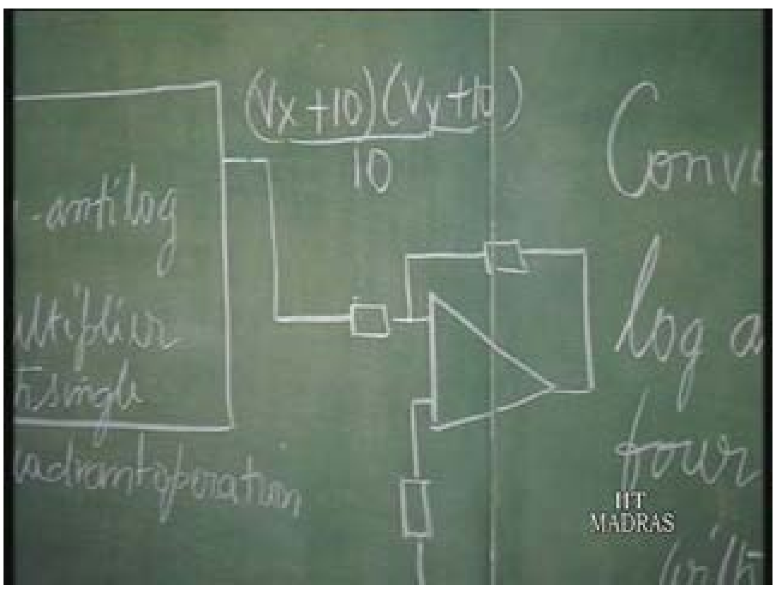

So 10 volts to be subtracted from this has to be applied to... You have minus 10 volts; you can therefore add minus 10 volts to this. So, this minus 10 volts is already here. So in this, you have plus 10 volts. We are therefore subtracting minus 10 volts. So, if these are all R, R and R, that purpose is achieved already. So, the D C offset is already removed.

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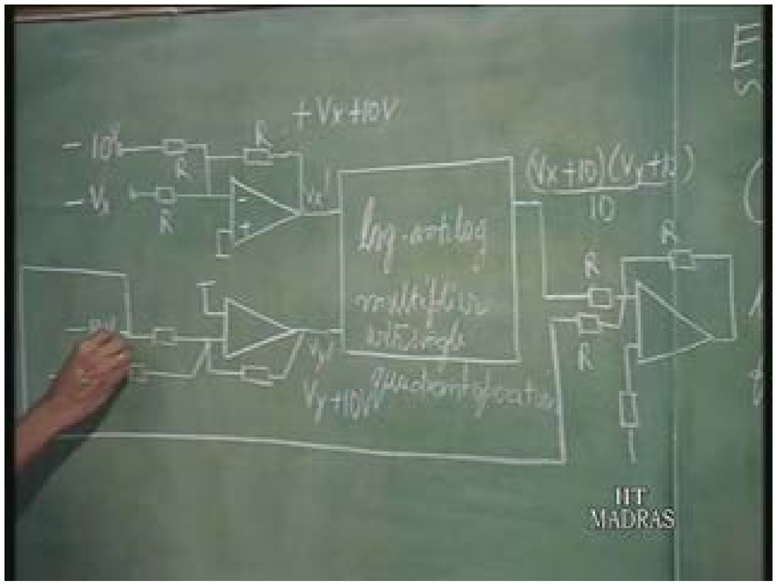

Next, we have to remove V x. We already have minus V x here. So, that also can be added simply. So, it is a very simple circuit which is going to be giving us whatever we want, R at this node. Then similarly, we want to remove V y, can also therefore put this R. So, that is the circuit, very simple circuit that will at the output now give... What will it give at the output? In fact, it will give you minus V x V y by 10 volts.

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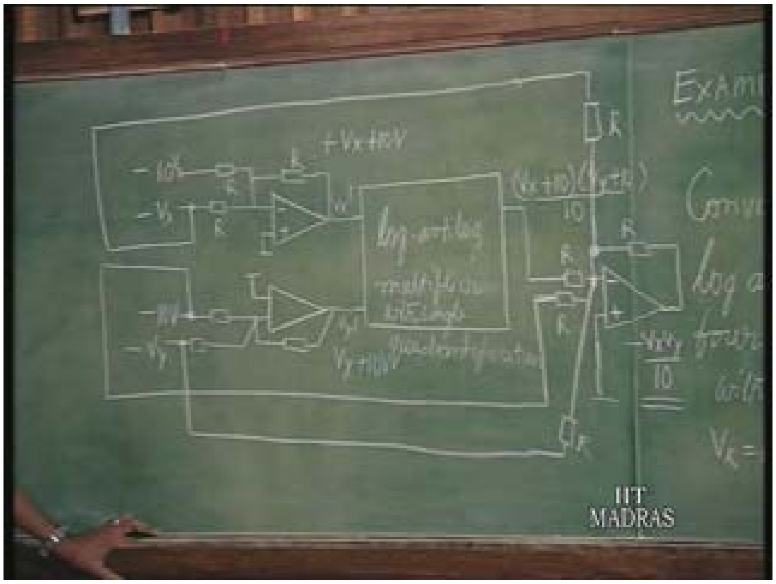

If you are not happy with the inversion, you can put another inverter and get rid of that; but that is not...because basically, this is a four quadrant multiplier, whatever be the polarity of V x and V y. We have not really given now any polarity to V x and V y.

So, it is...it is just simply that, if this is minus V x and this is minus V y, this will be minus V x V y by 10. If this is plus V x and this is plus V y, which could as...you can as well call that, then this will be still minus V x V y by 10. So, it does not make any difference.

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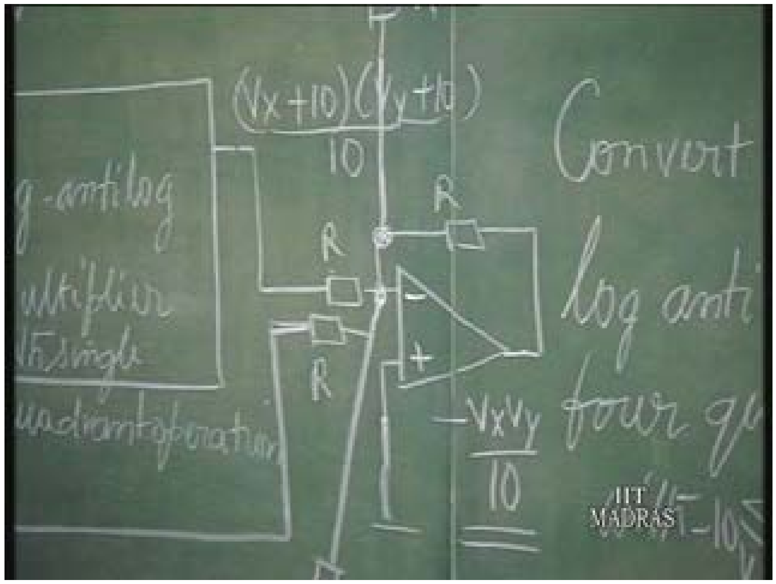

So, this is a four quadrant multiplier conversion using single quadrant multiplier as the basic building block.

This is a commonly adapted technique and the dynamic range remains the same as what we want: plus minus 10 volts. So, this is a precision multiplier which can be used up to hundreds of Kilo hertz. Primarily, the frequency limitation is due to these op-amps which are not readily available for very high frequencies. So, up to hundreds of Kilo hertz, if you want to design a very good precision multiplier, this is the technique. This is very cheap.

Let us now discuss another important popular multiplier. This is available also in I C form. This is called transconductance type multiplier; or actually, the basic idea, even it is from what is called Gilbert's gain cell. We will discuss what this Gilbert's gain cell is. This uses a very important principle called translinear principle in bipolar transistors.

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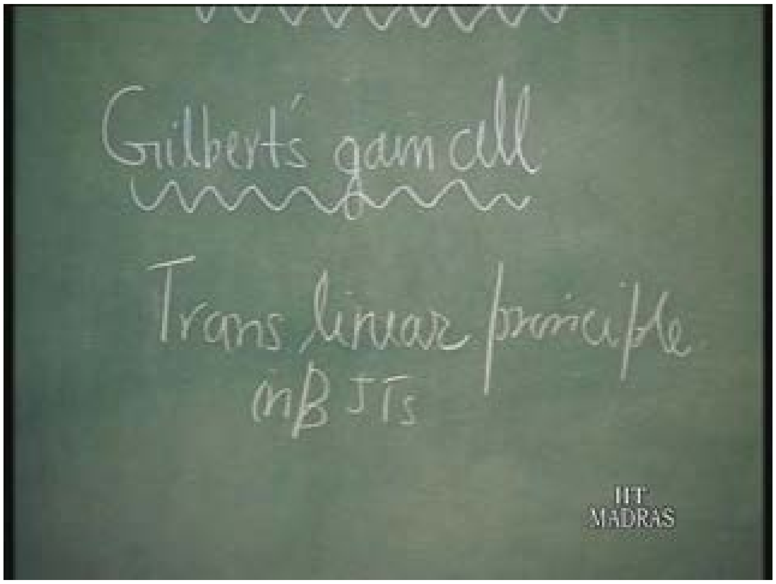

What is that translinear principle? The Gilbert gain cell is given here. This is a very important cell.

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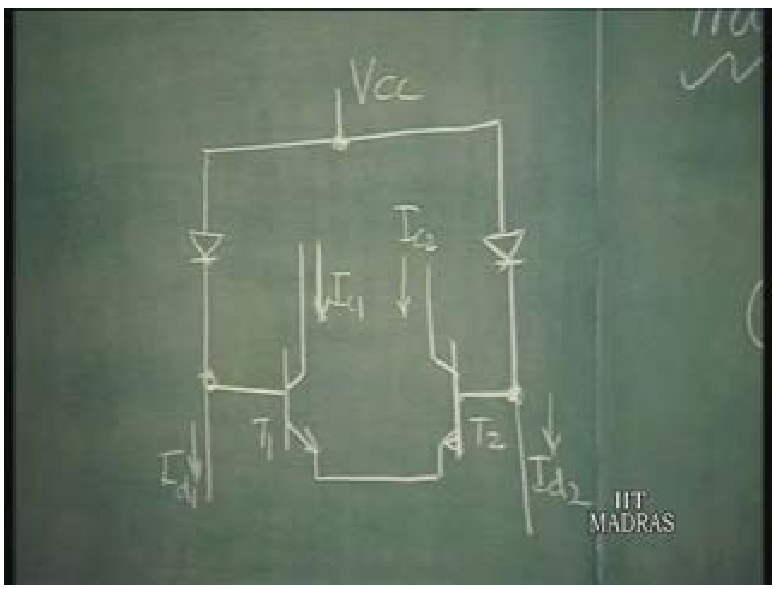
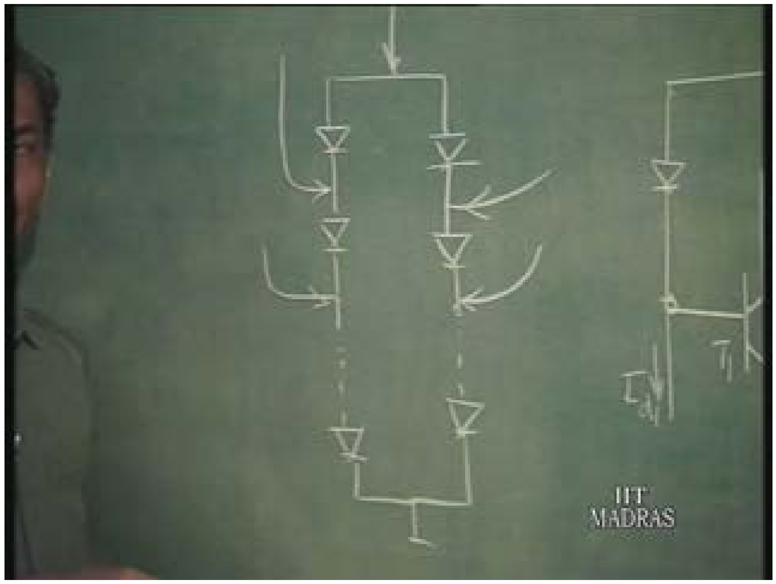


This comprises junctions, base emitter junctions or diode junctions, forward biased; but forming a loop. So, this translinear principle is applicable to any loop formed by forward biased diodes. It could be just simply this...just... I have so many diodes, let us say, with some kind of currents coming in here and may be current coming here also. So, suppose we have a string of diodes all of them form a loop, let us say.



Then the Kirchhoff's voltage law is valid here. That the total voltage in this is zero; summation of all the voltages in this should be equal to zero. What is required in this translinear principle is number of diodes connected in the clockwise manner; let us say these are all clockwise forward biased; these are anti-clockwise forward biased. These numbers should be the same.

If that is the case, then the product of the currents in each of the diodes, let us say, this is I 1 up to I n and this will be, let us say, I zero 1 up to I zero n. The product of the current of these anti-clockwise connected diodes is the same as the product of the currents in this.

This can be easily proven because summation of sigma of all these voltages should be equal to zero. That means the forward biased diodes in clockwise direction should have the voltage equal to the forward biased diodes in the anti-clockwise direction.

Therefore we have, let us say, n number of diodes. So, I is equal to 1 to n. VBEi should be equal to, let us say V B I of this... We will call this 'a' for clarity and this as 'b' so that those are which are 'a' should be same as VBEbi. i is equal to 1 to n. This is from Kirchhoff's law.

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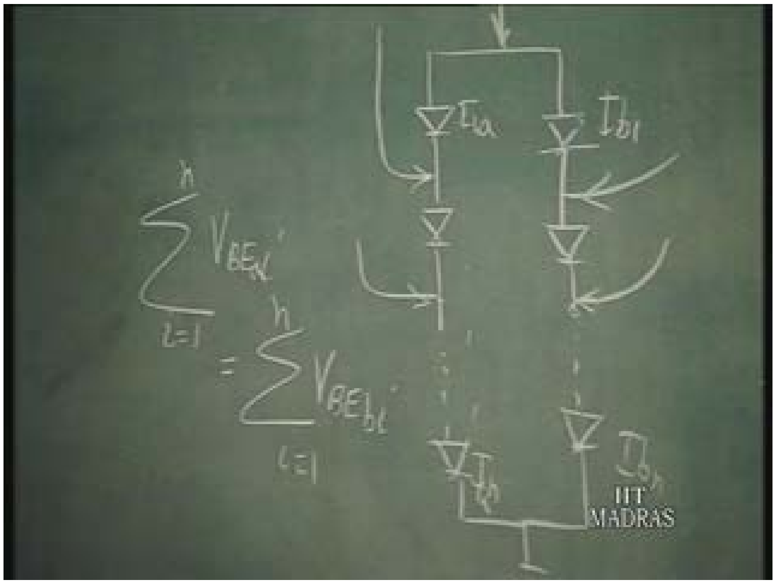

So, once these sigmas are same, we know that this is same as V T log. These VBEs are same as V T log, corresponding currents which we are calling I 1 I i a by I E naught; and this is also equal to sigma V T log I...let us say we call it j, j b. j is equal to 1 to n.

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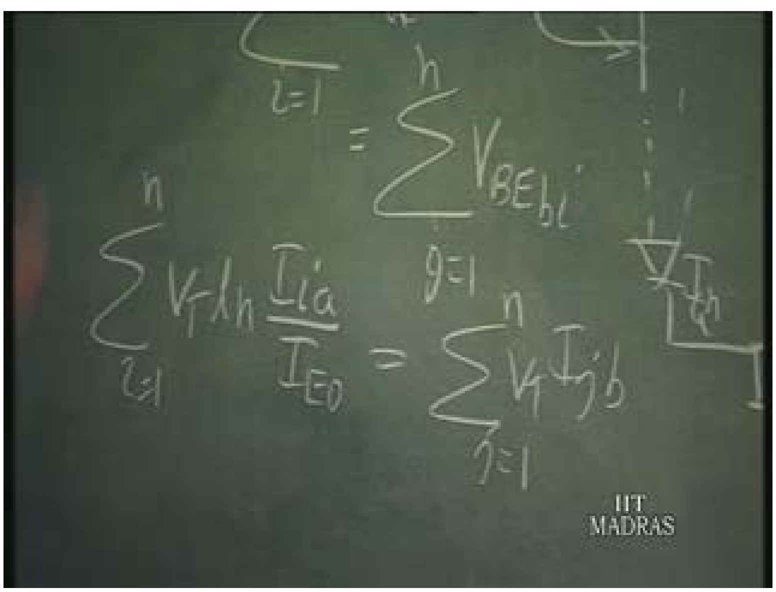

So, these V Ts get cancelled... V T log I j b by I E naught. These Vts get cancelled.

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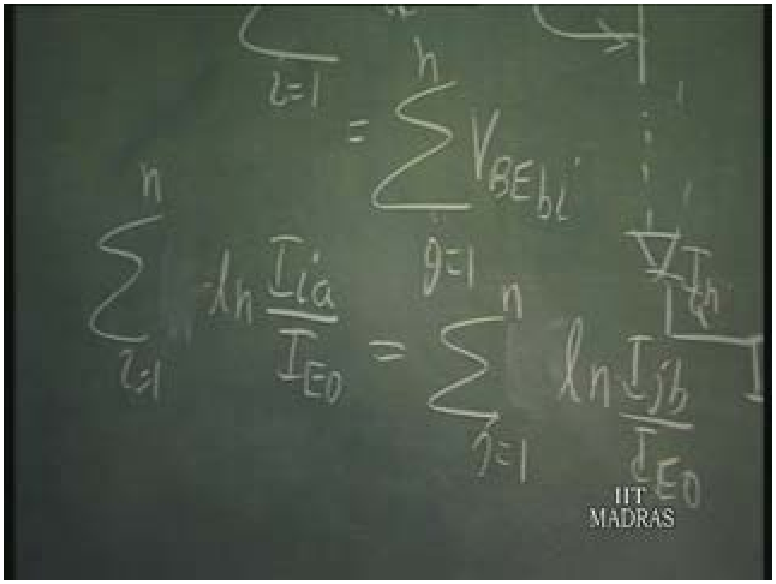

Logarithm of sum of these products...sum of these, is equal to product itself. Product. i is equal to 1 to n - is same as log... So, that means product of...j equal to 1 to n.

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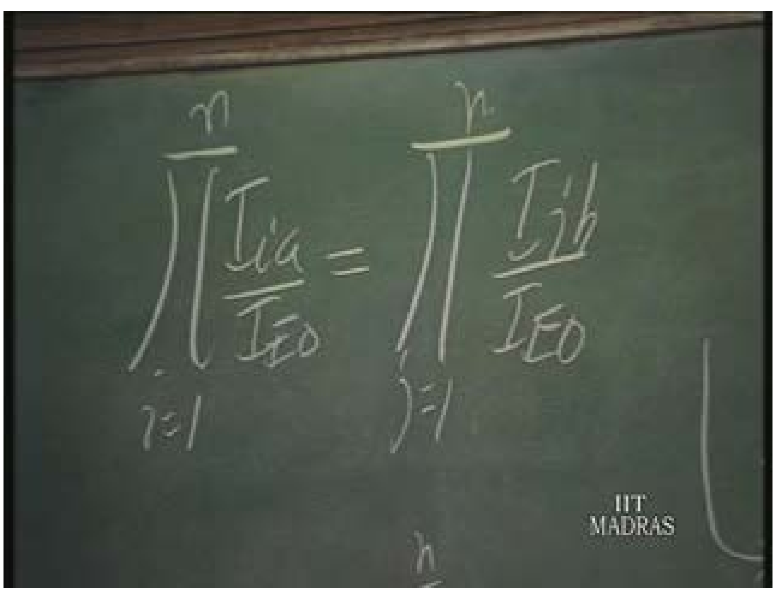

This will give you 1 over I E naught to the power n. This also will give you 1 over I E naught to the power n. So, this is the basic principle, translinear principle; very important.

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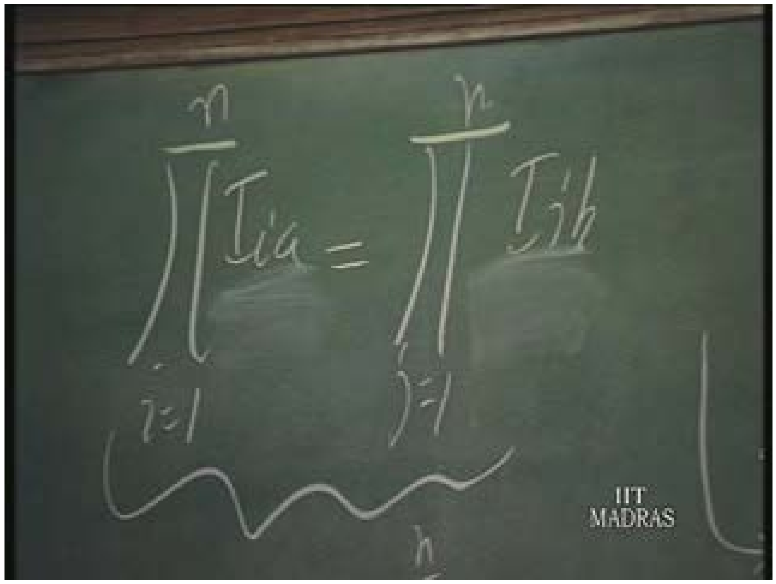

What it simply says is that if there is any loop, close loop formed of n number of diodes in clockwise direction, n number of diodes forward biased in the anti-clockwise direction, then the current flowing through the clockwise direction diodes, product of these, will be equal to current flowing through the product of the diodes, which are in the anti-clockwise direction.

Let us apply it simply to...for example, a current mirror. A current mirror is the first example. For example, one diode with another junction. So this current in this should be same as this current; that single diode. So, that is the basic principle of translinear this thing applied to a pair like these.

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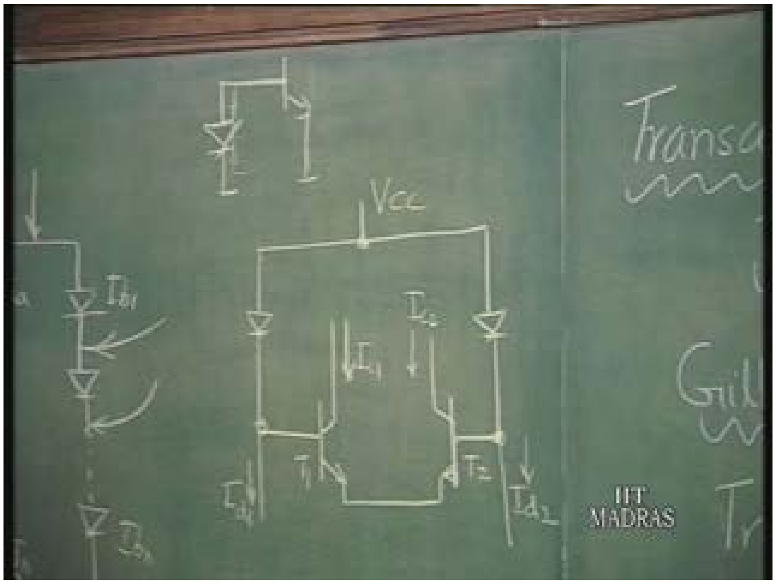

Now here, this is slightly more complicated. We have two diodes and two junction transistors connected in a loop.

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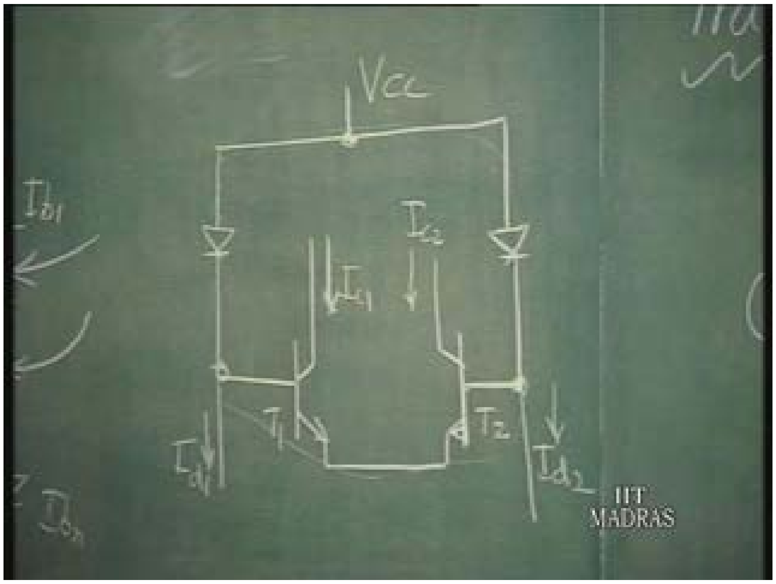

So, according to this now, these are, let us say diodes which have one polarity; and these are diodes which have another polarity. The current through these diodes, product of these, should be same as the current through these junctions. That means, actually speaking, you can now see that I d 1 is the current through this. So, I d 1 into current through this is essentially I c 1, because it is I E 1 which is very close to I c 1. This is equal to I d 2 into I c 2.

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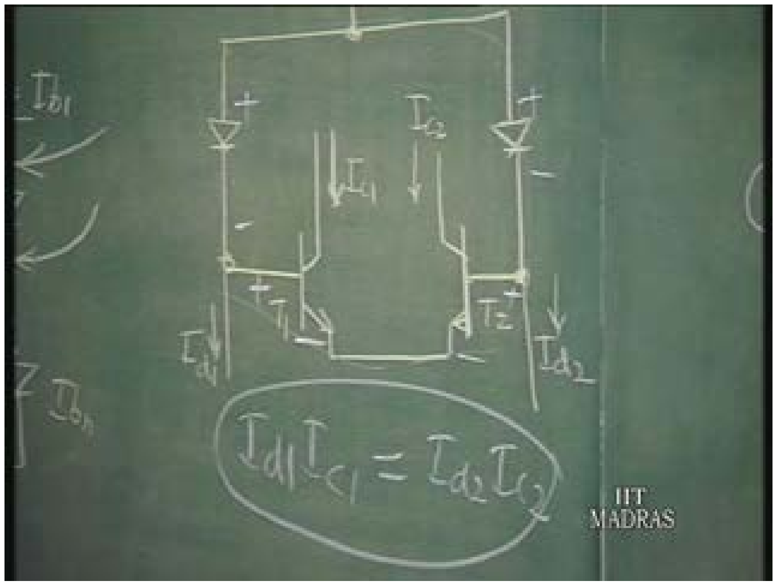

This is what the Gilbert's gain cell says. Product of the current of the diode into this transistor, corresponding transistor, is equal to product of the current of this diode into this transistor; or I d 1 by I d 2, I d 1 by I d 2 is equal to I c 2 by I c 1.

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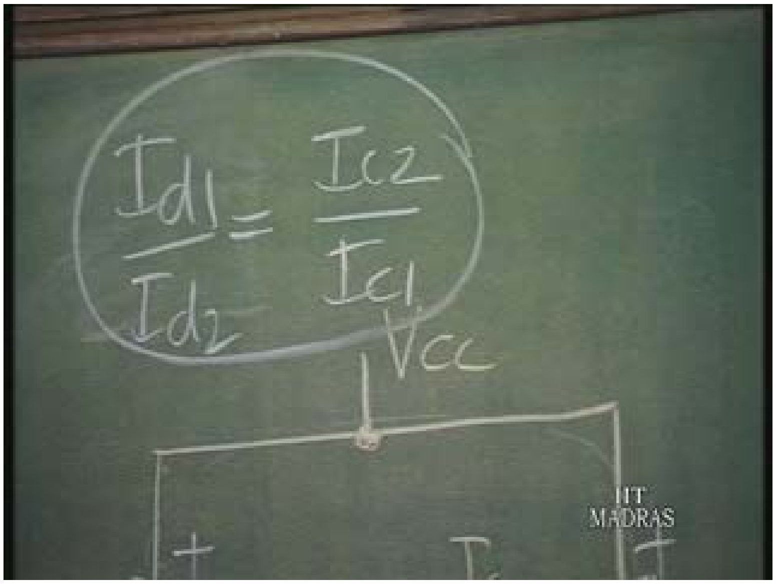

This is valid over a wide range of variation of current because this is not a small signal thing. We have assumed large signal property for the transistor, exponential relationship; and that relationship is valid for almost six decades of variation of current.

And therefore, this is a very powerful signal processing aspect which has been used in many applications of integrated circuits. But now, we would like to use this for multiplier. You can see here. Here already, current multiplication is taking place. I d 1 by I d 2 into I c 1 is equal to I c 2. Or, we can see here that I d 1 minus I d 2 divided by I d 1 plus I d 2 equals I c 2 minus I c 1 by I c 2 plus I c 1.

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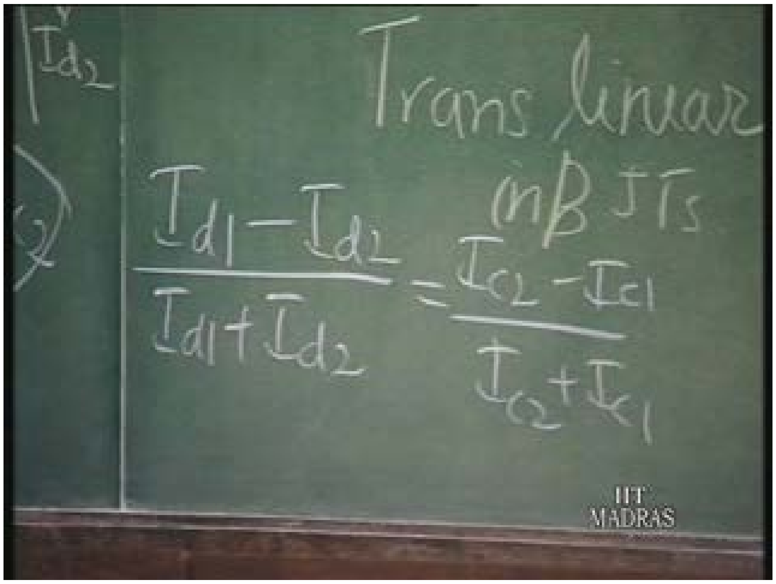

I can make these two currents equal a constant current. That is the Gilbert's gain cell; a constant current I naught; force the current to be constant.

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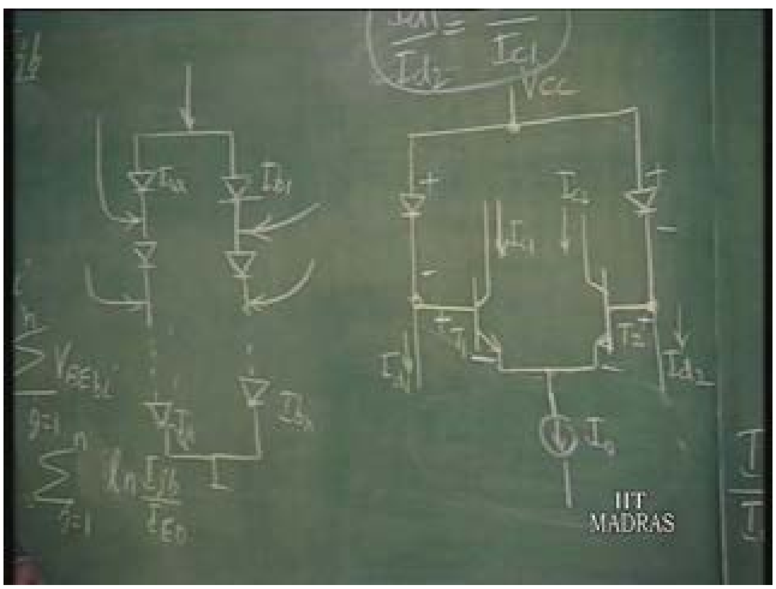

So, that means I c 2 plus I c 1 is equal to I naught. So, I d 1 minus I d 2 - the differential input current, divided by I d 1 plus I d 2 - the common mode input current, twice that, into I naught which is a D C current is equal to I c 2 minus I c 1. This is the basic principle of Gilbert's gain cell.

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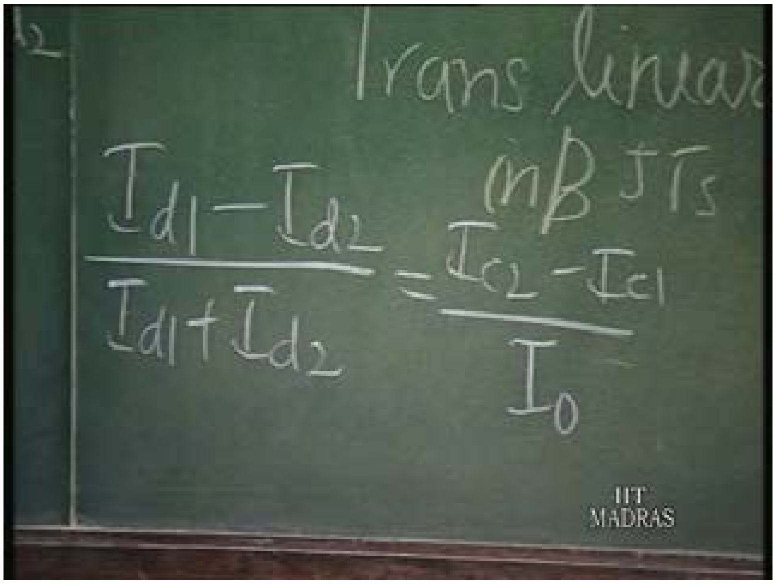

I naught into I d 1 minus I d 2 divided by I d 1 plus I d 2 equals my differential output current, I c 2 minus I c 1.

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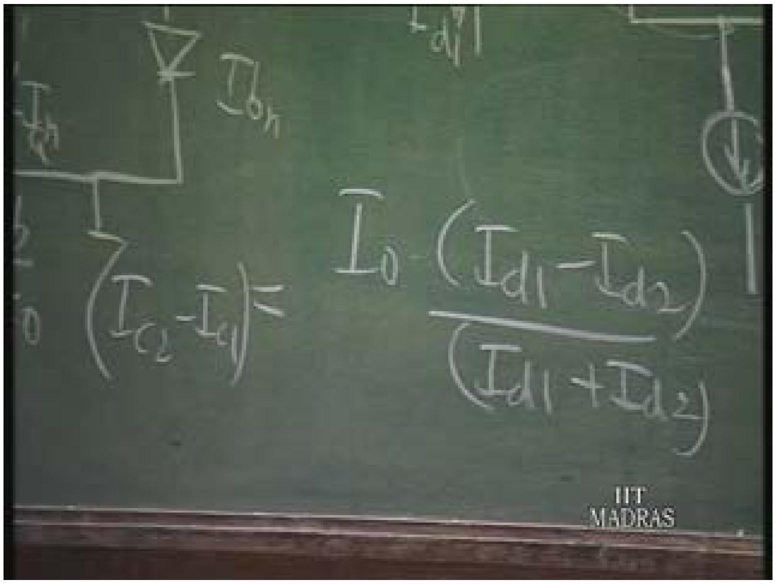

If I select currents I d 1 and I d 2 such that it has a common mode current which is a D C current, and a differential mode current which is the signal current...how do I do it?

I can make I d 1 equal to, let us say I naught naught; a D C current by 2 plus, let us say I... let us say Delta I i by 2, input current, differential current; and I d 2 equals I naught naught by 2. This is the common current which is common to both; minus Delta I i by 2...

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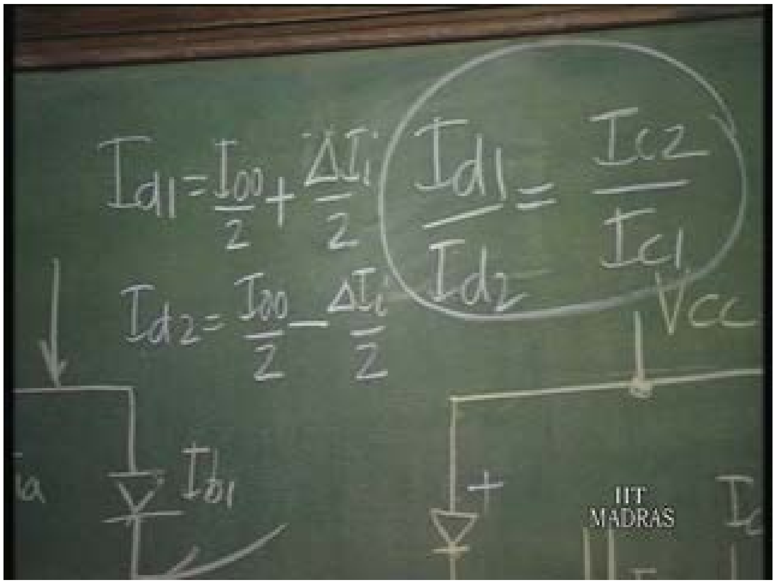

You can see here, I d 1 plus I d 2 will have this getting cancelled. So, it will be simply I naught naught, D C current. I d 1 minus I d 2 will have this getting cancelled; and it will be simply Delta I.

This is how we had represented common mode current, common mode voltage and differential mode voltage in difference amplifiers. Same way, any two currents can be represented as a common current and differential current, a common current and a differential current. So this one, I d 1 is equal to I naught naught by 2 plus Delta I by 2; I d 2 is equal to ... Then, what happens to this? This becomes I naught; I d 1 minus I d 2 is Delta I i. That is the differential input current. I d 1 plus I d 2 is simply I naught naught.

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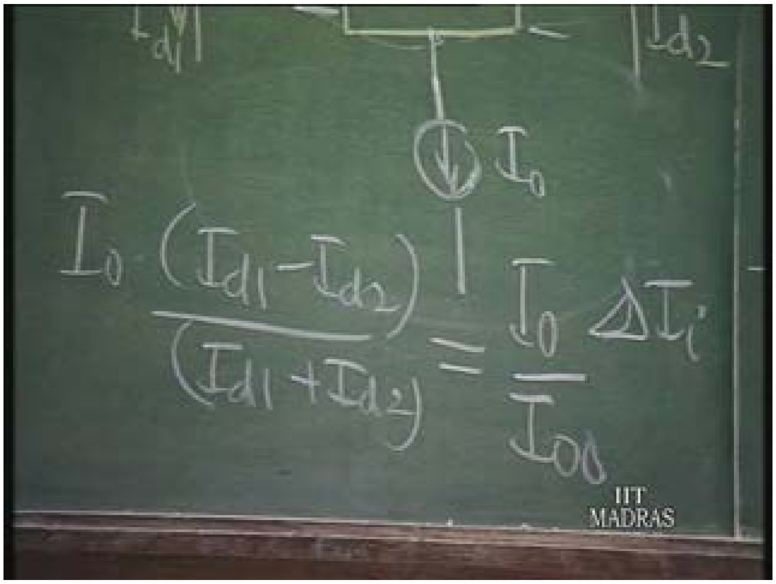

This is of great significance because you can see, I naught naught is a D C current, I said. Suppose this is 1 milliampere and I naught is 10 milliamperes. You are getting a gain of 10 for the current amplifier as the output differential current. This is the input differential current. Output differential current is simply 10 times input differential current. This is unique in this because such constant gain, we could only obtain in other schemes by giving negative feedback. This is having no negative feedback. This is independent of temperature, active device, anything. This is dependent purely on the current ratios.

How can I get current ratio like that? I use current mirrors. Let us say 1 milliampere current mirror, I use ten times in shunt, I get 10 milliamperes. So, it will be an absolute constant independent of temperature and all that.

So, we can get current gain without any effort and these are all of what are called wide band current amplifier circuits. That is why this Gilbert gain cell is very famous today as a basic building block for current amplifiers.

Here, the voltage never changes above V B E. All these voltages are V diode voltages and therefore the capacitors need not be charged to large voltages. That means time taken for operation of this circuit is very small. That means these are all high speed circuits.
So, these circuits are nowadays being used as wide band amplifiers with constant gain and you can reach the required gain by simply cascading such structure, because this differential input could be the input to the next stage, which looks exactly identical. Only thing is the operating current of that is, let us say, 10 times more than this.

So, you can put one structure over this other structure. That is why it is called a cell. So, the next stage will be having two other diodes connected to same V c c with this as input now. This has now, as you see, a differential input and a common mode input; the common mode input is nothing but I naught.

So, this can become the input in the next stage and that will be exactly looking like this with this current operating at a higher value. That much should be sufficient for Gilbert's gain cell. Now, how to use this for multiplier is something that we have to discuss.

This circuit as is shown here is the circuit which is able to convert a voltage into differential input current required for the Gilbert's gain cell.

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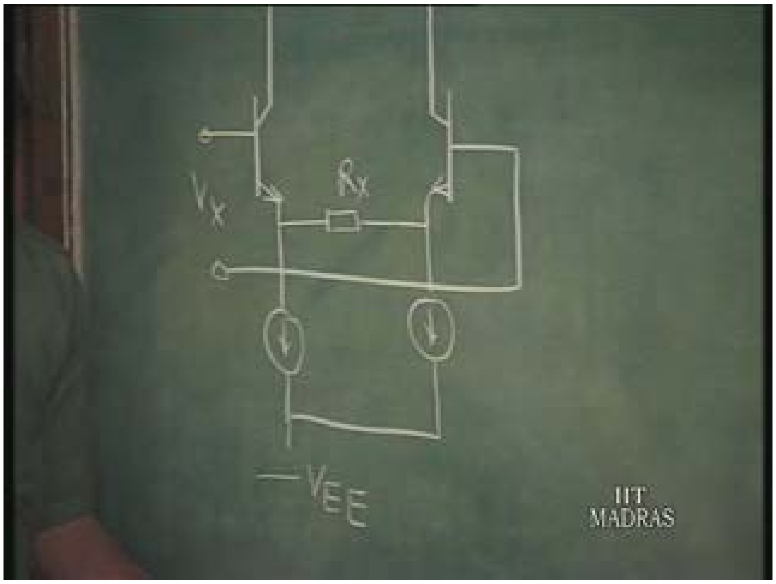

After all, most of the signals that are available to us are going to be voltages. So, even though this Gilbert's gain cell tells us that the output differential current is input differential current into I naught by I naught naught, there is some kind of multiplication taking place in terms of currents. But, we would like this to happen in terms of voltage. So, we need a voltage to current converter; but that voltage to current converter should be voltage to differential current converter which is required as input to these gain cells, I d 1 and I d 2. How to do that?

This is called a transconductor block. This does it beautifully. You can look at it. V x is the input. We have here a current which is going to be, let us say, I naught naught by 2. I naught, naught naught by 2. That is the common mode current, constant current and this is linking the two emitters. You have a resistance R x. So, what happens now?

This current is I naught naught by 2 and this current is going to be V x. V x will come across this R e 1, R x, R e 2. If you neglect this R e 1 and R e 2, this V x will directly come across R x. You can select R x such that it is large compared to R e 1 and R e 2. Then the current in this is V x divided by R x. So, the total current here is I naught naught by 2 plus V x by R x; and the current in this is I naught naught by 2 minus V x by R x.

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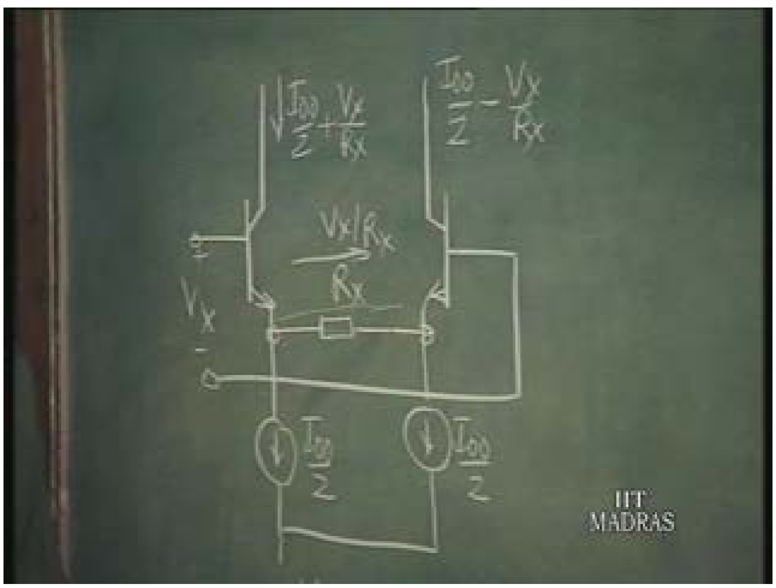

So simply, we get a linear transconductor here which converts a voltage into what we want - a constant current with signal current equal to V x by R x added to it; another constant current with signal current V x minus R x deducted from it. That is exactly what we want as the input to the cell here - I d 1 and I d 2, so that this be I d 1 and this be I d 2; inputs to these. Then what happens?

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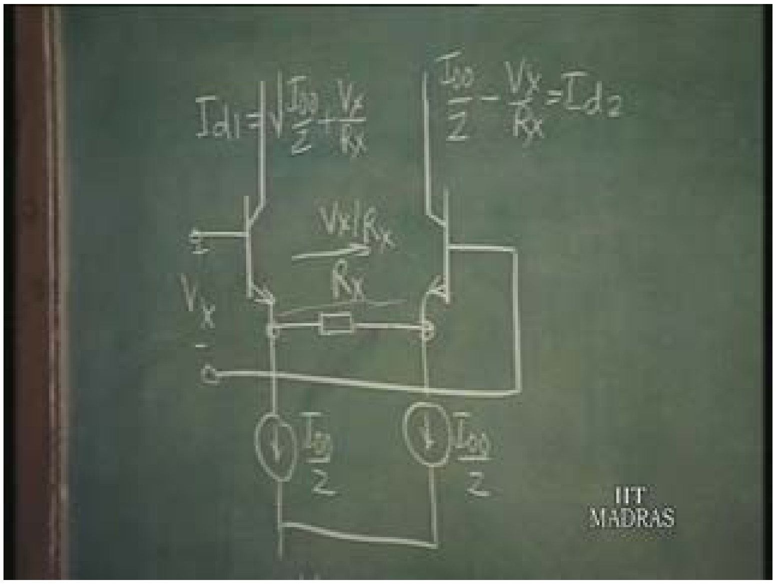

We now know that output which is I c 2 minus I c 1 equals I naught divided by the...I naught divided by I naught naught, because it is I d 1 plus I d 2 into Delta I i which is nothing but V x, twice V x by R x. This is Delta i by 2. This is minus Delta i by 2. So, Delta I i is twice V x by R x. So, we are able to now get V x here. The differential output current is directly dependent upon V x now; and we want it to be multiplied by another voltage. How...What we can do?

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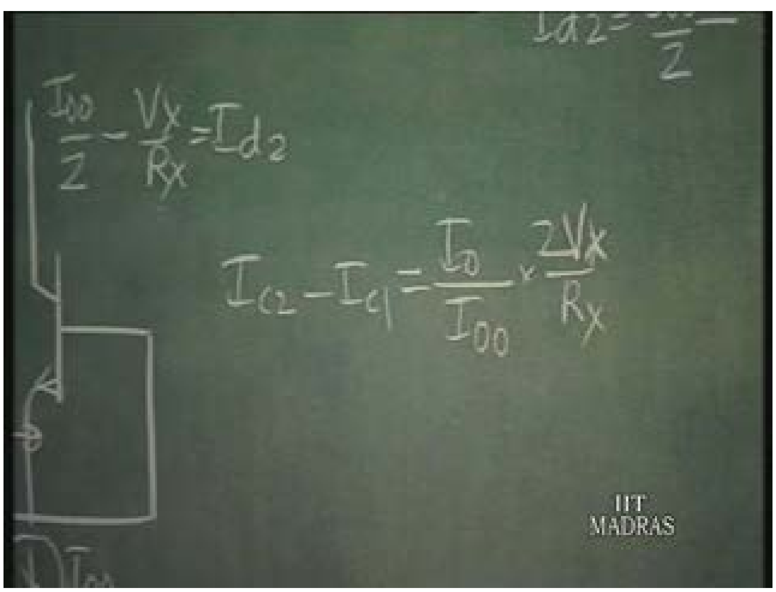

Obviously, there is only one choice. I naught has to be dependent upon another voltage. Let us say that I naught is really equal to I naught by 2 plus V y by some R y.

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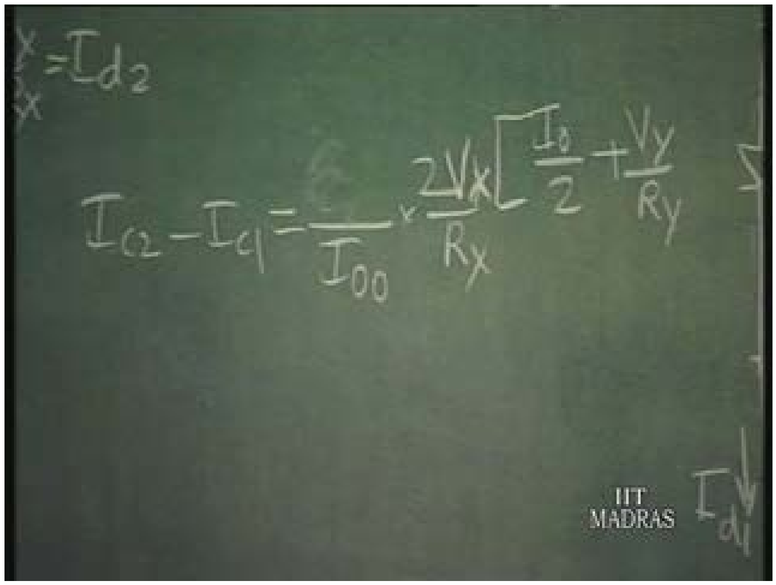

Just as we had here, a voltage to current converter, we can have voltage current converter there also. Only thing is it will be V y here and R y there. So, that can generate a current which is in one side I naught by 2 plus V y by R y. So, this current can be generated. Instead of therefore a current source of I naught, I will simply put I naught plus V y by R y there; a current source. How do I get that?

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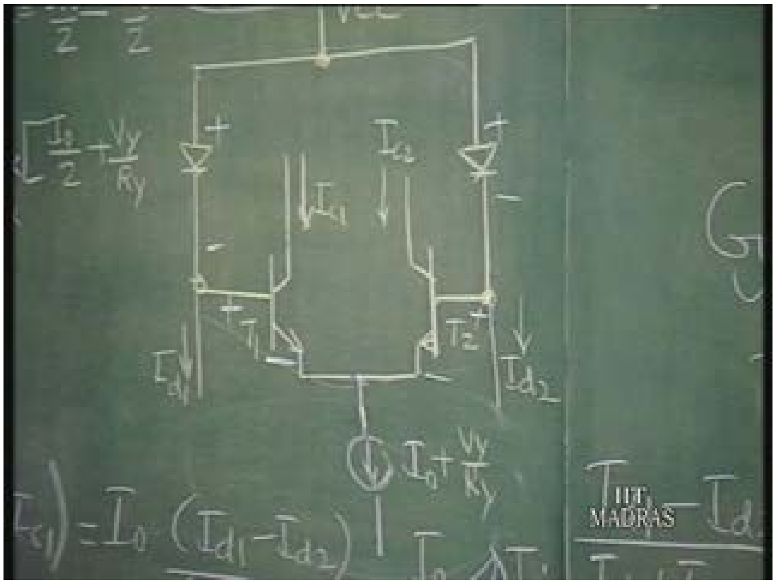

That can be got by putting here the same thing R y, I will put; and then I naught by 2, I naught by 2. So here, I get...if I put V y here, I naught by 2 plus V y by R y.

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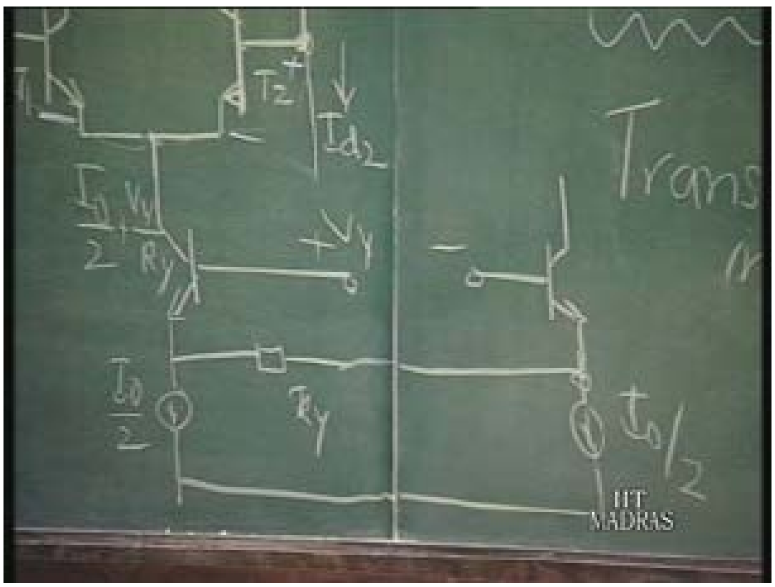

So, you have this being connected here and this current source. So, you have a multiplier component here in this; differential output current, you have this. What to do with that?

That can be applied to another one which is also connected to same pair, similar pair, like this. This same input can be given to another pair like this.

So, this is going to be taken here. That means, this is also going to have similar ratios for the current because same input is being given. So, we will call this T 1, T 2, T 3, T 4. The current in T 3 and T 4 will be, let us say, I c 3 and I c 4. So, these ratios will be exactly similar to what we had as I d 1 by I d 2.

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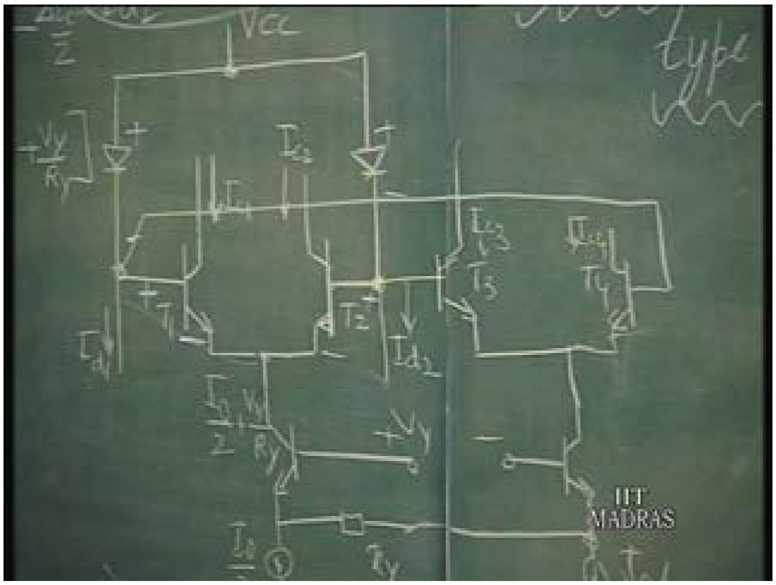

So, we will have this equal to, let us say, I c 2 minus I c 1 here. I c 2 minus I c 1 is similar to I c 3 minus I c 4. I c 3 minus I c 4, divided by I naught naught R x twice V x. Only thing is here, it will be I naught by 2 minus V y by R y because this current, source current, is different.

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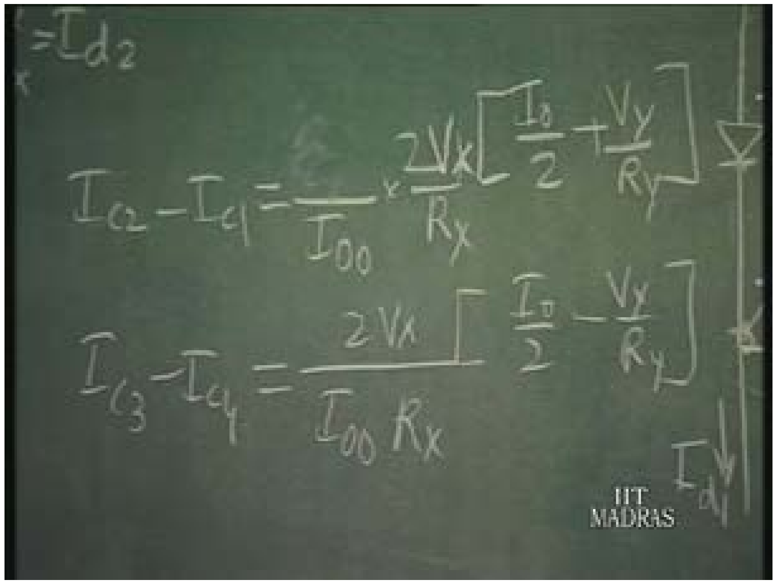

So, you can see here that this whole arrangement, we have the product that is got; but only trouble is that the...there is some feed through component of V x here. So is the output here.

So, that can be simply got rid of by subtracting this from this. So, this differential current can be subtracted. That means I c 2 minus I c 1 minus I c 3 plus I c 4 therefore becomes equal to... these two will get cancelled. We will get twice V x by R x I naught naught into... What is this? Twice V y by R y.

So, you will get here 4 V x V y R x R y I naught naught, which is the product of two voltages; that as the current. This can be converted into voltage by multiplying this whole thing by a resistance R. So, how do I do that?

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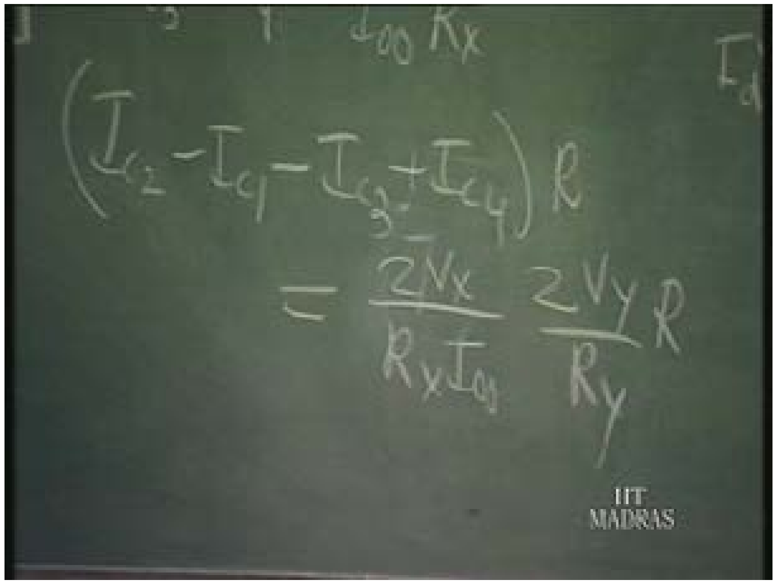

I c 2 plus I c 4, I c 2 plus I c 4 simply can be done by connecting those two together. This is I c 2 plus I c 4, node. Then, I c 1 plus I c 3 - that is going to be these two currents. So this current is going to be I c 1 plus I c 3 and make these flow through resistances R and connect it to V c c and take differential output voltage V naught. That is going to be nothing but this.

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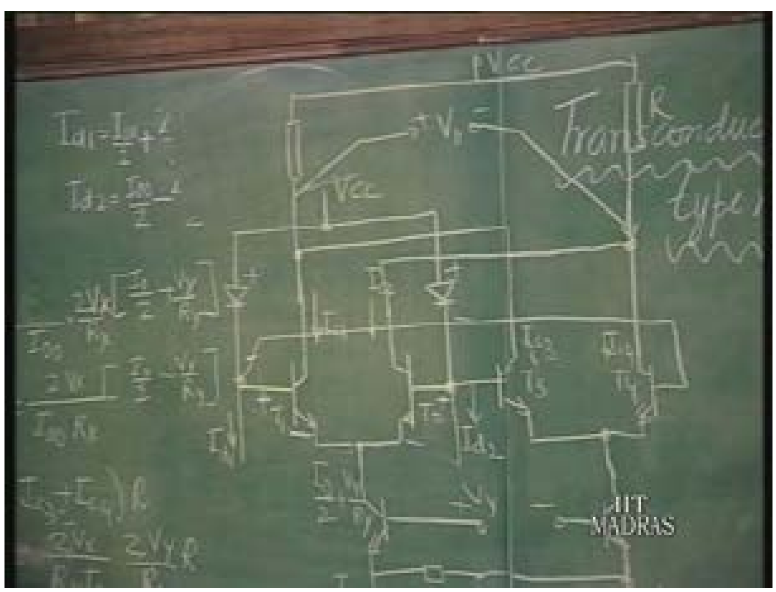

So, this is called a four quadrant multiplier because V x and V y, both could be positive or negative. So, this is the complete transconductance multiplier which is available as an I C. We will discuss the application of this and variations of this circuit in the next class.