Analog ICs
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Lecture - 02
Current Mirrors (Translinear Principle)

In the last class we have seen something about current mirrors and how using both bipolar transistors as well as MOSFETS one could obtain what are known as current mirrors. In fact the application of current mirrors you will just begin to realize when we discuss further about analog integrated circuits.

Today we will continue where we left. In fact there are certain modifications of the basic current mirror that become very useful in certain cases. These are a minor modification, which is the reason for not discussing this in the last class.

Let us consider the basic current mirror. Here the diode is biased by means of a reference current whatever it is which is supposed to get reflected exactly as I_0. There is a problem here in making I_0 very close to I reference because of the fact that I_0 by beta and I0 by beta these base currents have to be supplied obviously by reference itself.

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That means this reference has to supply these base currents which is twice I_0 by beta. So that has to come out of I reference then only the collector current is going to be supplied. All the collector currents are exactly identical, that is assured there is no doubt about it because all the transistors are identical. But our attempt is to make this collector current as nearly same as I reference. So in that attempt we can also doubt what is called current amplifier, why go for feedback and other things. We have abundant amplifiers at our command, what is it? The current amplifier is nothing but the transistor itself. Instead of supplying this current directly from my reference I would rather supply the base current of a current amplifier and make the emitter current supply the base currents of these two.

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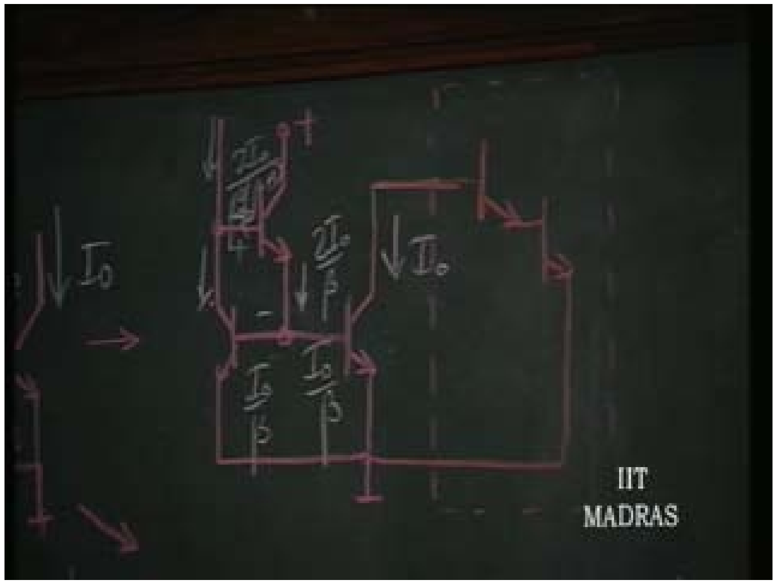

So this is still equal to I_0, this is I_0 by beta. Now this emitter current is going to be twice I_0 by beta and this current is going to be twice I_0 by beta by beta plus 1.

So to that extent the burden on I reference is reduced. This is another technique, a minor technique of using a current amplifier within this current mirror so as to make this I_0 very close to this. This is nothing but twice I_0 by beta into beta plus so I reference is going to be very close to this. This is a commonly used current mirror. The only difference between this current mirror and that current mirror is in terms of reverse bias here.

What is the reverse bias of this transistor now? This is no longer a diode connected transistor but a transistor itself because it has a reverse bias of V gamma. Therefore if you want current reflection to be exact you would like to have the collector potential of this with reference to ground to be at 2V gamma that you have to remember. That means if this is going to supply may be to the next stage you would rather use a Darlington pair. Now it looks similar to this reverse bias so the current mirror is exact. This is the next stage. If ever you use this kind of a current mirror then this is one way of interconnecting the next stage to it.

The base current for this has to come from this. This will be the structure here so this is going to be having this and this. So there is a similarity between this structure and this structure. So if this current mirror is going to act as some load then this is the next stage amplifier. Now another minor variation of this which we had not discussed in last class was what is called as emitter degeneration. That is, why not put resistances in the emitter. What will happen if we put resistances in emitter is, the output impedance will shoot up because this is nothing but current sensing. The output current is sensed and fed back as a voltage. This is similar to the Wilson current mirror we had discussed where output current is sensed and fed back as a current. Here output current is sensed and fed back as a voltage here.

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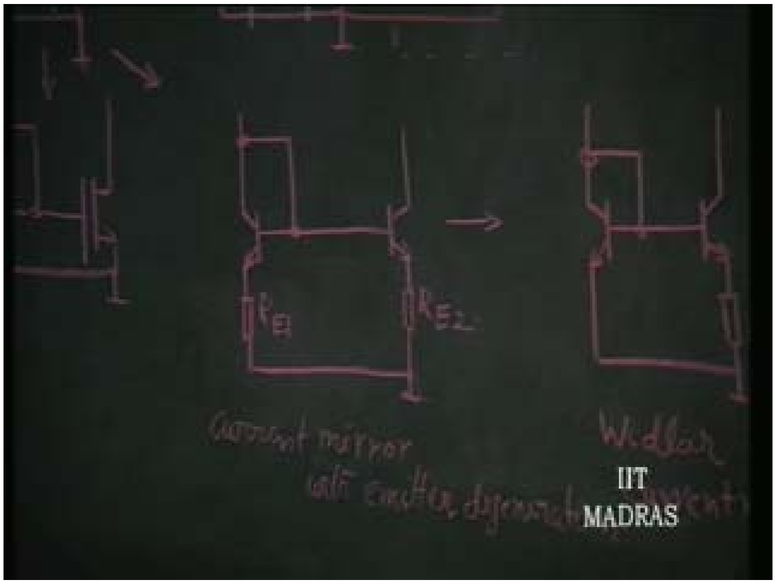

So, emitter degeneration also causes improvement in output impedance. Output impedance of the structure will go towards 1 by hob from 1 by hoe. So exactly similar situation exists here that the output impedance improves and disadvantage of course, this kind of a thing is not recommended in IC design particularly because we are shy of using resistors in ICs. There is an advantage here, you can now make the two resistances equal if you want the current to be equal and if they are different the currents will be determined by ratio of resistors.

You have V gamma here and V gamma here so I_{E1} into R_{E1} is equal to I_{E2} into R_{E2} actually speaking. Thus, I_{E2} into R_{E2} is equal to I_{E1} into R_{E1}. So you have the current ratios determined by resistor ratio. Hence, apart from improving the output impedance the emitter degradation resistor also makes you choose the current ratio the way you want. So current ratio can be made different from one based on the resistor ratios R_{E2} by R_{E1}.

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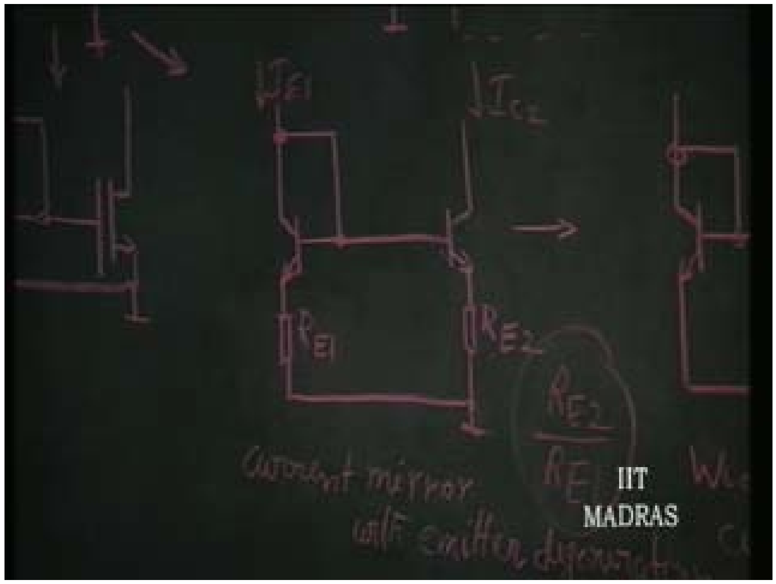

Now, this is a further degenerate version of the same circuit. One end resistance is removed altogether. This is a very important current mirror called Widlar current mirror. Let us see what it does.

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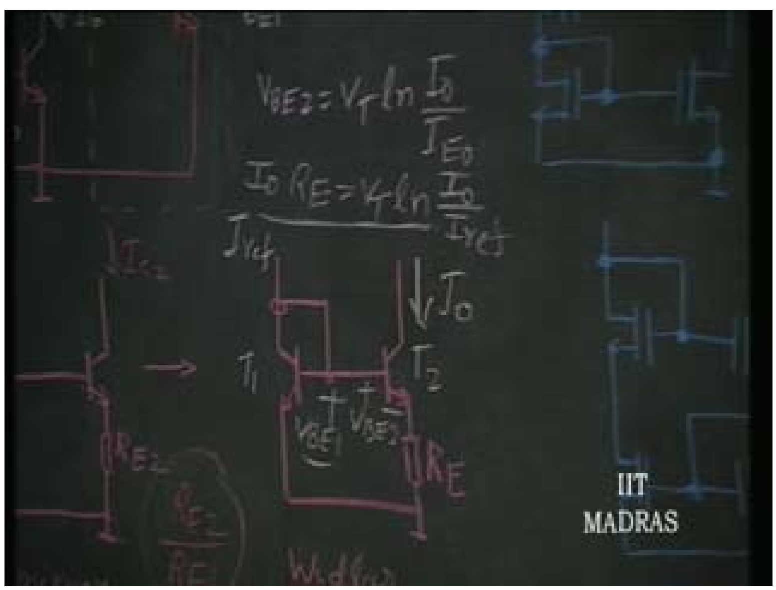

This is the output current and this is the reference current. We had already established that I reference and I_0 are related by a very important relationship in the sense, let us say this is T_1 and this is T_2, if this is V_{BE1} what will be the value of V_{BE1} in terms of I reference? V_{BE1} VT log I ref by I_{E0}, this is known to us. We already saw how this relationship is used in obtaining what is called as translinear principle. So I reference is

V_{BE1} is equal to VT log I reference by I_{E0}. V_{BE2} in terms of I_0 is V_{BE2} is VT log I_0 by I_{E0}. So what is V_{BE1} minus V_{BE2}? That is the voltage across the resistance RE. So what is it equal to? V_{BE1} minus V_{BE2} which is the voltage across Ra which should be I_0 into RE, I_0 into RE is the voltage across RE, that is equal to VT log I_0 by I_{ref}. It is an important relationship. The voltage across the resistance RE is I_{0RE} is equal to VT log I_0 by RI reference.

Of course this is a nonlinear equation which you have to solve in order to obtain value of I_0. But this is not the way the IC designer is going to leave it. The IC designer wants to have an I_0 that is very low when compared to I reference.

I reference may be of the order of milliamperes which could be easily obtained by using voltages of the order of tens of volts and resistors of the order of kilo ohms. We have already seen that our transistor ICs do not prefer large valued resistors in order to therefore develop low valued current for biasing we cannot use resistances of the order of mega ohms. So in this particular case without using resistances of the order of mega ohms using only resistances of the order of kilo ohms we are going to design a circuit for low valued currents.

Suppose you have 1 milliampere as I reference and you are required to get I_0 which is 1 by 1000 (Refer Slide Time: 13:17) that means you are attempting to get a current of micro amperes. Normally you should have used mega ohm resistance.

We already know in a design I_0 by I reference as being equal to 1000. You know this is 1000 so VT log 1000 VT is 26 millivolts room temperature So 26 millivolts natural log of 1000 by RE or by I_0 will give you the value of RE required to be put in order to get I_0 of 1 micro amps. So straight away this design is very simple, it is straight forward. We have the voltage here, 25 log 1000 divided by I_0 will give you the value of the resistance mostly in kilo ohms range. This is again commonly used in all situations where I would like to generate a low valued current from a large valued current as the reference. Let us see a situation here whereas I connect one transistor like this.

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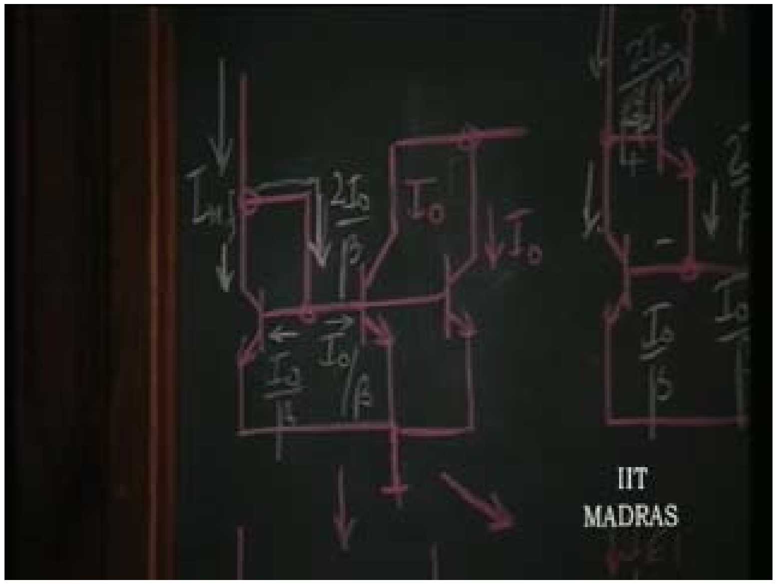

The current is going to be I_0. Suppose I connect another transistor like this current will be again Io, then a number of transistors and I parallel all of them and I can get n times Io as the output current. So getting a current which is a multiple of the original reference current is no problem because I can parallel current sources. But parallel current sources technology wise means all collectors are connected, all bases are connected, all emitters are connected that means area of the transistor is double the original area if two transistors are connected.

If three transistors are connected it is triple. Therefore multiplying the whole thing area by area you can generate currents which are going to be ratio of areas. It is not necessary to have integral multiples. The ratios can be shown to be ratio of areas and you can have the current as ratio. The disadvantage of such a scheme is, the output impedance is progressively decreasing. As you shunt the current sources the output impedance is going to progressively decrease.

We will again see this particular principle reflected more efficiently in what is called translinear principle. So, making the currents different by means of areas is another thing. The current can only multiply. You can generate a current which is higher than the original current. Now these are the current mirrors which are MOSFET versions like these NPN versions.

We can have MOSFET version but the only warning is that the MOSFET should be not depletion mode, it has to be enhancement mode, only then I can connect gate and drain and still have a current source. The transistor will be operating in the current saturation region. So, for that purpose all current mirrors make use of enhancement mode of MOSFET in realization. As far as JFET is concerned again JFET is basically depletion type and you cannot have a current mirror using JFET. In JFET you can only have the current source of the type as we discussed yesterday wherein we are just going to short the gate. And if you want a different current in this case or if you want higher output impedance for this current source then like emitter degeneration you can have source degeneration resistance put here and therefore you can get R_s.

What will be the output impedance of this structure now?
The current can be made different depending upon R_s, what will happen to the output impedance? If the original output impedance is rds then what happens to the output impedance when there is source degeneration? So it is 1rds into 1 plus gm into R_s. This is what we had discussed in basic electronic courses. This output impedance will be rds into 1 plus gmR_s.

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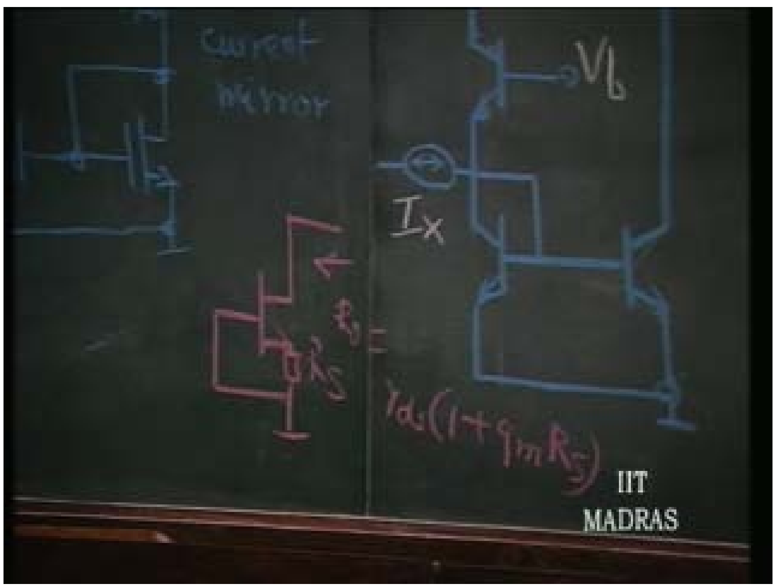

Show that the output impedance of this JFET current source when there is a degeneration resistances resistance of R_s is equal to rds into 1.The same principle is used in improving the output impedance of the current mirrors using MOSFET here. Here this is nothing but what is called as cross code current mirror.

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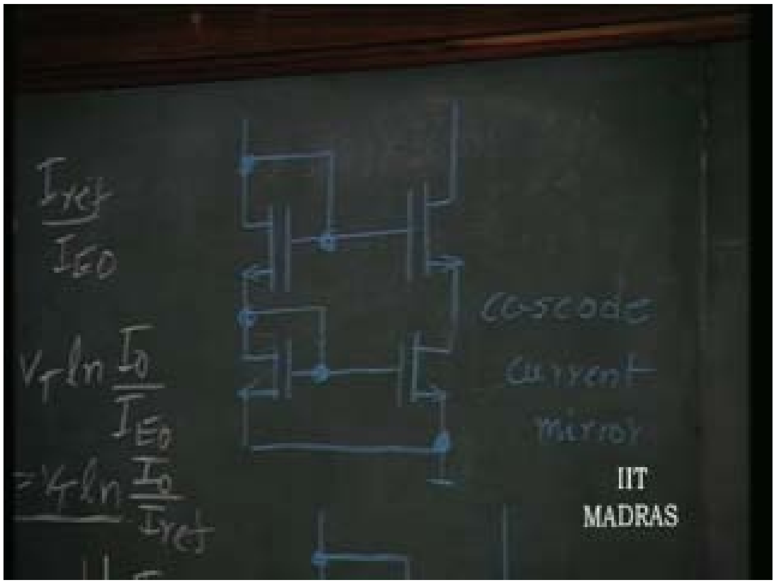

We have discussed this earlier using bipolar transistor. We had seen that in such a situation the output impedance is going to increase and go towards 1 by hob. So similarly in this case output impedance is again going to increase. Originally it is rds and it is going to increase by 1 plus gm into rds. This is how the output impedance of this is going to improve by a huge factor and therefore this is another current mirror in the case of MOSFET. This is nothing but Wilson current mirror drawn. It is exactly similar to the Wilson current mirror that is using current feedback. Again in this case output impedance is going to improve.

Let us try to understand what translinear is, trans here means transconductance which is linear with respect to current or voltage. Transconductance which is linear with respect to current or voltage is what we are talking about. Let us see what can be the devices that can have transconductance linear with respect to voltage or current, this is some basic principle. Think of this as a synthesis procedure.

Suppose we are asked to call for a device which request to be translinear what should be the relationship between current and voltage? So current is a function of voltage. I want delta I by delta V this is out output current versus input voltage. I want delta I_0 by delta Vi which is called the transconductance transfer output current and input voltage. This is the transfer that has taken place from input to output. The transconductance should be linear with respect to output current, this is one thing. Another way is, transconductance should be linear with respect to input voltage. These are the two things possible.

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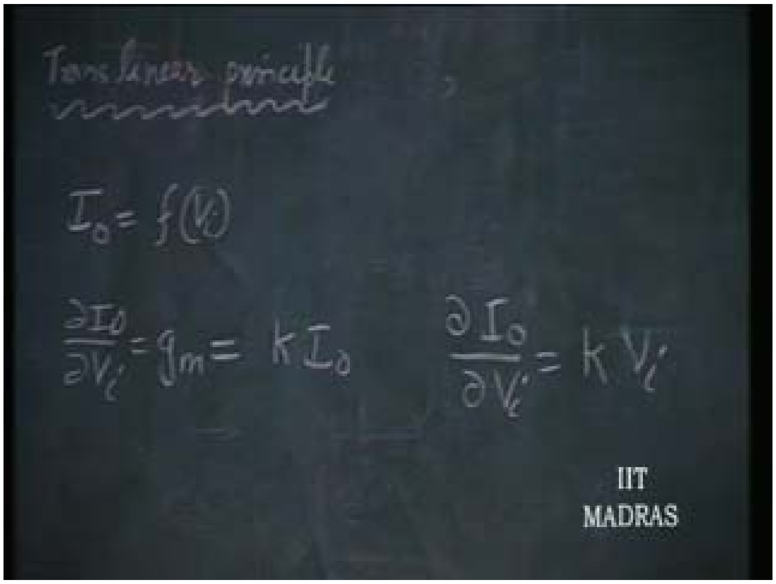

What does it mean? So delta I_0 by delta V_i is equal to k I_0 or delta I_0 by I_0 is equal to k times delta V_i, what is this? Solve this and what you get?

Log or I_0 is equal to exponent k times V_i which is an another case here. This is what is required of the functional relationship between current and voltage. The device should have this, whatever is the device. The basic requirement is this and from that I am starting. So it says it shall have this kind of exponential relationship.

Look at this, this delta I_0 is equal to k V_i into delta V_i so I_0 is equal to k V_i power 2.

What you require, it shall be linear with respect to voltage, it shall be linear with respect to current i.e. transconductance. So God has created the entire thing and it is complete, man has to only search for such a thing and he has found it out, that one is nothing but bipolar and another is nothing but field effect transistor. So it is not that we got these devices and then realize it is complete.

In our inner most mind we had this requirement and we were searching for it and we got it. This is what is meant by translinear principle. That is, both are translinear devices and therefore what is it that you can do mathematically with this principle of translinearity. This is all about analog signal process. We just said, when we connect equal number of diodes or base to emitter junctions in clockwise direction as well as anticlockwise direction in order to form a loop then they can be connected in any random fashion but there should be equal number of diodes both in clockwise direction as well as anticlockwise direction.

Why is this requirement of equal number of diodes? Why should there be such a requirement? If it is not equal what happens?

Kirchoff's law will still be satisfied, there is no doubt about it. In our expression for these things we had I_{E0} coming at the denominator, those will not cancel and entire purpose of our signal processing gets lost and it becomes device dependent. This is the reason for having equal number of transistors or diodes in clockwise direction and anticlockwise direction forming a loop. Therefore this is now formed into a loop and we set pie times I_i where i is equal to 1 to m by I_{E0} power m and then this is in the clockwise direction, this is in the counter clockwise direction I_j where j is equal to 1 to m. It is because of this requirement of cancellation we require these numbers to be the same. Let us see a minor variation.

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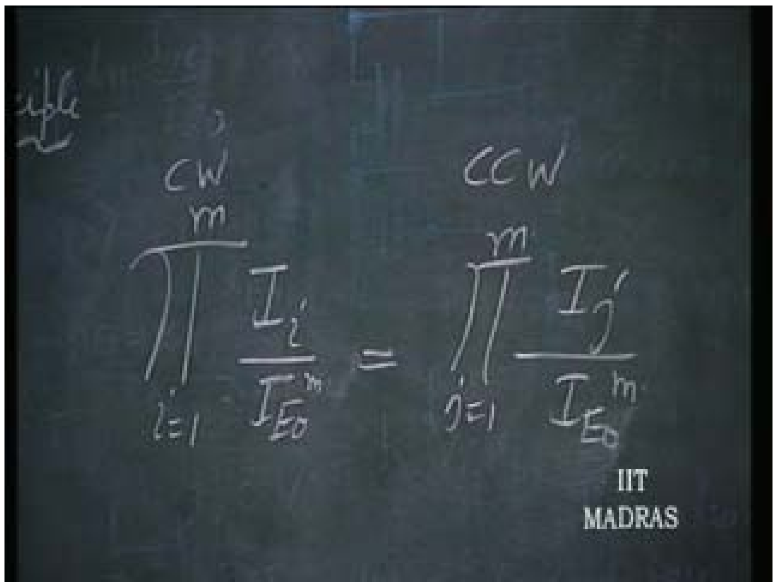

What is I_{E0} in terms of current density J_{E0}?

J_{E0} is the basic parameter of the current IC current density because current density into area is what gives the current. So I can split this I_{E0} as J_{E0} power m times A_i. Here again this will be J_{E0} power m into A_j.

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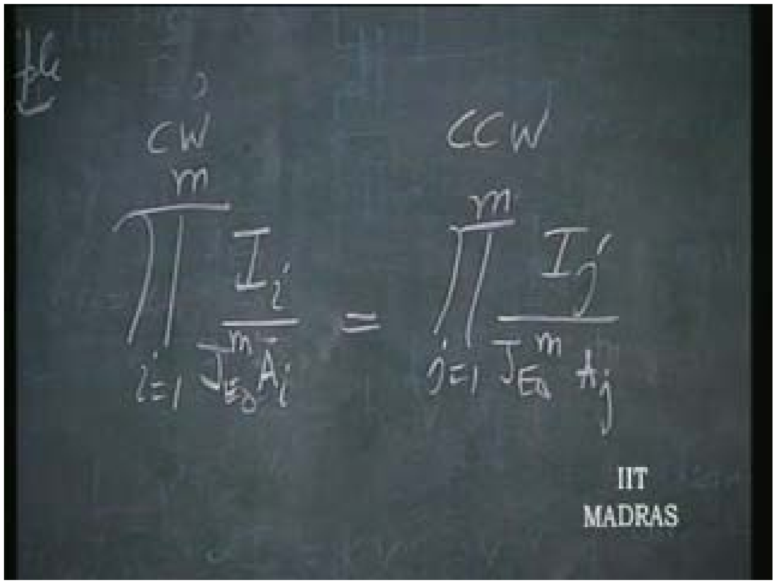

Now obviously J_{E0} is assigned that is why we have put it as J_{E0} power m and they can be cancelled. This is the most generalized translinear principle relationship that the product of current densities of those transistors or diodes connected in clockwise direction shall be equal to the product of current densities of those transistors or diodes connected in the counter clockwise direction.

Now again we are coming back to this. If you are using just two diodes or one diode what happens? That is nothing but the current mirror, so you have I reference by A reference is equal to I_0 by A_0 or I_0 is equal to A_0 by A reference. We have shown what we have earlier indicated using circuits. We had seen this current mirror wherein we parallel the current sources and shown that it is ratio of areas. But here now mathematically we have indicated that it can be made a fraction or any number you want. Therefore this is a technique of obtaining different current ratios by using different areas for the devices. This is the part of the current mirror aspect.

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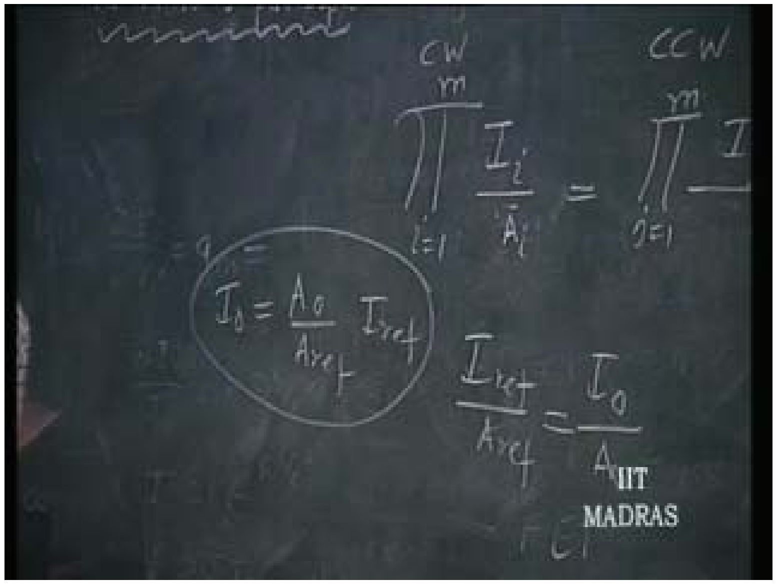

But we are trying to extend this principle to more general tips. Let us see very exciting signal processing circuits now. Consider this first circuit.

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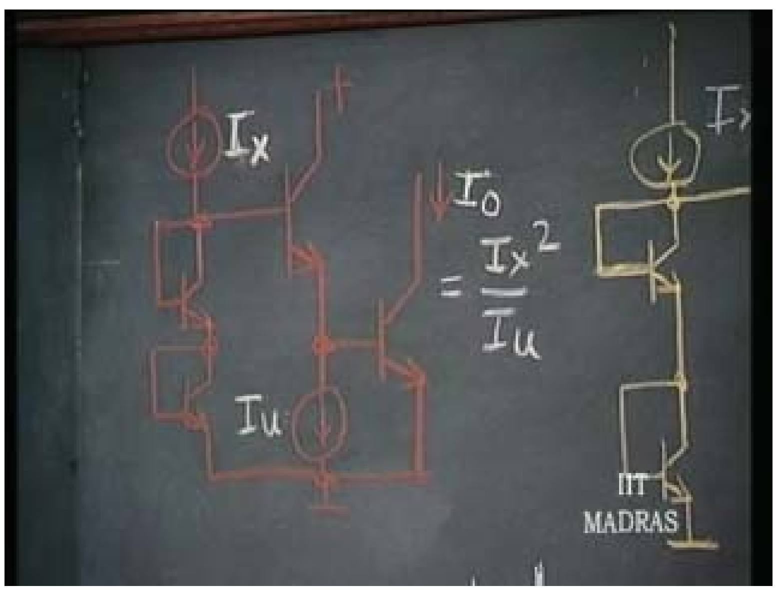

These are the two diodes connected in one direction and these are the other two diodes. What are the currents in this? It is Ix and Ix. Therefore Ix square is equal to I_u I_0 as this diode carries I_u and that is I_0. Therefore I_0 is equal to I_x square by I_u. This is a simple operation of squaring. If I_x is your signal current and I_u is the reference current just you are squaring the current. This kind of signal operation is required when you want to find out RMS value of a given waveform or anything. So you have to square and then integrate and find out the square root. These simple operations can be straight away done with the help of these translinear principles. The dynamic range of this is fantastic.

The translinear relationship is the only known relationship in electronics which is valid over several decades of variations of this current. That is, starting all the way from micro amperes it can go up to tens of milliamperes without any problem, this relationship is valid. So that is the unique property of the bipolar transistor. That is the only device which can handle current in that dynamic range but not voltage. This relationship is a God given relationship which is to be exploited fully. Exponential is basically data compression and squaring has nothing to do with that. That is why bipolar device is a more popular device signal processing device than the FET. Even in the FET you are looking for sub threshold region of operation where the operation null relationship is exponential. So people are trying to use in the sub threshold region where the relationship is exponential. Now let us see this circuit interesting circuit.

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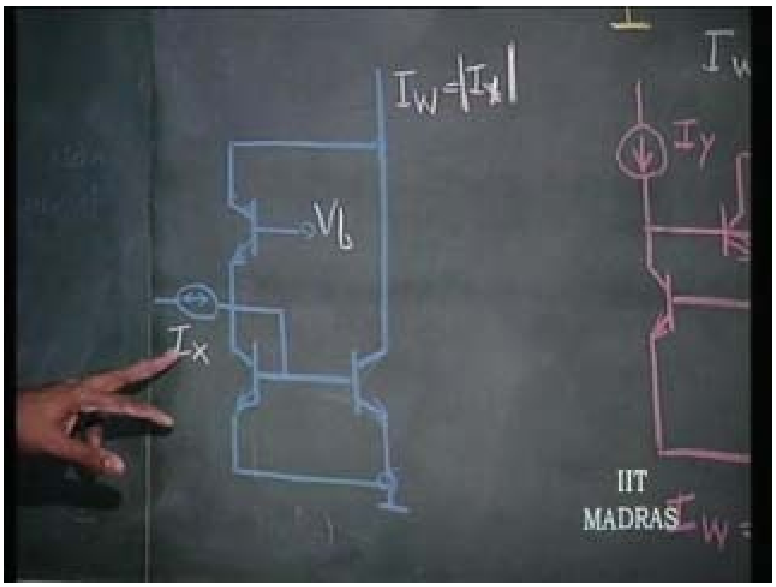

And Ix can be bipolar that means it can be of any direction, it can go in or come out. When it goes in this transistor does not take that current and this is the only transistor which is connected as a diode that takes that current then this diode is getting a reference of Ix into it. Now this is a current mirror so Ix is going to flow through this. For a current flowing in this direction Ix will be reflected here by the current mirror.

What happens when the current is in the opposite direction?
That is not permitted by this diode, it cannot take that current, that current can be only taken by this if this is biased properly.

What do you mean by biased properly?
The bias voltage should be nothing but 2 diode drop. If that is 2 diode drop then this is going to conduct properly, it should be just less than 2 diode drop, this is basically half so

when this is conducting (Refer Slide Time: 36:10) this is going to conduct and this is going to carry a current in the opposite direction. Therefore in either direction we have this circuit operating so I_w is nothing but the magnitude of the current. Here this is only a bias voltage, the current is injected from that by means of a current source. So the bias is going to be only for making the base to emitter junction conduct. Let us consider this circuit.

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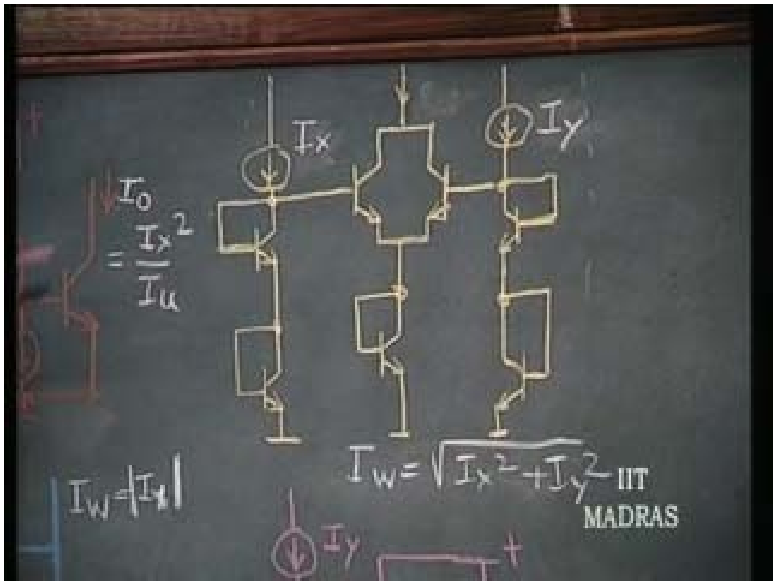

I_x looks like a differential stage but you can see I_x is going to flow through these two diodes so it is I_x power 2. Let us call this as I_1 and this as I_2 and this is nothing but I_w. The I_x power 2 is equal to I_1 into I_1 plus I_2. You see that I_1 plus I_2 and it flows through this. I_x power 2 is nothing but I_1 which is the current flowing in this transistor into the current flowing in this transistor which is I_1 plus I_2. Similarly, I_y power 2 is nothing but I_2 into I_1 plus I_2. So it is I_x power 2. I_1 plus I_2 is nothing but I_w. So according to that I_1 plus I_2 is nothing but, just add these two, I_2(I_1 plus I_2) is equal to I_x power 2 plus I_y power 2 I_1 into I_1 plus I_2 that is nothing but (I_1 plus I_2) to the power 2 is equal to I_x power 2 plus I_y power 2 I_1 plus I_2 is therefore nothing but I_w which is root of I_x power 2.

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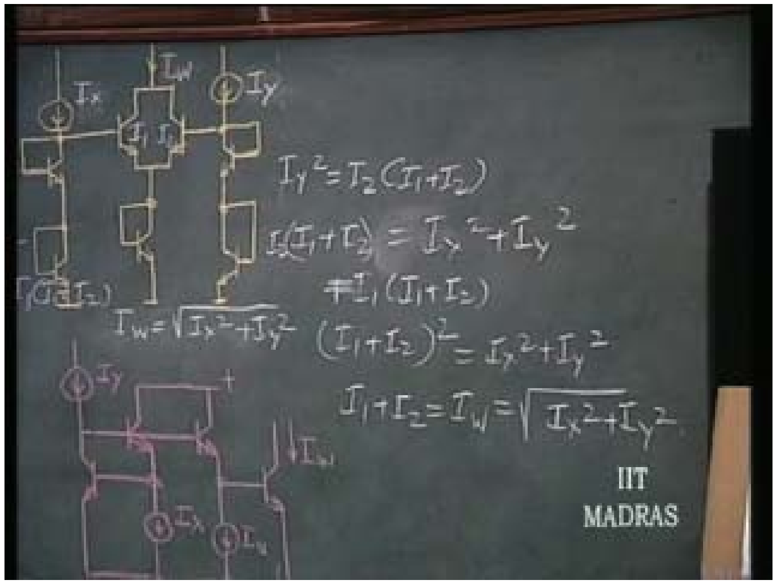

This is an important circuit, this is I_x and I_y the two inputs and output will be a current which is root of I_x power 2 plus I_y to the power 2 which is the vector magnitude. This is a very neat circuit and just by using transistors and diodes I am able to obtain a very complicated signal processing formula which is nothing but vector magnitude I_x root of I_x power 2 plus I_x power 2.

Next, this is basically a simple circuit which we can formulate; if I connect two diodes in the clockwise direction and two diodes in the anticlockwise direction then the currents in these two diodes I_1 and I_2 will be equal to the product of currents equal to I_3 into I_4. That basic principle can be used for multiplication, division and so on. So you can formulate large number of such four diode loops and all of those four diode loops will become multiplier circuits. One such technique of multiplication is this. You can see that this plus this is going to be equal to this plus this. So this is I_y and this is I_x. So I_x into I_y is equal to I_w into I_u.

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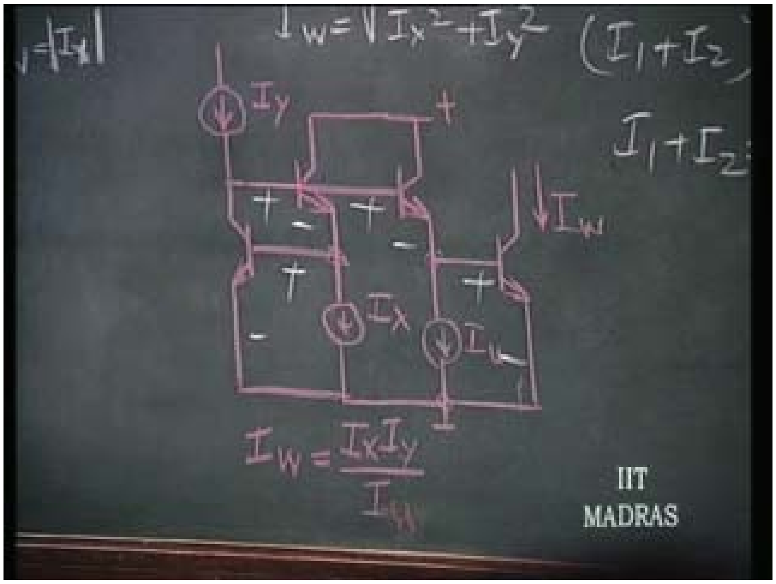

I_u could be the reference current if I_x and I_y are the signal currents, it is a multiplier. If you make I_y as reference I_u and this has a signal it becomes a device. So you can use this, this is nothing but basic technique of multiplication adopted by exploiting the principle of log antilog relationship that is inherent in the bipolar transistor. Therefore we can see that this property has been used in all modulators and demodulator circuit ICs which are nothing but multiplier circuits. And we have a variety of multipliers, ICs generated only using this principle of four diodes, two of the diodes in one direction and two other diodes in the opposite direction forming a loop.

We will see this property as well as the property of the differential amplifier in converting the input voltage into functional relationship between the input voltage and output current in the next class. So the differential amplifier as a basic building block is nothing but two diodes connected in opposite diodes.

If you apply voltage it will convert it into some nonlinear function. If I apply current inputs which are going into diodes it can become a multiplier. This basic cell is called as Gilbert gain cell is what we are going to discuss later. This is nothing but two transistors connected like this and again two other transistors or diodes connected.

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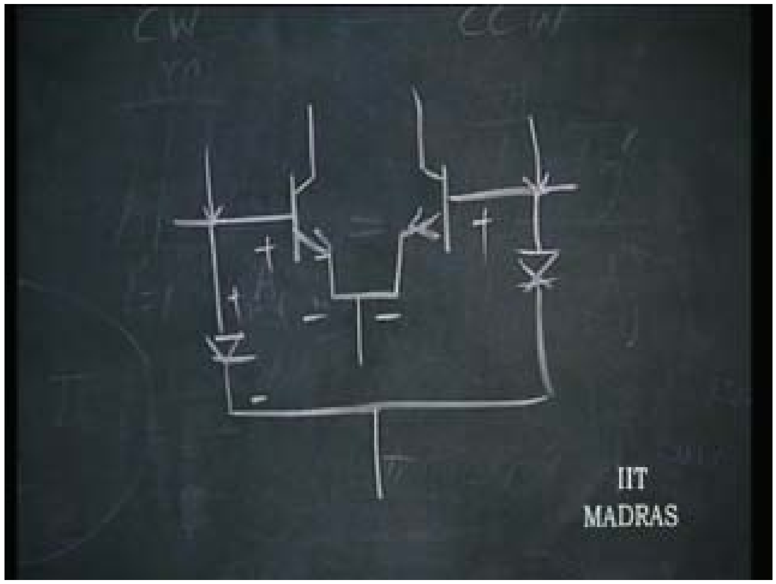

These diodes are also transistors. Actually speaking now you will have all the current sources coming in. Assume these things automatically that current input should forward bias the diodes. So in such a situation the current in this is multiplied by current in this, these are in the same direction, is nothing but current in this multiplied by current in this. So you can just look at this circuit and arrive at the solution if you know the translinear principle. We will further learn about the use of this translinear principle in current mode operation of circuits in the next class, thank you.