Electronics for Analog Signal Processing - II
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Lecture - 33
Multipliers (Continued)
Applications
(Modulator/Demodulator)

We had discussed transconductance multiplier and its applications. I would like to point out here that for the communication application of the same multiplier, there is no need to use the precision multiplier as such.

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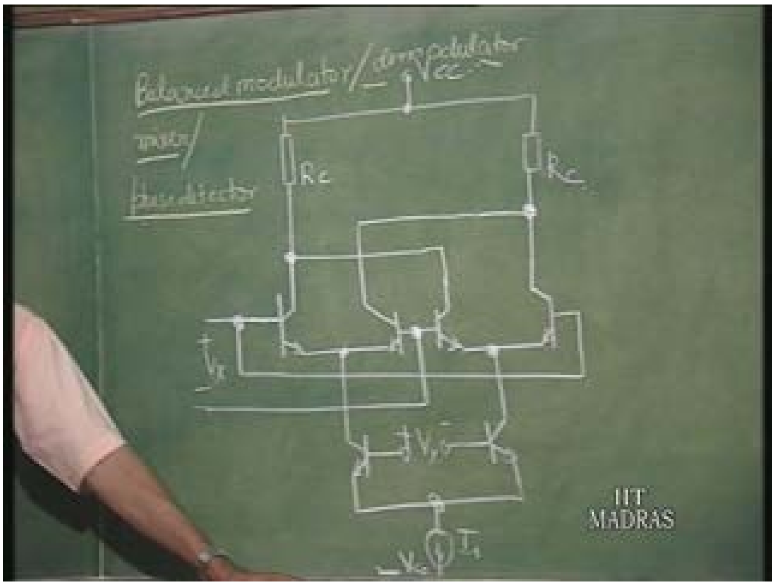

You can see the basic block comprising of the pair Z y, V y; and there was a transconductor converting V x into differential current feeding on to a diode. That can be removed, specifically when V x and V y, in communication normally happen to be very small voltages, of the order of few tens of micro volts or so. For such values, there is no need for conversion of the voltage to current. That kind of conversion automatically occurs for this small signal equivalent circuit of the device itself within this.

So, there is no special need for conversion. So directly, the signal can be fed to this block which we had seen as the output block of the precision multiplier. Here again, we can get rid of that R y resistance and make use of the fact that when we apply V y here, this V y divided by twice r e of the transistor itself will convert it into a current.

So, this particular structure therefore is going to be I naught here and current here is going to be I naught plus V x divided by 2 r e of these two transistors; and I naught by 2 and I naught by 2, minus V x by 2 r e, so that the total current is I naught. Earlier, we had been using in series with this arrangement a capital R y which is not there. That is it because this itself is a small signal.

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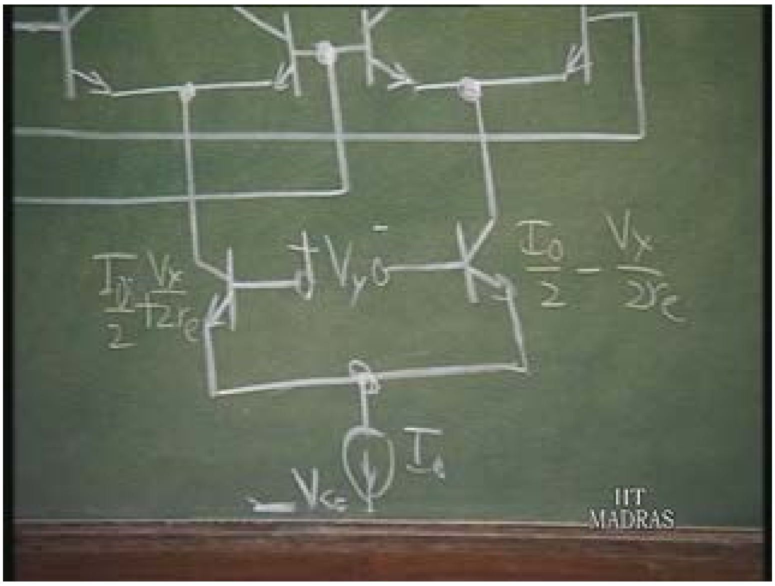

So basically, this is converting the voltage into differential current of this type, linear; and then, as far as these are concerned, this is V x. And V x is being fed to this differential amplifier whose current, operating current is this. Therefore, the transconductance of this...if it is g m, which is again V x divided by 2 r e of this...1 over 2 r e is the transconductance. So, that is why that transconductance is being varied by V y here.

So, that is why this whole structure is basically called as transconductance multiplier. Even though that was not apparent in the earlier precision multiplier, here for this small signal situation, you can clearly see that it is nothing but a differential amplifier whose gain, if it is g m into R c... this is the differential gain; g m into R c where g m is r e of this transistor or that transistor depending upon that.

So, g m 1 into R C or g m 2 into R c. So, this particular thing is going to be I divided by V T where I is the operating current and I in turn is controlled by another voltage, V y. So, output is this into V x; and since I is itself dependent upon another current here, we can get that as I naught by 2 plus V y by 2 r e in one case; and I naught by 2 minus V y by 2 r e in the other case. And if you take the differential output again, the constant part will vanish and you will get that as a product of V x and V y.

So, this is the basis of this kind of multiplier: I naught by 2 plus V y by 2 r e. This is the current going here; half of this will be the current going in this as well as this. Half, so half; that is the current in each one of these. So, that current divided by V T into R c is the gain.

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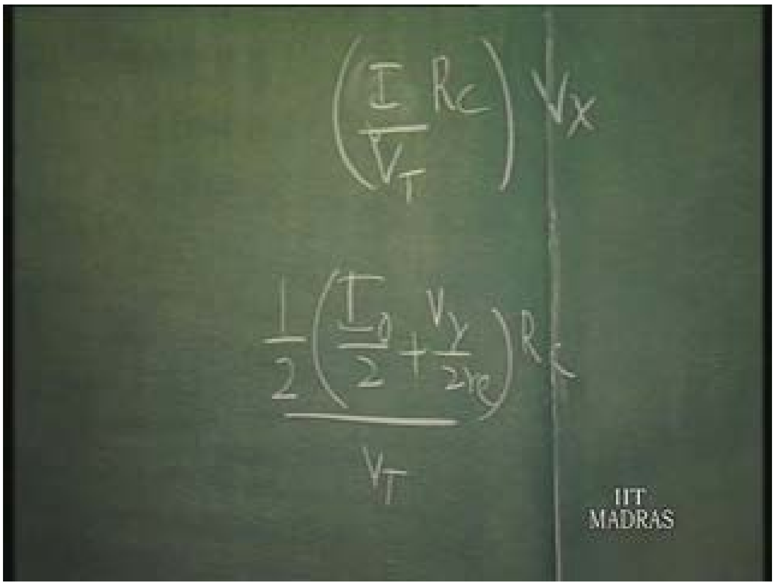

That is, the current divided by V T into R c is the gain of one and another one is half I naught by 2 minus V y by 2 r e into R c. So, when you take the differential output, this minus this is what is got. So, this into V x is the output. This into V x is the output.

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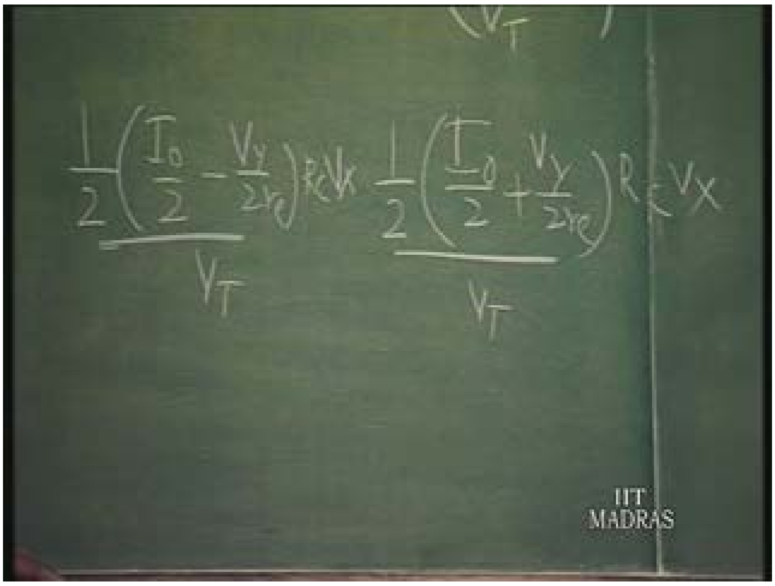

So, if you take the differential output, this minus that; so you get this constant term or this term getting cancelled and you get an output which is dependent upon V x into V y. This is the name attributed to it, this multiplier. That is the transconductance multiplier and this is normally called...this, this itself is available as an I C. This just is part...this is a communication I C which is called balance modulator.

It is one of the applications of the multiplier or demodulator; balance modulator or demodulator or mixer. It is also called phase detector. So, this block is commonly used as a phase detector, balance modulator, demodulator and mixer in communication application. This circuit by itself can be used up to hundreds of megahertz without any problem.

So, this is a common communication I C. Let us look at it in a fairly detailed manner. We know that, as far as the output is concerned, it is going to give you a product V x V y by V R. So, and now this V R is no longer 10 volts; it, it is going to depend upon I naught and this R c, etcetera.

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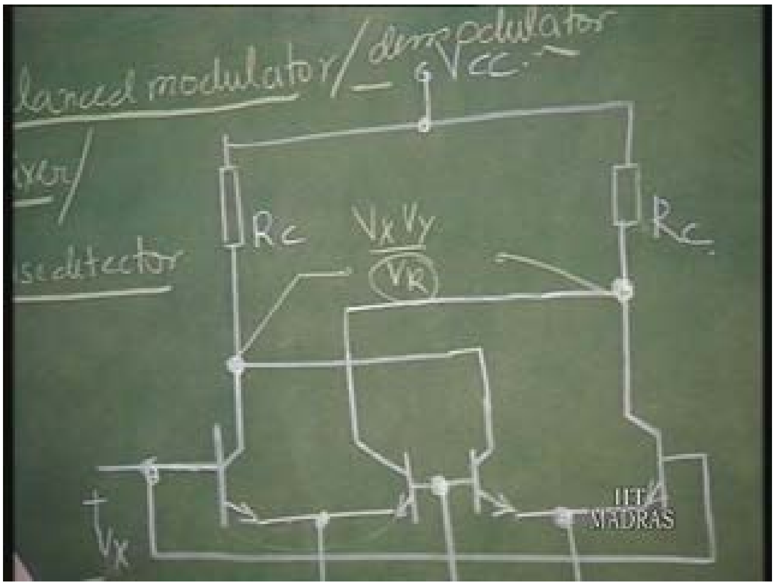

So, as an exercise, I would like you to find out the value of V R for this structure. We already have shown that output is proportional to V x into V y. We have also shown you how the output can be evaluated. So, please find out the value of V R which is going to depend upon I naught and R c. Now, as far as...it is also going to depend upon V T of this whole thing.

Now, this particular circuit is also called E X O R gate digital. That is, when I apply A here and this is B, output will be exclusive or A B bar plus B A bar. Let us check that.

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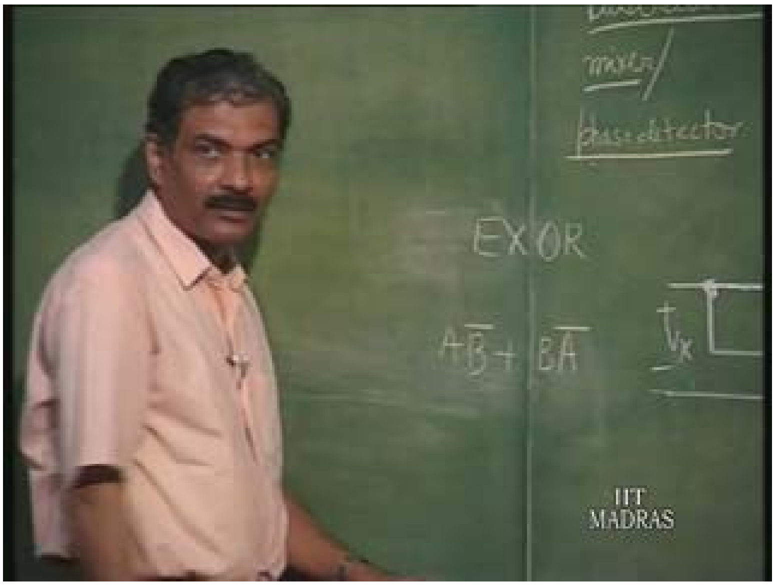

That is, we must have, let us say A here and B here. Let us say, A is high, B is high; A is high and B is high. Then what happens?

We can see here, this is positive. So, this current is diverted to this transistor. So, this is the path current is going to take and this is positive. So, this current I naught is going to be diverted here and this is going to be off and this is going to be off. So, the entire current is going to go...flow through this I naught. Let us investigate what happens to this side. Since this is off, this entire thing is off. So this, zero current flows. So, output is going to be V c c here. Here it is going to be...this is V c c and this is V c c minus I naught R c. So, if you take the output as this one plus and that one minus, it will be this minus that; that will be minus I naught R c.

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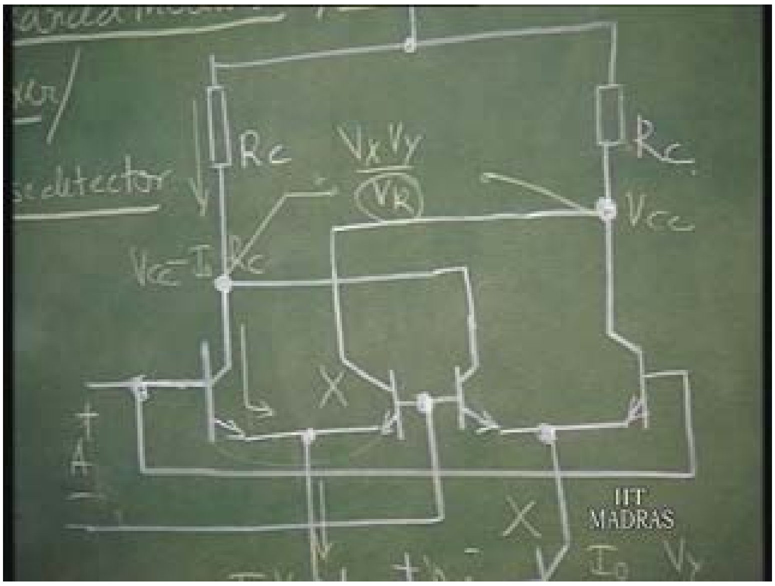

So, let us put the output as minus I naught R c. It depends upon on this thing. If you take the V naught as this, this is...

So next, if B is remaining the same, A is changed. Let us say, A is zero, B is 1. That means, A is changing the polarity. This will be plus and that will be minus. This current has already come here because this has remained the same. This current is now going to pass through the other transistor. This entire structure is off. So, this polarity will now change and here it will be V c c minus I naught R c; and this will be V c c. So, this is going to be I naught R c.

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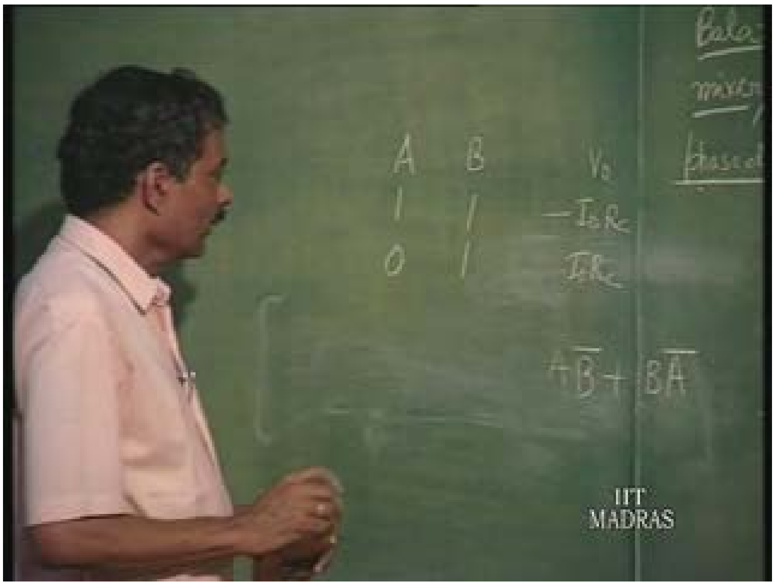

Now, we will retain this as 1 and this is going to be changed to zero. So, this is going to be plus and this is going to be minus. This is the state. So, when this is plus, this is minus, current is going to this total I naught. So, I naught is going to flow through this and this is plus, this is minus. So, this is plus. So, the current will flow through this like this.

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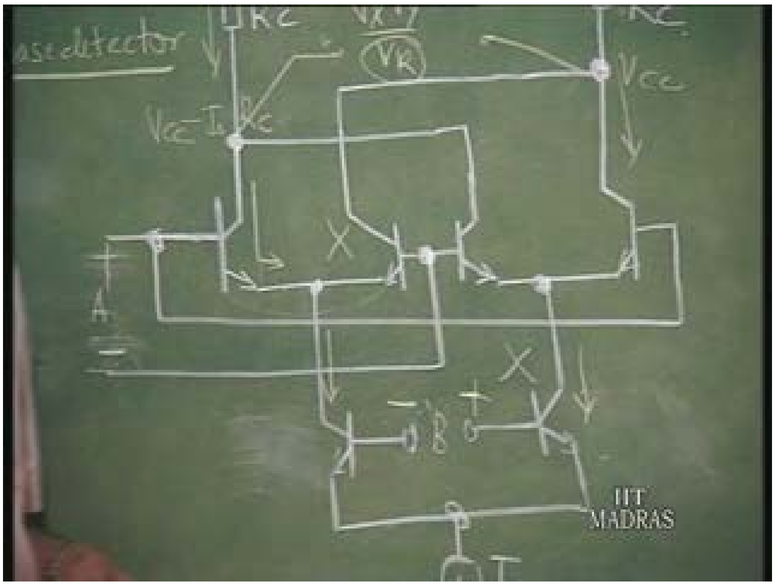

So, this will be retaining low and that will be high. So, output will be again I naught R c. Now, this is... this is 1 and...this is zero and this is zero. That is the last thing that is left. So, this is changed over to plus and minus. So already, current has gone over here. This is plus and this is minus. So, this plus is going to be transmitted to this now. So, the current will be shifted to this and it will come here. So, it will be minus I naught R c. So, you can see that only when you have A bar B and B bar A true, either A bar B or B bar A true, output is true, I. So, if you call this as 1, 1, zero, zero, that is the E X O R logic. So, you can see that this is nothing but emitter coupled logic circuit and therefore this is a high speed circuit.

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So, once again, if this signal level here is much greater than tens of millivolts, current switching occurs and then you can treat this as a logic circuit and assume that this is a square wave, this is a square wave and output is a square wave of, let us say, these two are of the same frequency; this will be of double the frequency here because you know the number of times it changes here.

And therefore, this is going to be an E X O R gate which is also going to be useful for phase detector application, linear phase detector. If this is a square wave and this is a square wave of some phase difference but same frequency, then the output will be a square wave of double the frequency but not really a square wave. It is going to be rectangular wave of double the frequency; but as an average, which is directly proportional to phi. That we have shown with multiplier wherein we applied amplitude limited voltages to depreciation multiplier and showed that output is going to be a rectangular wave whose average is directly proportional to phi.

So, this itself can be used as a phase detector, linear phase detector, as long as these amplitudes are large enough to drive the currents to switching from one transistor to the other. So, this has a very important application in what is called as phase lock loop. This particular unit as a phase detector is used in what is called phase lock loop which we will discuss later. It is again one of the important communication systems.

So, we had just now discussed the balance modulator circuit; in the communication parlance, it is called also phase detector or balance demodulator or mixer. And I had told you to determine the multiplier transfer function as V x V y by V R. V R will come out to be V T square divided by I naught into R c. So, V T is equal to K T over q. We follow the same steps that we had earlier indicated. We can get the value of V R as this; that is, as a multiplier.

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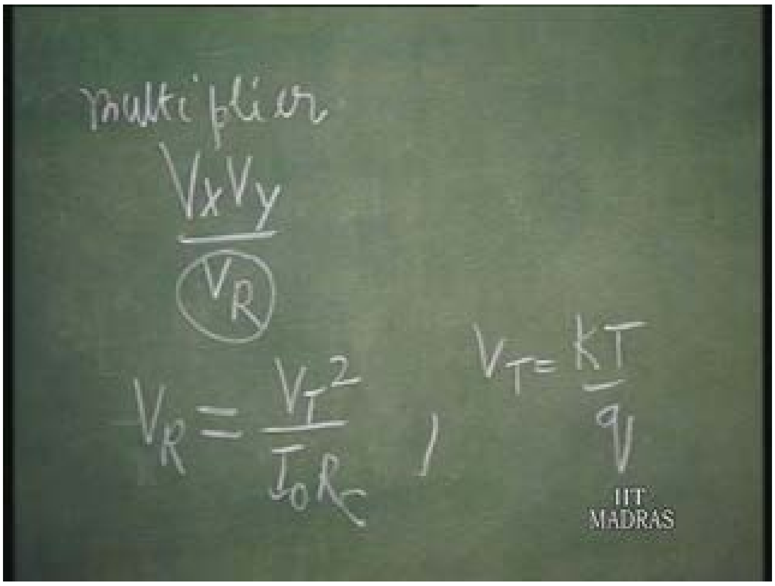

As a phase detector if it is used, again, we can show that the amplitude will vary in the following fashion between I naught R c and minus I naught R c. That is what we saw as an E X O R gate.

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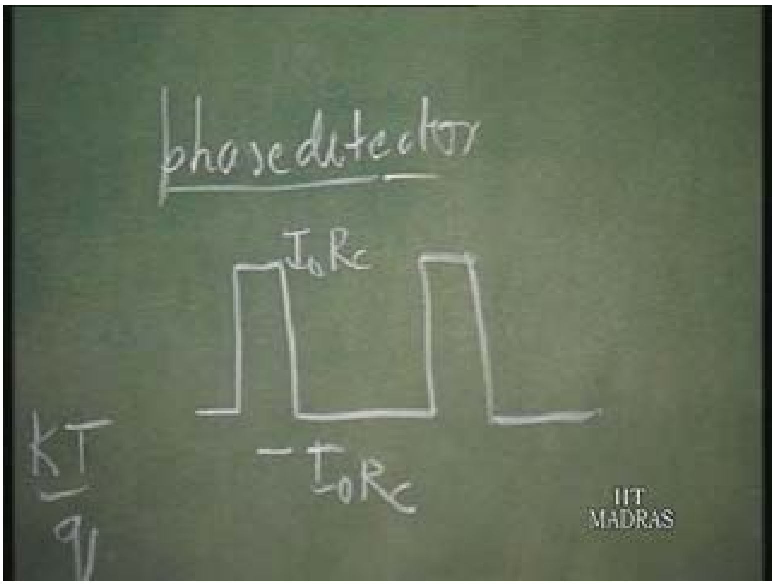

So, amplitude varies between minus I naught R c and I naught R c; and therefore, this is going to be, let us say phi. The phase difference between the two square waves and this is pi minus phi. So, you have I naught R c into phi minus I naught R c into pi minus phi divided by pi as the average of this waveform.

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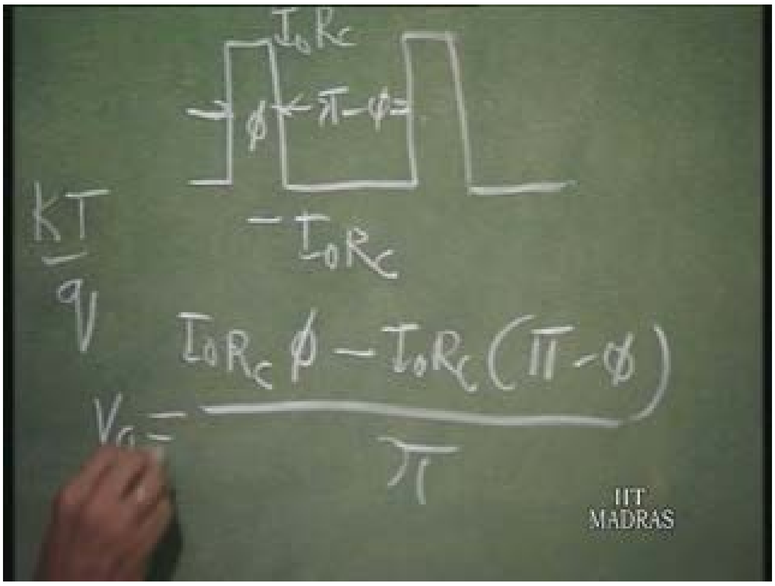

So, this is going to be I naught R c into...2 phi, here it comes; two phi by pi minus 1. So, this is the average output if you use the E X O R gate as the phase detector.

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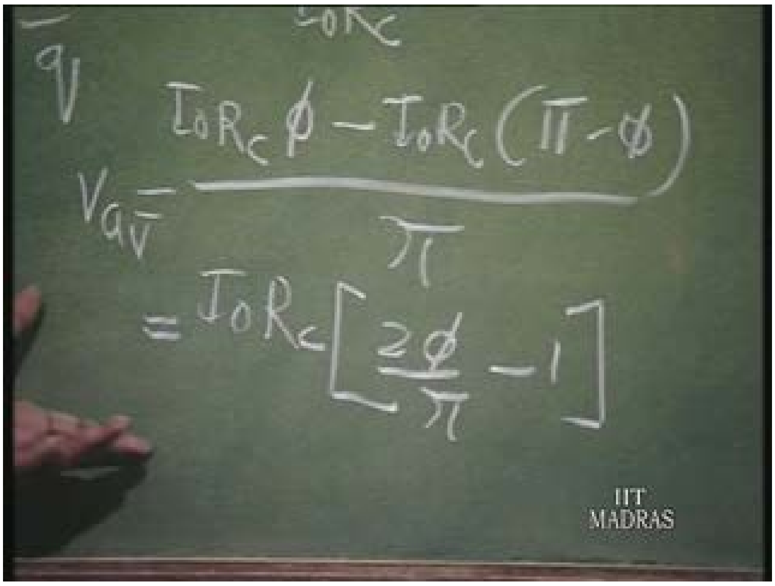

This is important and the phase detector sensitivity, phase detector sensitivity is nothing but Delta V average divided by Delta phi. This is the definition for phase detector sensitivity. Change of the average for a change in this thing. This is nothing but... we will call this as K p d, phase detector sensitivity. K p d, phase detector.

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It is nothing but... If you look at that, I naught R c 2, I naught R c by pi; differentiate that. So, this is K p d.

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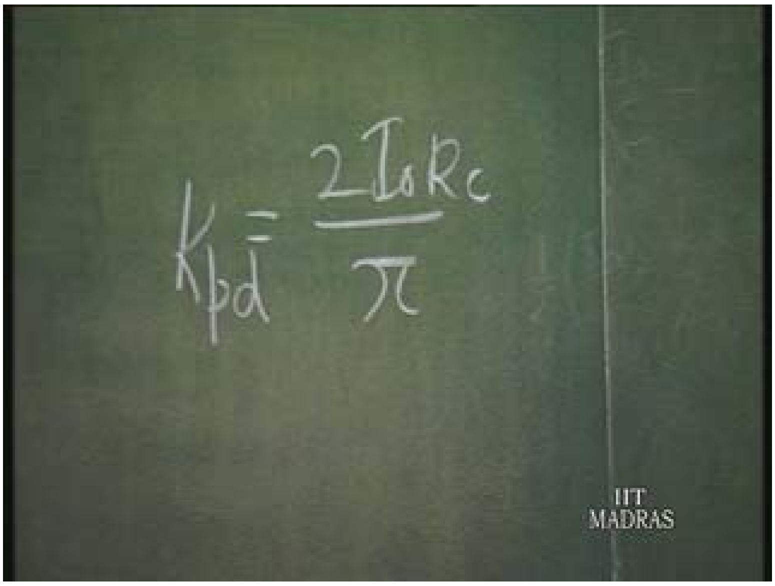

For the linear phase detector it is the same, whatever be the quiescent phase at which you are working. So, its characteristic will be looking like this. That for phi equal to zero, it is going to be minus I naught R c and phi is equal to... at pi by 2 it is zero; and then it reaches a maximum here for a phase shift of phi. It is equal to plus I naught R c. Thereafter again, it will repeat itself. Same thing for lagging phase angle. It cannot make out whether the phase is leading or lagging. So, whether it is lagging or leading, it will give you the same output and therefore its characteristic will be like this, linear. ...goes on like this. This is for pi. This is for 3 pi by 2, so on...

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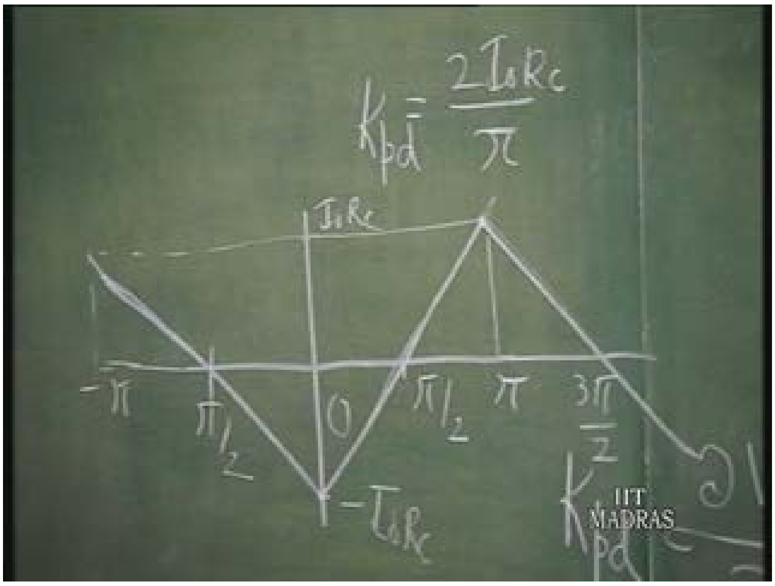

So, this much information if you know, we can actually use this as basic building blocks in a variety of communication circuits.

Now we will discuss about other multipliers other than transconductance and log-antilog now. The important multiplier that we have already discussed when we discussed class D type of power amplifier is what is also available as appreciation multiplier. What is that?

If we have V X and a switch and this switch is operated periodically, connected and connected to minus V X, connected to plus V X for tau, connected to minus V X for T minus tau...

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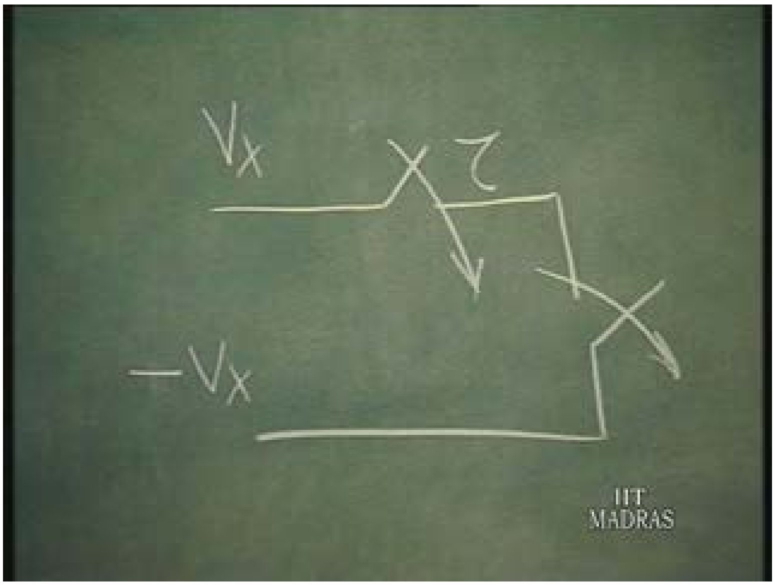

So, it is...waveform is like this. V X and minus V X.

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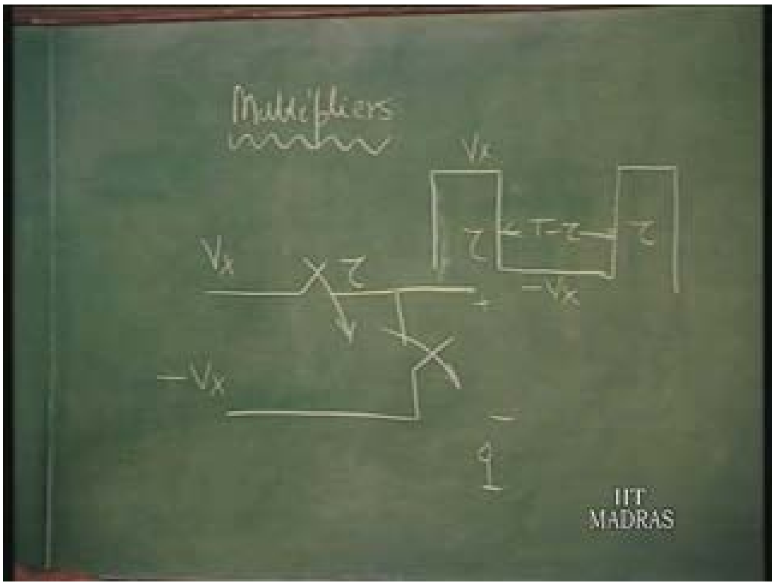

Now if you take the average, you get V X into tau minus V X into T minus tau by T. This is the V average of this voltage V naught. V naught average.

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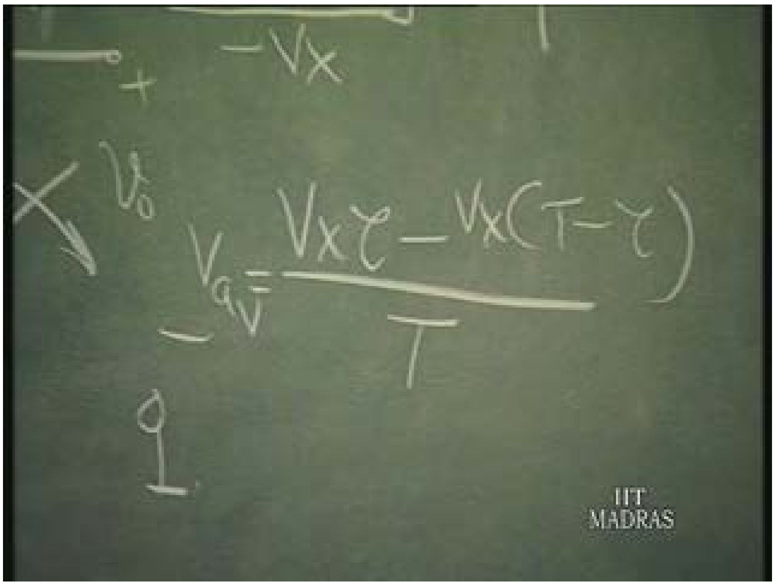

What is it going to be? It is going to be V X into, let us say 2 tau by T minus 1. So now, I will vary the so-called duty cycle by using another voltage. So, this becomes pulse width and amplitude modulation. This pulse width as well as amplitude, they get modulated by voltages.

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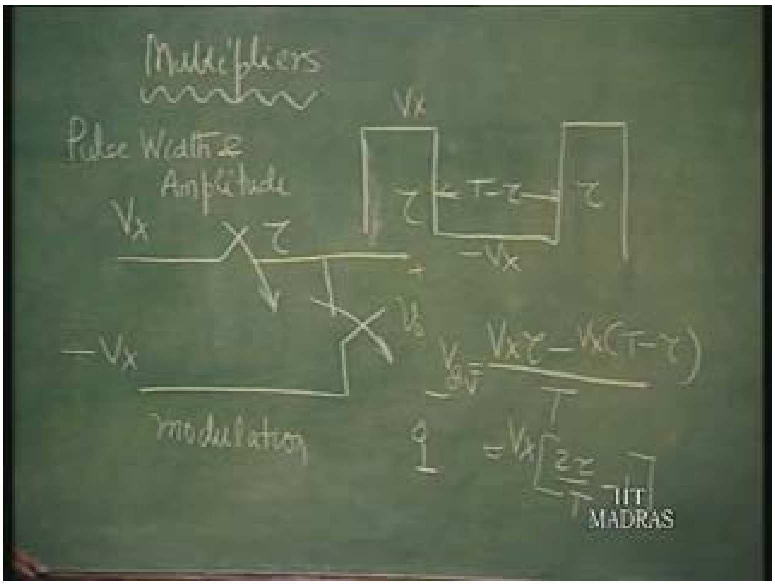

This is the type of multiplier. So, how do I actually modulate the width? That can be done by using, let us say V y, the other voltage and a triangular waveform along with the comparator. The triangular waveform should have a period of T and it has a peak voltage of V p and use a comparator here; and this should be the controlling voltage for the switch.

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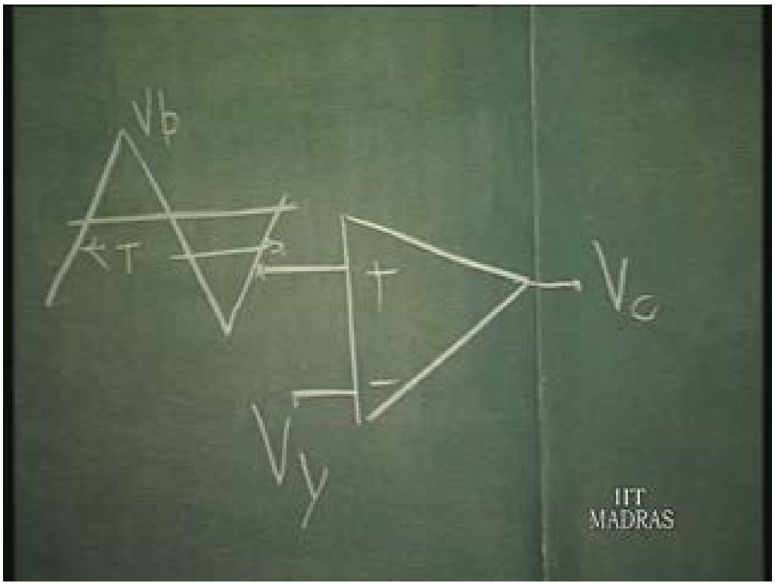

So, this is used for the switch. Then you can see that if I draw the triangle here like this and put V y here, somewhere here, this is V p and this, during this period, the output of V c is going to be high; and during the rest of the period, it is going to be low. So, by using similar triangle principle, this is actually what is going to be, V c. This is going to be high and low. Let us call it minus V s and plus V s. So, this width we will call it as tau. Then automatically, this is going to be T minus tau.

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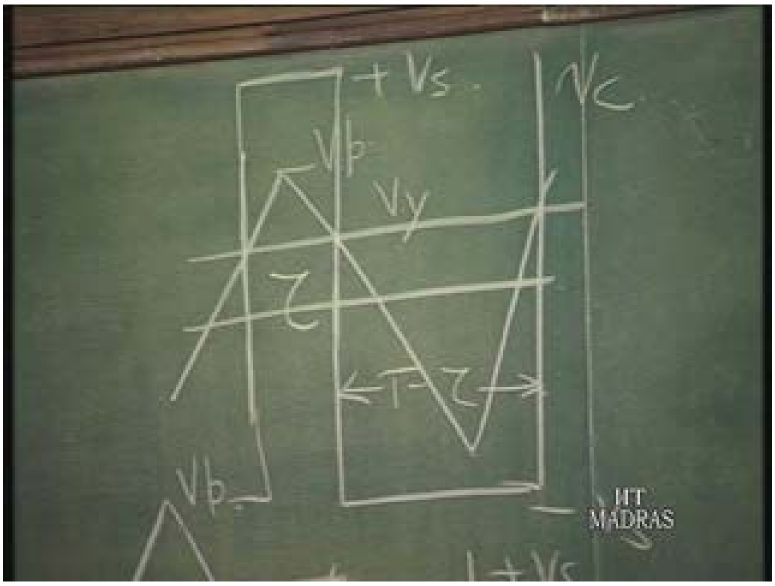

So, if this is tau, then using the similar triangle principle here, V p divided by T by 2, this is T by 2, that is T by 2 in this triangle is same as this height divided by this. That height is V p minus V y divided by tau. Once again, using similar triangle principle for this triangle as well as this triangle, this height which is V p divided by T by 2 is same as V p minus V y divided by tau.

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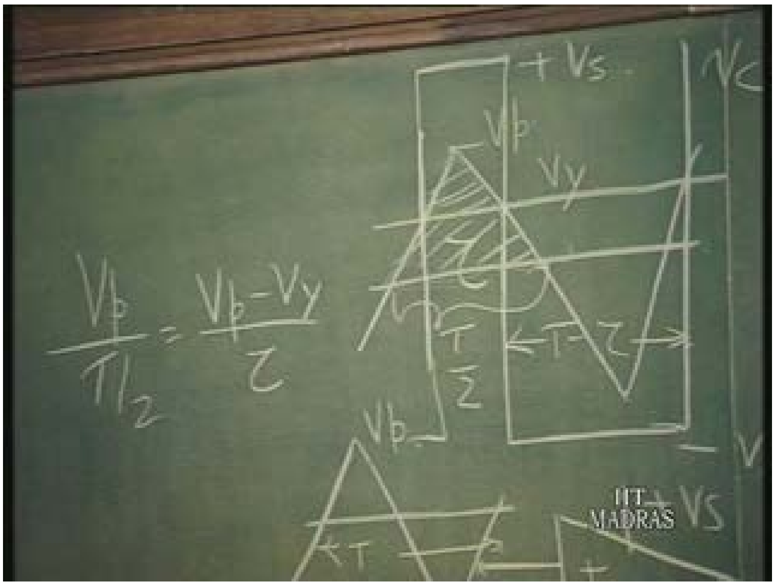

So, it is this you will get 2 tau by T, 2 tau by T, equals 1 minus V y by V p; or 1 minus 2 tau by T is equal to V y by V p.

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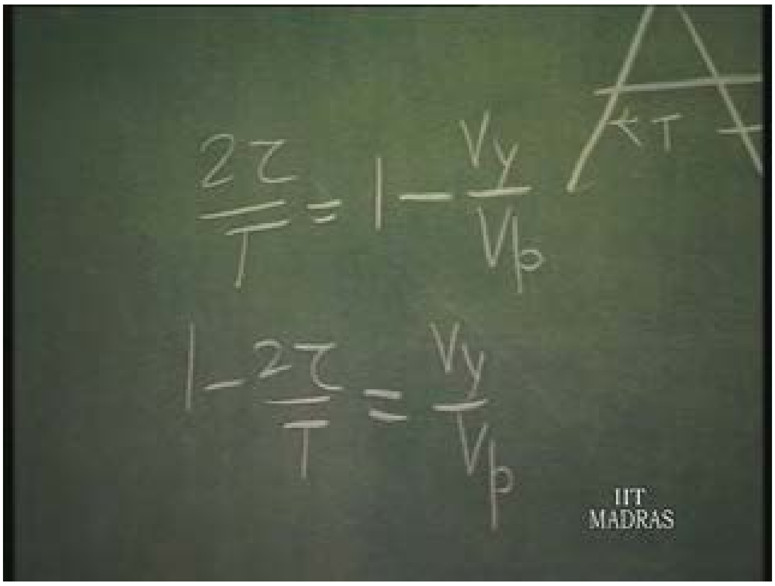

So, you can substitute this, that and you get this as minus V x V y by V p, which is exact multiplication of two voltages.

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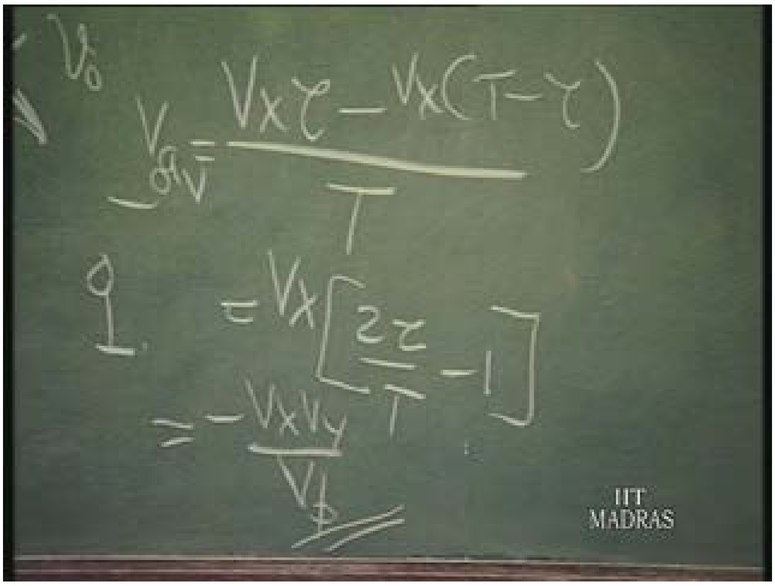

So, this basic principle uses a comparator, a triangular waveform generator and V x and V y and switches. So, we get exact multiplication without the property of the device, active device being used. So, this is very accurate because it uses only switches and comparators. The pulse width and amplitude modulator type of multiplier that I had just discussed is also a four quadrant multiplier where V x and V y can be taking any polarity.

However, since V y is the waveform which is switching V x and the average is to be taken, the switching frequency should be much higher than the frequency components corresponding to V x; and therefore, this is to be used only for low frequency application because averaging is required to wait for the product output to be got.
Once averaging is involved, you have to wait until the average is created for you to get the accurate value of the product. So, this particular circuit is usable only for low frequency application.

The final multiplier which now is going to be popular is using field effect transistor. We had already used bipolar junction transistors and their basic properties in designing multipliers; the translinear principle and the Gilbert’s gain, so on. Now, how do we use FETs and their properties in order to design good multiplier?

We know that FET is a square law device. What does it mean? The current of a FET is going to be, let us say, K times V G S minus V T whole square. This is the enhancement type of field effect transistor that we had discussed in the early part of our lecture. I D the drain current, drain to source current is equal to K times V G S minus V T; V T is the threshold voltage.

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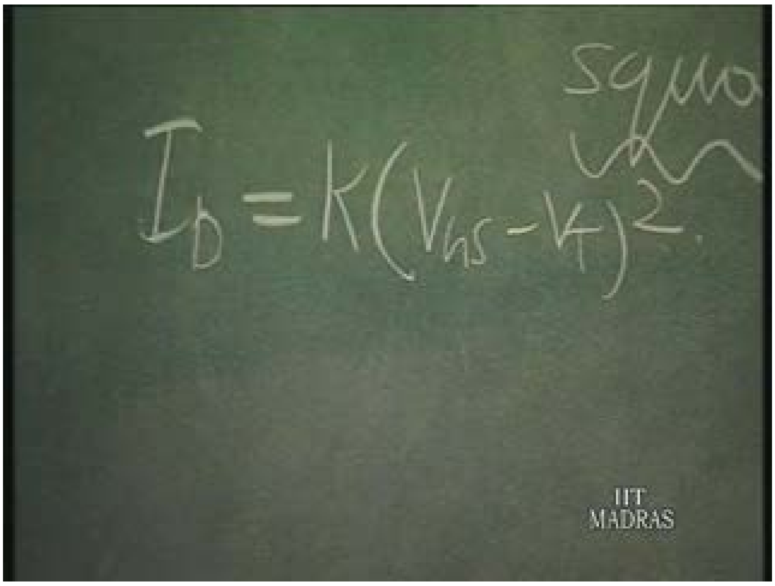

So, this square law principle...how can we use in designing multipliers? One way is we know that basically if we have V x plus V y whole square minus V x minus V y whole square, some voltage squared is coming anyway and V x plus V y whole square minus V x minus V y whole square, if you get the output in the following fashion, then, that divided by, let us say V R, because that is a voltage. So, if we do this, then we will get V x squared and V y squared cancelled. We get 4 V x V y by V R.

So, in all multipliers based on the principle of using field effect transistor, the square law device, that is the Multi FET, Moss FET or Junction FET can be used in order to obtain this kind of structure where, let us say V G S of a pair of field effect transistors, because V T has to be cancelled, could be V x plus V y and another pair has V x minus V y. The currents will be now correspondingly proportional to V x plus V y square and V x minus V y square; and then we can subtract the current by using a node.

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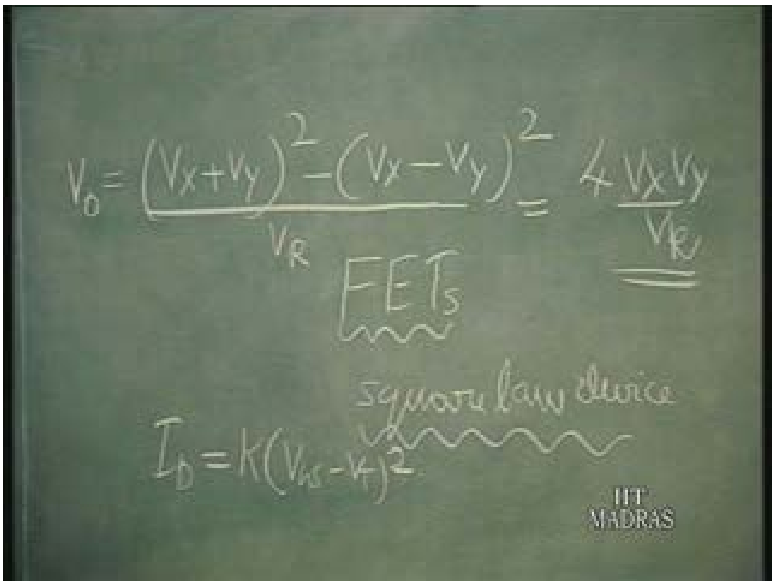

So...and you can get a multiplier as an output. This is one method. Another method is a field effect transistor I D is equal to 2 K times V G S minus V T into V D S minus V D S squared by 2. This is in the triode region. That is, when V D S is less than or equal to V G S minus V T, this relationship is valid. This is valid when V D S is greater than or equal to V G S minus V T; that is in the current saturation region. This is called current saturation region. So, if the...if the field effect transistors are used in the current saturation region...

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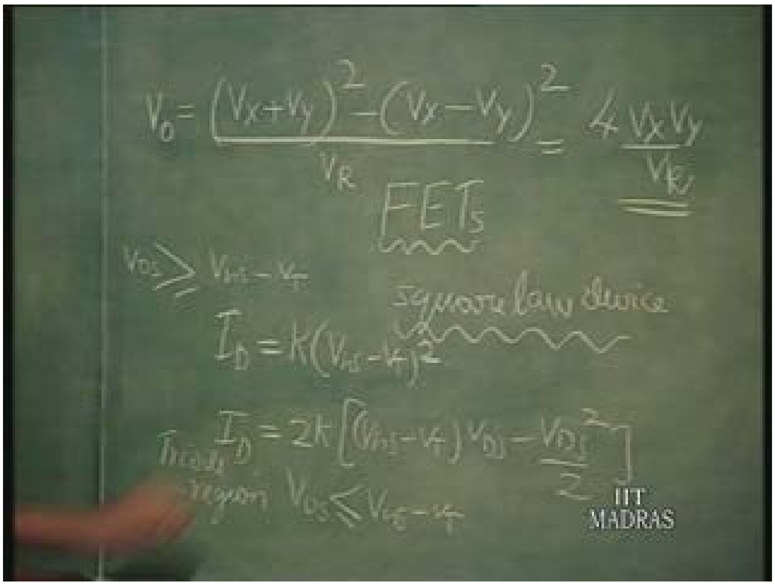

In the triode region on the other hand, it can be used as a voltage dependent resistor. So in the triode region, it can be used as a voltage controlled resistor, V C R.

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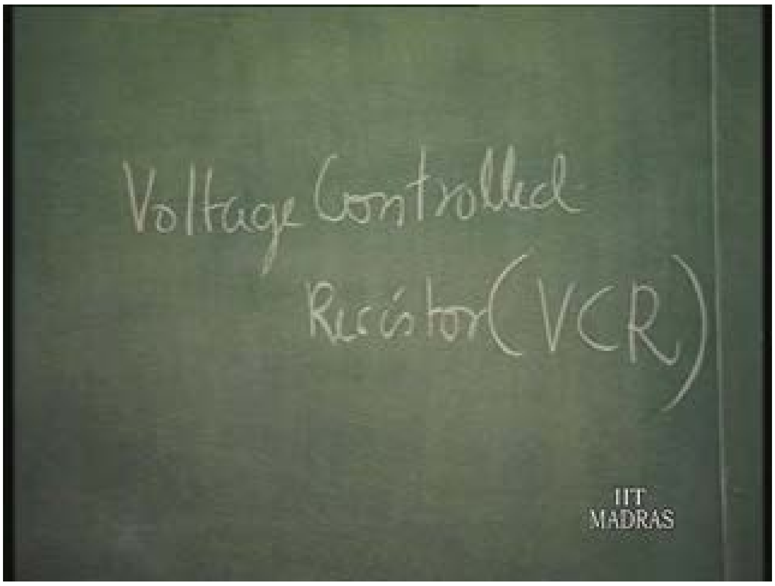

That is because I D is equal to 2 K into V G S minus V T into V D S, if I ignore the square law term there. That means if V D S is very low, I can ignore the V D S squared by 2. V D S is much less than V G S minus V T. I can ignore V D S square by 2 and say that it is a linear relationship between I D and V D S; or Delta I D by Delta V D S is nothing but 2 K into V G S minus V T. For V D S which is much less than V G S minus V T, this is valid. Or, it is a resistance; or D S which is equal to 1 over 2 K into V G S minus V T.

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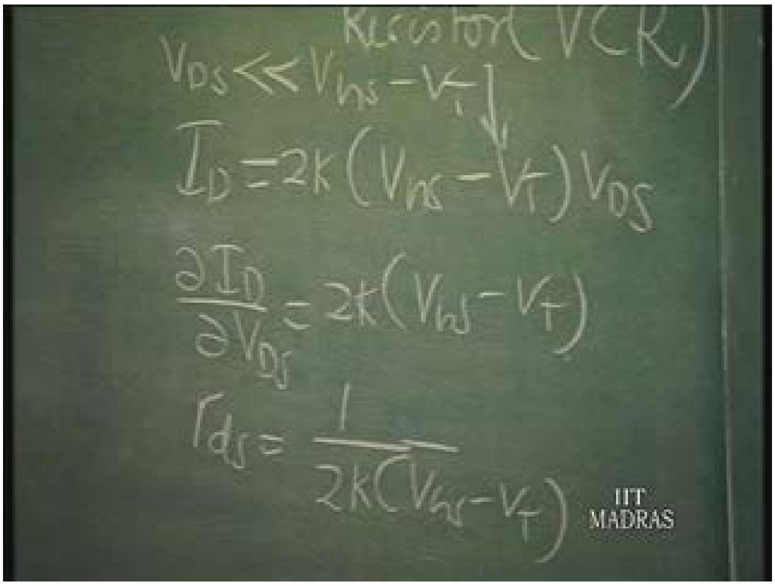

So, it is a voltage dependent resistance. This is...this property is used in a large number of applications where we need voltage dependent resistance; but the condition is, V D S must be much less than V G S minus V T. Why should we have this condition? Why can't we compensate for this non-linearity? Why... How can we get rid of this V D S square by 2? That can be easily done if you now see that the F E T is going to be used in the following manner.

This is V D S and this is V G S. This is G. So, I take part of the V D S and feed it back. That part of V D S I take to V G S, is going to be V D S by 2 R and R output. So, I put a control voltage here. So, now V G S here... V G S in this case, is equal to V C plus V D S by 2 because I have put a attenuator R and R. So, it is V D S plus V C by 2.

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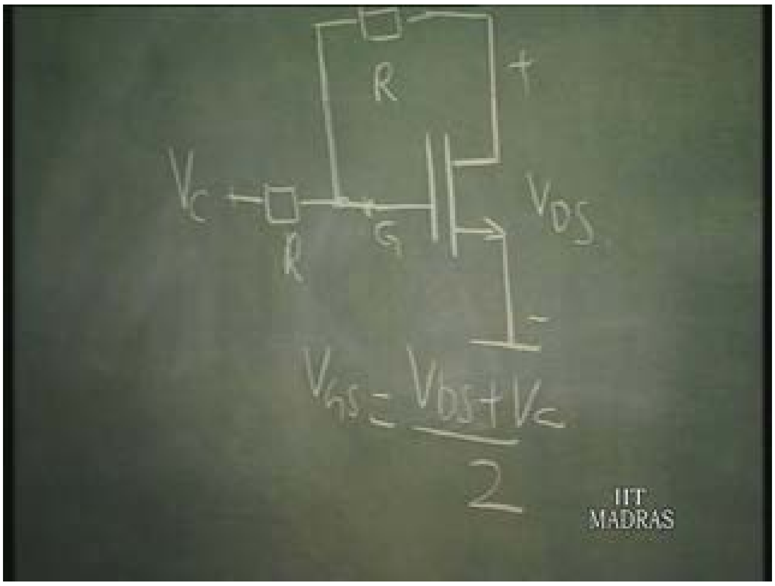

If I do this and substitute in the earlier expression, triode region expression here... Let us do that. I D is equal to 2 K times V G S. V G S is V D S plus V C by 2 minus V T into V D S minus V D S squared by 2.

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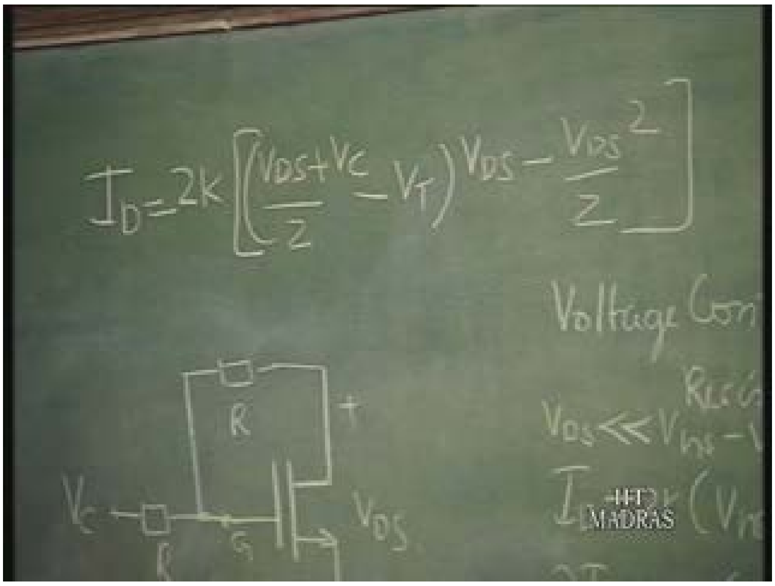

So, you can get this V D S squared by 2 cancelled exactly and you get a linear field effect transistor which is usable in a range which is V D S less than V G S by minus V T; not necessarily much less than. So, in that region, triode region, you can straightaway use it as a linear voltage controlled resistor; linear in the sense the conductance, conductance is linear.

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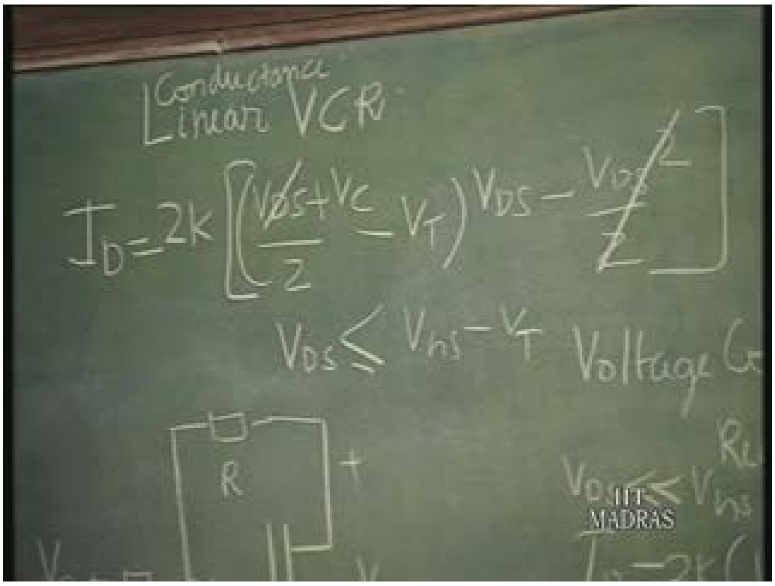

So, conductance which is 1 over R D S in that case is simply equal to 2 K into V C by 2 minus V T. This is the conductance. This is simply I D by V D S; it is not Delta I D by Delta V D S in that case. Simply I D by V D S is conductance. It is linear.

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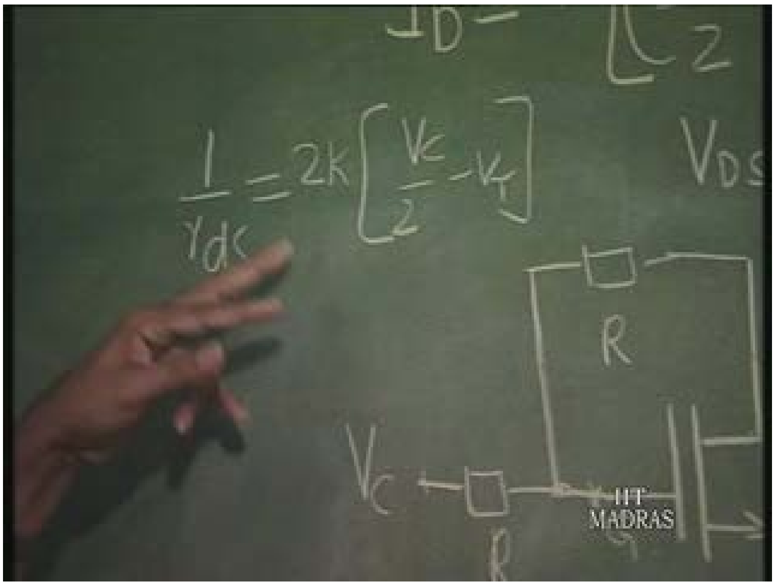

So this conductance, if it is used in designing amplifiers... For example, if I use this as my, let us say conductance for amplifier design, let us say I am going to use this in designing an amplifier like this. R. So, what happens to this amplifier now? This is V naught, this is V i. V naught over V i in this amplifier is nothing but... This is a non-inverting amplifier. 1 plus R by R D S...R divided by R D S. 1 plus R by R D S is the gain of this non-inverting...R D S is nothing but 2 K into... 1 by R D S is nothing but 2 K into V C by 2 minus V T. That is all. So, this is the gain of this.

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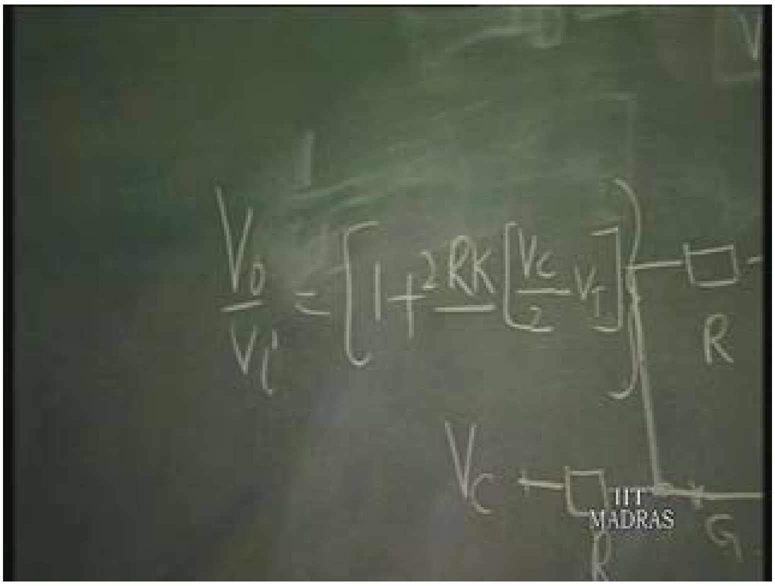

That means it is now a linear voltage controlled amplifier. The gain of this amplifier V naught over V i is directly proportional to V C. So, that means V naught is going to be 1 plus 2 R K into...we will call this as, let us say V y by 2 V T into V i which is V x. You get therefore the product of V x and V y here.

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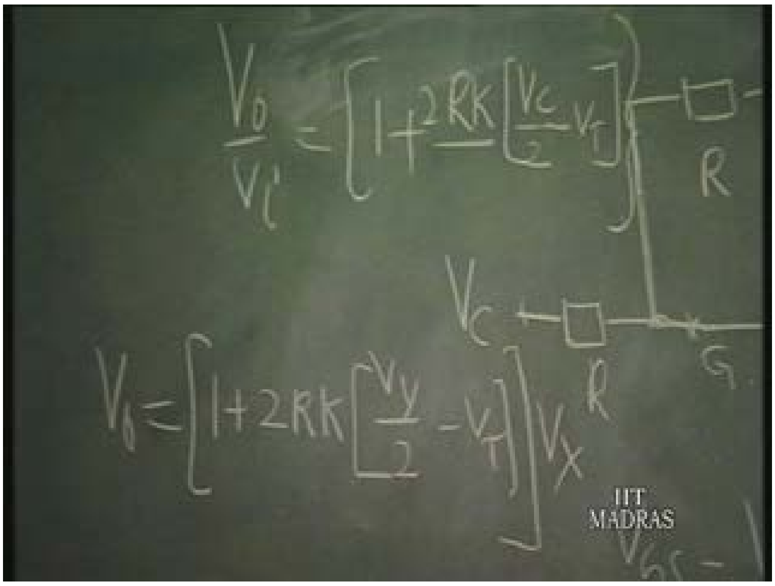

V i is equal to V x and V c is equal to V y. So, you get a multiplier and of course a non-ideal multiplier. You can actually remove this feed through component by using another subtractor. So, we can remove the feed through component which corresponds to 1 minus 2 R K V T into V x. So, this has 1 minus 2 R K V T into V x. That is the feed through component and, plus 2 R K by 2 into V y V x. This is the product component.

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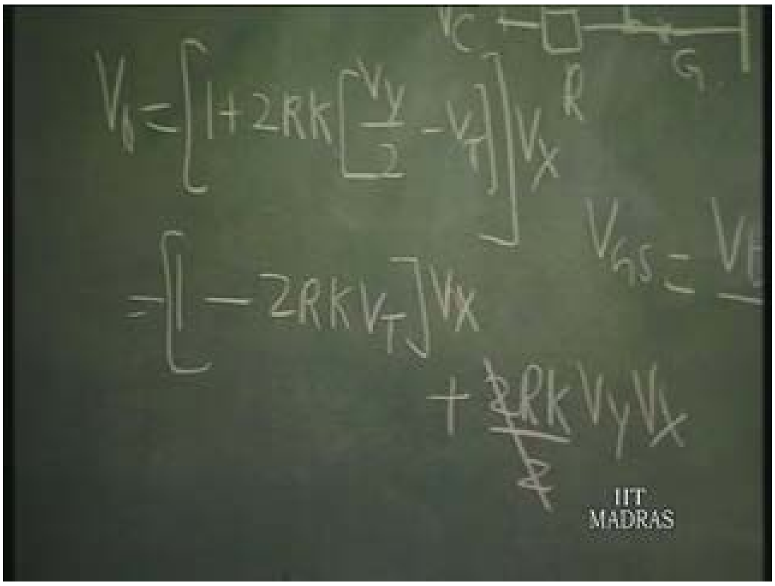

So, we can get rid of this by using a subtractor. We can design multipliers using such voltage control amplifiers also wherein a field effect transistor is used as a resistor. So, this can be easily done and multipliers of this type are commonly built in discrete circuit design.

This is another interesting circuit which uses FET in the triode region as a resistor, as multiplier. Let us see how it works.

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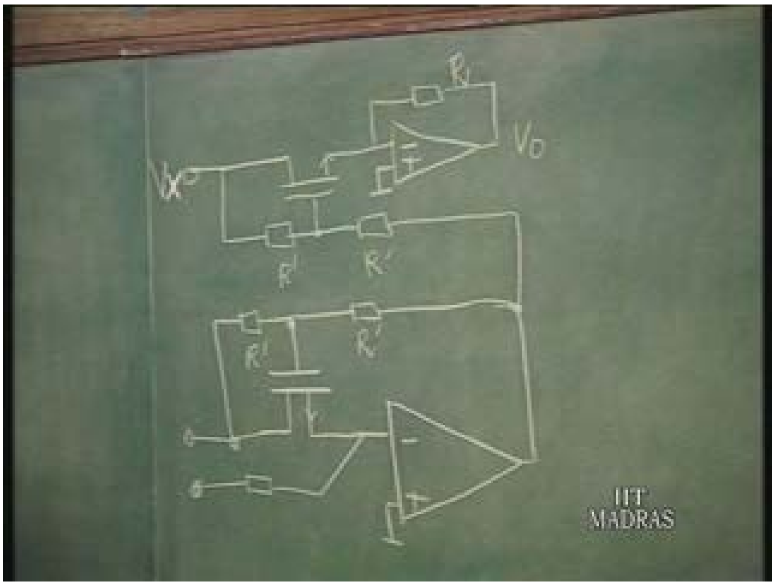

There are...the requirement is that these two FETs should be identical in their characteristics. That means the...for the same gate resource voltage, these two FETs will give the same value of r d s.

So, that is, Ks are the same, VTs are the same. So, if that is the case, this is a circuit which will also do the multiplication. We can see that this, if it is V x and if we put a resistance here and this stimulates an r d s, then V naught is always equal to...it is a non...inverting amplifier. So, minus R divided by r d s times V x. V x can be positive or negative.

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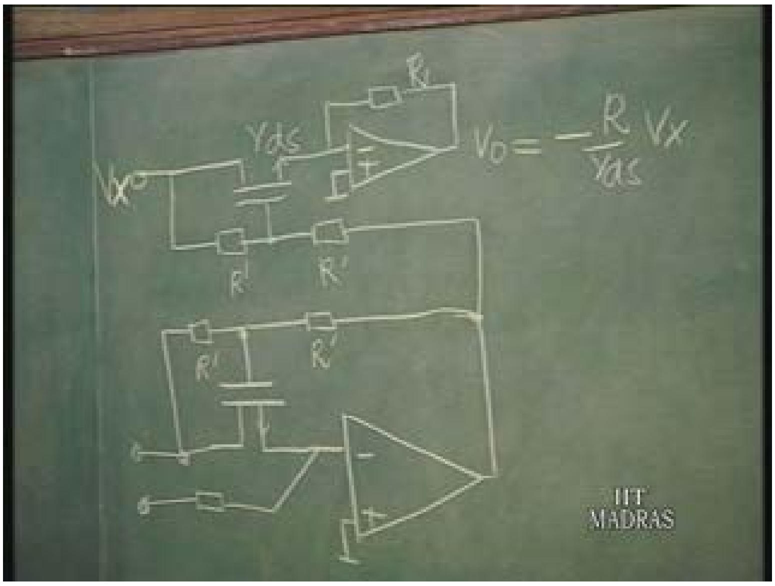

This field effect transistor is used once again in the triode region and these are the two resistors which are coming as linearizing resistors which will give you v d s by 2 in addition to the control voltage V c by 2. So, this is for linearizing. V naught is equal to minus R by r d s into V x. Now, the r d s itself is fixed by another voltage here. Let us call this V a and V b.

So, if this, let us say R, there is a negative feedback structure here and if it is negative feedback and this is grounded, this will be grounded. So, the current in this is V b divided by R and this is at zero volts. So, the current has to go out here. One requirement is that if this is positive, this has to be negative. If this is negative, this has to be positive.

These two should be of opposite polarities because this current is going and this has to be coming out from this. So, if this is V b by R, the current here is going to be the same as V b by R. Therefore, the resistance, if it is V a divided by r d s in this case, V b by R should be same as minus V a by r d s or V b by R plus V a by r d s should be zero.

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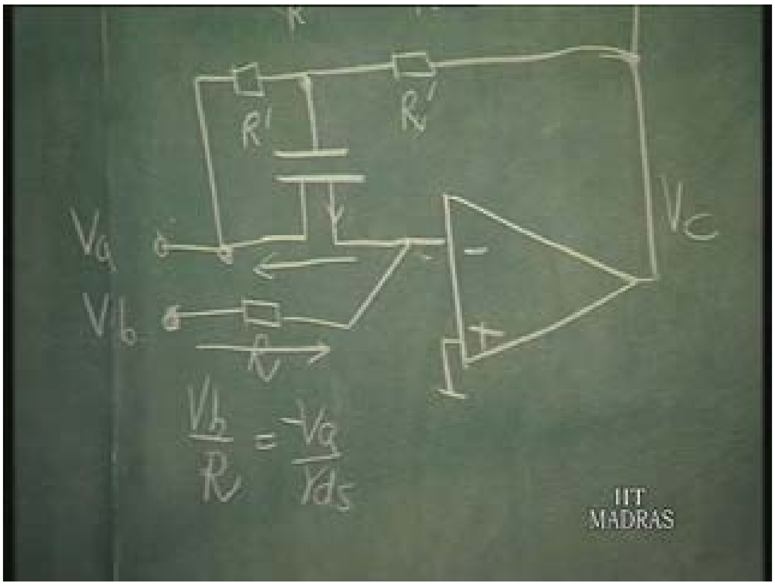

So, that means actually r d s is going to be fixed by this negative feedback circuit in such a manner that whatever current goes, since this voltage is fixed, this r d s will adjust itself. That means this V c will change in such a manner as to adjust this r d s to satisfy this relationship, as long as we provide a positive and negative or negative and positive voltages here. So, r d s is going to be therefore equal to, let us say R by V b into V a, with a negative sign.

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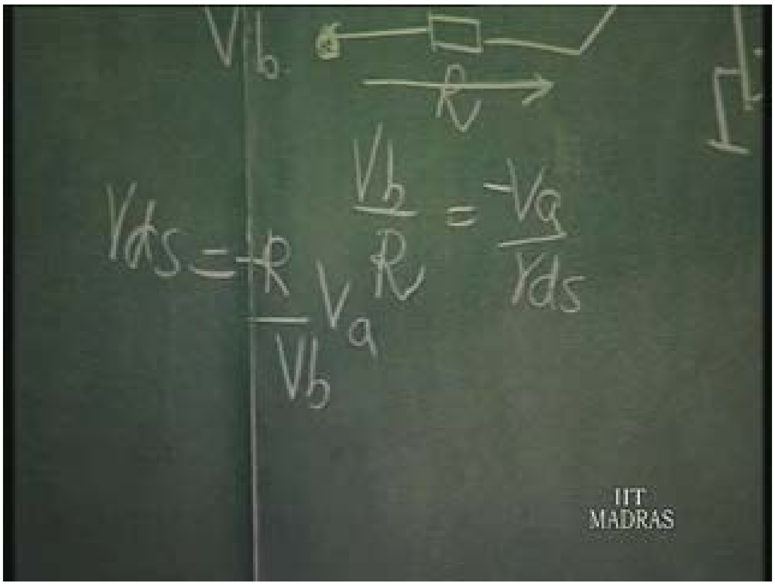

Now, this we can substitute there if that r d s and this r d s are one and the same because they are getting the same control voltage... So, since they are getting the same control voltage, this r d s is same as this r d s. And therefore, V naught is going to be equal to minus R V x divided by...here minus R V a. So, you get V x V b divided by V a.

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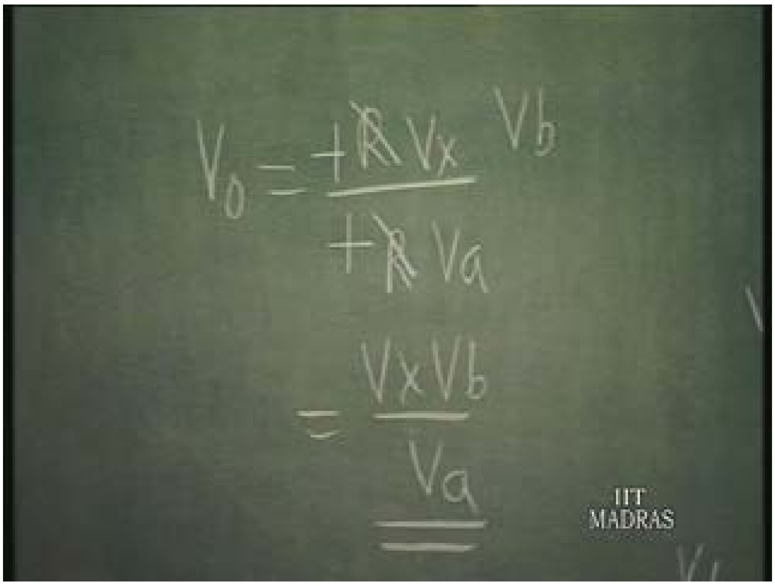

So, if V b is V y and V a is V R, we get a multiplier here. If V b is V y and V a is V R, we get multiplier. If V b is V R and V a is V y, we get a divider. So, this scheme gives you both a multiplier and a divider.

The condition here is, it is a two quadrant multiplier because V x can take both polarity plus and minus; whereas, if V b is V y and V a is fixed as a D C voltage which is positive, V y can only take on negative values. So, this is a two quadrant multiplier. That is something that you have to note. Again, if it is a two quadrant, it can be made a four quadrant by proper biasing and feed through and then eliminating the feed through component later.

So, these are the basic principles of multipliers that are used in a variety of circuit amplifications. In the next class, we will discuss how this multiplier, which is voltage controlled amplifier, can be used in what is called as automatic gain control circuit and amplitude stabilization of oscillator; automatic gain control or automatic volume control circuit and amplitude stabilization of oscillators. What is the basic principle?

We can see here that I have an amplifier whose gain is going to be controlled, let us say. This is the practical amplifier. This is the circuit that we had just now seen. So, V naught, this is V i; V naught or V i depends upon the gain here which is in turn controlled by V c.

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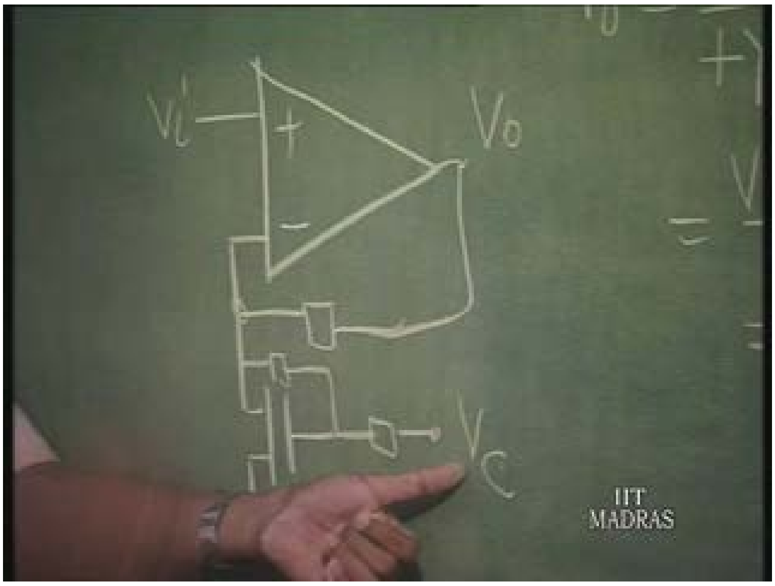

This structure we had earlier seen. Now I want to maintain V naught constant irrespective of V i. So, I have to... I have a means of finding out whether V naught is varying or not. So, I will sort of rectify and filter this sine wave and I get an amplitude information from that. That I compare with the reference. If it is, let us say higher than what I want, I reduce the gain; if it is lower than what I want, I increase the gain. So, this gain is controlled so that whatever be the value of input voltage, output remains constant.

That is what is meant by automatic gain control or automatic volume control. That requires obviously, a multiplier or a gain control amplifier.