Analog ICs

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Lecture - 07
Cascode Amplifier

In the last class we saw something about white band amplifiers. The basic principle being that the time constants at the ports must be made as small as possible. What it means is, the resistive component into the capacitive component which is forming the time constant at each of the ports of these amplifiers should be made as small as possible. That is achieved by using, in the case of load and drive requirement we can say that the drive is the voltage source then the load should be an open circuit load. That is, impedance mismatch between the source impedance and the load impedance.

Likewise if the drive is the current source then the load impedance should be short circuit because source impedance is very high. So impedance that is of the drive source is high then it is to be connected to a load which is low. And when impedance of the source is low it is to be connected to a load which is high. That is what is meant by impedance mismatch and consequent effect is that the time constant is at all times going to be low because either by the source impedance or by the load impedance it is going to be kept low.

The capacitance being the same in all these cases, by suitably having this choice of source and load appropriately that is mismatching the source and the load we can achieve white band. What is the ideal source? An ideal source is voltage control voltage source and current control current source. Voltage control voltage source using single transistor is nothing but common collector stage. So, if you are talking of common collector stage connected to a load then obviously it is going to result in a load time constant and therefore automatically a common collector amplifier is a white band structure. Why? It is near voltage control voltage source ideal, and therefore its source impedance is going to be very low, it can be connected to any load and therefore it is going to be a white band structure, this is common collector.

What is the other single amplifier stage which is near ideal? It is the common base, why? It is a current control current source and automatically because its input impedance is low output impedance is high and the current gain is at a stabilized value. In the case of voltage control voltage source which is common collector its input impedance is high output impedance is low and voltage control voltage source gain is stabilized to 1. Therefore we know that common collector stage and common base stage are single stage white band structures simply because they cause impedance mismatch to any source and any load connected to them.

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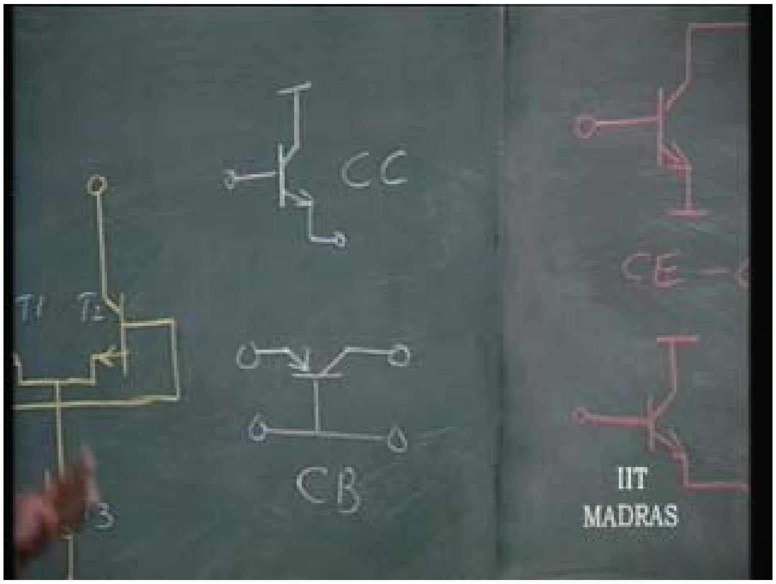

We already discussed about how common emitter results in a white band structure when connected to common base; how the Miller effect capacitor is reduced and so on. It is because of the fact that the common emitter now drives a common base and there is impedance mismatch occurring at the intermediate point resulting in reduction in the input time constant. Hence, this structure was named cascade.

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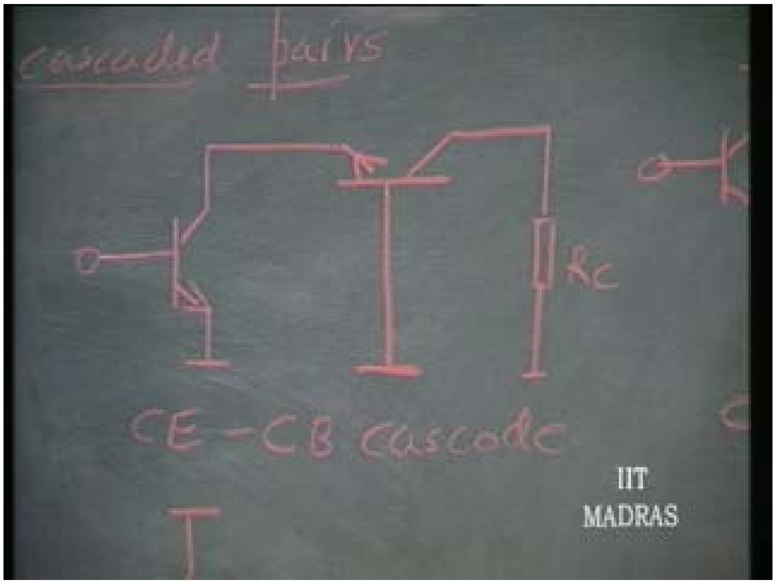

This is an important white band structure which retains the low frequency properties of the common emitter amplifier as such but as a good high frequency property. Like this we can cascade single stages of different categories. Common emitter is cascaded to common base results in cascode structure.

Common collector can be cascaded to common base, each of these being white band structures. At the input and the output they retain the property of mismatch because at the input it is high input impedance and at the output it is high output impedance. Therefore impedance mismatch is possible but at the intermediate point there is perfect matching. If you see the intermediate point the common collector output impedance is RE and the common base input impedance is RE.

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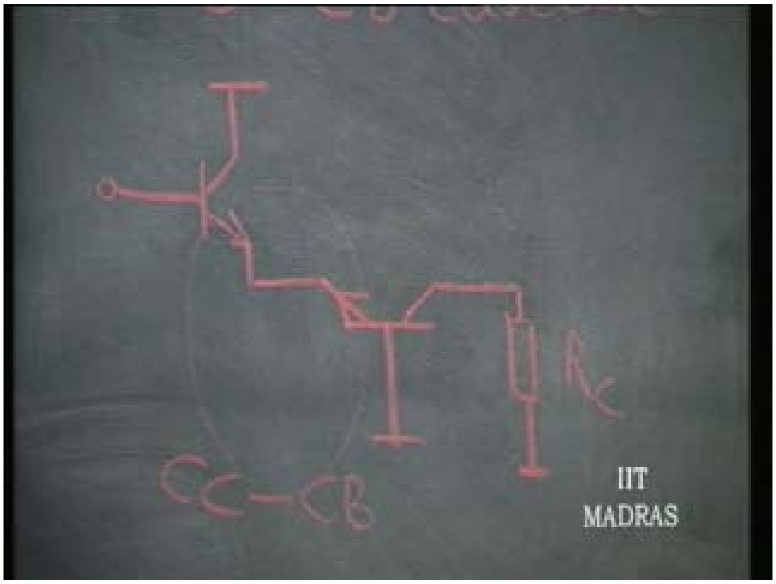

There is impedance matching. Fortunately impedance matching occurring with low impedance will result in again not much reduction in gain but the voltage gain is going to be reduced to half. So the gain is reduced to half but the time constant is going to be retained very low. So this still retains its white band structure which originally had simply because it is a cascading of common collector which is a white band structure with common base which is a white band structure. But gain reduction has occurred because of impedance matching occurring at the intermediate point and the gain reduction is by R. So, the gain of this stage is gmR_c by 2 and there is not going to be any phase shift between output and input. This is not a replacement for a common emitter amplifier at all even though this also is going to belong to a white band structure. This is actually the structure you are talking of, you might not be aware that this is the structure, this is the differential amplifier and I would like to use it as a white band amplifier.

What do I do? I simply connect this to V_{cc} and connect R_c here and feed input to this point. What happens now?
This is going to act as a common collector structure because collector is grounded and this is going to act as common base now. So how you are allowed to use a differential amplifier? It is not a differential amplifier but a white band amplifier can be very simply

seen here because the first stage is not used as an amplifier. It is used as common collector stage by connecting the collector to V_{cc}. If I had put the same resistance R_c it would have lost its what white band property simply because Miller effect will occur and make the time constant very high. So, by simply connecting this to this we have made it a white band structure which is nothing but a pair which is a common collector cascaded to common base.

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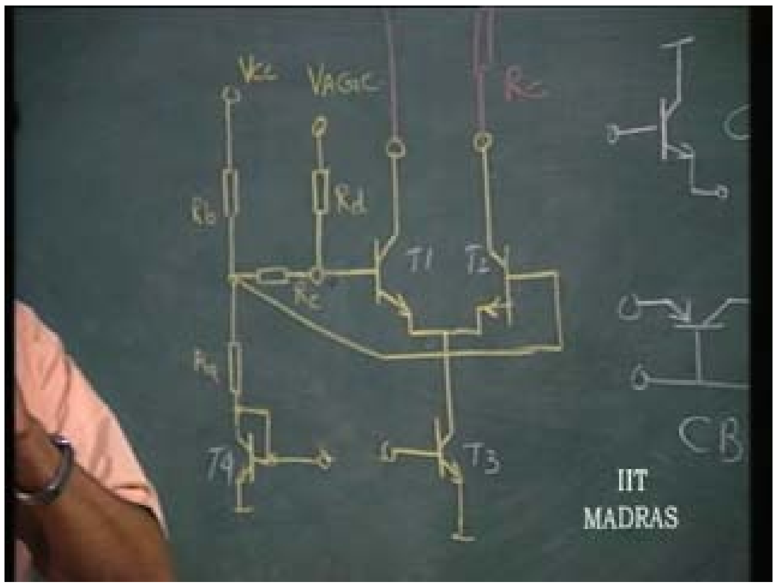

This is how it is used as this pair if you want. But it does not have the advantage. gain is reduced by a factor of 2 and not only that the AGC scheme is not going to be that convenient when I change the current here of this current source the input impedance and everything changes and the tuning gets disturbed, cutoff frequency gets changed giving rise to problems as such. So, if you are bent on using this structure as a white band amplifier in a differential mode of operation then you can connect this but still it is not as good as this. So in most of the white band applications this is the preferred structure compared to this. Then we have the other structure which is not that great because this is the same over common emitter amplifier but I am buffering this y by means of a common collector stage.

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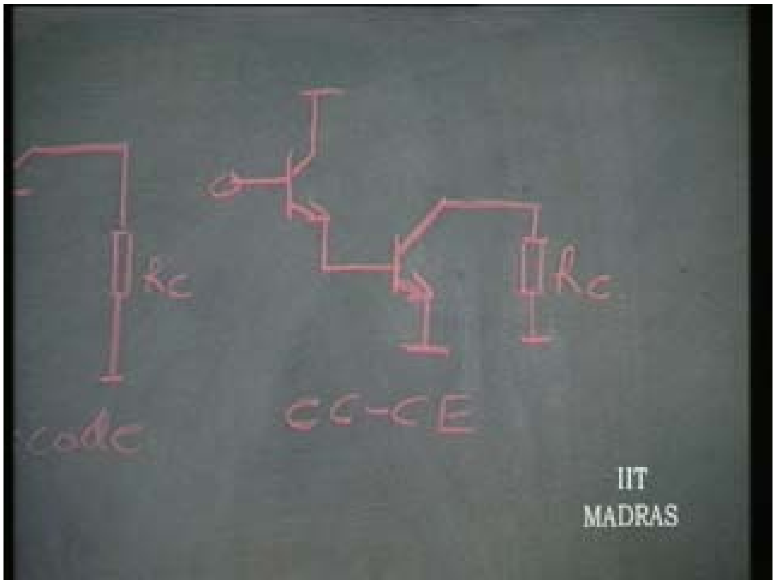

What it means is, the time constant here simply gets reduced because the source resistance here is artificially reduced by using a buffer stage. So the miller capacitor still exists here. But since you are driving it by means of an ideal voltage source it is going to have some kind of white banding effect. But again this white banding is not as much as the white banding achieved here. We are not talking of any feedback here, these are all structures without feedback.

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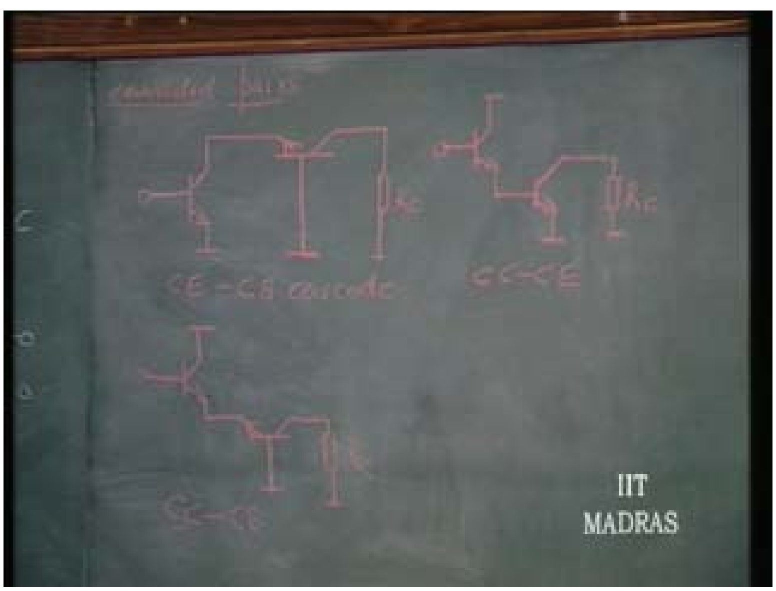

These cascaded pairs are structures without feedback. Feedback is a serious problem; negative feedback is a serious problem in high frequency operation. We are now talking of white band amplifiers, structures without feedback. They will give you the highest gain possible with highest bandwidth possible.

Coming back to the stage, this particular structure is going to be used as a common emitter cascaded to common base. For that externally I have to connect this like this. This current is going to be V_{cc} minus V gamma by R_a plus R_b; V_{cc} minus V gamma by R_a plus R_b that is the current going to be reflected as operating current I_0.

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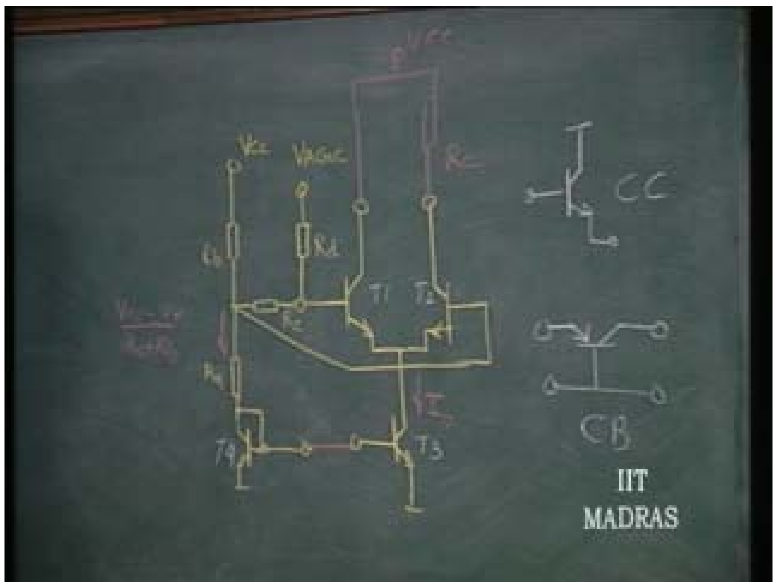

And the input can be fed through this in this following, capacitively coupled externally. So these are all external connections for this. Therefore since this has to be common base structure we are going to bypass this externally. This is its operation in cascode mode. Let us now see how this current is going to be in relationship to this current.

Actually I explained earlier that the input is now going to take current because this is common emitter this current is going to be extremely small but this is a diode so this is going to take away too much of input current. In order to prevent it this is what should we do?
We should put a resistance here as well as here, so a resistance is normally put when you are using a current mirror itself as a common emitter amplifier stage.

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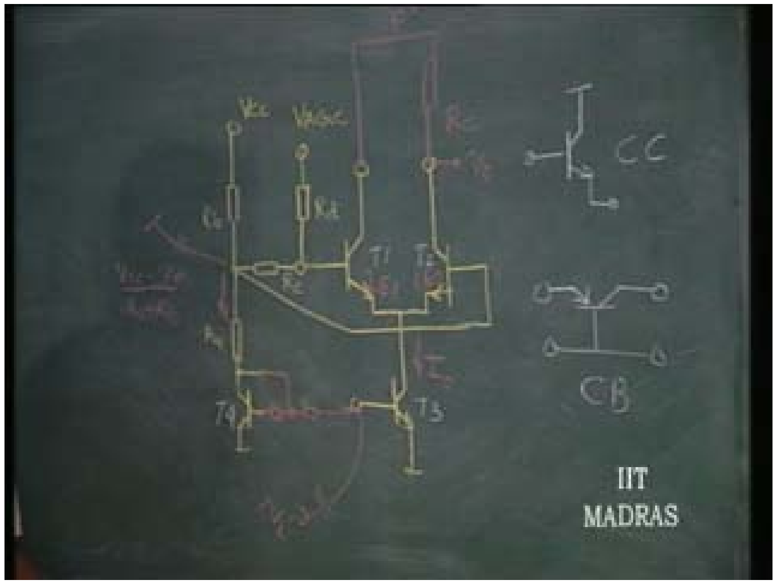

A resistance is going to be put here in order to prevent this current from getting drained away from the source, this is one way. If it is a tuned amplifier that is why these terminals are given for you separately then there is no such problem, what you do is simply connect the transformer between these two input transformer and connected this. This is the high frequency transformer that is connected so that this current mirror action still takes place without the help of the resistor but input is coming straight into the amplifier.

This is the transformer coupling as against the capacitive coupling that we can adopt. If you want tuned input and tuned output you can have the load here so this is nothing but something like RF amplifier or IF amplifier stage tuned input tuned output. So, the same white band amplifier can be very conveniently used as narrow band amplifier by making it tuned at the input as well as the output. So, mixers, RF amplifiers, IF amplifiers are simply designed using the input coupling and output coupling in the following manner. In such a situation when we have tuned amplifier or video amplifier or DC amplifier we can used this terminal as AGC terminals to control the gain.

We know that this V_{BE1} and this V_{BE2} form nothing but the voltage across R_c. So, exponent V_{BE1} minus V_{BE2} by V_T is nothing but I_{E1} by I_{E2}. This relationship we had derived earlier. The ratio of the emitter current is always equal to exponent V_i by V_T.

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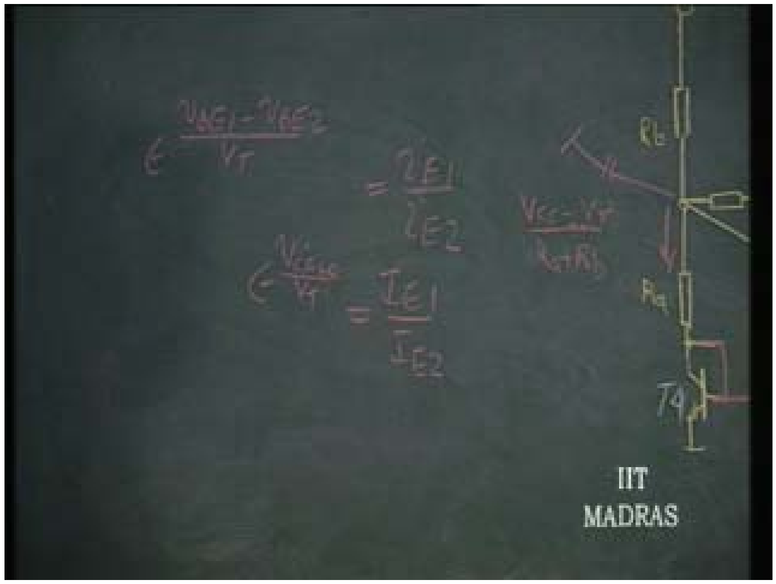

So I_{E1} by I_{E2} ratio, if it is a DC current is exponent V_i agc by V_T. This agc voltage is nothing but the voltage due to VAGC that is shared between this and this that is R_c by R_c plus R_d. So we have to see what kind of ratio we have to maintain here in order to transfer the complete current of this to this side and vice versa. So, I_{E1} by I_{E2} when it is equal to 0.9 we can never make it hundred percent.

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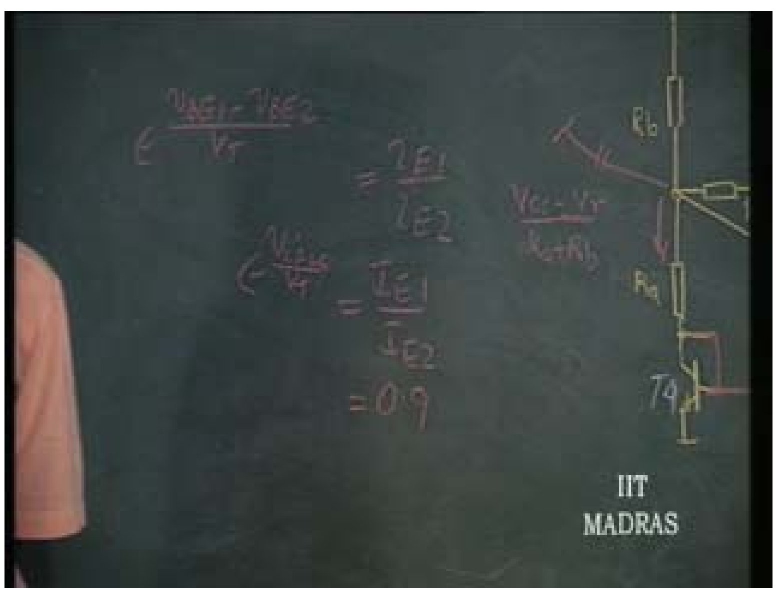

It is because this kind of voltage is going to be extremely large, so it is asymptotically reaching this value. If I_{E1} by I_{E2} is 0.9 then we say that one type of switching has taken place. Let us call this as Vagc1 corresponding to which the ratio of the current is 0.9 and exponent Viagc2 by V_T is equal to 0.1 corresponds to a voltage Viagc2 which is the value which makes this ratio equal to 0.1.

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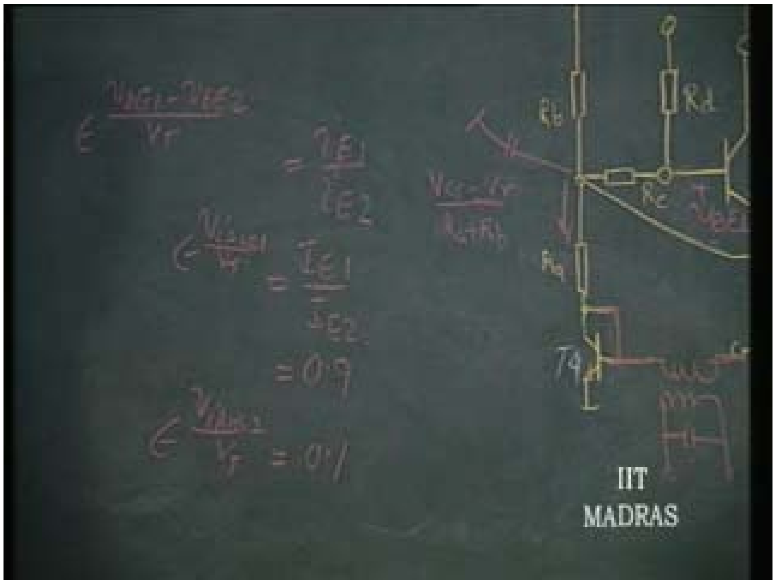

Therefore if you now take the ratio of these two it is nothing but exponent V_i Viagc1 is this. Viagc1 minus Viagc2 by V_T is equal to 9. That means, for making the gain go from its full value to zero value the change in agc voltage which is Viagc1 minus Viagc2 should be nothing V_T log 9 and V_T is 26 mV.

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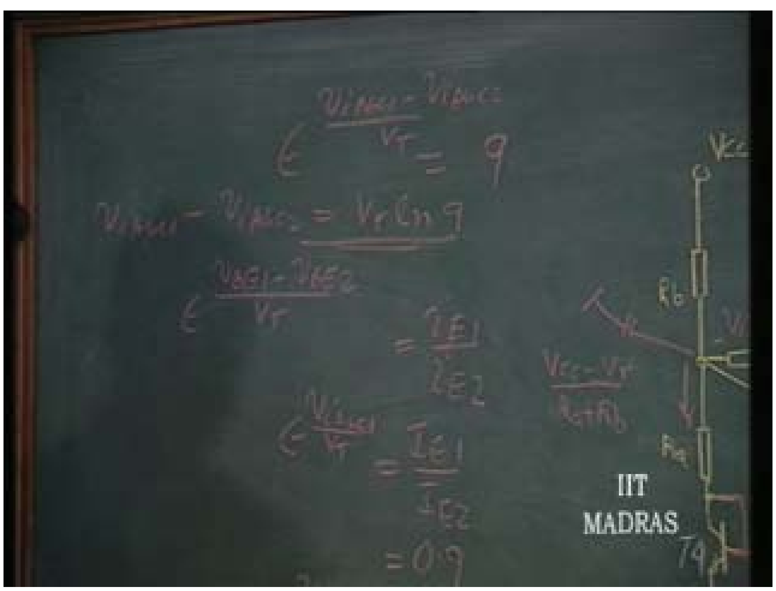

So you know the value for making the current switch completely from one transistor to the other transistor. This is the dynamic range of agc voltage between the two bases. This plus some k factor times is going to be the change in Vagc required at this point. That k factor can be obtained from this attenuator. This is how you can find out the dynamic range for the change in agc voltage in order to cause the gain of this particular stage to change from 0 to gm into R_c. Accordingly you can design your agc system so that the entire dynamic range is made use of.

So far we have been discussing about DC amplifiers, white band amplifiers etc. The same structure is always suitable for narrow band amplifiers at high frequencies. Narrow band amplifiers are required only at high frequencies primarily because they are going to act as the RF stage or IF stage of some of the structures where the information is contained in the modulated carrier. So it is the carrier frequency which is the high frequency and it is to be amplified. In such a situation automatically the structure will change here, the coupling is now a transformer coupling with a tuned structure at the input and another tuned structure at the output.

What is the parameter used for analysis of such narrow band amplifiers?
What are the parameters that will be used for the transistor for analysis of such white band amplifiers which are used in the narrow band mode?
For the white band DC amplifier we used hybrid pi equivalent circuit. What we use in the case of narrow band amplifiers operating on a restricted range of frequencies? It is always y parameter.

Not your h or others but it is always y. Always these limitations come about for high frequency application due to capacitors then capacitors simply add. The capacitive reactance is going to be such that the susceptances will be adding simply to the y parameters of the device. This is a very convenient mode of measurement as well as analysis. So universally for all high frequency amplifiers, narrow band amplifiers, why it is narrow band?
It is because only for narrow band we can say that y parameters will remain constant. Over that band we can assume that y parameter to remain unchanged with respect to frequency. So at the center of frequency you take the y parameter and use it over the band. Please remember that y parameters are chosen for the device.

Suppose we select cascode structure here what will be its y parameter?
Let us say it is Y_{11} so Y_{11} is the self admittance at the input port so what is it going to be?
It is going to be same as Y_{11} of the common emitter stage because input stage is common emitter, a single stage. As far as Y_{22} is concerned output is common base is going to be the same as Y_{22} common base. And what is it that is going to be Y_{21}? What is Y_{21} by definition?
Output current divided by input voltage what is the low frequency value? It is gm.

So it is the same as that of the common emitter because common base current transfer is simply unity. So Y_{21} is that of the common emitter and Y_{11} is that of the common emitter, Y_{22} is that of the common base and Y_{12} is going to be tending towards 0 because it is due to the reverse transmission of the common base and that of the common emitter and therefore this is going to be extremely small. This is an important thing.

In any narrow band tuned amplifier you must have Y_{12} as close to 0 as possible and there should not be any feedback. If there is feedback what you want to do? Now let us see what tuning is?
Y_{12} should be 0 therefore there should be no feedback. This should be only feed forward. We are not always talking in high frequency admittances, what is tuning now?
Impedance is infinity and admittance is going to be having zero imaginary part that is what is meant by tuning. Admittance is going to have zero imaginary part. So if it is going to have zero imaginary part at the input as well as the output what is the input admittance of this structure in general?
Input admittance is Y_{11} minus Y_{12} Y_{21} by Y_{22} plus Y_L this is the input admittance. Output admittance is, you just change 1 to 2.

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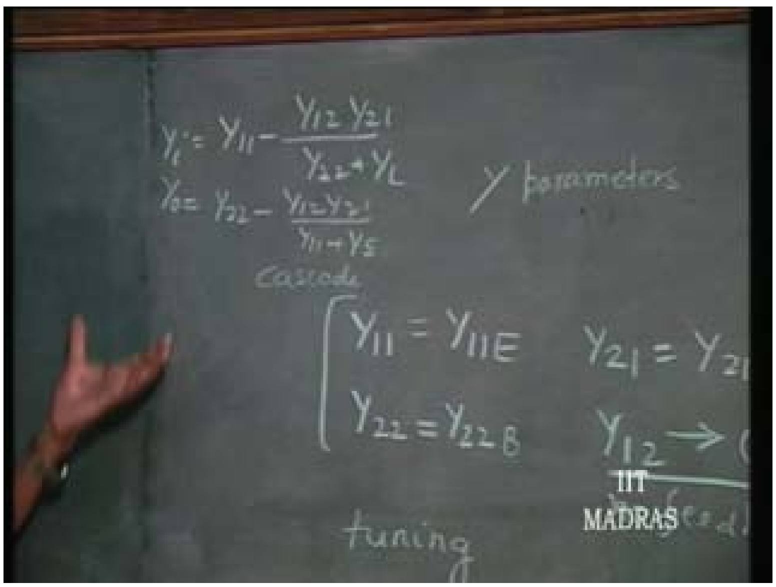

So you can see that, it is virtually impossible to tune input and output independent of one another. If I tune input then the output tuning will be disturbed and if I tune output the input tuning will be disturbed. This is mainly because of this not being equal to 0. So the moment this becomes equal to 0 tuning of the input and output become independent of one another. That is what is really achieved in the cascode structure that we have this y_{12} going towards 0so that Yi is essentially Y_{11} and Y_0 is essentially Y_{22}.

So what happens now? The total admittance Yi at the input port is going to be Y_{11} plus Y_s. In this particular case Y_{11} plus Ys because Y_{12} is equal to 0 and total admittance at the output port is going to be similarly Y_{22} plus Y_L because Y_{12} is equal to 0. So what does tuning mean? Here Y_{11} plus Y_s become purely real. Y_{22} plus Y_s become purely real. So we can just say that Y_{iT} because of this tuning becomes strictly speaking g_{11} plus g_s plus j (b_{11} plus b_s) tuning simply means this become 0.

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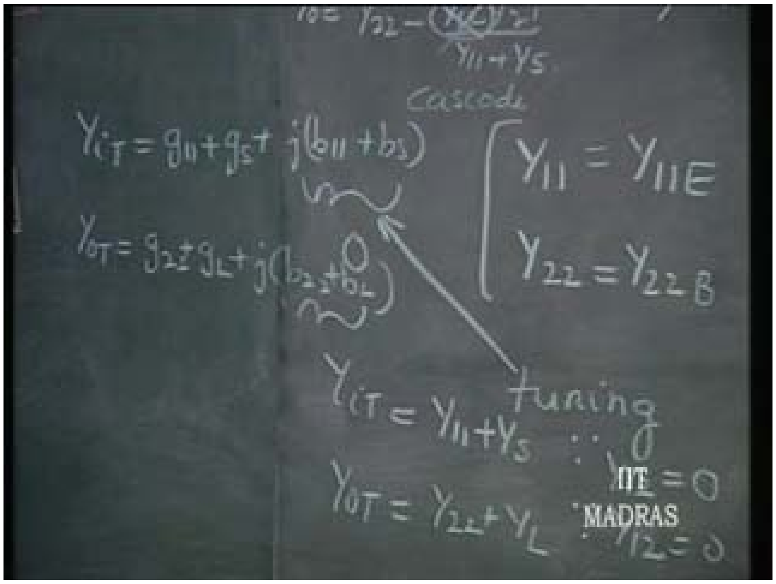

Similarly Y_{0T} is equal to g_{22} plus g_L plus j (b_{22} plus b_L) and tuning simply means this becomes equal to 0. Now this is important because in a design we should know what tuning means. Tuning means net admittance at the input port is real and the imaginary part is totally 0 that is what is meant by tuning. That will also help you in evaluating what the additional reactance or susceptance should be that is to be connected to the device in order to make this 0.

So, knowing the parameters of the device you will be able to find out what additional susceptance it is, it may be inductive or may be capacitive. It depends upon the range of frequency at which you are operated. Normally it is capacitive and therefore you have to provide inductive susceptance to cancel out the capacitive path, so this is what is done by tuning. In these tuned amplifiers particularly power amplifiers you would like to give as much of the source power to the input as possible. Similarly you would like to extract as much of the output power to the load. What you do then? You match it.

So, at that point of time we do matching. What does matching mean? In terms of this imaginary part we know that effective susceptance should be 0 that is when Y_{11}s conjugate is made equal to input admittance. Similarly, Y_L conjugate is made equal to output admittance. That means total admittances now will have the susceptances vanishing because you have made the conjugate matching. This is called conjugate matching for maximum power transfer. In such a situation what will be Y_i total?
On the conjugate matching this has been made equal to zero, this has been made equal to zero and now what will be the Y_i total? It will be $2g_{11}$ and Y_0 total is going to be $2g_2$.

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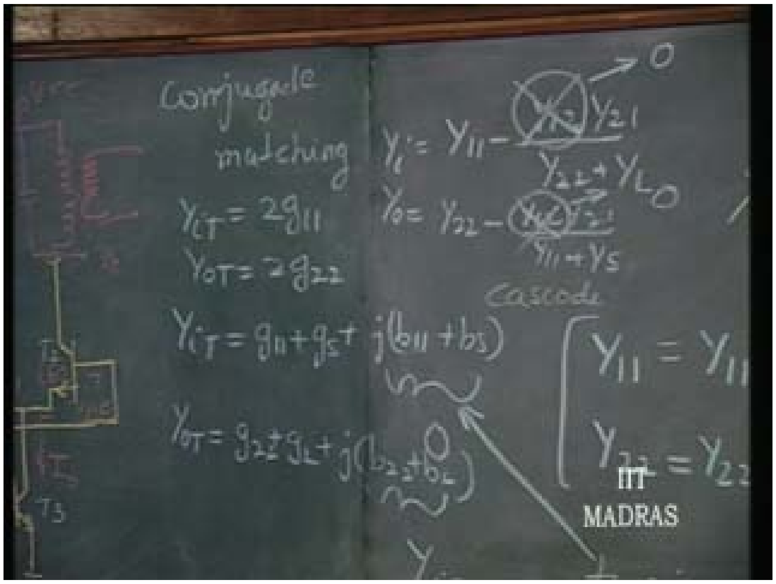

Under that condition the maximum available power gain is obtained from the device. This maximum available gain is called MAG is equal to Y_{21} mod square, how did it come?
In the gain you will see Y_{21} into Y_{21} conjugate comes, voltage gain into current gain so Y_{21} Y_{21} star so Y_{21} magnitude square divided by $4g_{11}$ g_{22} so that for a device under conjugate match conditions the maximum available gain from the device is going to be equal to Y_{21} mod square by $4g_{11}$ g_{22}, this is the power gain. And this is quoted by the manufacture of the device as the parameter of this high frequency transistor. So, for the transistor this particular parameter is going to be expressed as 10 log this value so that it is expressed in terms of decibels.

This is [p…..] by the manufacturer so if you are asked to design a power amplifier of 20 decibels power gain then if the device under consideration is going to have only 10 decibels power gain then you automatically know that the best of your design requires two such stages to be cascaded each giving you 10db, 10db power. So the number of stages required for achieving the required power gain can be easily computed once you know this particular parameter.

This is the parameter given by the device manufacturer for all these high frequency stages and this MAG as how it is referred is one of the most important parameter. Apart from that you should also know the value of Y_{11} and Y_{22} nominal values. Y_{11} is a factor dependant upon operating current and Y_{22} is a factor dependant upon operating voltage because Y_{22} will have Cb prime c coming into picture and Y_{11} will have the input capacitor Cb prime e coming into picture. These are going to be current and voltage dependant where therefore the manufacture has to give this with respect to operating current.

One parameter will be given as a plot with respect to operating current and this will be given as a plot with respect to operating voltage. So you can take the nominal data given by the manufacturer and design your tune circuit so as to achieve impedance matching. How do you do impedance matching?

You have the facility for nullifying this. If it is capacitive you will use inductive reactance so as to cancel out this. Apart from that you have to make g_{11} is equal to g_s, how do you do this? You use a transformer with a certain turn ratio. The turn ratio of the transformer is going to be selected in such a manner as to make g_{11} is equal to g_s and similarly g_{22} is equal to g_L. So turns ratio of the transformer both at the input and the output gets fixed once you decide that it should be a conjugate matching structure. So, this in brief is how you are going to design an RF amplifier or an IF amplifier or for that matter given a mixer. Hence, the mixer may have an input tuned to some frequency and the output tuned to the intermediate frequency.

In the case of mixer this particular gain is called conversion gain because it is, from one frequency to another frequency it is getting converted, the information is getting converted. So you do not call it gain but you call it as conversion gain in the case of a mixer. After you do the design you will also see that the agc is also working properly at the situation where Vigc potential is same as this potential, the gain is half the original gain. This is as far as the voltage gain is concerned which is half the original gain.

And on either side of that voltage this Vig should be capable of going so as to make the gain change all the way from 0 to its full value. Therefore this agc voltage is going to be derived from the detector which is normally placed after the IF stage. The detector is placed in order to detect the modulating frequency. So the modulating frequency is fed to the power amplifier and the DC derived which is dependant upon the amplitude of the IF is going to be the Vigc that is fed to this. Therefore it should be varying around the quiescent value on both sides and that is how you have to design the entire system of IF type or IF RF amplifiers.

These are all structures without any feedback. Feedback in all these situations is going to cause serious problem for us regarding impedance matching etc.