Analog ICs
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Lecture - 6
Video Amplifier and RE by IF Amplifiers

Today we will be continuing our lecture on differential amplifier. In the last class we saw something about the DC amplifiers. Actually we said, the offset is an important parameter which has to be compensated for properly by doing good matching. And we saw something about delta V_{BE} matching as for as bipolar transistors are concerned, equivalent term for MOSFETs will be the delta Vgs mismatch. So offset can arise due to delta V_{BE} as well as delta Vgs. Further we set offset can also arise because of bias current mismatch. And the compensation for this can be taken care of to a certain extent in the circuit design. This is your responsibility as an application engineer to select the input stage properly for a DC amplifier.

DC amplifier should have low input offset whatever it be, either the voltage or the current, depending upon the type of source you are using. So it is important that you should know what kind of source you are using and based on that you will select the input stage properly and then estimate the effect of offset and compensate for it by designing that particular circuit properly. We will see how such compensation can be effected in specific applications later on when we discuss application problem. So, that part is regarding low frequency amplifiers or DC amplifiers where the output offset and the resultant drift duet to offset is the primary problem that should be avoided as much as possible.

In fact we have a fairly complex mechanism of what is called trimming the transistors, this is a technology process. You can laser trim the transistors so that delta VBE offset can be made very small much less than the normally expected 1 to 2 mV. So you would see the advertisements etc, laser trimmed low offset low drift amplifiers. It means this delta V_{BE} has been trimmed after the device gets manufactured so that output offset is minimized, then the drift effect is going to be minimized. But obviously since you are giving particular attention to each amplifier the cost of the amplifier goes enormously high. So it is better to get a circuit configuration basically wherein the inherent offset itself is the lowest possible if you are thinking of designing DC amplifiers.

Today we will further discuss other special purpose ICs based on the differential amplifiers. We have specific integrated circuit manufactured by particular national semiconductor. Let us see how this particular stage can be used for a variety of applications. Before we go to that particular IC I would like to discuss in general about white band amplifiers. What is the basic theory behind white banding and how RF and IF amplifiers which are narrow band amplifiers at high frequencies can also be designed once we understand about white band amplifiers?

We are now discussing the theory of white band amplifiers. Let us consider the common emitter stage which is the amplifier and it is having the collector load which is the AC load. It might also involve the input impedance of the next stage or actual load in parallel with the collector load. This is the basic common emitter amplifier.

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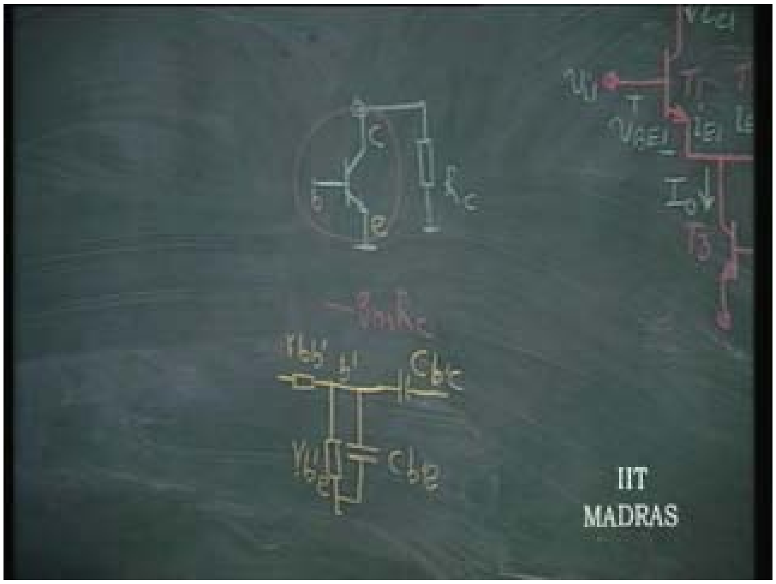

When we replace the transistor by means of its high frequency equivalent circuit which we have already discussed in our already introductory lecture we saw that the bandwidth of the amplifier is now controlled by what are called the time constants of the circuits.

We have to understand what this time constants are?
We know that the low frequency gain of this amplifier is simply equal to gm into R_c. So how the bandwidth of the amplifier is controlled? You have to replace this transistor by means of its hybrid pi equivalent circuit for discussion of the bandwidth. Let us therefore see how this transistor equivalent circuit is going to be replaced now by means of its hybrid pi. So we have rbb prime the base, this is the collector, this is the emitter etc and rbb prime is the ohmic resistance from the base contact to the base junction which is of the order of few ohms. And coming to v prime we have the resistance which is rb prime e which is because of the diode resistance re appearing at the input of the common emitter amplifier as beta plus 1 times re or hfe plus 1 times re, this rb prime.

Across this we have the capacitance which is called Cb prime e which is termed by the devised people as the diffusion capacitor because the junction is forward bias and because we are injecting impurities or the carriers from emitter to base, this kind of capacitor arises here Cb prime e. This we can intuitively feel that since the junction is forward bias this capacitor is likely to be very high. The depletion layer width is going to be extremely small. It is not depletion layer capacitance, we can intuitively feel that it is forward biased and this capacitance is likely to be very high compared to the other capacitor which is between the base and the collector called as the depletion layer capacitance or transitional capacitance. This is because the collector base junction is reverse biased and inherently it acts like a capacitor with depletion layer width as the width of the capacitor. So this capacitor is going to be very small because normally collector base junction is reverse biased to a great extent and therefore depletion layer width is going to be large. Therefore this capacitance is going to be very small.

This Cb prime c is going to depend upon the reverse bias voltage. The Cb prime c is a function of reverse bias voltage, and higher the reverse bias voltage magnitude smaller is the capacitance. Depending upon the type of the junction the nature of variation is going to differ. But the capacitance is going to vary with voltage whereas here the base to emitter capacitance is dependent upon the operating current. So the base to emitter capacitance is the impedance is a factor directly dependent upon operating current whereas this is dependent upon voltage. Then we have the collector and from collector we have the current source which is nothing but gm into Vb prime e.

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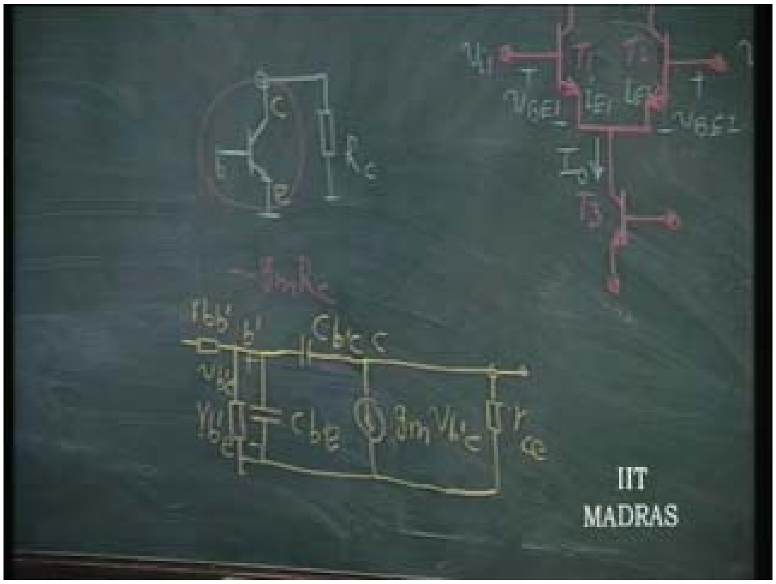

So, across this we have rce as the non ideal impedance across the current source which is going to be of the order of hundreds of kilo ohms. This is the hybrid pi equivalent circuit which is commonly used universally for the transistor. So, Vb prime e is the voltage across this b prime and e terminal, so Vb prime is between these two. Now obviously since a source is going to be connected to this Rs we have the source voltage as Vs, we are going to have this Rs coming in series with rvb prime always. So, for all purposes we can merge rvb prime with Rs.

What it simply means is, even if you are able to get with very good source with low source resistance we have rvb prime still coming in series with the structure. So if it comes with the series with the structure obviously the voltage across this capacitor is going to be lower at higher frequencies than the source voltage itself. So obviously the high frequency performance depends upon how low Rs plus rbb prime could be. Since

the current source current is dependent upon Vb prime e if we make this particular resistance very low then the high frequency performance of the circuit is going to be excellent. Now how to be really tackle this problem about common emitter stage?
This output is going to be now connected to Rc. So this is the high frequency equivalent circuit representation of the common emitter stage.

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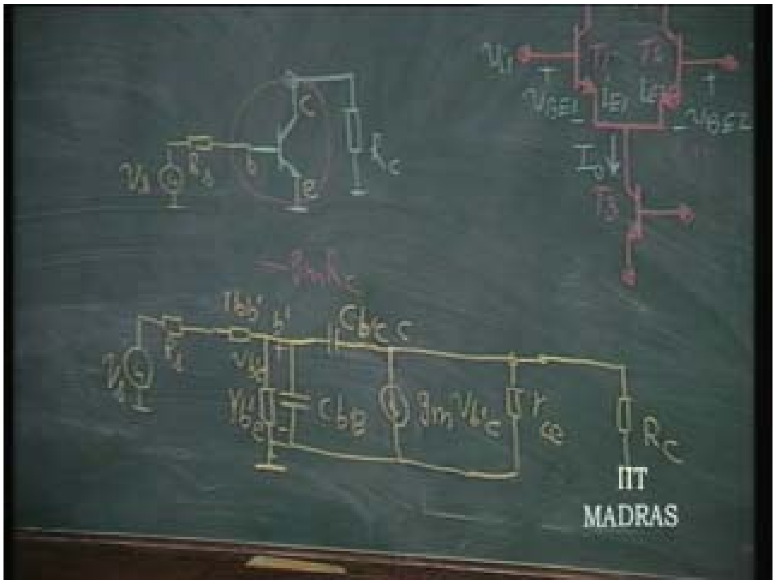

How do we simply solve this?
We make an assumption here. We know that this has an input port and an output port. And we would like to clearly get an idea about input time constant and output time constant. So what happens to this capacitor? The only thing that links the output to the input is this capacitor Cb prime c.

If this Cb prime c is not there then there is no connection between output and input and input time constants could have been independently found out compared to the output. Because Cb prime c is there we had to do some approximations here in order to simplify the results. What is the simplification? What we simply say is that this capacitor is between b prime and c. It can be converted to an equivalent capacitor between b prime and e by what is called Miller’s theorem. This Vb prime e voltage is going to generate a current of gm into Vb prime.

And we would like to know how much the output voltage is going to be, what is it going to be? It is rce parallel Rc is the effective load resistance and that into gm. So gm into Rc parallel rb prime e plus here and minus here so if you put this as V_0 and V_0 is going to be this (Rc parallel rce) Vb prime e. So Vb prime e is the voltage here and I am neglecting the effect of the capacitor. Capacitor is after all going to bring down the gain. Therefore, I am now going to consider the worst case effect of this capacitor at the input. Hence while finding out the output voltage in relation to Vb prime e I am neglecting the capacitor and that is the approximation. Then the output voltage V_0 is going to be this. So this particular gain in fact is approximately equal to normal circumstances is the same as gm into Rc because Rc is of the order of hundreds of kilo ohms.

In order to do white banding I must have all the time constants as small as possible because the bandwidth is going to be govern by 1 by the time constant both the input as well as the output. So, in any white banding the main aim of out banding is to make these time constants as small as possible. The resistive part obviously comes and therefore the resistors used in all white band circuit will be very low. That means automatically we have to sacrifice a lot in terms the gain that we can obtain from white band amplifiers.

If you want very white band amplifiers the resistances have to be low. That is why this approximation is normally valid in all white band circuits that Rc parallel rce is very nearly equal to Rc without any problem. Therefore the gain is the usual minus gm into Rc gain that we have utilized. So what happens to this capacitor Vb prime e is this voltage and this is this gain that turns this voltage with a negative side.

This capacitor appears as Cb prime e into 1 plus gm into Rc as the input capacitor because the current through the circuit is going to be, this voltage minus this voltage that is Vb prime e minus minus that means plus and gm into Rc into Vb prime e or Vb prime e into 1 plus gm Rc by 1 by g omega Cb prime c.

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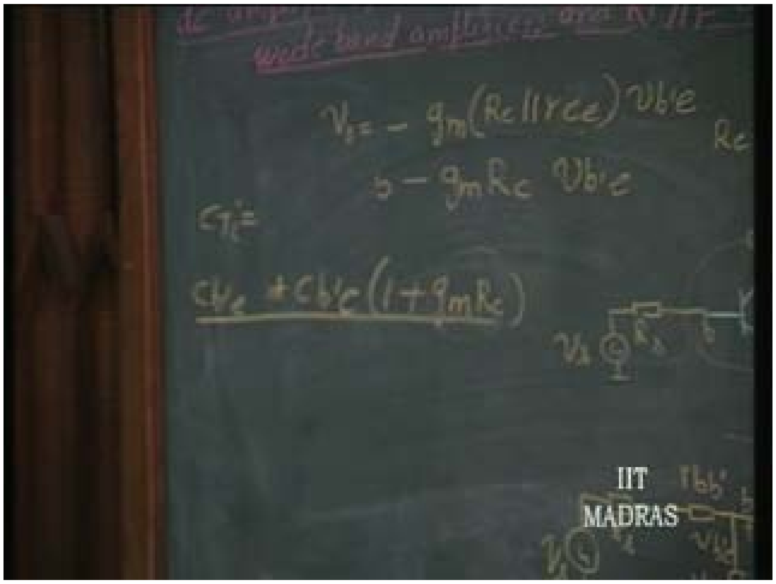

Cb prime c can be thought of as becoming equal to Cb prime c into 1 plus gm into R_c. This is the effective capacitor plus this capacitor will be coming in shunt with Cb prime e, this is the total capacitor CT at the input. Cb prime E comes in parallel with Cb prime c into 1 plus gmR_c so this is the total capacitor. So you can note the fact that, higher the gain higher will be the input capacitance. Once again lower gain is automatically required in order to make this time constant very low. Now, as for as the resistance at the input is concerned between this point and this point what is the effective resistance? It is rb prime e parallel rbb prime plus Rs. Effective resistance or total across the total is going to be at the input, is rb prime e parallel Rs plus rbb prime .

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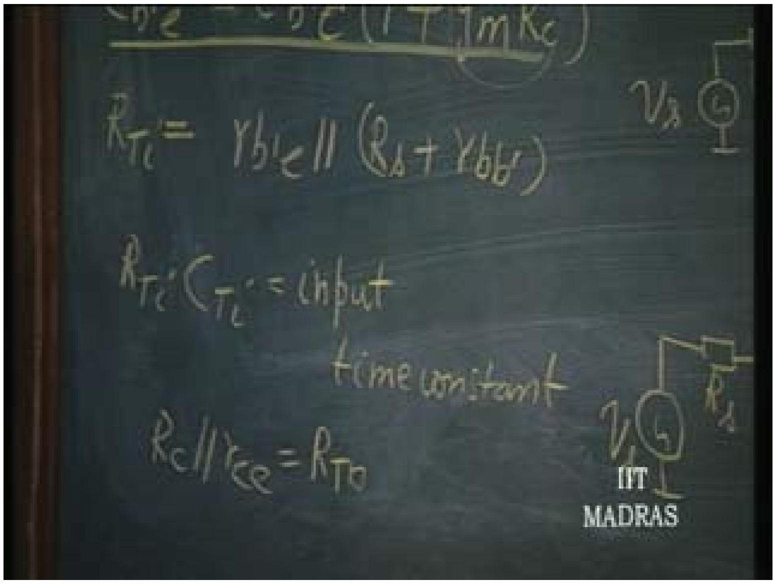

$R_{Ti} = r_{b'e} \parallel (R_s + r_{bb'})$

$R_{Ti} C_{Ti}$ = input time constant

$R_c \parallel r_{ce} = R_{To}$

So what is the input time constant? That is going to be R_{Ti} into C_{Ti} is the input time constant of the common emitter amplifier.

What is the output time constant?
Output effective resistance on a similar basis is R_c parallel rce which is approximately equal to R_c itself. R_c parallel rce is the RT output and what is the effective capacitor at the output?

This Cb prime c is going to very nearly at the output because when the output voltage is high, the input voltage is going to be very low and effectively this Cb prime c is going to be the capacitor. Or actually it is Cb prime c into 1 plus 1 by a but a being very high it is Cb prime c itself. So, output capacitor is going to be equal to Cb prime c plus, please remember the other capacitor which in an integrated circuit comes into picture. That is the substrate capacitor. Since the collector is always connected to the substrate through a junction we have what is called as substrate capacitor to ground.

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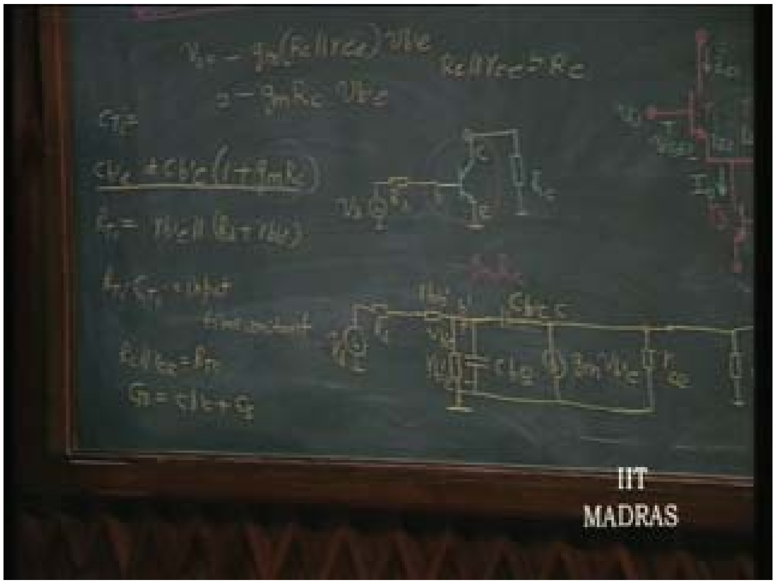

So the output time constant is equal to R_{To} C_{To}. Now look at it this way. C_{To} is very small compared C_{Ti} there is no doubt about it. And the value of R_{To} which may be of the order of kilo ohms to may be hundreds of ohms depending upon the white banding effective you like to have is going to be very nearly equal to this. Again this may be another stage driving it so Rs may be of the order of kilo ohms to hundreds of ohms. So these resistances may be of the same order, R_{To} and R_{Ti} may be of the same order. This is several order higher than this from magnitude so input time constant is the dominant time constant which is going to determine the cut off frequency of the white band amplifier. As if the input time constant is the dominant what is the cut off frequency or the bandwidth of the amplifier? It is omega 1 by rdi ct. So if the bandwidth of the amplifier is the dominant time constant it is going to be omega 3dB is equal to 1 by R_{Ti} C_{Ti}.

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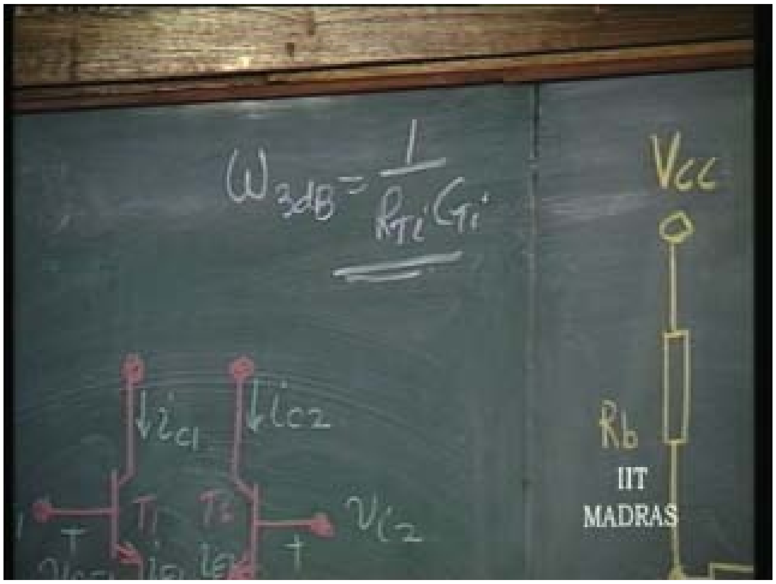

This is for a common emitter amplifier. Let us once again see, C_{Ti} is going to be Cb prime e which is a huge quantity compared to cb prime c and this cb prime e is getting added to Cb prime c into 1 plus gmR_c because of what is called Miller effect. This is the Miller effect. This capacitance means being several orders of magnitude higher than C_{To} we say that R_{Ti} R_{To} are of the same order, may be that R_{Ti} is just one order less if you are actually using a low impedance source then clearly the input time constant becomes down. Otherwise both input time constant and output time constant will determine the upper cut off frequency R_{To}.

So now what should we do?
We cannot do something at the output because output time constant is the lowest process. The device engineer devises the transistor in such a manner that Cb prime c is made as small as possible. With the advent of the planar technology we have been able to make Cb prime c extremely small so that the earlier need in the earlier discrete circuits of what is called neutralization, neutralizing the feedback capacitor by using external circuit became unnecessary in the current circuit.

What is neutralization?
Neutralization is neutralizing the effect of feedback cost by Cb prime c. This Cb prime c is linking output the input and it is a big headache for us. If you are trying to design high gain amplifiers, if there is a feedback from output to input that will cause invariably high frequency oscillation. It will cause at some frequency positive feedback and causes high frequency oscillation. So this capacitor is a troublesome effect for high frequency application.

Earlier people used to take pains to neutralize the effect of this by using sophisticated neutralization schemes. But you people do not have to worry about neutralization at all. We have devices now-a-days available with this feedback being totally nullified by the technology itself. It has been made very small. Even though it has been made very small because we are designing a high gain amplifier this effect is going to be still felt at the input in fixing up the upper cut off frequency of the stage.

Now we have to see that this upper cut off frequency is as high as possible. That is what is called white band. How to adopt circuit means of making this time constant as low as possible is what we are going to discuss next. The basic concept of white banding is to make the time constants at all points as low as possible. Let us give the concept again in a different manner. If it is a voltage source which is the source that is driving then the most appropriate load for white banding is an open circuit. If it is a voltage source that is driving then the capacitor will come from somewhere like this which will be R_c time constant. If you want the total time constant to be very low you do not have to worry because this source is going to shunt this and therefore effectively Rs comes in parallel with R_i. So Rs is going to take care of it to make the time constant very low irrespective of the value of C_i. This is called mismatch.

That is, always the source and the load should totally mismatch. If the load is high the source should be of that of low impedance or it should be a voltage source. If the load is low the source should be that of high impedance that means it should be a current source drive. That means once again if you have C_i itself very low then i is driven by means of a current with Rs being very high. So, if you have a current source load it is appropriate for driving a short circuit which is ideal load for it. And if you have a voltage load source it is appropriate for driving an open circuit. That means if the white banding is essentially achieved simply by mismatching the source and the [….] It is only a concept looking at the entire set of rows in terms of what is driven and what is to drive.

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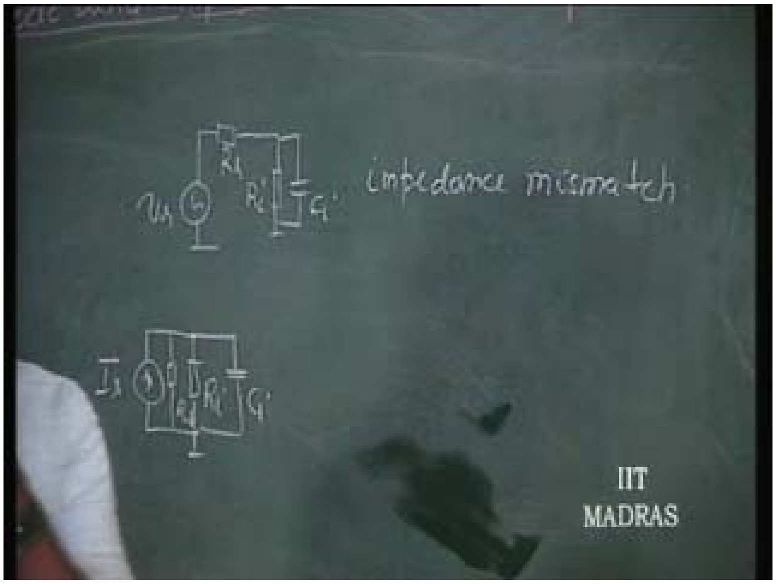

Impedance mismatch:

We had this common emitter amplifier here, our trouble was that the output was going on to a resistance of the order of kilo ohms or so. The output is supposed to be a current source gm into Vb prime e and output load is really not mismatched to the current source. Actually it should have been fed into a short. So what is the stage that is going to act as a short?
We know that a common base input is going to act as a short. So, a common emitter amplifier cascaded to a common base is going to cause a gross mismatch at this point because a current source is going to witness a short circuit as the load and this should result in white banding.

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Now, as far as the Miller effect is concerned the voltage gain is evaluated from here to here. Both these are operating at same current, the RE of this and RE of this will be the same. So what will be the gain of this stage? It is gm is equal to 1 by RE into re so the gain is going to be is equal to 1 in magnitude. So it is just going to act as an inverting amplifier. That means miller effect is drastically reduced or the miller capacitor is not going to appear as Cb prime c into 1 plus 1. That is it is going to appear as 2 into Cb prime c. Here have we lost the low frequency gain?

No, we have not lost any low frequency gain because this current is going to be same as this current and this is going to be the same as this current because common base is nothing but the current amplifier with unity gain. So this current which is gm into Vi or gm into Vb prime E is simply conveyed here in the same direction. This is an exact replica of common emitter as far as low frequency is concerned. But in high frequency there is a drastic change in the time constant at the input so the miller effect is totally eliminated. This is the famous white band pair called cascade.

Common emitter cascaded to common base is called a cascode structure. So I can directly connect R_c here and the gain shall remain exactly equal to minus gmR_c as far as the low frequency gain is concerned. But as far as high frequency time constant is concerned C_{Ti} is going to get drastically changed and the rest of the things will remain unaltered. Let us see the output time constant here. This is no longer the output but this is what is called intermediate time constant now and the output being here. This is a short circuit here which means impedance is re, the capacitance is going to be the output capacitance which was earlier output capacitance now the intermediate capacitance.

Thus, intermediate capacitance has changed marginally but now this resistance here has come down drastically so this time constant is very low, it is negligibly small. The actual output time constant remains unaltered, this is R_c and across this we have Cb prime CE plus Cs. That remains the same as earlier time constant. So output time constant of this structure remains same as that of the common emitter stage but the input time constant comes down drastically so this is going to have a upper cut off frequency which is much higher than the common emitter stage and in integrated circuits this is totally replacing every common emitter high frequency structure.

You should never use common emitter stage instead you should always use this because this is coming as a pair at the same cost as a single transistor but has excellent high frequency properties, this cascade structure. Now, do we identify a cascode structure in our differential amplifier ICs?
Yes, we have T_3 which can act as common emitter stage and I can connect the load to this to V_{cc} here then this whole thing becomes a cascode structure.

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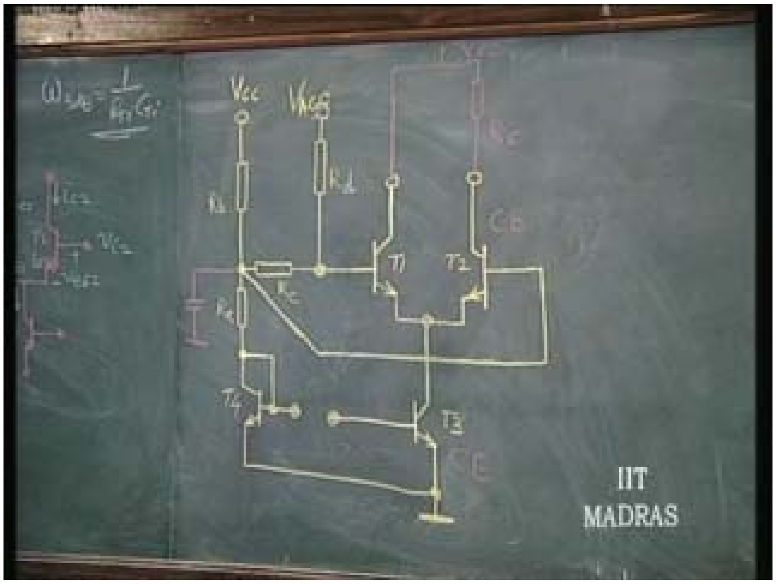

So how do we connect?
We will connect in this structure, this to supply voltage and T_3 will act as a common emitter and T_2 will then act as the common base if base is connected to ground. That means AC wise this base is going to be connect it through external capacitor to ground so that this structure now acts as a cascode structure. This is an important innovation now.

This differential amplifier is now being used as a cascode amplifier. That is another pair, that is, a differential amplifier acting as a differential pair.

Now we have to see whether it has the same property as a common emitter amplifier. It does not have the same property. It is different from cascade. Cascode is a one is to one replacement of a common emitter amplifier as far as low frequency operation is concerned. So, in using it as a cascode stage T_1 is not going to come into picture.

Why not use T_1 also, for what purpose can we use T_1 for?
If T_1 is off the entire current of this will go into this. If T_1 is on fully the entire current will come into T_1 and nothing will go to T_2. That means I can use it for controlling the gain of this structure. The signal current including the DC current is going to be share depending upon the DC voltage that I am applying between bases. I am therefore applying a DC voltage between this base and this base is facilitated by an attenuator here. So both the bases are not connected to the same DC potential, the DC potential can be varied by varying [V….]. Hence, if this potential is same as this potential what is the gain of the stage? It is gmR_c by 2 because at that point of time these two currents will be the same. So, if this potential is same as this potential then the gain is going to be gmR_c by 2.

If this potential is higher than this potential appropriately by few millivolts then immediately I can make this current go to 0, the gain is 0. If this potential is lower than this potential by few millivolts this current can be channeled to this transistor and I can make the current go to the full value that means gain is going to be gmR_c. So this voltage is called VAGC Automatic Gain Control where the automatic part is later to come.

Presently it is DC which can control the gain of the high frequency amplifier. Therefore whether this is a white band amplifier or a tuned amplifier, Rf amplifier, if amplifier whatever be the stage is dependent upon the kind of load that you are going to connect here. If it is a tuned amplifier R_c will be replaced by a tuned structure. This is a great advantage. If I want to vary the gain of this stage gm has to be varied. So, gm has to be varied and the operating current has to change so I change the operating current. That is how discrete circuit if amplifier stages add the gain varying. So the operating current use to vary depending upon the AGC voltage which is derived out of the detector in a radio receiver circuit, it is derived out of the detector the DC voltage dependent upon if amplitude. So that was controlling the operating current. And when the current was getting varied the input capacitor is getting varied. It is a dangerous thing because the input may also get tuned.

You can think of a tuned input tuned output situation. If the input capacitor is getting varied the input is getting retuned. So, even when the operating current was changing output bias voltage also is likely to change. If output bias voltage changes then the Cb prime c also changes and when this voltage changes the DC current remains absolutely constant. Thus, in a cascode structure realized out of this the input time constant remains independent of the AGC voltage variation. So what is going to happen here is, if it is a tuned circuit normally the collector voltage is going to be very nearly at the same potential as V_{cc} because you are putting an l. So the collector to base potential is not going to vary much and therefore that capacitance is not going to vary. Hence, the effect of AGC voltage on the tuning is not coming into picture at all. The tuning can be independently controlled by varying the currents of T_1 and T_2 without effecting the input stage T_3. That is also independent of the load. Now let us look at the load, the load earlier was directly connected to this in the [p….] manner. But now it is connected through a common base structure.

So what is the feedback factor?
Whatever is fed back from load to the input of the common base and then from the input of the common base to the input of the common emitter is known as the feedback factor. That means two transistors cascaded which are basically feed forward structures with very little of feedback that means feedback factor also gets multiplied and it goes towards zero faster.

So using more number of stages with very little feedback will cause further feedback to go towards 0 as fast as possible. So the reverse transmission of the cascode stage is several orders of magnitude less than the reverse transmission of the common emitter circuit. That means the output stage is totally isolated from the input stage. Input can be tuned independently of the output. This is an important criteria in tuned amplifier design.
Therefore, cascode structure is the structure which is universally adopted in all present day Rf If amplifier mixer stages. The mixer is also a high frequency tuned amplifier. So mixer R_c, if amplifiers use this particular structure universally for all applications.

We will continue with the discussion about how AGC varies this gain. We have already seen this problem, how the current division effects the gain?
How I even by I_{E2} effects the gain. Let us get to know what Vigc variation should be here. This voltage should be made equal to this voltage for making the gain equal to half. What is this voltage? It is Ra by Ra plus Rb times V_{cc} plus V gamma if you want. If you neglect v gamma normally, for 6V supply if this is 3K 3K this will be 3V. So if you put AGC is equal to 3V whatever be the resistance you have a gain of rmR_c by 2 that is the starting point. On either side these 3V you can vary assuming that the current in R_c R_d is extremely small because we can make R_c plus R_d very large compared to R_a and R_b.