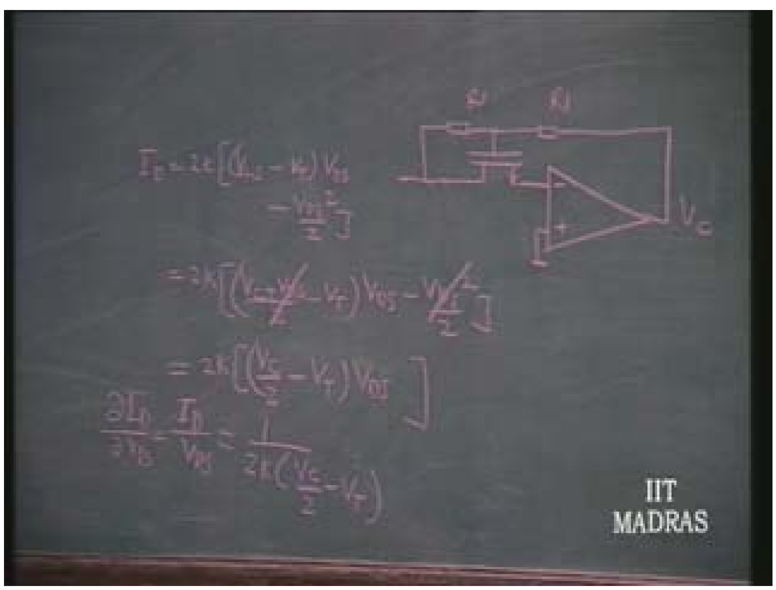
Analog ICs
Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture - 23
Self Tuned Filter

So, in the last few classes we had discussed about variety of techniques of designing multipliers. A multiplier is nothing but a voltage controlled amplifier which can also be designed by introducing MOSFET as a resistor determining the gain of the stage.

We had discussed earlier how MOSFET in the triode region can be used as a linear resistor. Therefore whenever we would like to design multipliers we can also take recourse to this technique of designing multipliers. There is one important technique of multiplication which uses a very novel method for the purpose of multiplication.

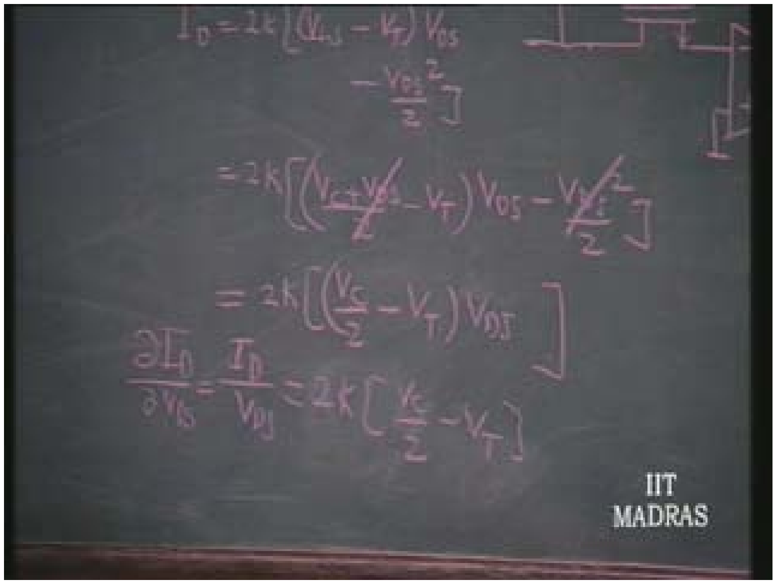
Let us consider this; I am using FET as a voltage dependent resistor. Let us say we can put the linearizing blocks here so that it is a linear voltage dependent resistor because the characteristic for this FET is in the triode region ID is equal to 2K times V_{GS} minus V_T into V_{DS} minus V_{DS} square by 2. If I now make this as the control voltage then we know that this is equal to 2K into V_c plus V_{DS} by 2 this voltage is V_c plus V_{DS} by 2 minus V_T into V_{DS} minus V_{DS} square by 2 so you can see how nicely it gets linearized. We also have found out ways and means of doing this without the help of resistors also.

(Refer Slide Time: 00:05:00)



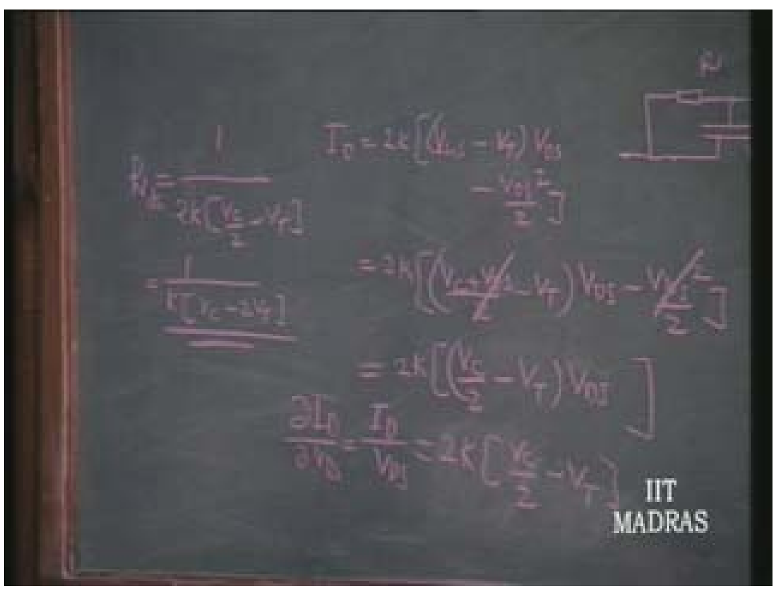
So in any case this demonstrates a particular method of making the FET linear, the V_{DS}.

(Refer Slide Time: 00:05:21)



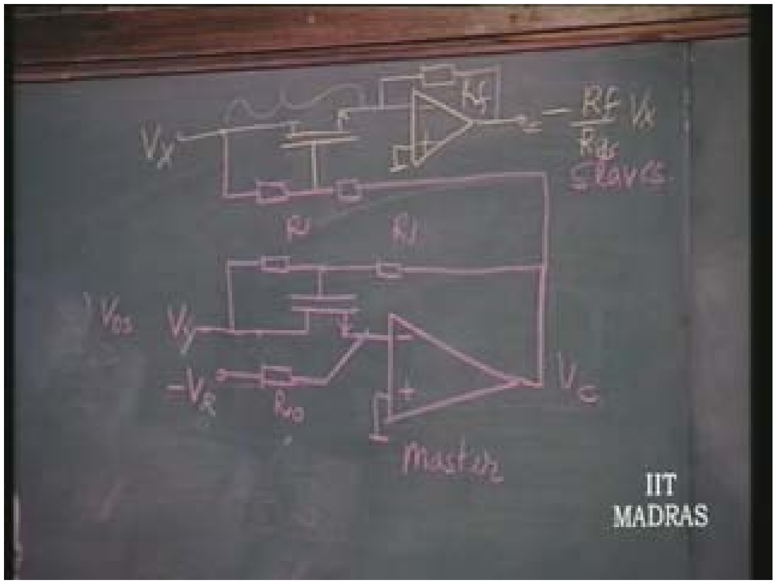
So we get delta ID by delta V_{DS} is same as ID by V_{DS} is equal to 2K(V_c by 2 minus V_T) or R is equal to 1 by 2K(V_c by 2 minus V_T) is equal to 1 by K(V_c minus $2V_T$).

(Refer Slide Time: 05:41)



So how do I establish this resistance that I want to be simulated?
That can be done by feedback.

(Refer Slide Time: 00:11:02)



Now what I do is, I put a resistance here; I make this R_0 reference resistance and apply a voltage minus V here and V here. So this is V_i, I put minus V_i here then what happens here, this resistance has to automatically adjust itself because of the negative feedback such that this current which is V_i by R_0 is same as this current. That means this R_{ds} now is going to be automatically adjusted to be equal to R_0. So this is a negative feedback circuit which will adjust the FET at all times irrespective of its value of K and V_T. That means even if K and V_T were dependent upon temperature this control circuit will see to it that FET resistance is exactly adjusted to R_0 at all times. That means now you have got a perfectly temperature compensated FET resistance which remains absolutely constant as constant as this fixed value of resistor.

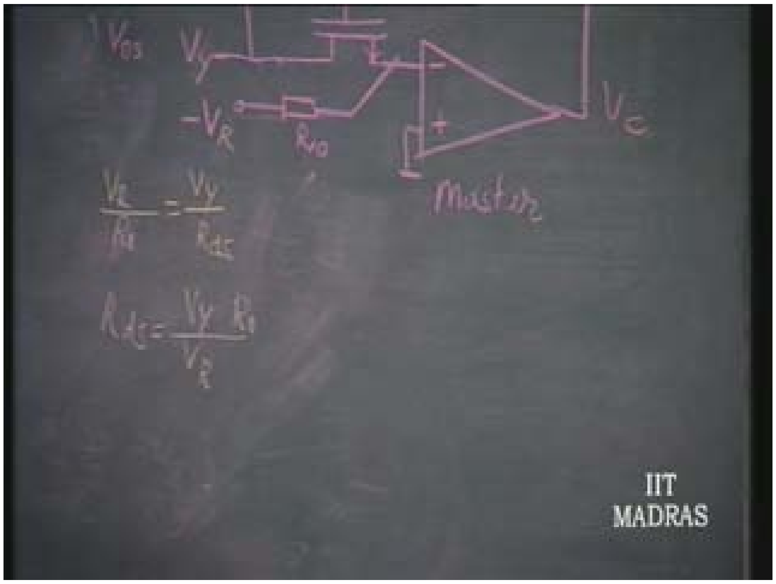
Now, for example, you call this as a master then this master says, I will make sure that, you FET behave yourself properly so that the resistance value you simulate is constant. Now once it is made sure then I can use this same control voltage for all the slaves. FETs which are exactly identical and the circuit which is exactly identical, these are all slaves any number of such slaves you can have and all of which get the same control voltage.

You can independently feed any voltage here, let us called this as V_X and put a negative feedback resistance so that this is nothing but an inverting amplifier designed using the FET resistance which has been made to be constant by another independent negative feedback circuit so it will remain constant forever. Let us therefore have this as R feedback and this resistance that it is going to simulate is going to be R_0 so the gain of this is minus R_f by R_0 into V_X. And R_0 itself is nothing but R_{ds}, this has been made equal.

So let us see what this R_0 is?
This R_0 is determined by in fact the voltage V_i. I do not have to make this and this is the same. So what I will do is I will keep this as V_R and keep this as V_Y. Now we know that this is always correct, the R_{ds} of this. R_{ds} of this is as same as R_{ds} of this. Earlier when I

had these two as the same R_{ds} was same as R_0. Now I can write down the equation here, V_R by R_0 is the current drawn and that should be same as equal to V_Y is positive and V_R is positive if it is so it is V_Y by R_{ds}.

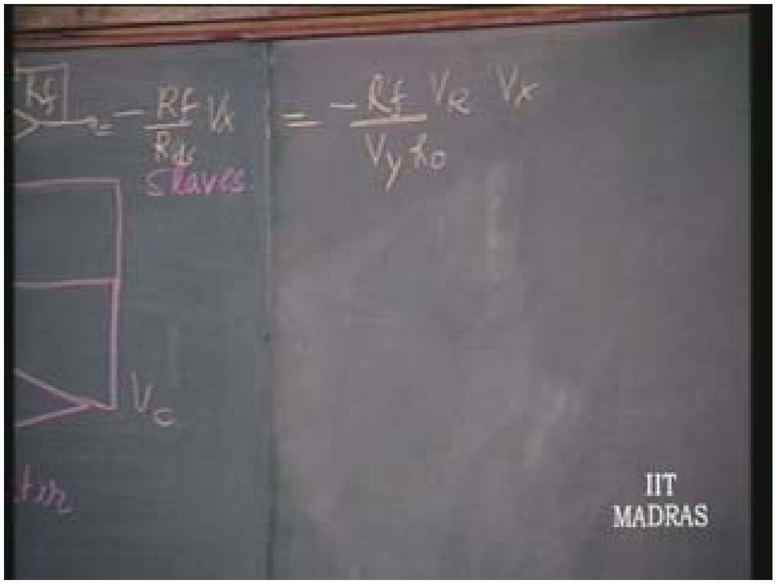
(Refer Slide Time: 00:12:11)



It is necessary that V_Y can only take on the positive polarity in this case if this is my negative. If this is positive this has to be negative, this is the requirement. Under this situation V_R by R_0 is equal to V_Y by R_{ds} or this can be written as R_{ds} you replace R_{ds} is equal to V_Y V_R by R_0. If you now replace this R_f by R_{ds} which is V_Y into V_R by R_0 into V_X this becomes a div$_i$der in this case.

You want to make a multiplier out of it what do you do?
You interchange V_R and V_Y. If you interchange V_R and V_Y this you make as a reference voltage, this you make it as variable voltage then you get a multiplier. You can design either a multiplier or a div$_i$der simply by using this principle of master slave concept which is similar to the current mirror. In the current mirror we had a transistor which was connected as a diode so that is a feedback structure which was learning to develop the voltage required to pass a current and this voltage was used to bias all the other transistors at the same current.

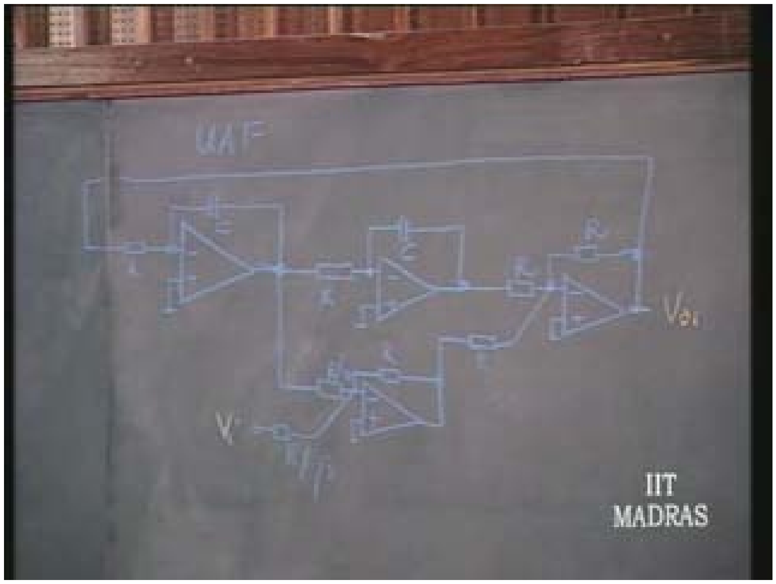
(Refer Slide Time: 00:12:29)



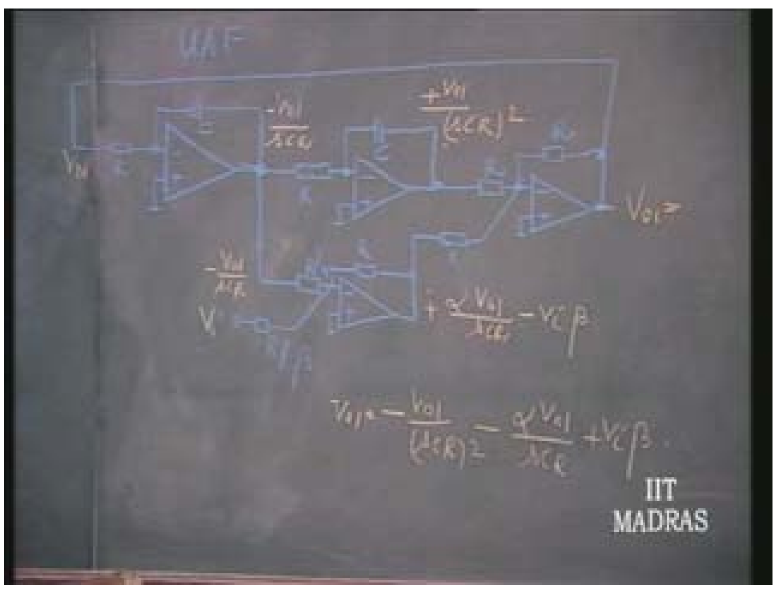
So the same thing is used here in the design of a FET multiplier. In this it is not necessary to use voltage ampere characteristics of the FET. Voltage ampere characteristic of the FET is of no consequence strictly speaking. This relationship of the equal resistance being valid at all times is true irrespective of the volt ampere characteristics. The only thing is that here I am assuming that this current is the current that is passing through this and that current is determined by this divided by that. In that assumption I am considering that the FET is linear. So this is another technique of designing multipliers. Particularly this technique is very popular in regular laboratories where you can use two matched FETs to design a fairly good multiplier. This is not four quadrants but two quadrants because V_X can take on two polarities but V_Y can take on only one polarity.

Now we will see another application of this multiplier in what is called a very important block that is universal active filter block. Universal active filter blocks are available as ICs. Now-a-days these are being used as VLSI sub cells in realizing higher order analog filters. So this itself can become a sub cell of a very large scale integrated circuit. Therefore we would like to have some control over these filter parameters. Let us therefore quickly analyze this filter.

(Refer Slide Time: 00:16:13)

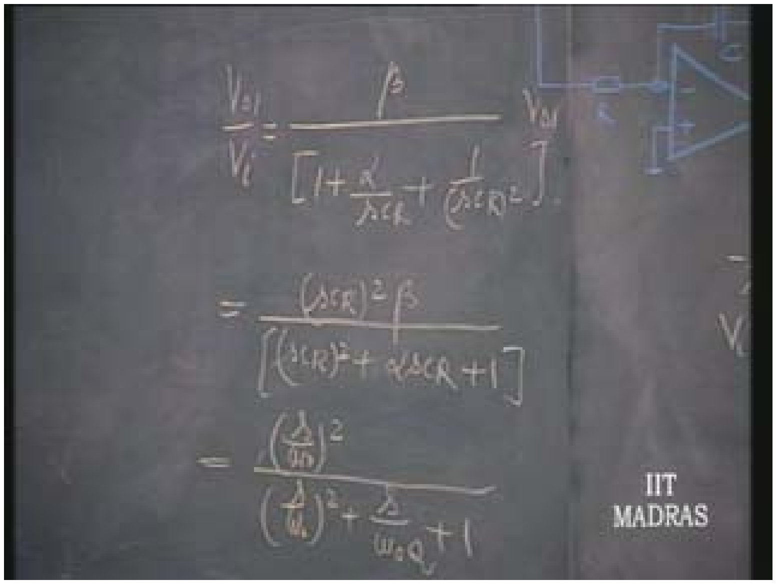


(Refer Slide Time: 00:17:49)



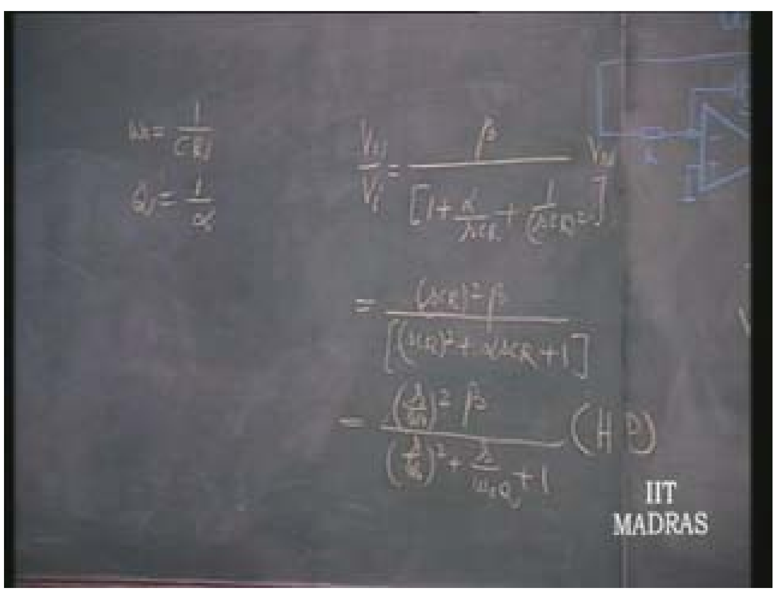
Let us see if V_i is the input applied here we can see that we will call this output as V_{01} and let us express everything in terms of V_i and V_{01}. This is V_{01} and therefore this output is V_{01} by sCR with a negative sign and this output is minus V_0 because plus V_{01} by (sCR) square and here we have minus V_{01} by sCR and V_i. So this V_{01} by sCR will appear in this case as alpha times plus alpha times V_{01} by sCR minus V_i into beta. That is as far as this is concerned. Therefore V_{01} has output resulting due to these two inputs so V_{01} is going to be equal to, this will appear as an inverting thing, so V_{01} is minus V_{01} by (sCR) square and then minus of this.

(Refer Slide Time: 00:18:51)

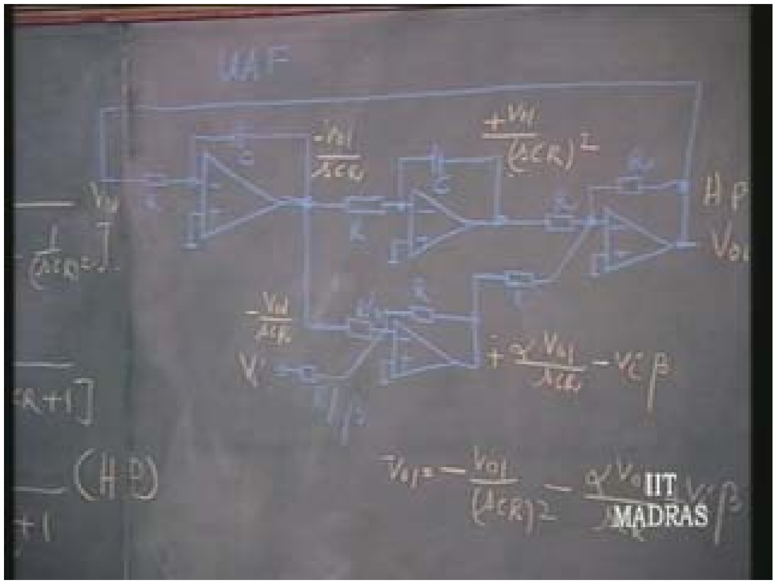


We have quickly seen how this can be simply analyzed and we get V_{01} by V_i from that equal to beta (1 plus alpha by sCR plus 1 by sCR) square or [(sCR) square beta by (sCR) square alpha sCR plus 1] which according to us can be written as s by omega$_0$ square s by omega$_0$ square plus s by omega$_0$ Q plus 1. Wherein omega$_0$ is equal to 1 by CR and Q is equal to 1 by alpha by comparison. And obviously here we have beta coming into picture in the gain of the stage. This is what is called the high pass output.

(Refer Slide Time: 00:19:25)

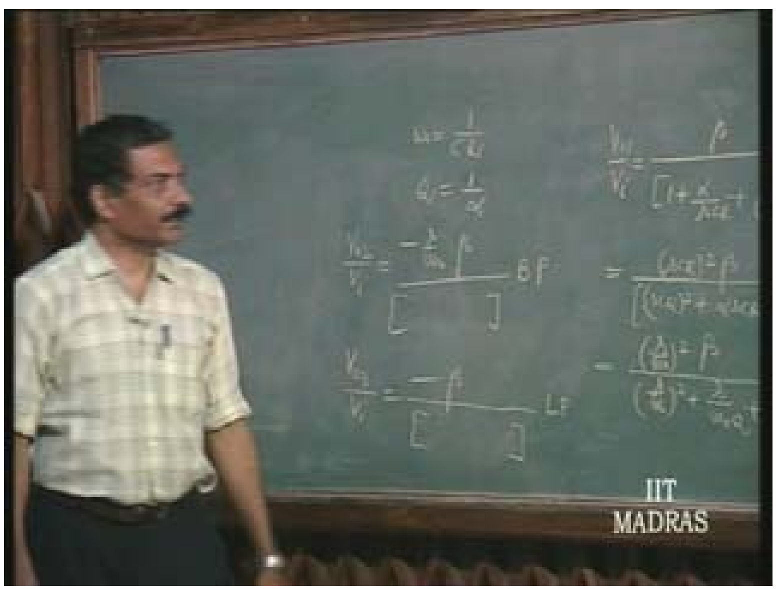


(Refer Slide Time: 00:19:39)

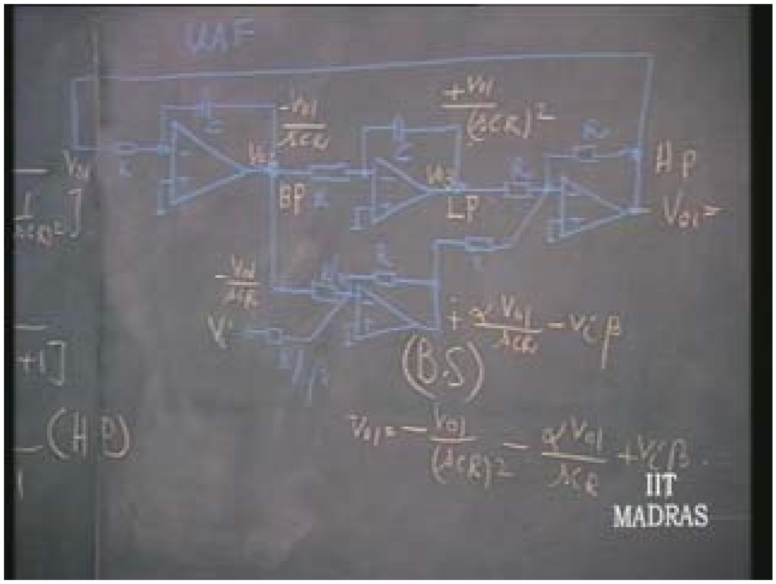


If you take the output here this is then the high pass and that high pass output into 1 by sCR or omega$_0$ by s minus which will give you band pass. So V_{02} by V_i is nothing but minus s by omega$_0$ beta divided by the same denominator which is band pass.

(Refer Slide Time: 00:20:28)



(Refer Slide Time: 00:21:05)



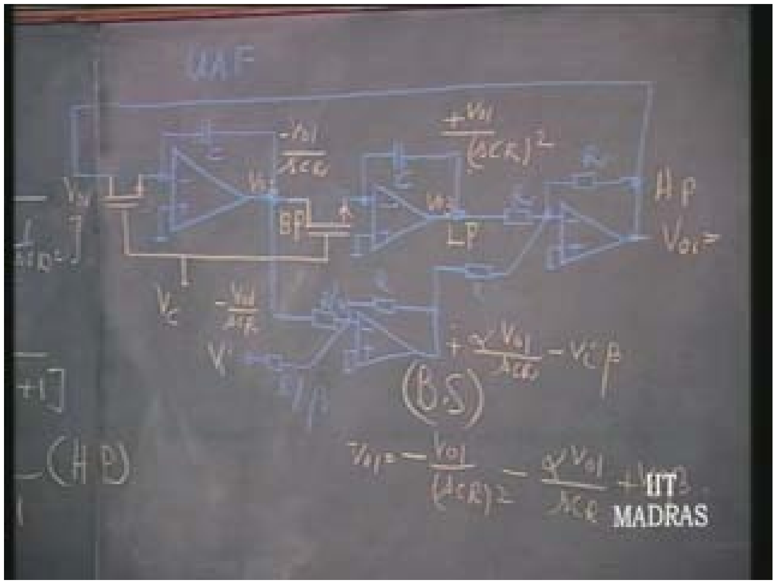
So this output is band pass. And again if you integrate this you will get low pass which is V_{03}, this will be V_{02} and this will be V_{03}. So V_{03} by V_i which is again minus beta divided by the same denominator which is low pass. There is some universal nature about it because band pass, high pass, low pass if you can add or subtract suitably you can get any second order system.

Any second order system block can be got by adding suitably or subtracting suitably these outputs. Therefore you might need one more op amp for doing this. If you have here an op amp this output is going to be band stop output. It is nothing but alpha times V_{01} by sCR minus V_i beta, it will be nothing but band stop output. That is why this circuit is very important because we can just use it for even biomedical applications where you want an ECG waveform which contains lot of your 50Hz, the output of this is going to be the same ECG waveform devoid of the 50Hz. So this is a nice setup for that kind of filtering in biomedical applications.

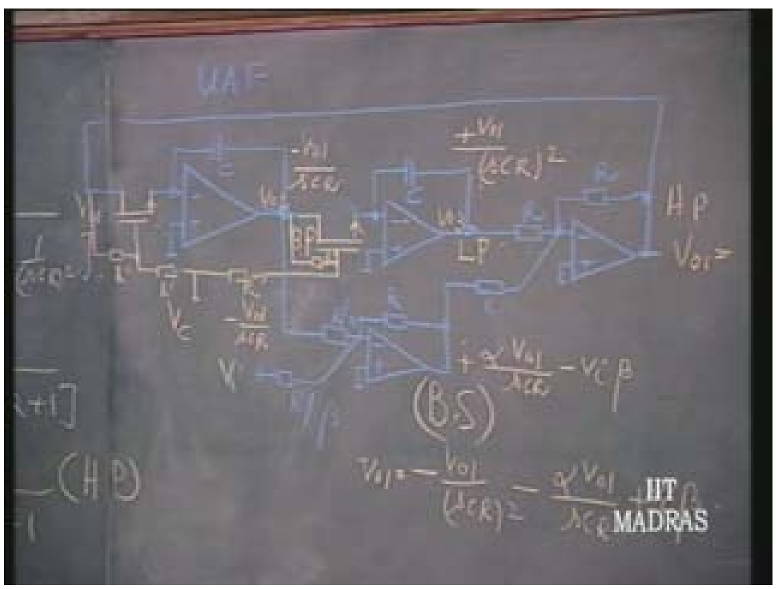
Let us now see how this can be converted into voltage controlled filter. We can do this very simply by replacing this integrator and this integrator because here R_C times constant means the 1 over frequency, omega is equal to 1 by R_C. So, if I make both these resistances depend upon a voltage that means if this is made voltage control or if I put a multiplier here it becomes voltage controlled filter.

Instead of that I can just say that it can be made using a FET here and using a FET here. If I use this kind of an arrangement it is not linearized, if you want to linearize you can do it by putting resistors. So R, R prime let us put it to distinguish from this resistance R prime linearizing resistors and control voltage is connected here. Now this will be nothing but same as $omega_0$ is equal to 1 by CRds, the Q remains the same as 1 by alpha undisturbed and the gain also remains undisturbed so you are now able to change $omega_0$ dependent upon R_{ds}. R_{ds} is equal to 1 by 2K or K into V_c minus $2V_T$.

(Refer Slide Time: 00:22:03)

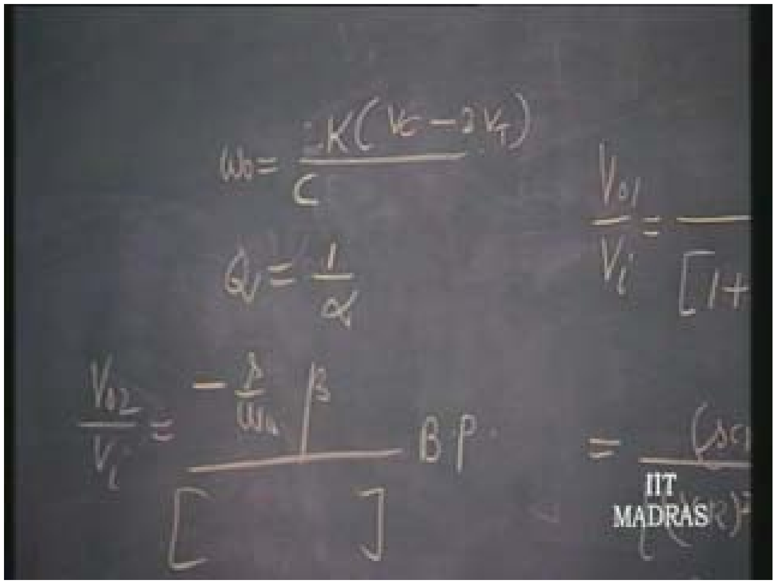


(Refer Slide Time: 00:23:46)



Using these FETs which we had linearized we can make this particular filter voltage controlled filter.

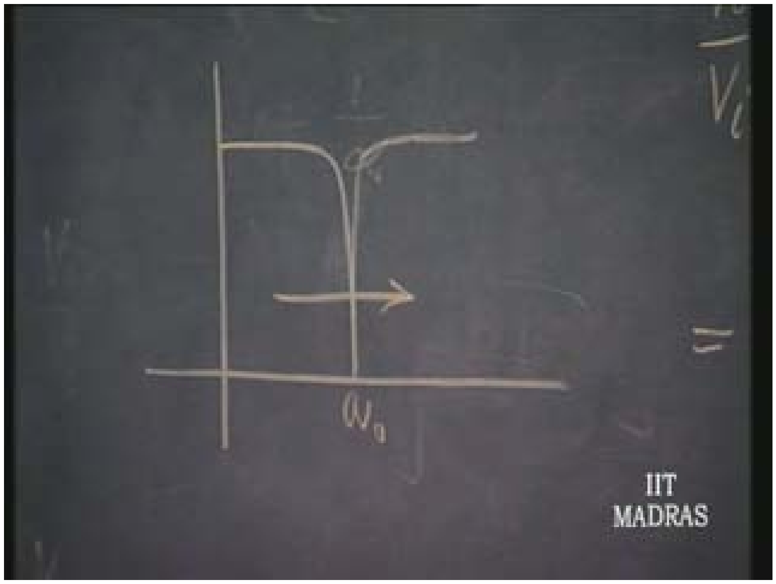
(Refer Slide Time: 00:24:31)



This works beautifully as long as the resistance of the FET can be varied from a certain value V_{c1} to some V_{c2} depending upon the current that you are permitted to have through the FET over this range. Now this linear voltage controlled filter can be tuned based on this control voltage. For example, let us take the same example, if it is some specific frequency you want to get rid of you can make Q fairly high to 100 or so. Therefore you can now obtain a characteristic here if you take the output at this point where the output is going to have a notch at $omega_0$ which can be varied. So you can get rid of the unwanted frequency.

Another application for such a thing is, you have a given wave form which is periodic and you want to find out the harmonic content in the given waveform. So you can put a notch at the fundamental and measure the power at rest of the output. So that will give you the harmonic content of the given waveform. Or if you take the band pass output you can find out the fundamental or the harmonics so it can become a spectrum analyzer. So, it can be used as a harmonic analyzer or as a spectrum analyzer the sweep voltage being given as V_c. So it has considerable amount of application in signal processing.

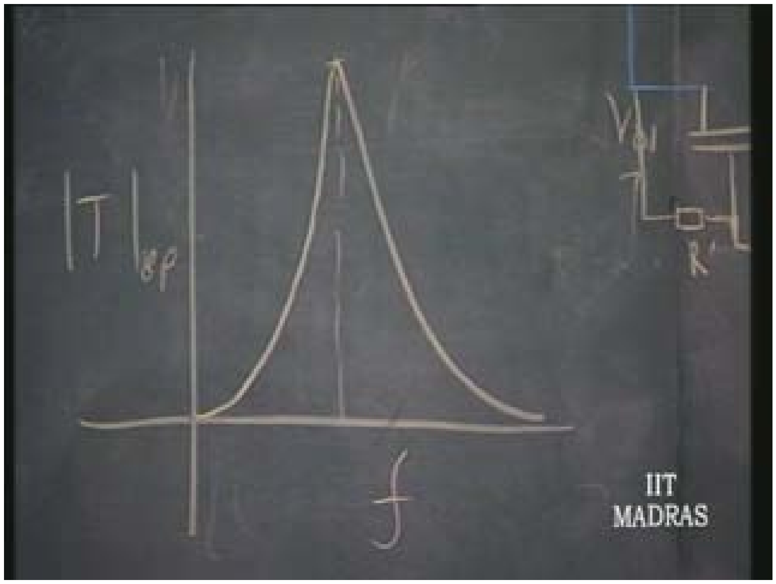
(Refer Slide Time: 00:25:47)



Now I want to make this filter self tuned, what does it mean?
I am feeding a certain frequency here let us say 50Hz then I want it to tune itself to 50Hz. If I change this frequency to 200Hz its center frequency or its pole frequency should go to 200Hz if it is band pass or not or whatever it is. So I want the pole frequency to be now tuned automatically.

Let us give this as a problem on tuning for a student; this is given to you in the lab. You are given this frequency as the incoming frequency or reference frequency then you are asked to tune this filter to the incoming frequency. Obviously we will change the V_c. We might take any of the outputs for finding out whether it is tuned to the incoming frequency or 0.

(Refer Slide Time: 00:30:07)

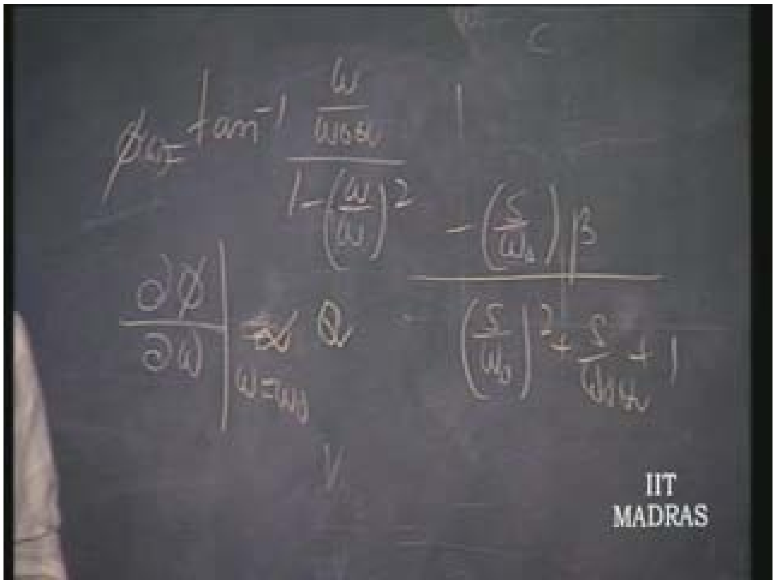


Now in this particular case, suppose you take the band pass output, how will you know that it is tuned? How will you know that it is tuned to the incoming frequency 50Hz or 100Hz how will you know?

Here gain is determined by beta, what is the band pass output characteristic?
It will have a peak. Peak mathematically means the magnitude does not vary with respect to frequency band pass. Whereas in order to find out whether around that frequency it is tuned or not then something has to vary by a great extent. This is something that even though is $V_i$sible for an IQ circuit this is $V_i$sible as a technique of tuning, this is the wrong method of tuning whereas we should make use of another parameter that is phase variation with respect to frequency.

How does phase vary with respect to frequency for a band pass?
Let us have these characteristics s by omega$_0$ minus beta s by omega$_0$ square s by omega$_0$ Q plus 1. The phase of this is 90 numerator and the denominator is the one which causes phase variation with respect to frequency which is nothing but tan inverse omega by omega$_0$ Q by 1 minus omega by omega$_0$ square.

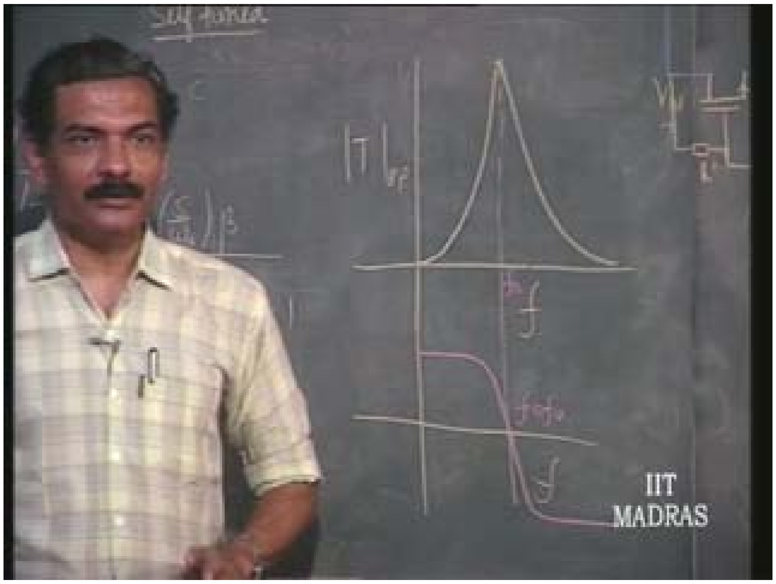
(Refer Slide Time: 00:32:29)



That is the phase variation with respect to frequency. And if you maximize this find out delta fi by delta omega and you will find that this will be maximum at omega is equal to $omega_0$ and is going to be equal to, at $omega_0$ phase shift is S and S gets cancelled, this is going so phase shift is 0 or 180 degrees in this case it is 180 degrees. Phase shift at the resonant frequency is 0 that is known to you for the band pass output 0 or 180 degrees. But phase variation is directly proportional to Q.

What is delta fi by delta omega at omega is equal to $omega_0$? Find out that it is directly proportional to Q of the circuit. That means if I plot the phase variation initially the phase shift is starting at minus 90 or whatever and going over to 0 going to plus 90 and it is this slope that we are talking of which is delta fi by delta omega and that is highest at omega is equal to $omega_0$ and is dependent upon Q. Higher the Q steeper this is going to be. Therefore if you want to check whether you have exactly located your center frequency or not you have to find out the phase difference because the phase is going to vary the maximum around that frequency whereas the magnitude is not going to vary at all by definition because it is flat because it is the maximum.

(Refer Slide Time: 00:33:14)

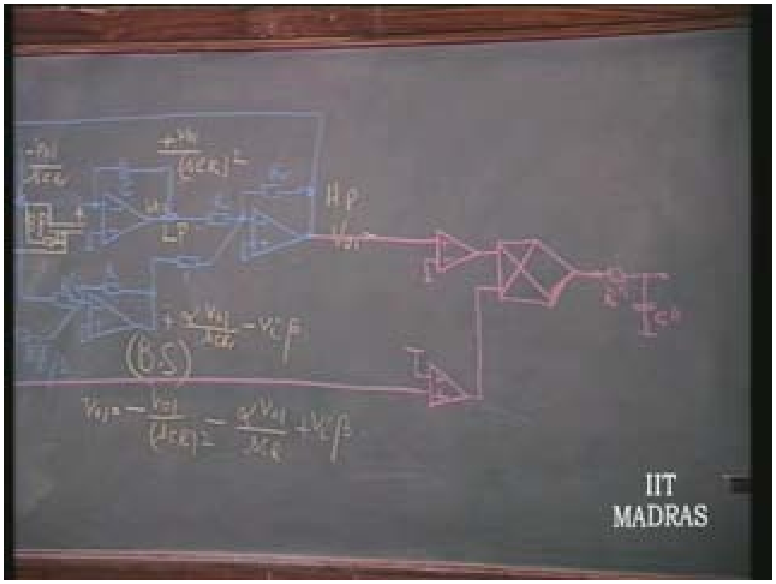


Phase variation is maximum, in any circuit therefore if you want to adjust the frequency exactly you must use always the phase variation with respect to frequency and not the magnitude. So, phase detector is invariable used and not magnitude detector. That means I need a phase detector, let us now therefore use a phase detector, but then the phase detector that we used was capable of detecting only phase not form 0 but from 90 degrees.

The multiplier type of phase detector we used earlier or AND OR gate phase detector was not capable of detecting phase that is leading and lagging phase if it is starting from 0 we had a quiescent phase shift of 90 degrees. That means it is advisable not to use the output of the band pass but we must use additional phase shift which is already available to us. Therefore if you use additional phase shift of 90 degrees that means either low pass or band pass in this structure we can use it in combination with our phase detector to find out how exactly I have to shift the frequency in order to tune it exactly to the incoming frequency.

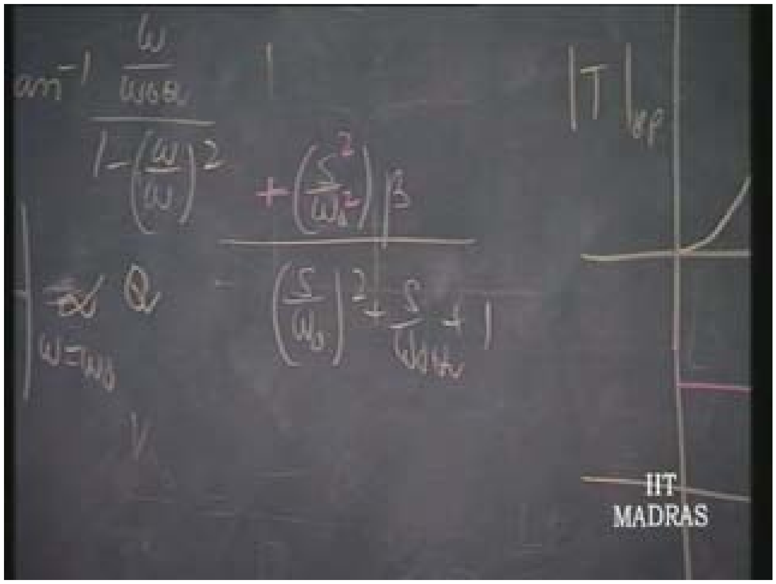
In a given case if you have only band pass output available you must shift it by additional phase of 90 degrees or put an integrator or differentiator. But in a given circuit if you have low pass and high pass available or high pass available then you can take the output from these.

(Refer Slide Time: 00:36:39)

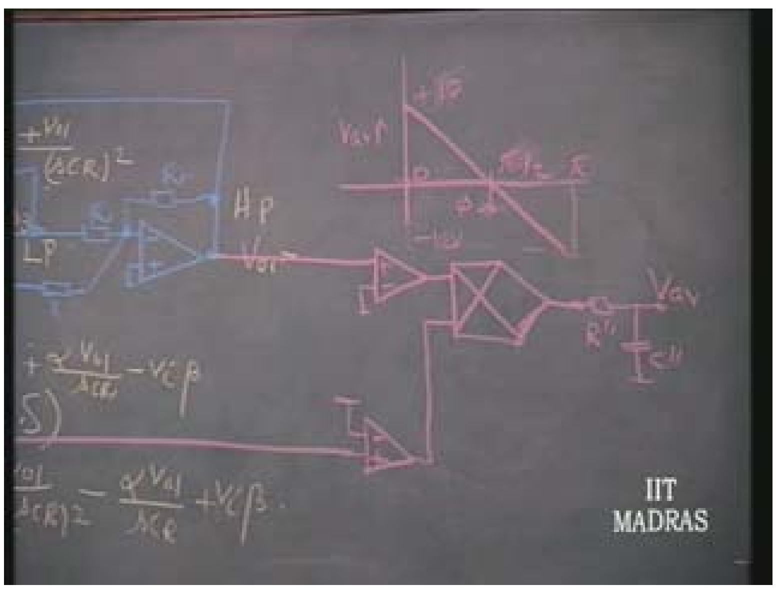


Therefore let us take the output from this the high pass and the input from this and put a phase detector, how is the phase detector designed, we put a multiplier a linear phase detector, we do not have to put a linear phase detector but for simple analysis we have put a linear phase detector now. It will become a phase detector primarily when I take the DC out of this the average and this average will tell me whether it is tuned to, since I have taken the high pass the high pass output corresponds to plus s square by omega$_0$ square. And you can see if it is exactly tuned to omega$_0$ omega is same as omega$_0$, the incoming frequency omega is same as omega$_0$, this will get cancelled and I will get a phase shift of 90 degrees exactly at that frequency. When there is phase shift of 90 degrees for this circuit the output is going to be 0. The phase characteristic was going like this from plus V_s to, or plus 10V to minus 10V to 0.

(Refer Slide Time: 00:36:58)



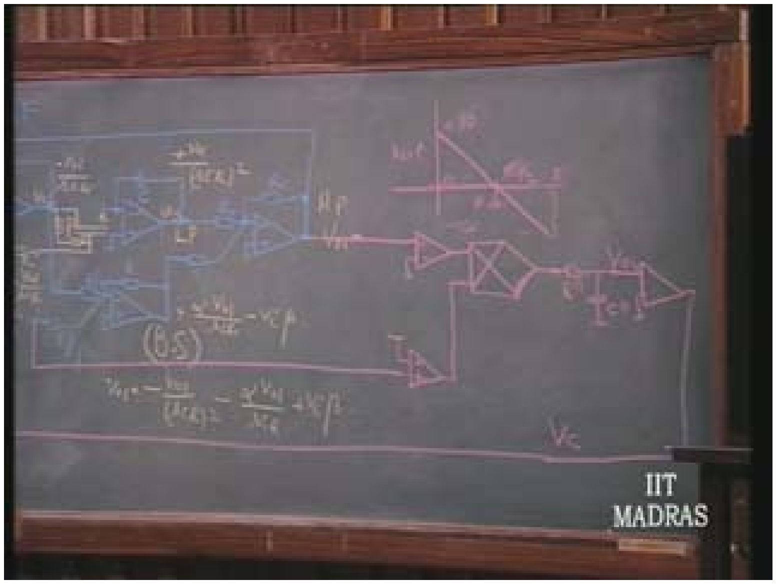
(Refer Slide Time: 00:38:00)



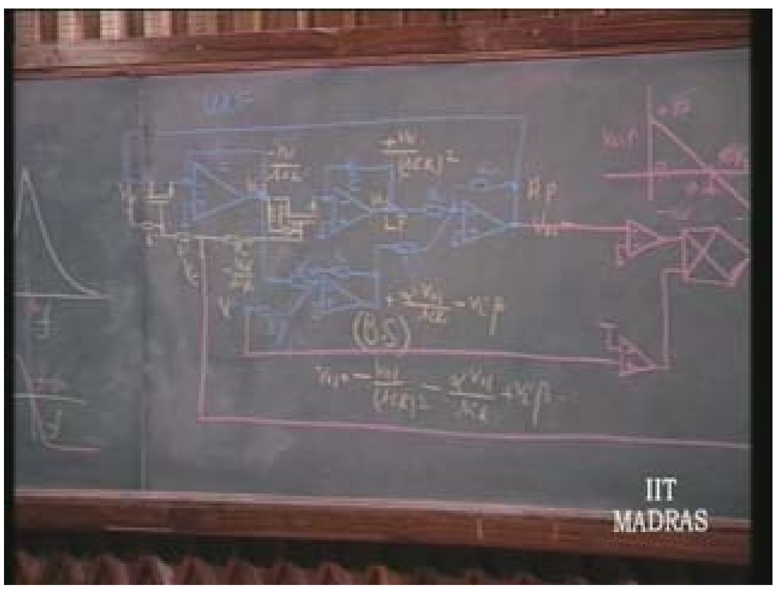
This was the phase characteristic with respect to, this is pi by 20. So we can find out whether it is tuned to the incoming frequency or not the moment we get a zero average voltage at this point. Now how do I therefore make sure that this is going to be the case automatically?

I put a comparator here and connect this R, this is the reason.

(Refer Slide Time: 00:38:35)



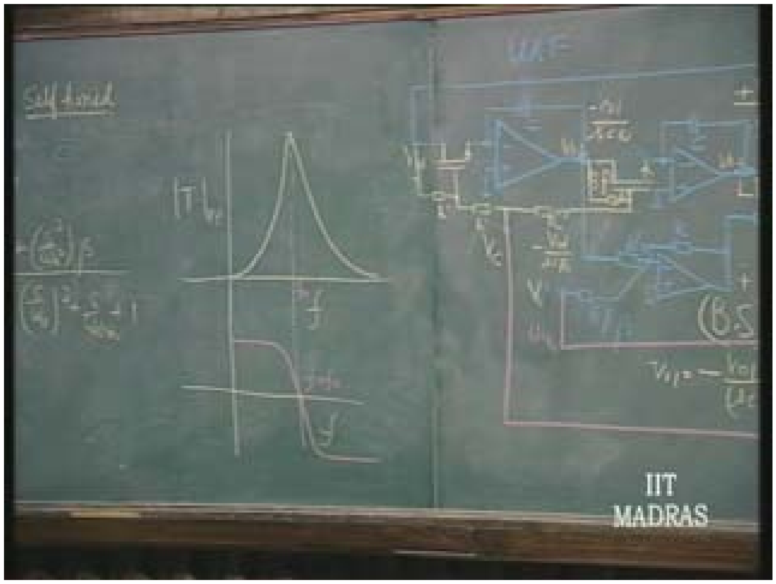
(Refer Slide Time: 00:39:28)



This is an automatic frequency locking scheme, it is automatically self tuned. This voltage has to automatically become equal to 0. If this is a negative feedback system since I am using an op amp here this output should adjust itself so that this voltage and this voltage become one and the same if it is a negative feedback system which you have to make sure. The proper polarity has to be put here to see that it is a negative feedback system.

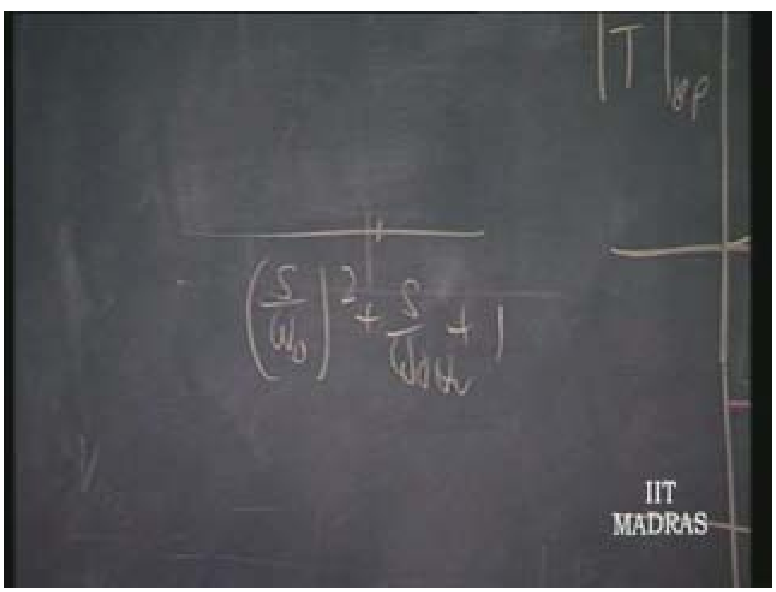
We have to find out whether this particular scheme works as a negative feedback structure. When this is at omega is equal to omega R if the original frequency to which it was tuned was less than omega R now the feedback should be such that it should be brought towards omega R that is negative feedback system. For this particular case I am using a n-channel MOSFET sometime to find out whether it is negative feedback or not. Now I have not marked the polarity of the last amplifier and I will change that depending upon whether it is going to be negative feedback.

(Refer Slide Time: 00:40:45)



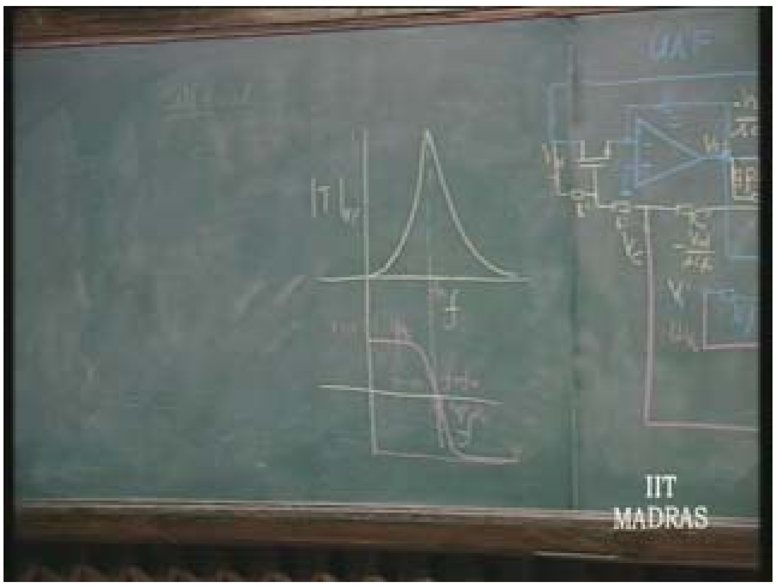
This is omega R and this is the incoming reference frequency, now I know how phase varies for this particular thing with reference to omega R.

(Refer Slide Time: 00:41:28)



You can just put this as s is equal to j omega and omega is equal to omega R. Therefore, as far as the numerator is concerned we are not bothered but as the denominator is concerned we know that as omega R is very low what is the phase shift?
This quantity is going to be very low, the phase shift is determined primarily that it is minus 90 degrees from the denominator. The numerator itself is going to give you a phase shift of 180 degrees and you can ignore that. Therefore afterwards as omega comes close to omega$_0$ this quantity vanishes, it becomes exactly equal to 90 degrees. As omega goes very high you can see that this becomes negligible and this quantity becomes dominant so it goes to 180 degrees. As far the numerator is concerned this magnitude itself is going to go close to 0 when s is equal to 0.

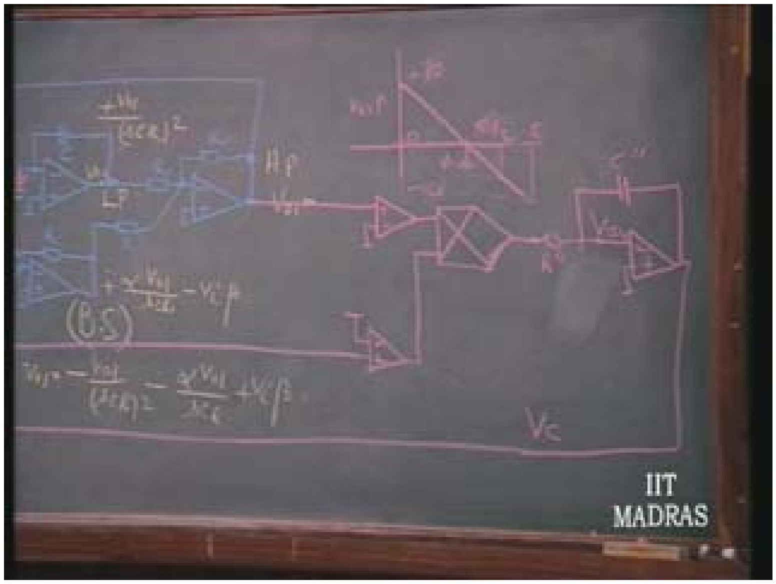
(Refer Slide Time: 00:44:23)



So the phase variation of this if you plot we have already plotted it here, it is going to vary in this fashion, this is going to be pi by 2, the initial phase variation is primarily determined by the numerator rather than the denominator because s is j omega R and omega is very small so it is starting with a phase of 180 degrees and going to minus 90 degrees and going to 0 degrees like this. Whether is a minus or plus it does not make any difference, so 180 or 90 or 0 and that is how it is changed. Therefore you should know this nature of variation. If this is the nature of variation at, this is omega R is equal to omega$_0$ the phase shift in this.

Let us say omega R is less than omega$_0$ then the phase shift is closer to 180 degrees this is important and it is changing form higher phase shift to this. Now, as far as the phase detector is concerned if the phase shift is closer to 180 degrees we have started with omega$_R$ less than omega$_0$, so omega$_R$ is somewhere here in this region. When the phase shift is greater than pi by 2 you are getting a negative value so this voltage is negative. If this is negative let us put this as negative just for argument sake then this would have gone to more positive voltage here or less negative.

(Refer Slide Time: 00:45:56)



More positive means the resistance is going to decrease, this is n-channel so the resistance is going to decrease. If the resistance decreases the frequency is going to increase and the omega R is remaining the same but omega_0 is going to increase so this is positive feedback. In order to make it negative feedback what should we do? We can change any one of these things, either we make this because I would like to change this rather than anything else, instead of n-channel I make it p-channel and retain this as minus because I would like to not use large capacitors here instead I would like to use miller effect and make this an integrator. This is what is called a self tuned filter which is now going to work satisfactorily.

What does it mean? Where is it used?
This is used when the signal to noise ratio is very high, that is the signal is buried in noise. But we know that the signal is almost a single frequency, that is, the bandwidth of the signal required is very small. Therefore I make a high very high Q self tuned filter and let it get tuned to the incoming signal then it will eliminate all the other noise around it if it gets locked on to the signal. This is one way of searching whether there is a signal anywhere in space.

We do not know who is sending our information in space but we know that this information is a highly narrow band signal. So we can keep scanning the entire range of frequencies using this kind of self tune filter. What you do is you can skip ranges by making V_c get disconnected and making it a saw tooth and search in different ranges of frequency and see whether anything is getting locked. Once it is locked it will keep on tracking. So this is really used in space applications for finding out signals from unidentified sources. And we just keep recording this for years and years to see whether there is any intelligible information coming from these sources. So in such amplifiers the self tuned filters are used.