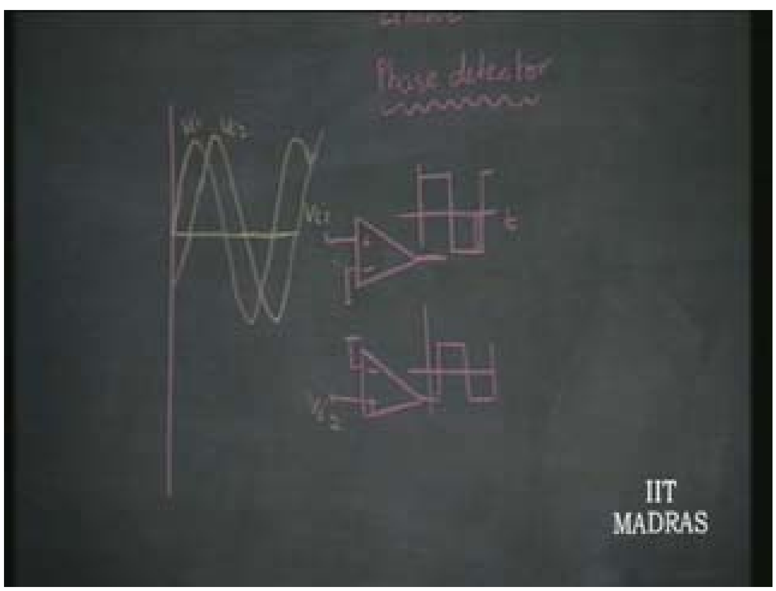
Analog ICs
Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture - 21
Voltage Controlled Oscillator and Linear Phase Detector

So, continuing with the multiplier applications before we come to other types of multipliers we will just look into certain aspects of the phase detector. We saw that when we give an input to a multiplier a sine omega t and another b sine omega t plus fi will give you ab sine omega t sine omega t plus fi/20 which will have a dc component cos fi dependent upon the phase but it is non-linearly related. Therefore if we are interested in a linear phase detector what should we do?

It is enough if we make the amplitude of no consequence. What it means is, we feed the inputs to limiters or comparators which will just limit the amplitude to a certain value. So the communication engineers called this the limiters. Basically they are voltage comparators.

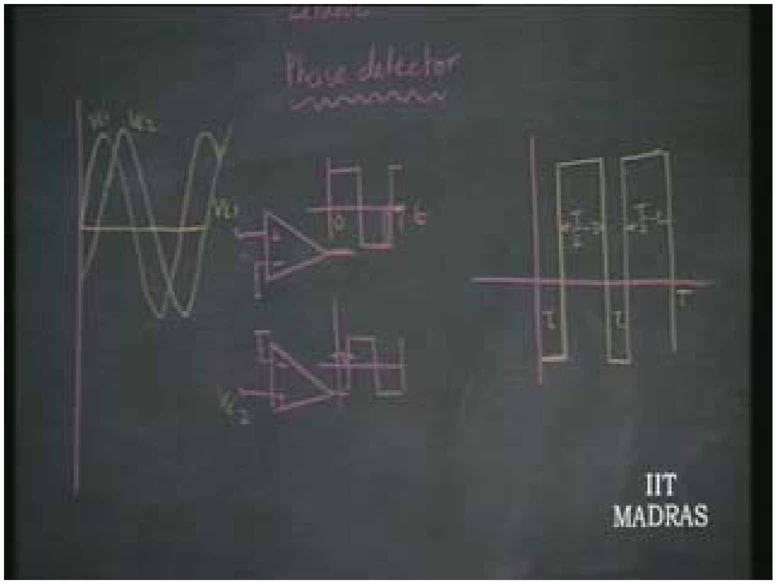
So we have comparators to which we are feeding the two inputs which are going to have this kind of a relationship, this is going to be V_{i1}, this is V_{i2} and therefore if V_{i1} is this way and V_{i2} is going to be differing in phase by a certain amount. So, if you feed this kind of an input to these automatically we see that at the output this simply gets limited to t and this will be delayed by an amount corresponding to the phase shift.

(Refer Slide Time: 00:04:32)



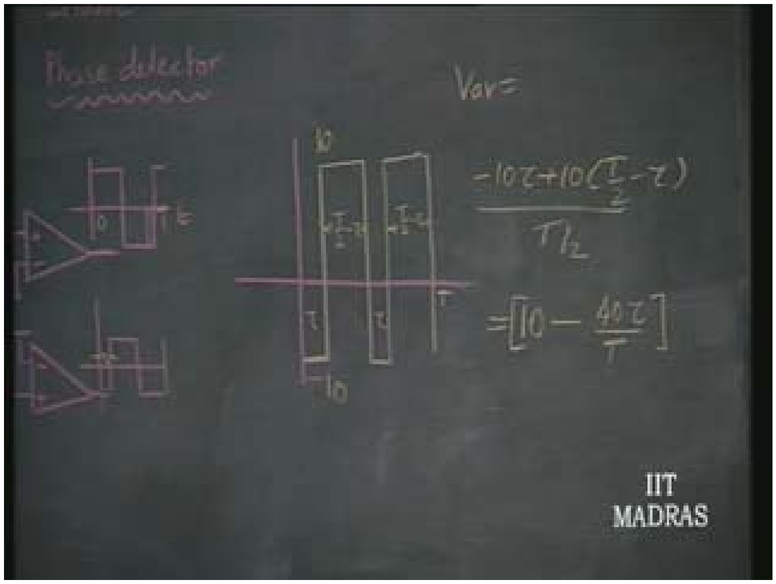
So this is how it is going to be. Therefore now if you multiply one with the other assuming that both these things go to the maximum limit 10V or whatever it is so we get an output. That is, when both are positive or both are negative we will get a positive output and when one is positive and the other is negative you get a negative output so in which case we will get an output corresponding to[….], for this amount of time we will have it negative and then for the rest of the time we will have a positive.

(Refer Slide Time: 00:06:02)



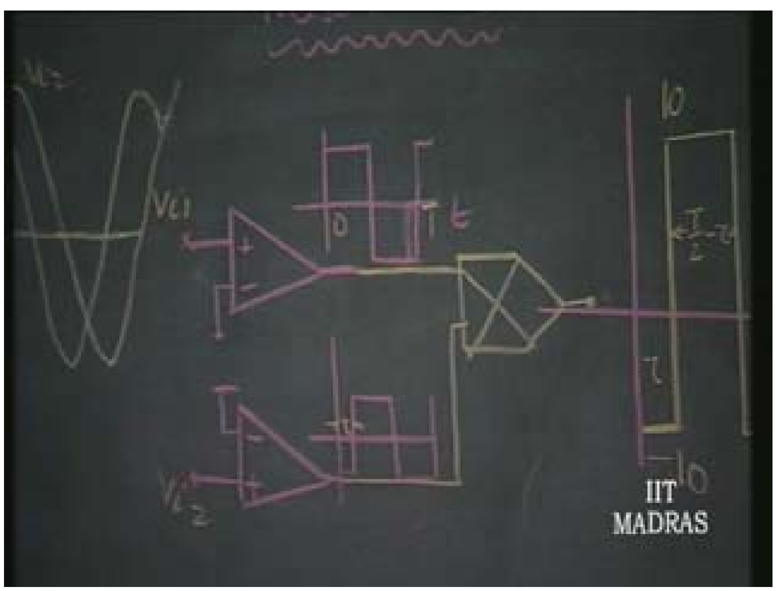
Within a time period t and if this is tau we have this going through a periodicity twice because this is going to be tau, this is going to be T/2 minus tau and this again tau and this is going to be T/2. This is indicating clearly that there is a two omega component corresponding to the omega component of the input as expected because in earlier situation also we had two omega component and a DC component here corresponds to, if this is 10V and minus 10V it is going to be minus 10 into tau plus 10 into T/2 minus tau/T/2 that is what is called the average component which will correspond to T/2 that is 10 minus minus 10tau minus 10tau minus 20tau or minus 40tau/T.

(Refer Slide Time: 00:07:16)



Therefore you get here a clear cut linear phase relationship between the average and the phase tau. This is a very simple phase detector. Therefore what you have to do is get rid of the amplitude information by passing it through a limiter and then do the multiplication. So this is the multiplied output. This is one of the important applications of that multiplier which we called as the balanced modulator which we will again recollect when we are going to discuss phase lock loop.

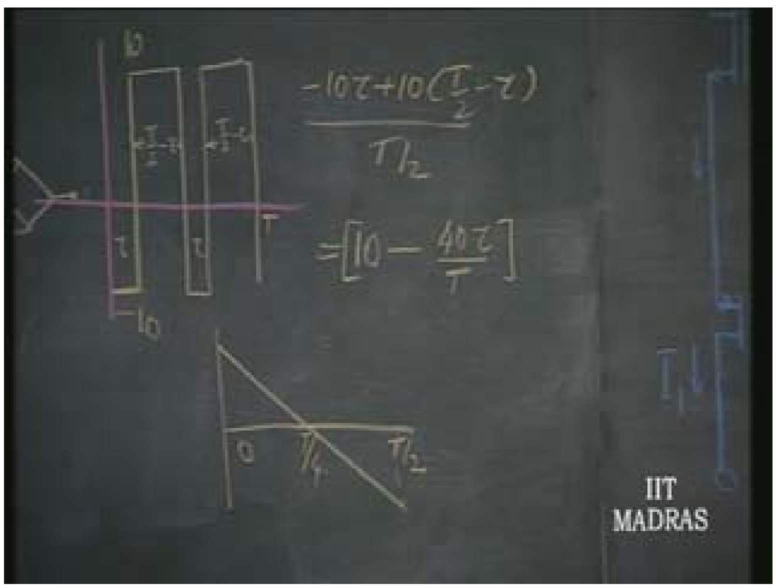
(Refer Slide Time: 00:08:09)



If you pass it through a set of comparator the relationship between the phase and the average becomes linear and if you do not do it then also there is a relationship between the output average and the phase but it is non-linear cosine relationship. One input comes from outside and the other input to the phase detector is generated within so that we can limit it to a value so that can be made high. So when one is a sine wave another is a square wave and there is a phase relationship between these two waveform then what is the average. So, when both are sinusoids the phase relationship is cos phi.

When one is sinusoid and another is square wave what is the relationship between the average and the phase?
Then when both are square waves we see that it is perfectly linear and you can see here for a phase shift of 0 the output is 10V and for phase shift of π/2tau is T/4 so the output is 0. For a phase shift of π it is minus 10. Therefore it is a linear relationship going from 100 to minus 10 so you can club this characteristic.

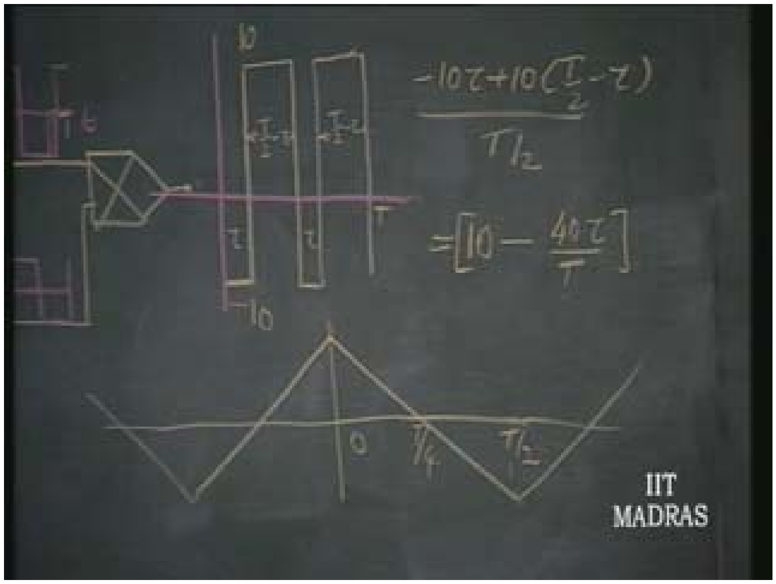
(Refer Slide Time: 00:11:23)



What will it be on this side for the negative? The same thing so it repeats itself. This is the characteristic of this phase detector because it is not able to distinguish between phase lead and phase lag, so because it is not able to detect this kind of phase lead or phase lag we are necessarily required to locate our quiescent phase shift at π/2. That means we subject one of the inputs to an additional phase shift of π/2.

How do we subject one of the inputs to quiescent phase shift of π/2?
If you have two waveforms whose phase you want to detect properly you make one of the waveforms go through an integration or differentiation. That is the only thing which gives independent of frequency a phase shift of π/2.

(Refer Slide Time: 00:11:42)



That means additional phase shift of π/2 must be subjected to as far as one input is concerned and then you apply and then what happens is we can now distinguish from the output whether the two waveforms are leading or lagging because you can get correspondingly different signs and the magnitude of DC voltage will remain the same for the same phase magnitude but depending upon whether it is leading or lagging you will get a positive or negative DC voltage. That is why we must have necessarily a quiescent phase shift.

It is important you understand this concept here like you have quiescent DC level for operating an amplifier both on positive going signal side and negative going signal side in order to give at proper dynamic range for the phase detector you must have some phase shift constant and it is not necessary that it should be π/2 but if you have π/2 then it is obvious that you will get the maximum dynamic range. It could be any value between 0 and π/2 but we select it as π/2 so that we get the maximum dynamic range for phase variation on either side of this. And it is easy to give it a phase shift of π/2 than any other phase shift which is fixed with respect to frequency. So this is something you have to understand in order to understand anything about phase detector wherever phase detectors are used.

For any phase detector of this type for that matter whether you use the comparator or no comparator the phase characteristics will be either this triangular or sinusoidal. And when the phase error is very small it looks linear, these are all valid. So it changes its characteristics from sinusoidal characteristics to linear characteristic the moment we make it amplitude independent.

Compare this with a phase detector just by using an AND gate instead of doing all this. You can just AND these two output even then you get a linear phase detector. So just AND OR or the output you can get exactly linear phase. The difference is, the frequency component of the output will now be omega itself it does not become 2omega. The multiplication makes it go to 2omega and average whereas here the difference between this and this is that the next component here so happens to be 2omega whereas in the other circuit it is omega. So that also is a phase detector. If you do not mind the error voltage that is the unfiltered path corresponding to that of omega because corresponding to that of 2omega you can filter it more easily than corresponding to that of omega.

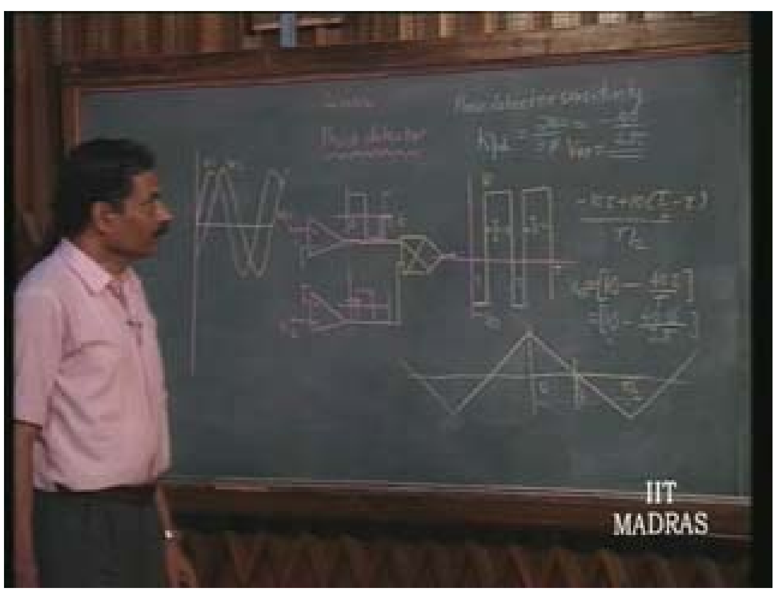
You have to find out the average, what it means is the low frequency component. Therefore you could prefer this one because the output will be 2omega and DC. So this is an important application of the multiplier or balanced modulator we have to remember whenever we discuss about phase lock loop application.

What is the important parameter associated with the phase detector?
It is the phase detector sensitivity.

What is phase detector sensitivity?
This is equal to delta V average/delta tau or delta fi. In fact you can put this as V average as this or 10 minus 40 fi/2π in any mode angle mode or time mode. So phase detector sensitivity is an important parameter which is called Kpd we will call it remember, which is the sensitivity of the average voltage to phase variation, delta V average/delta fi is called Kpd.

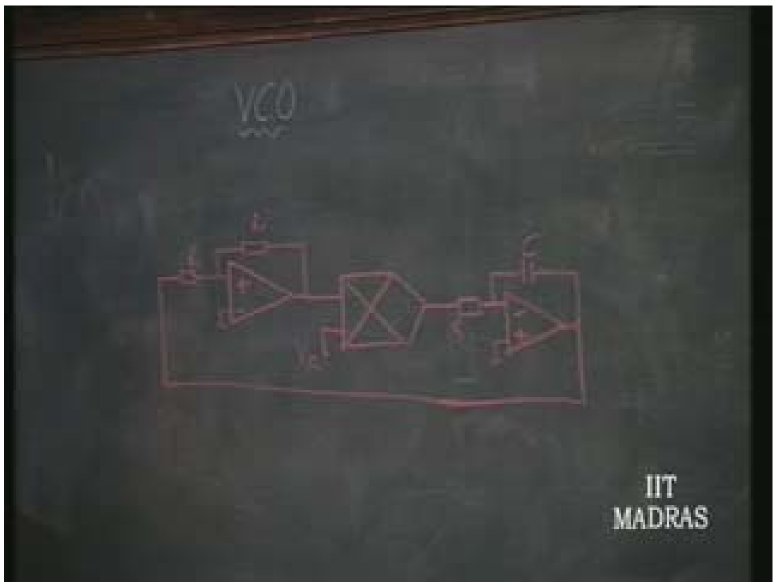
In this case how much is that?
It is minus 40/2π for this one and for this one it happens to be linear and therefore this is valid at all operating points. In case you are using the other type where amplitude limitation is not brought about then also you will get the same value but the only thing is it is valid only around the operating point.

(Refer Slide Time: 00:18:28)



We will see later how this can be used in assessing the performance of phase lock loop. Therefore please do remember how you can build phase detector using multipliers or balanced modulator. Now we will again see another important application of the multiplier that is in the design of what is called voltage controlled oscillator because this also forms a part of a PLL and it just happens to be an important application of the multiplier.

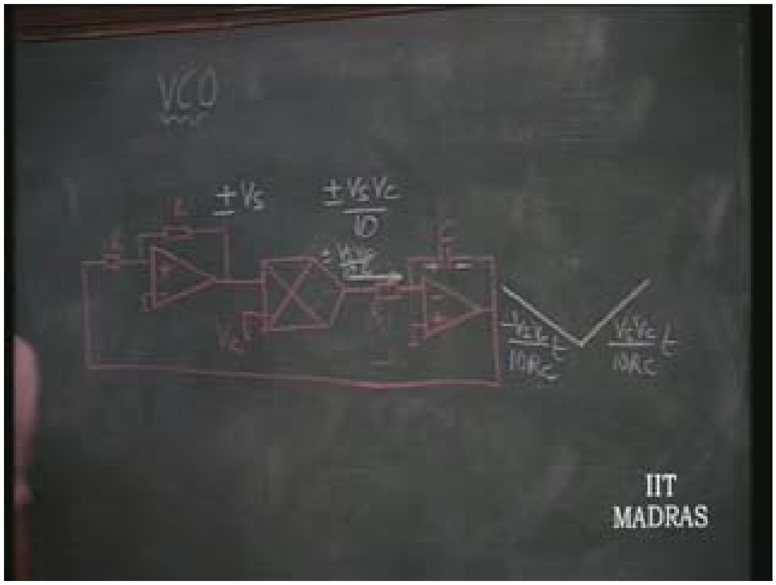
(Refer Slide Time: 00:20:29)



Voltage controlled oscillator: I already discussed this partly. I told you that one way of building a voltage controlled oscillator is to have a Schmitt trigger that is a circuit with regenerative positive feedback which is called Schmitt trigger and a multiplier and an integrator. So this becomes a nice voltage controlled oscillator. Let us just go through the motions of how this works, because this is a Schmitt trigger we know that the output can be only plus or minus V_s it cannot be at any other point because of the regenerative feedback. So if this is plus or minus V_s this can only be plus minus V_s into $V_c/10$. Therefore this current can be either charging or discharging the capacitor by an amount which is $V_sV_c/10R$ which is plus or minus.

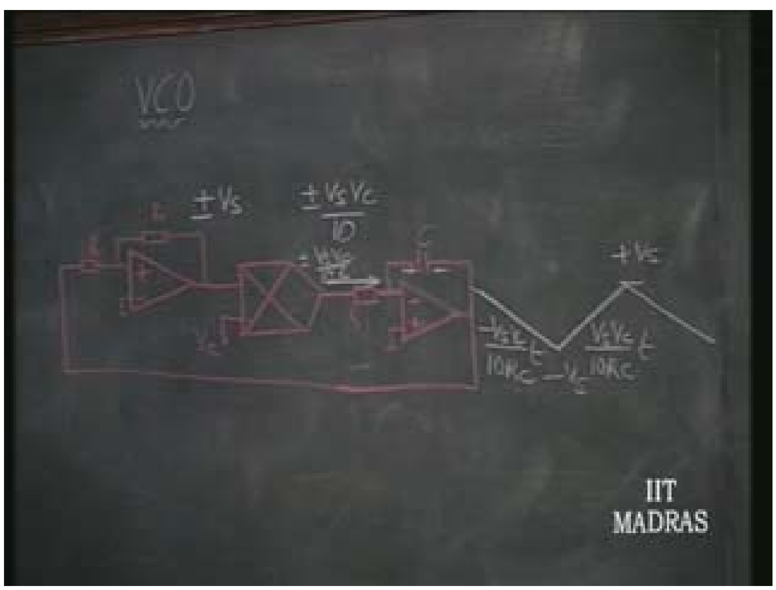
When it is going like this it will charge the capacitor this way that means voltage will be either going this way by an amount which is $V_s/10R_cV_c$ into t or it will be going this way by V_s this will be minus slope and this will be plus slope because this is the DC current going into the capacitor I/C into T is the voltage variation across the capacitor which is going on decreasing or increasing at this rate so this will generate a triangular waveform. Obviously the change of state occurs here when this goes to, when this is at plus V_s this should go to minus V_s then only the voltage here becomes equal to 0.

(Refer Slide Time: 21:51)



Only when this voltage becomes same as this voltage it gets into the regenerative feedback mode it goes into the active region where it has the regenerative feedback and therefore immediately it will change state from plus to minus. So what happens is, this is going to be plus V_s and this is going to be minus V_s.

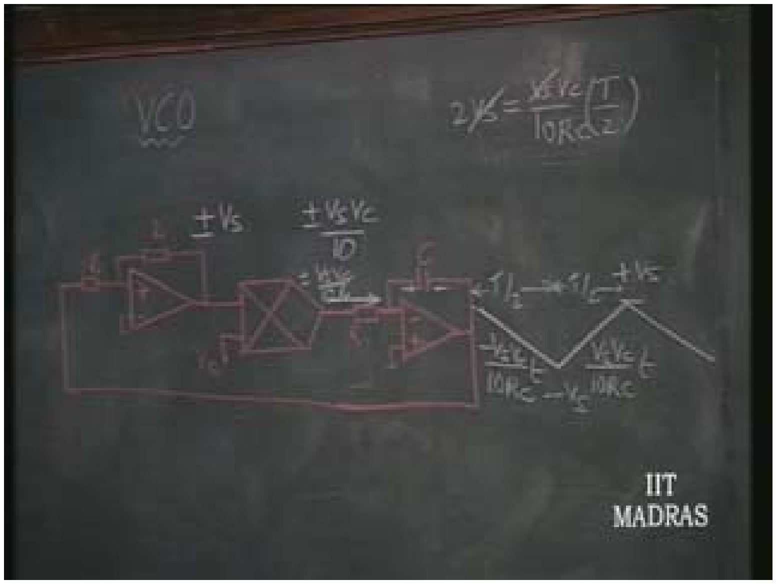
(Refer Slide Time: 00:22:54)



So what happens to this?
This is twice V_s if the voltage change is across the capacitor, this is plus V_s this is minus V_s within a time interval of T/2, this is periodic so if this is T/2 this has to be T/2 where

charging and discharging occur with the same interval of time so $2V_s$ is equal to $V_sV_c/10R_c$ into T/2 this is what we get, V_s gets cancelled so we get T is equal to $40R_c/V_c$ or f is equal to 1/T is equal to $V_c/40R_c$. This is what I mentioned about as being the frequency of oscillation.

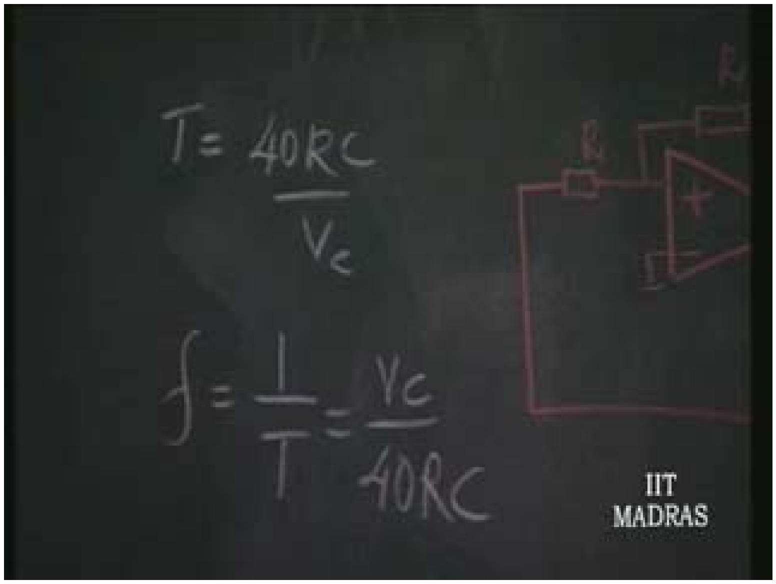
(Refer Slide Time: 00:23:53)



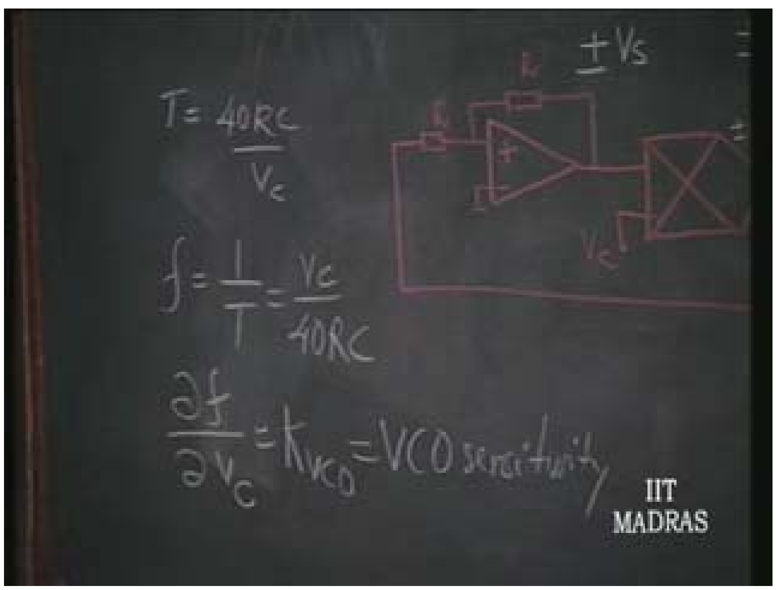
Now this is the frequency of oscillation of our V_c over here which is going to have a triangular waveform here and square waveform here. Now the important parameter associated with the VcO is delta f/delta V_c or this is called K_{VcO} or it is called VcO sensitivity.

How much is that in this case?
It is 1/40R. Or this can be written same as f/V_c. So f is equal to $V_c/40R_c$ so delta f/delta V_c is f/V_c.

(Refer Slide Time: 23:54)

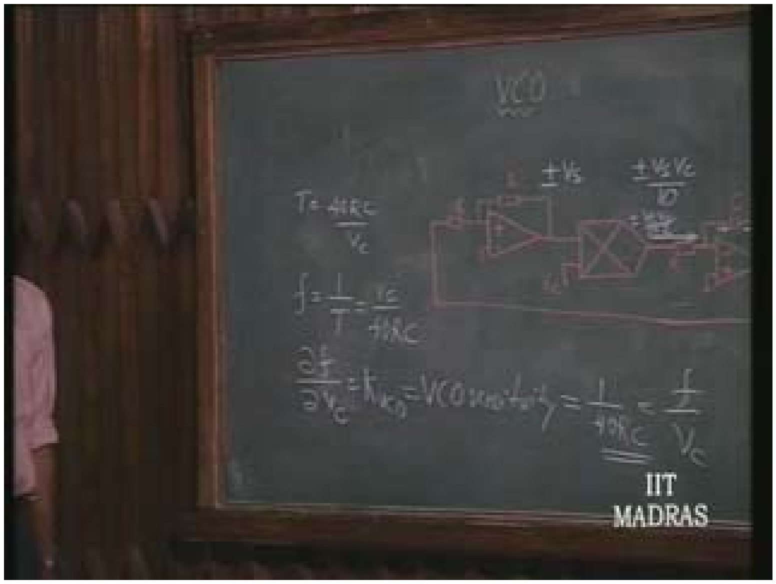


(Refer Slide Time: 24:39)



So this again forms an important parameter to be made use of in our discussion later about phase lock loops. And essentially a phase detector and VcO form the important building blocks of a phase lock loop. Here we have seen how the multiplier has fed it become a nice linear voltage controlled oscillator.

(Refer Slide Time: 24:57)

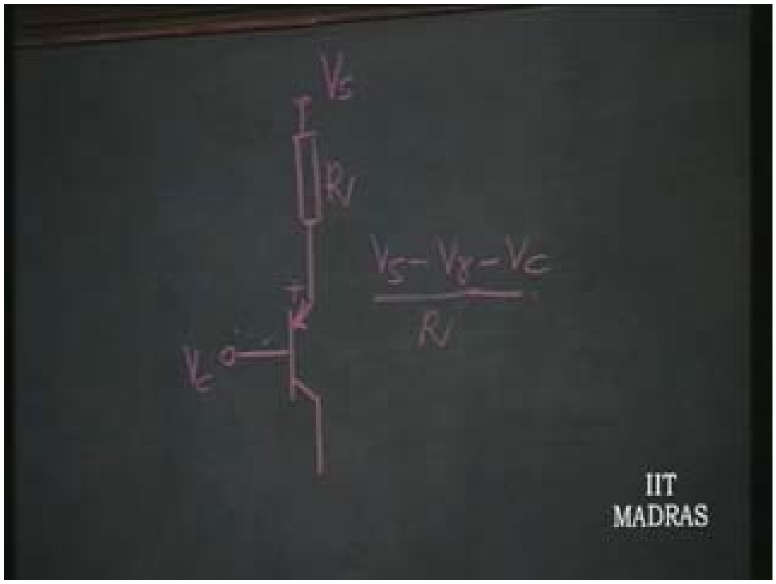


The VcO as you have seen gives you triangular output, square wave output but obviously no sine wave output is present. In case if you need a sine wave output you can generate that sine wave output using a diode function generator which is a piecewise linear approximation of converting a triangle to sine wave. So this is what is done really in what is called a function generator IC chip wherein depending upon the accuracy you desire the normal accuracy with which you can generate a sine wave is about 3 to 5 % distortion.

In fact an easy way of converting a triangle to sine wave is by simply hitting at the top and the bottom. That means making it go though a saturation non linearity. So, just remove the peaks and it becomes a rough sine wave. Now we will see how we can obtain a high frequency VcO.

We already know how a fi frequency phase detector can be obtained by using a balanced modulator circuit which we have discussed in our multiplier discussion. Let us now see how a high frequency voltage controlled oscillator can be obtained which is suitable for use of PLL at very high frequencies. Now the basic principle underlying is similar to what just now we have seen with op-amps. Obviously I must have a current which is dependent upon voltage. How do I get a current dependent upon voltage in a very simple manner? It is through the transconductor.

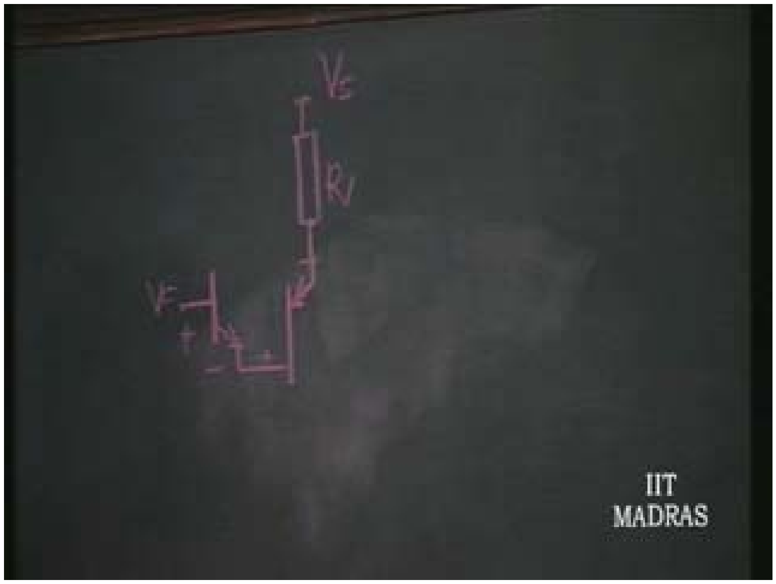
(Refer Slide Time: 00:28:29)



A voltage can be converted to current by using a transconductor. Using a transistor therefore it becomes very simple. If I use V_c here and V_s here what happens? The current in this is, this is R, V_s there is a drop here plus minus V_{gamma} so V_s minus V_{gamma} minus V_c/R. So you have now got a current which is dependent upon voltage in a linear fashion. This is the simplest circuit you can think of by putting a resistor here of course externally if you desire so that you can change this current of charging. Just by using a transistor like this we are able to convert it into a current which is dependent upon this resistance, so this is a current. But we are not happy with this because V_{gamma} is changing with temperature etc. Therefore we would like to convert this.

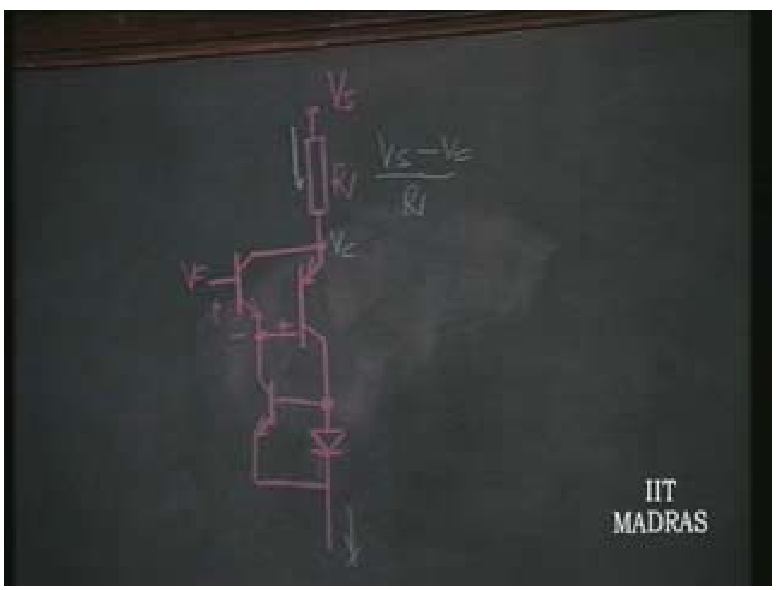
I am trying to synthesize this now. So I will put it this way and I will apply the V_c to this, there will be a drop of V_{gamma} and there is a rise of V_{gamma} so the voltage appearing here is V_c. Drop of V_{gamma} rise of V_{gamma} so the voltage here is simply V_c if the two $V_{gamma\ s}$ can track with respect to temperature and this is so.

(Refer Slide Time: 00:29:32)



So, in order that they should be the same the primary criteria is that they should operate at the same current because there is a forward voltage drop dependent upon the operating current.

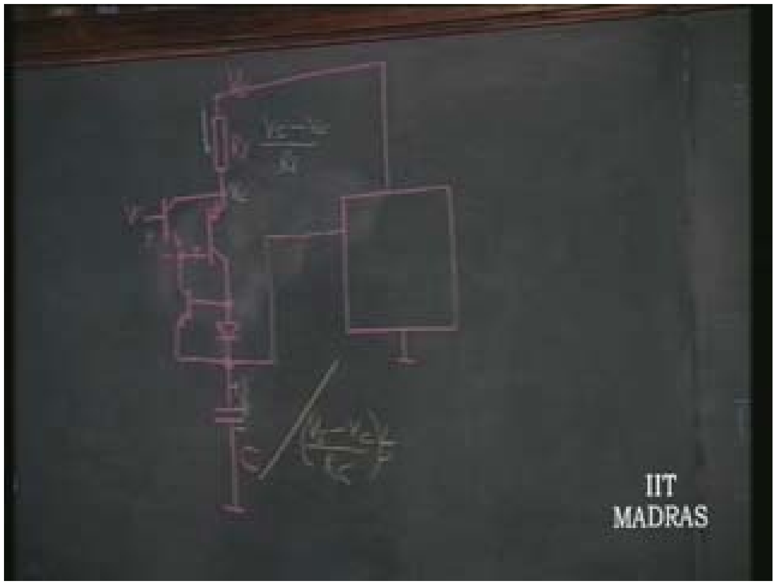
(Refer Slide Time: 00:30:50)



So now I have a current mirror coming to my rescue so I will put a current mirror here so as to make this operate at the same current as this. Therefore this transistor and this transistor are operating at the same current and if I now connect this the current leaving this is going to be V_s minus V_c/R and this is going to be same current, and here it is V_c

now. I have now been able to obtain a very nice compensated transconductor which is capable of charging a capacitor.

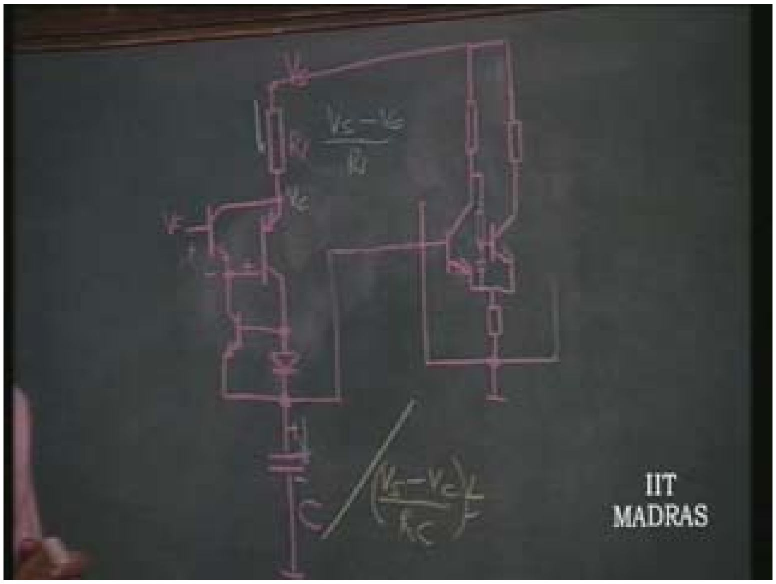
(Refer Slide Time: 00: 32:13)



I want to charge a capacitor now so let us say I will connect this current over to the capacitor so what happens now is this capacitor is going to get charged and the voltage is going to increase at a rate which is nothing but V_s minus V_c/R_c into t. This voltage is now going to be buffered that means you can use a common collector stage and connect it over to………….

What is a Schmitt trigger?
This Schmitt trigger has to be a fast Schmitt trigger that means it is going to be a differential amplifier with positive feedback.

(Refer Slide Time: 00:33:29)

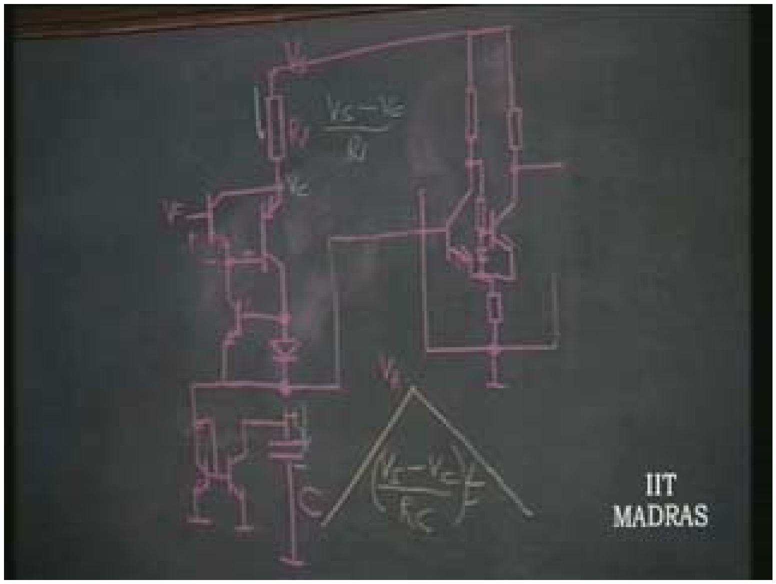


We will remove this, this is your differential amplifier but I am not going to draw it in that manner it is emitter couple and then you have that common emitter resistance and you have a collector resistance for both of these and then you have to give positive feedback, this is the other input so from this input you will give positive feedback to this. You do not want to use the resistors but you have to have some feedback coming through so called simulated resistors, this is nothing but a forward biased diode here and resistor so this essentially forms a Schmitt trigger.

Analyze this Schmitt trigger and obtain its characteristic in terms of, at what value of input voltage it will come down from high to low and at what value of voltage it will go from low to high. That means it has transition points. As soon as it reaches a high it changes state.

As soon as it changes state we want to distort this capacitor by means of the same current which should flow in the opposite direction. So the current is flowing like this. Now I would like distort this so assume that I am now going to disconnect this somehow, I have to use a switch and make this current flow through this in such a manner that it is going to discharge.

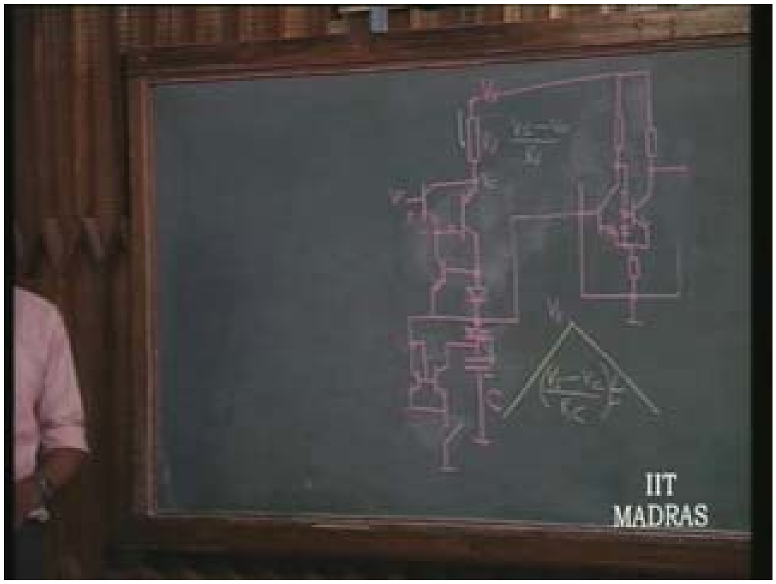
(Refer Slide Time: 00:35:54)



I will once again use a current mirror, now this current is diverted on to this so that the same current is extracted from this. This capacitor voltage is already high so it is going to bias this properly so you can go on discharging it until V_{gamma} is in there is no problem. It will keep on discharging this until this lower voltage exist at which point of time once again this switch should be closed and this should be switched off so we have to have another switch here. There should be one switch here and another switch here.

Now, this is going to be closed and this is going to be open then this is disabled not biased and therefore the current is going to be formed between these and it will skip on charging. Now here this switch is merely a diode. There is no need for any sophisticated switch here but a simple diode is sufficient. When this switch is open naturally this current has to be pumped into the capacitor through the diode where the diode gets forward biased, it is closed. The current is charging the capacitor and this voltage keeps on increasing. The moment the switch reaches higher it is connected and we can find that out by detecting the Schmitt trigger output where this will give us an indication on how to disconnect this or connect this.

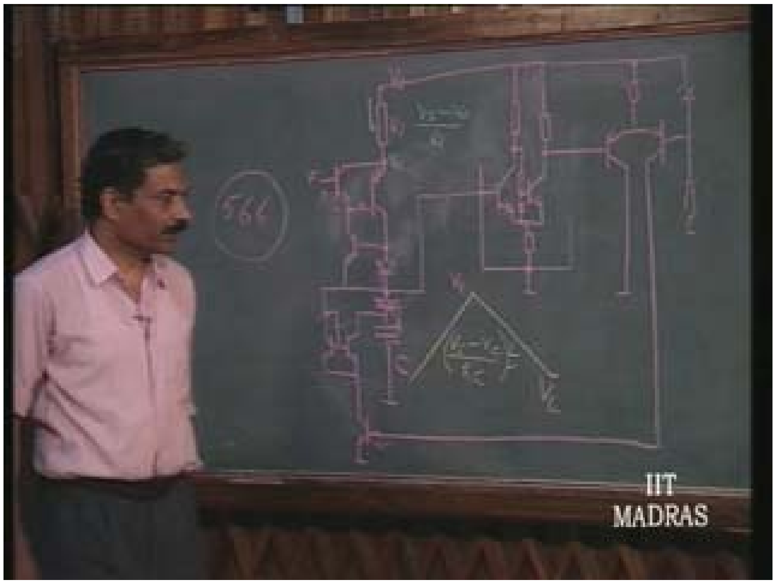
(Refer Slide Time: 00:36:43)



So the moment this is connected this diode is reverse biased because the potential has been pulled down to ground potential so this has been pulled down to ground potential and this is at high so automatically this diode is reverse biased. So this is off and the current is getting pumped into this and current mirror is going to discharge the capacitor by the same amount of current. This circuit can work up to very high frequencies up to mega hertz or even higher without much of a problem because only these transistors are involved.

Now what is the switch that is going to be here?
This is again very simple, it has to be a transistor switch and it has to get the command from this. Now I have to make sure that this transistor goes to saturation. That means the base drive has to be sufficient such that this divided by beta minimum is given to this so this is the current driven switch. You cannot connect it here because this will always be high or higher. You have to put another differential stage here. If you put a resistor it will depend upon the voltage whereas we do not want it to depend upon any voltage, either there is current or there is no current is what we have to make sure of.

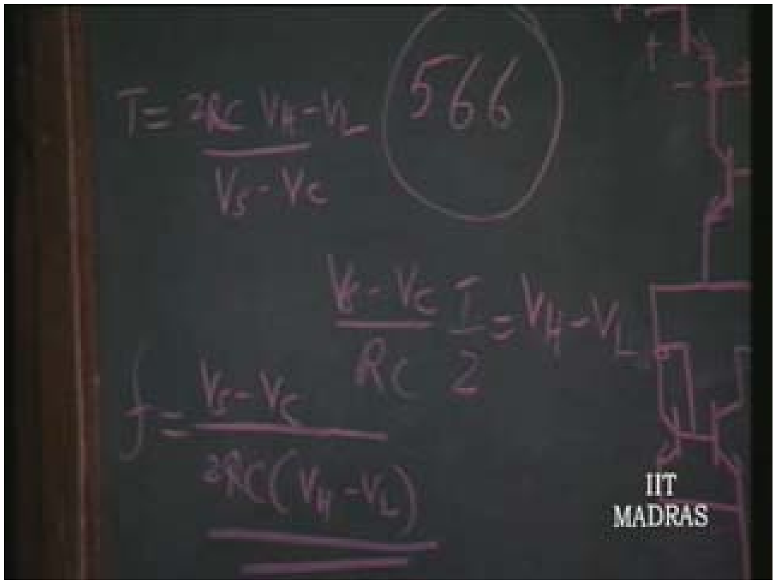
(Refer Slide Time: 00:41:07)



That means we put something like this, a comparator here and this is a current switch, this is a differential amplifier which will either give current to this or to this depending upon the voltage here. So this current is going to be 0 or the full current whatever it is required, that current can be adjusted because this voltage is fixed. Therefore you can make a neat circuit and this is the internal circuitry of 566 which is available as a linear voltage controlled oscillator, the internal circuitry of it is already given to you as part of a PLL 565 the circuit is the same, the VcO used in 565 is same as 566. So the basic circuit is essentially the same. Find out V_H and V_L for the Schmitt trigger which is necessary in order to find out the frequency of oscillation.

What is the frequency of oscillation?
It is V_s minus V_c/R_c into T/2 is equal to V_H minus V_L that is necessary. So T is equal to $2R_cV_H$ minus V_L/V_s minus V_c or f frequency of oscillation is V_s minus $V_c/2R_cV_H$. So in order to know the K_{VcO} value you should definitely know what V_H minus V_L is going to be. And that is one of the VcOs popularly available in bipolar technology.

(Refer Slide Time: 41:44)



The other VcO is what is called Emitter Coupled Multi-vibrator which is also a multi-vibrator kind of a thing used in some other PLLs. Emitters are coupled by means of a single capacitor and there is regenerative positive feedback from collector to base and collector to base.