Analog ICs

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Lecture - 10
IC
Voltage Sources and References

In the last class we concluded our lecture on wide band amplifiers. It was emphasized that the time constant must be made very small somehow by impedance mismatch or by negative feedback or by selecting resistors as low as possible with gain being maintained at a reasonable value. Now the resistors are physical resistors not simulated resistors like current sources. So I would find that one characteristic feature of all wide band amplifiers as well as high speed comparators etc is never using these current sources particularly made of PNP transistors and in place of which you will actually use physical resistors.

Of course in low frequency applications we could afford to use these current sources and current sinks are made of NPN transistors which are very good. It is the current source which is troublesome things in low frequency. That is, in applications you use current sources but in high frequency applications you do not use current sources at all in the circuit. That is how you have seen in the wide band IC we discussed that it is devoid of any current source. It might be using current sink but it is devoid of any current source. But it is not so in the case with low frequency applications like voltage regulator IC, operational amplifier IC etc.

The final building block we are going to discuss today in making up such integrated circuits is the voltage source and voltage reference. The output stage will be as discussed as part of this voltage source and voltage reference. What are these voltage sources and voltage references?

In our electrical engineering we have been again accustomed to using terms like sources and references in a synonymous manner. Similarly, we have been accustomed to using sources and sinks in a synonymous manner but not so with integrated circuit. We will make a clear cut distinction with sources which are only obtainable using PNP transistors, sinks which are obtainable using NPN transistors. Similarly, we are going to make a distinction here between sources and references. What is this voltage source?

Voltage source is something you derive out of the power supply. You have the power supply for the operational amplifier IC or comparator IC etc or for that method any IC and you would like to derive another source which is having its magnitude of voltage almost independent of the supply voltage. That is, supply independent source is what we mean by voltage sources we are going to talk about. It is supply independent. But it may be temperature dependent that we are not bothered about. It may be temperature dependent to a certain extent but it is essentially supply independent. And it should be capable of delivering as much current as I demand from it so we should be happily able to load the particular source without the source voltage changing much. That means its output impedance should be near zero. So its output impedance should be as low as possible and it should be capable of delivering whatever current we demand from it. This is the characteristic of a voltage source.

On the other hand, voltage reference is more sacred than this voltage source. Voltage reference by its terminology itself means something that we would like to use as reference and compare. This voltage reference has a variety of applications in integrated circuits. And people have spent number of years in coming up with ideas suitable for voltage references both in bipolar technology as well as MOS technology and also BiMOS technology, a suitable voltage reference.

Obviously the voltage reference is a voltage which is independent of supply voltage as well as temperature. That means its temperature coefficient is very near 0 or it is few parts per million per degree centigrade rise in temperature. So the voltage reference is very important in almost all control applications whether you are controlling a DC voltage or whether you are controlling an AC voltage, whether you are controlling speed or whether you are controlling position or whatever be the thing a reference is needed.

During olden days of course voltage reference was very commonly used as a reference. The present day application of controls we are tending towards changing the voltage reference to frequency reference and no current reference. But in a large number of conversions when you want to convert analog information into digital information even in such conversions voltage reference plays a vital role. So, voltage reference need not have low output impedance, this is important. Subsequently it should not be loaded. It is not capable of delivering current to you.

Voltage reference is something that retains its zero temperature coefficient property only when it is not loaded. This is an important characteristic of voltage reference because it has such a heavy responsibility we do not want to put additional responsibility of such things like low output impedance. Therefore we make a clear cut distinction here between source and reference.

Why do we need voltage sources?
Obviously the important application where we need voltage source within an IC is when we want to avoid unnecessary feedback from output stages.

How come that feedback occurs if you use normal power supply? If a power supply is common to all the stages that are involved in a system especially for the output stage which is dealing with high power as well as pre amplifier stage you are landing yourself in a very serious problem. Particularly if the voltage reference or voltage source in this case is going to have low output impedance but finite then obviously when a large current is being drawn from it the terminal voltage is going to change. That means the terminal voltage changes according to signal. Subsequently since the same terminal is connected to all power supply points of the circuit system the feedback results through the power supply. So this results in high frequency oscillation.

At some frequency now it can cause oscillations because the so called feedback turns itself into positive feedback and so the whole system starts oscillating. The amplifier starts oscillating not because the amplifier has been designed badly but because you are using same power supply for all amplifiers. This is some point which a designer should always bother about particularly in an IC designer where the amplifier as well as audio amplifier and power amplifier will be the responsibility of the IC designer. So, if you making a single chip IC for the entire system you must necessarily isolate the power supply for the pre amplifier stage. It is the pre amplifier stage which has to have the power supply isolated from the final output stage. How do you do it?

Obviously now in the case of an integrated circuit you can put a separate voltage source derived from the main power supply to supply to the pre amplifier and may be the first amplifier etc. This is the technique adopted in almost all ICs which are single tip ICs supplying power to pre amplifier as well as power amplifier. Therefore how do you derive that kind of a voltage source?

Basically we have a single zener diode, it is the emitter base junction whose reverse break down voltage is low about 6 to 7V and it is this zener which is available as a zener diode. You can use zener diode which is just a single zener diode in a particular bipolar technology, this is about 7V zener this is available to you and this can be a voltage source. That means we have to bias this and then we get a voltage source which is going to be used perhaps for the pre amplifier stages. But then you are restricted to operate exactly at 7V supply you do not have any flexibility. So do we have a means of obtaining other voltage sources?

Obviously if it is zener diode you do not have any other zener diode except this zener diode. But we can use a diode in the forward bias mode and a string of the diodes as the zener.

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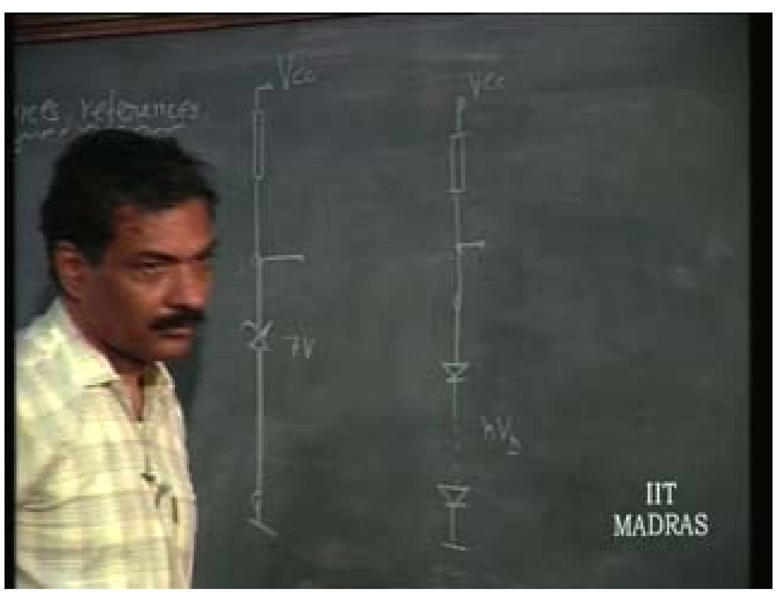

All these zener diodes, in fact any zener diode or voltage source we are going to discuss will operate above a certain current called knee current in this case maintaining the voltage across it relatively constant almost independent of the current flowing through this and it has a maximum current that is based on power dissipation. That is something you should know. It has a minimum current of operation and a maximum current of operation within which you will see to it that it operates. If I connect it like this it is to a certain extent still supply dependent. What will be the current in this? It is V_{cc} minus 7 by R_s. So, as V_{cc} varies this current is going to vary and it is going to result in small variation in zener voltage itself. It is not all that supply independent. It is going to be dependent upon supply to a certain extent here but we can say that for all practical purposes it is going to be around 7 and obviously I can draw current from this.

The moment I start drawing current from this to a load it will become load dependent also. I do not want to load it in order to reduce this I can now use a current amplifier. Even though if a large current variation occur here the current variation is going to be beta times reduced. So I can definitely have this kind of an arrangement in order to make this voltage source become a better source so that its output impedance is going to be low now. Strictly speaking this is a common collector configuration. So the output impedance of this was originally R_z itself R small z that is zener impedance but now in this case it is R_E plus R small z by beta plus 1 so you can reduce the output impedance.

Particularly in this case you will see that in order to change the zener voltage I am using n number of diodes. But its output impedance is going to be also increased by the same number n thereby if each diode impedance is small re this total impedance is going to be n times R_E. So, in order to again cause the output impedance to become low we will put this buffer stage here so that the loading of this is not going to effect the current variation too much like this. So, continuing with our discussion about voltage sources let us see how using a single zener diode that is available which is having a breakdown voltage of about 6 to 7V we are able to obtain a voltage source with low output impedance capable of delivering current of any magnitude we want. Depending upon the magnitude of current we can put a single transistor or Darlington pair of transistors to take care of the current that it can supply.

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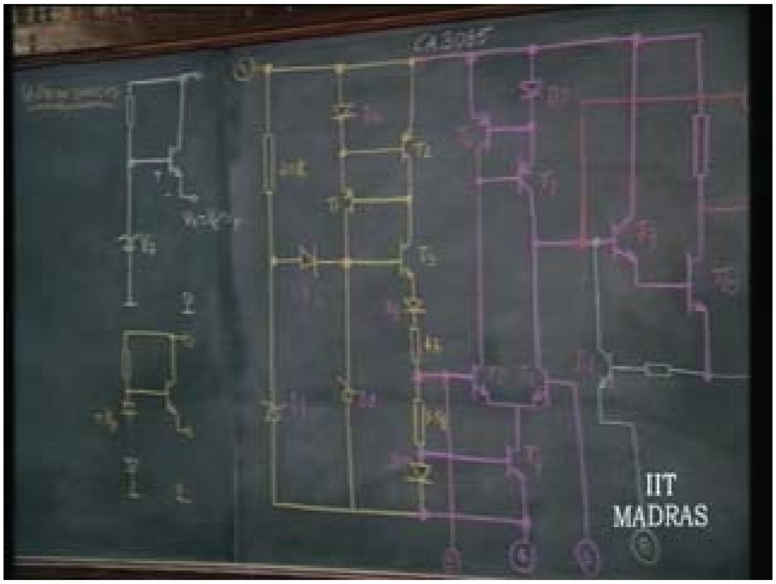

The output impedance is going to be to that extent getting reduced based on how many transistors we are going to use here. This is an alternative to obtain zener which is different from what is available as zener diode say a string of diodes connected in series. We have n times VD coming into picture and then n times RE is the output impedance of this without the buffer stage. If you introduce the buffer stage it will be nR_E by beta plus 1 reduced. So this also can act as a voltage source whenever required.

Now you might want to have a voltage source whose source voltage is going to be neither an integral multiple of V gamma nor is equal to the 6 to 7V available as a zener. How would you fix a voltage you want, how do you do it? You can simulate a zener, how do you simulate a zener?
Let us take this circuit. Consider this circuit this is R_1, this is R_2 so this is nothing but VD V gamma.

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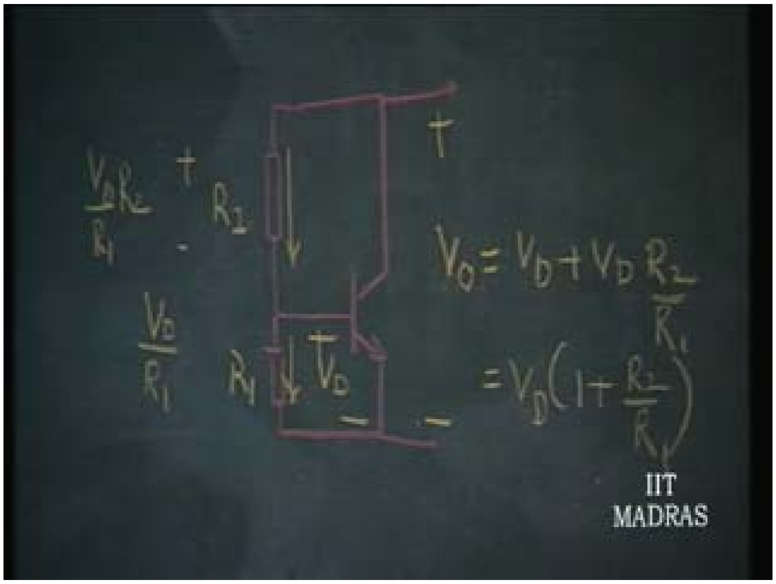

So the current in this is therefore V gamma or V_D by R_1. So same current is likely to flow through this if you say beta is very high for the transistor and develop a potential which is V_D by R_1 into R_2. The voltage V_0 is going to be nothing but V_D plus this drop of V_D into R_2 by R_1. So V_D plus V_D into R_2 or it is V_D into 1 plus R_2 by R_1. By adjusting the ratio R_2 by R_1 in a value like you can obtain a zener of any voltage you want. This is a powerful technique particularly in what is called class AB biasing of a particular stage.

Class A biasing in an output stage requires two diode drops if it is a push pull configuration whereas class AB biasing requires it should be less than two diode drops. How do you do it?
If you want something less than two diode drops you can make R_2 by R_1 less than 1 and therefore it is just on the verge of conducting the output stage. In such output stages where we want class AB biasing this zener is very commonly used wherein R_2 by R_1 is made less than 1. This is an exact replacement of the zener diode.

So how do you really bias the zener?
You have to again pump in current. That means this also will need R_s to supply voltage etc so this is a routine thing.

Actually this is nothing but the replacement for only the zener. It also operates above a certain minimum current below a certain maximum current. There is a minimum current of this V_D into 1 plus R_2 by R_1 by R_2 plus R_1 that is V_D by R_1 required for it to start functioning. The knee current is greater than V_D by R_1 so that there is some current flowing in this transistor. So V_D by R_1 is the current needed here and since this transistor also has to conduct there is some extra current needed so it can only function as is enough above a certain knee current. And whatever is this current apart from V_D by R_1 rest of the current rest of the current has to be pumped into this that means it can also tolerate a maximum of certain amount of current which is permitted through the transistor. Therefore it has all the characteristics of zener.

What is the output impedance?
The output impedance of this is [R…..] roughly. When you apply a voltage V_0 the current is going to be V_D by R_2 plus R_1 parallel hie. Therefore to evaluate the output impedance this is the step. We will say V_0 by R_2 plus R_1 parallel hie is the current that is injected into this out of which R_1 by R_1 plus hie is pumped into the base, this is pumped into the base. Therefore this many times hfe is the current that is taken from here. So, effective current is going to be 1. This current plus V_0 by R_2 plus R_1 parallel hie.

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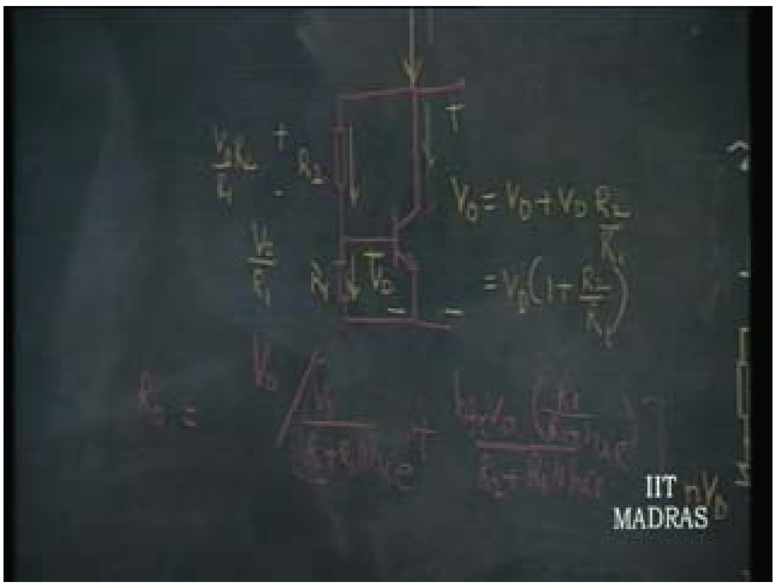

This is the total current that is going to be drawn which forms a voltage that is equal to V_0. So the output impedance is going to be V_0 divided by this. So V_0 divided by this total current is nothing but the output impedance. That is going to be equal to 1 by 1 by R_2 plus R_1 parallel hie plus hfe into R_1 by R_1 plus hie by R_2. That means actually speaking if hfe of the transistor is very large the output impedance is going to be very small because this is going to vanish and this is going to dominate so it is essentially R_2 plus R_1 parallel hie by hfe into R_1 by R_1 plus hie.

Strictly speaking it is going to come towards RE. If you look at the expression it is coming towards R small e which is but the common base input impedance. Basically this is a structure with low output impedance suitable for use as a voltage source. Instead of using just this if I remove this and use usual zener diode along with this, what happens is this merely changes from V_D to V_z plus V_D. These are the circuit techniques of obtaining what you cannot normally obtain from the technology. The zener diode of the desired value can be very easily obtained by these various schemes.

But where do you use these voltage sources? Primarily these voltage sources are used for isolating the input stage from the output stage so that there is no feedback causing a serious problem about oscillations in any system. That means if you are designing a VLSI circuit wherein you have a large number of subsystems connected together you will repeatedly use this voltage source to be derived from the main source for each one of those input stages.

Also, when you are connecting one stage to another, coupling them, the DC levels have to be different in order to obtain the required sink because as you keep on amplifying the swing at the output will keep on reducing due to the requirement of the reverse bias for the transistor unless you keep shifting it down to a lower value. That means this level shifting becomes automatically a necessity in the case of coupling.

Consider this, this is an NPN transistor and this NPN transistor is to be coupled with another NPN transistor directly and this will be coupled to another NPN. If you are taking to only NPN transistors then there is this problem. If you are saying that you are going to couple NPN with PNP there is no such problem. Therefore in a stage where we are restricted to use good NPN transistors only for wide band structures etc we might have to take recourse to what is called level shifting.

Why do you need level shifting?
This is a common supply, there is need for a certain reverse bias voltage for a certain swing here. There is need for higher reverse bias voltage here for a higher swing for the next teeth but as you progress slowly you are reaching the supply voltage gradually. And therefore unless you do the level shifting and bring it down further you cannot actually get a larger swing for the later stages. So, in order to do this we take recourse to level shifting by using zener diode. This zener diode could be any one of these configurations we have already discussed.

Actually you have to bias this by means of a current source so that the level shifted is equal to the zener. The application of this in any IC design is in the case of level shifting as well as in isolated power supplies for the various subsystems. Now, this is the characteristic of the voltage source.

What about voltage reference?
Let us now discuss about voltage references. The distinction between voltage source and voltage reference is only this. In the case of a voltage reference it is supposed to have an output voltage independent of supply voltage and temperature. Whereas in the case of a source we are not bothered about its temperature dependent but we are bothered about its ability to supply large currents without changing its terminal voltage. Of course it should be independent of the main supply voltage. So how do we derive a voltage which is independent of temperature?

We know that the zener diode here whose breakdown voltage is about 7V has a positive temperature coefficient of about 2 mV by a degree C rise in temperature.

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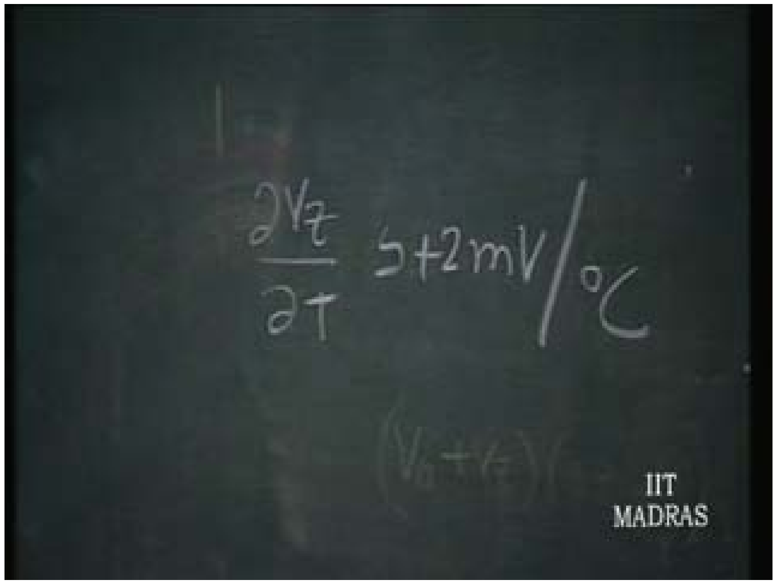

Now we have another device zener whose temperature coefficient is negative. It is the diode forward biased. So the diode ΔVD by ΔT is equal to minus 2.5 mV by degree C itself.

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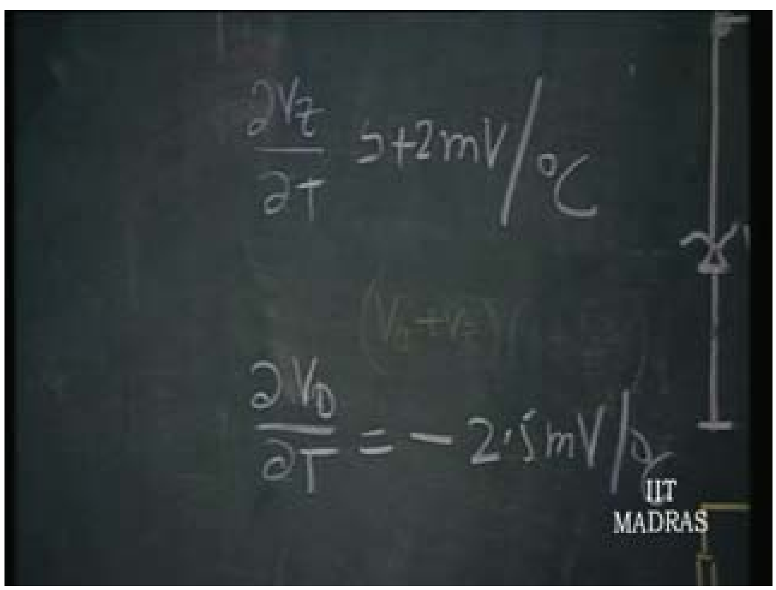

These are standard values. Irrespective of the manufacturer these values remain the same. So the forward bias diode has its forward voltage with a negative temperature coefficient whereas the actual zener diode has a positive temperature coefficient. Therefore if you put these together we can get a scheme where zero temperature coefficient is possible.

This is one of the techniques of obtaining a voltage reference. One such technique is given here. Let us consider this.

Here this has positive temperature coefficient of about 2.5 mV by degree C. If you put a transistor the output voltage here is going to be V_z minus V gamma. So what will be the temperature coefficient of this output voltage now?
This is 2 mV and this has a negative temperature coefficient so the effective temperature coefficient is going to be 4.5 mV positive because this is V_z minus V gamma. So the effective temperature coefficient of this is plus 4.5 mV by degree C rise in temperature.

Now I want another source which is having negative temperature coefficient that is nothing but a diode. So I have one source with positive temperature coefficient and another source with negative temperature coefficient. So what do I do? I add these voltages suitably, I take a resistive devisor and then I put alpha R here and 1 minus alpha R here so the output voltage is going to be alpha (V_z minus V gamma plus 1) minus alpha (V gamma or VD). So what you get? You get V gamma or VD.

We can now make ΔV_0 by ΔT is equal to 0 because we are adding a voltage with positive temperature coefficient with one parameter controllable that is alpha. You will add these voltages such that ΔV_0 by ΔT is equal to 0. You differentiate this and you will get alpha times ΔV_z by ΔT minus alpha times ΔV_D by ΔT plus 1 minus alpha times ΔV_D by ΔT is equal to 0. You put this and obtain the value of alpha.

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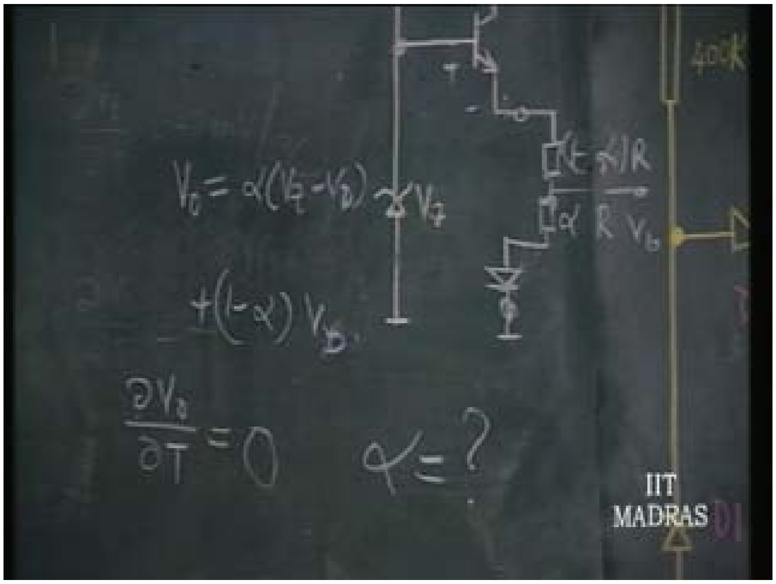

You will get a value of alpha for this if you substitute the temperature coefficients as 2mV by degree C and minus 2.5mV by degree C and you will get a definite value of alpha which is less than 1. Substitute that value of alpha and get the value of V_0. And that is the value of V_0 for which the temperature coefficient is very nearly 0 or in practice it is going to be of the order of few parts per million per degree centigrade rise in temperature.

This is the technique adopted in one of the most popular voltage regulator integrated circuits which is current manufactured by Bharat Electronics here in India. It is originally manufactured by RCA. So 3085 is available anywhere in India.

We have the zener, we have the transistor may be another series diode which will further increase the positive temperature coefficient and decrease the output voltage here.

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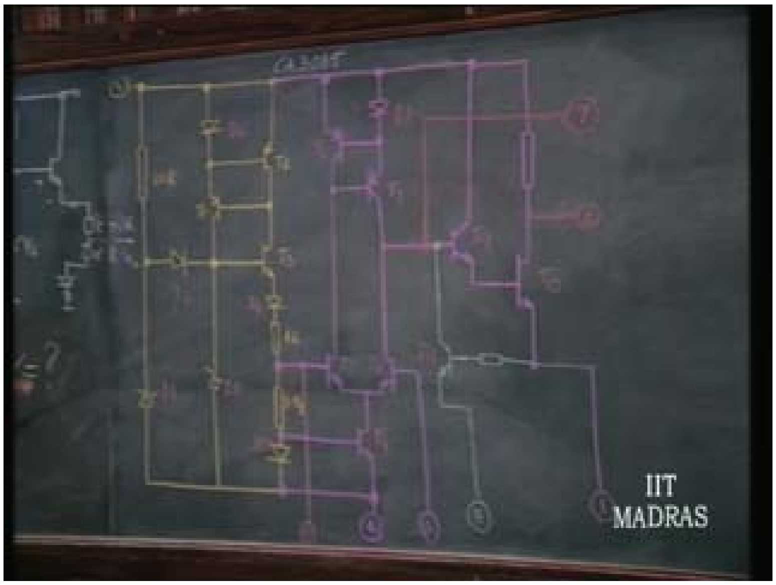

Instead of V_z minus V gamma we have V_z minus 2V gamma here and then these resistors chosen such that ΔV_0 by ΔT is equal to 0 and you have the other diode giving you the negative temperature coefficient and therefore the voltage reference is obtained at 0.5 in this source. This is a part of this voltage regulator ICCA 3085 which is exactly similar in his concept even though some minor variations like one diode being added etc.

Obviously this zener voltage is going to depend upon input voltage. As input voltage changes the current through this changes and therefore this is going to change. What is the way of making it supply independent? Its temperature coefficient is near 0 but it should be made supply independent. So how do we do it? We will assume that we are obtaining a voltage which is independent of supply. Therefore let us assume that this current is going to be independent of supply. I will put a current mirror on to this so that it is going to get biased by that current which is going to be supply independent and therefore there is no problem of supply dependence. This is the technique of deriving a zener voltage which is independent of supply. So I am putting a current mirror here. You can see this kind of an affair here.

What is this configuration here?
This is Wilson current mirror which is modify because I am using PNP transistors.

In order to achieve better current mirror action I am adopting for the PNP transistor alone here, the Wilson current mirror as discussed. So this is the Wilson current mirror which is biasing the zener here. It is sensing the current here and biasing the zener here.

What if the zener is not on even after being switched on?

In this particular case when the resistor is there, there is no such problem, the resistor was straight away biasing the zener. In this case when I switch on the whole thing this zener is not on. If this zener is not on then this current is not flowing. If this current is not flowing this current is not going to exist and this current is not going to be there. So zener will remain off. Obviously this is a circuit which cannot function unless you start the function. There is some starting trouble for this. In order to make it start properly we have to have a zener. Here this is the starting circuit.

We have to have a zener which is connected to input and therefore this is the one zener that is going to bias this transistor and cause this current to exist and pump this current and this current has to now bias the new zener. Once this zener gets biased this voltage is same as this voltage. Therefore this diode potential is 0 and it is disconnecting the starting circuit from this. That is, the current is 0, voltage is 0 and these are identical zeners available within the IC. The voltage across this is 0 and the current through this is 0. So, the moment this zener breaks down this gets disconnected or gets isolated from this. So you must have in any such scheme where you are trying to derive some constant from another constant which itself is dependent upon this constant. You have to have the starting circuit in all such schemes. Otherwise it will stay at another operating point as 0V. This composite circuit is essential in order to cause a voltage reference to exist here.

Now we have achieved a voltage which is independent of supply as well as temperature. This remarkable feature is something like a research topic in most of the analog IC design. How to derive voltage references which are independent of temperature and supply voltage. In this bipolar technology this is the way we have done. How can it be done in MOS technology how can it be done in BiMOS are all topics of interest because this voltage reference is an important integral component of almost all control circuits. One such control circuit is our voltage regulator. In all these schemes such as a to d converters, d to a converters etc we need a voltage reference. All these ICs will comprise this kind of a structure for deriving the voltage reference. So you have just now seen a technique of making use of the zener positive temperature coefficient along with diode negative temperature coefficient in order to derive a voltage reference whose temperature coefficient for 0.

Now another popular technique in deriving voltage reference is what is called as Band gap voltage reference. What is the band gap of silicon?
It is 1.1 or 1.2. It so happens that the voltage you are going to get will happen to be equal to the band gap if you derive it from the device we find. We can actually understand that from the circuit view point. We have the diode voltage which is temperature dependent and has a negative temperature coefficient. Do we have any other voltage which has positive temperature coefficient?

We have one such voltage. If we just look at this V_{BE1} minus V_{BE2}, two transistors or two diodes forward biased. The difference in voltage is going to be V_{BE1} minus V_{BE2} is equal to V_T log.
Do you remember this?
I_{E1} by I_{E2}. If I_{E1} and I_{E2} are constant currents even if they are not constant. It does not matter because even if they are dependent on temperature to a certain extent, since it is logarithmic the main temperature coefficient is coming about from V_T is K_T by q. And the temperature coefficient of this is going to be a fantastic number because it is K by q into log of I_{E1} by I_{E2} which can be made as accurate as you please.

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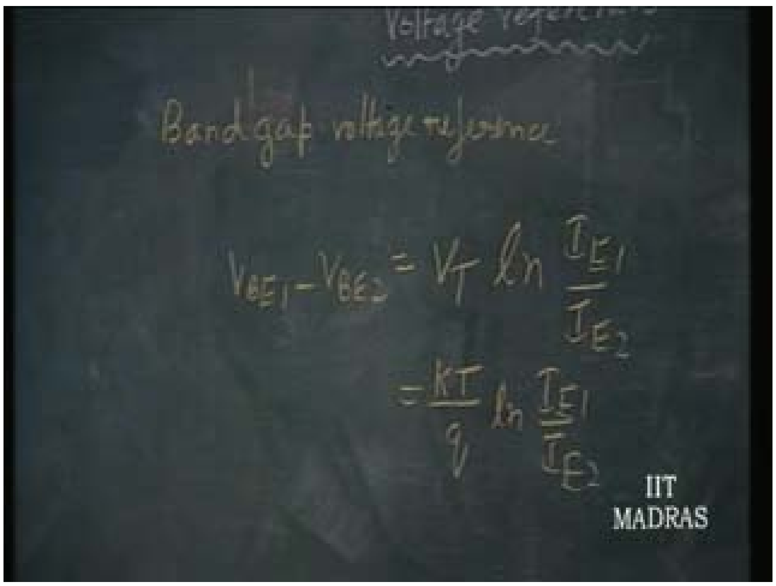

Therefore you can use this as a positive temperature coefficient voltage. That means a difference in voltage of two forward biased transistors or diodes can be used as a voltage which has a positive temperature. If this can be added to the diode voltage then obviously with suitable factor coming into picture if I can have a control over the factor I can again achieve zero temperature coefficient for the voltage. This is the basis for band gap voltage reference. Let us see how it can be done using the basic circuit concept. This is one technique by which we can achieve this.

I am having transistor T_1 operated at current I_{E1} using the resistance R_1 and the other transistor operated at another current I_{E2}. So the voltage across the resistance R_E is now V_{BE1} minus V_{BE2} which is nothing but VT log I_{E1} by I_{E2}. So I am able to obtain a voltage across R_E which is VT log I_{E1} by I_{E2}. This is I_{E2} and this is I_{E1}. So what will be the voltage across the resistance?

This is the voltage divided by R_E is the current through this and that into R_2 is the voltage across this. So now I have obtained a controllable voltage which is dependent upon V_T. By controlling R_2 by R_E I can control the extent of voltage I desire which has positive

temperature coefficient. Now I have to add this voltage to a diode drop, adding means putting it in series. So I have added this voltage to a diode drop and this voltage is the one which I am going to use as V reference.
That means this plus V_D is nothing but V_0.

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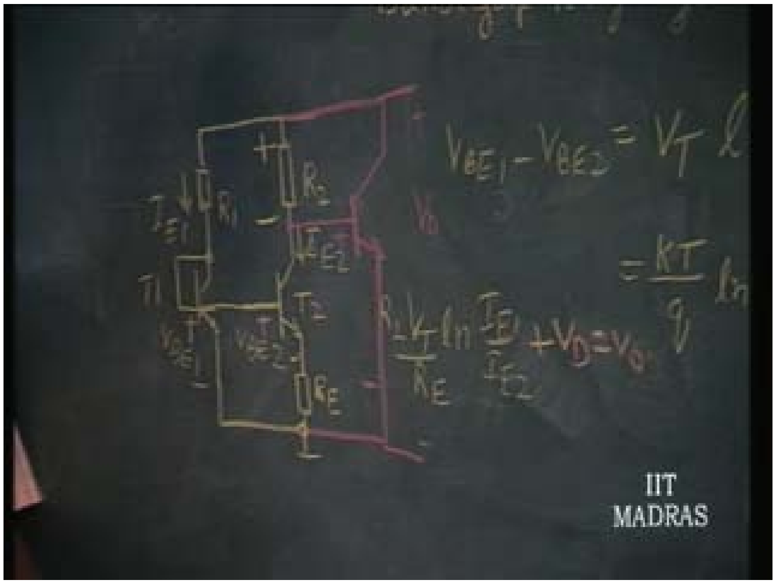

So we have V_D plus the drop across R_2 which is R_2 by R_E into V_T log I_{E1} by I_{E2} coming here as my output voltage. Here you can find how simply the structure has been obtained in order to obtain the voltage addition simply introducing them in series, voltage V_D in series with a V_T dependent voltage. Now I have to make ΔV_0 by ΔT is equal to 0. That means ΔV_D by ΔT plus, here this is KT by q that means K by q we do not want to remember but we can remember it as V_T by T which is nothing but V_T by T by R_E log I_{E1} by I_{E2} and that should be that into R_2 by R_E. So this should be equal to 0.

You can find out R_2 by R_E required to make this condition get satisfied. You already know ΔV_D by ΔT is equal to minus 2.5mV by degree C rise in temperature. So this is minus 2.5mV. And you can now find out R_2 by R_E, V_T at room temperature may be 300° Kelvin which is about 26mV or 25mV so you can substitute all these values and obtain the value of R_2 by R_E. Now let us find out what I_{E1} by I_{E2} is. What is I_{E1}? This is nothing but V_0 minus V_{BE1} by R_1 and the other one is I_{E2} is V_0 minus V_{BE3} by R_2. Let us call this as T_3.

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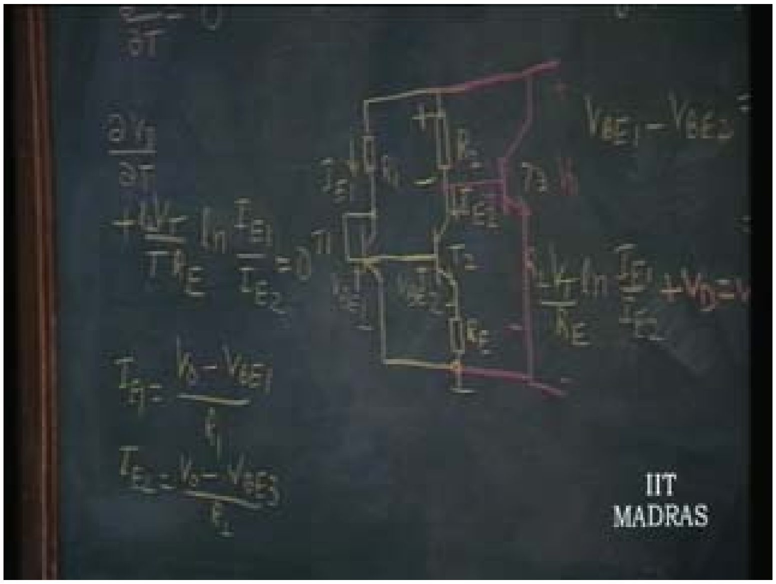

Essentially I_{E1} by I_{E2} will be roughly equal to R_2 by R_1. If you know R_2 by R_1 also we can fix it as a certain value and then find out a value of R_2 by R_E required to make ΔV_0 by ΔT is equal to 0. This internal circuitry is a voltage reference IC of 1.2V. Identify these various components and for those components find out the value of reference voltage at which this condition gets satisfied. That happens when this voltage becomes very nearly equal to this voltage which is $2V_D$ or 2V gamma that is about 1.2V.

Substitute the value of R_2, R_1 etc available in that IC and see for yourself whether it is satisfying the condition for zero temperature coefficient for V_0. This is the one way of obtaining the band gap reference. This is always done by adding V_T dependent voltage and V gamma dependent voltage. You can also do it using an op-amp. There are variety of such circuits wherein different schemes of addition of this V_T dependent voltage V_D is done and you come up with band gap references of different types. So you must encounter those problems as and when you see a specific IC and identify how this addition has been achieved.