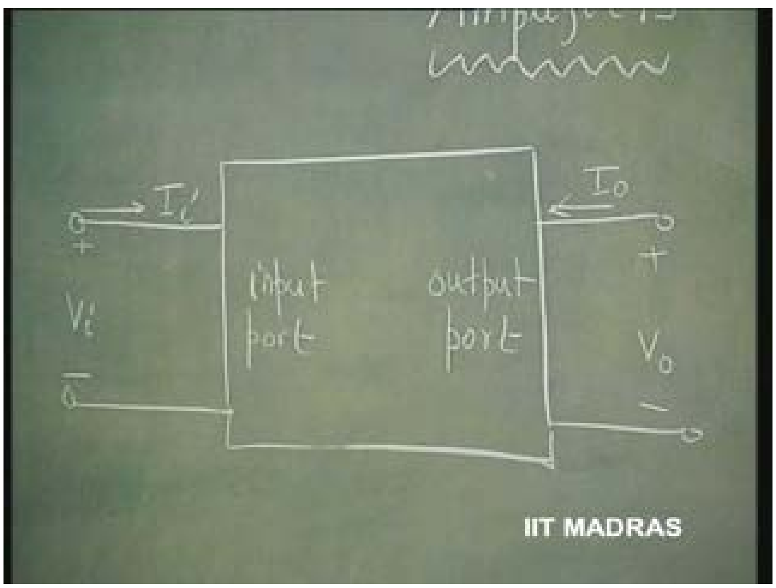
Electronics for Analog Signal Processing - I
Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology - Madras

Lecture # 12
Amplifiers

In Section 1, we had discussed diodes; basically, a two terminal element. In this section, Section 2, we will be discussing amplifiers; one of the important signal processing element block. As against the diode which is a two terminal element, this can be, now, this has to be a three terminal element. There should be an input port, input pair of terminals and there should be an output pair. This is called input port. This is called output port. This is the black box.

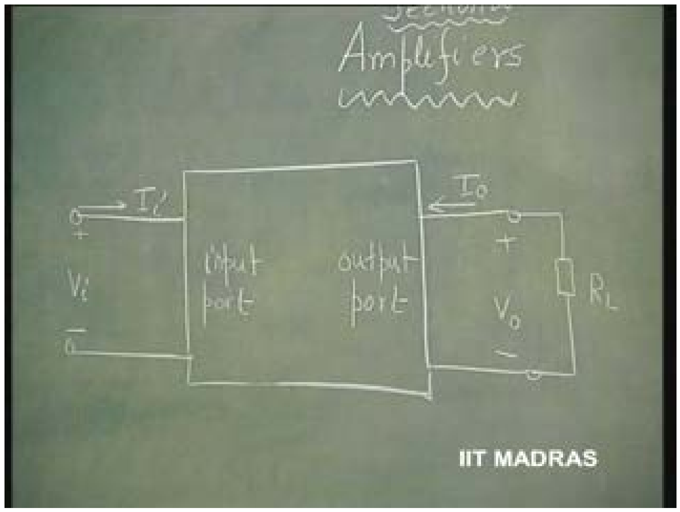
(Refer Slide Time: 02:22)



So, input port is nothing but a pair of terminals here, wherein, input variables appear which could be, input voltage and input current; input voltage and input current. Output port is the other pair where the output voltage and output current appear.

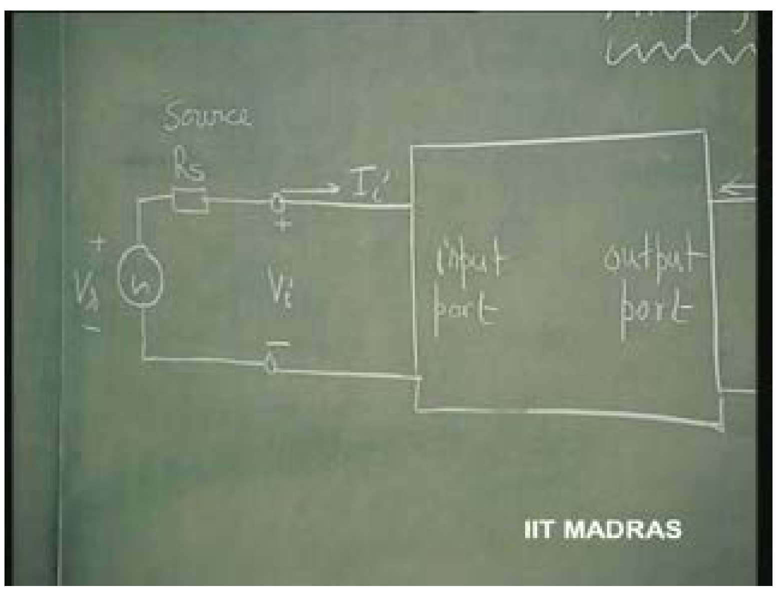
Normally, we are going to have something called load here; this is the load here, on to which the output is going to be paired. It could be another stage also, of amplification.
So, that means, it will be later on, may be, cascaded to another ((circuit - Refer Slide Time:3:10)); whatever be, that will be the load for the amplifiers.

(Refer Slide Time: 03:19)



This is going to be fed by what is called a source. That source can be represented as a voltage source with a series resistance R s. This is one way to represent the source.

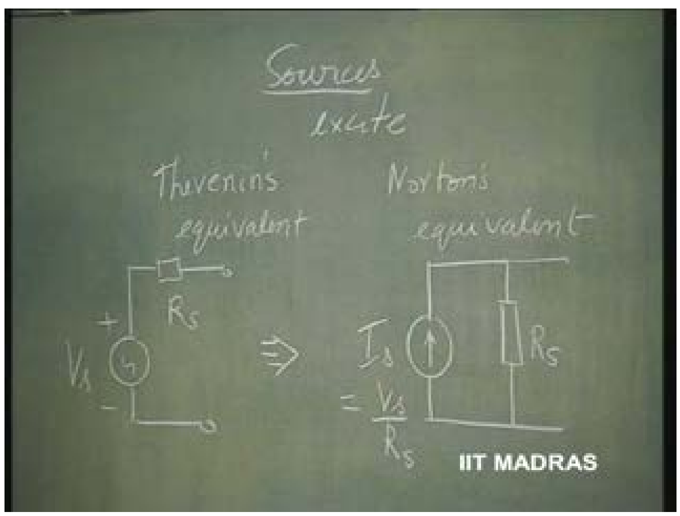
(Refer Slide Time: 03:45)



These are either as a voltage source in series with a resistance; or, this could be also represented as a current source in shunt with the resistance. And, using Thevenin's theorem, you have seen that any non- ideal source can be represented either as a voltage source in series with a resistance, or, as a current source in shunt with the resistance; in which case, we can say that this is equivalent to, as long as I s is equal to, what is called as the short circuit current in this particular case. This is short here; so, short circuit current is V s by R s. So, that is the value of I s. So, these are exactly equivalent.

This is Thevenin's equivalent for a source. This is what is called Norton's equivalent for a source. So, any source which is exciting our amplifier; this source is, therefore, sources, these are necessary to excite the amplifier.

(Refer Slide Time: 05:18)



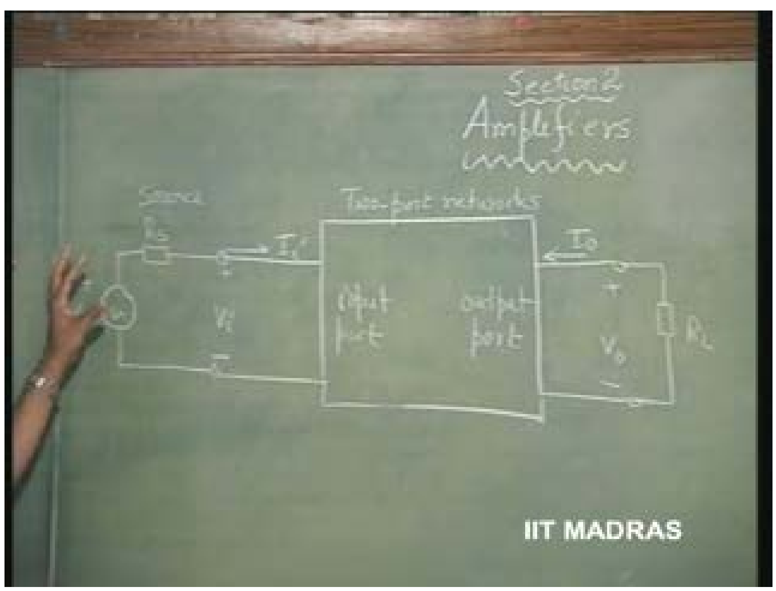
Any source that is necessary to excite the amplifier is going to be non-ideal, assuming that it is non-ideal, can be represented as a Thevenin's equivalent. So, voltage source in series with the resistance, or, as a current source, where the current value is nothing but the short circuit current V s by R s, in parallel with the resistance.

These theorems, you have already studied in your networks course. The same methods program, you have also learned something about what is called, two port networks. So, the part that we have learned in the two port network, we have to revise now, in order to understand and appreciate what is happening with amplifiers that we are going to derive and use.

So, let us therefore try to understand about first, ideal amplifier. Just as we understood ideal diode and its application, and later on saw how non-ideality brings about some modifications in what is called the equivalent, and then, how this can be incorporated in the analysis; same way, we will now use this two port theory, in order to understand about amplifiers; see what are ideal amplifiers, what are the types of amplifiers available, and how these can be realized in practice, later.

So, this exciting source could be another amplifier feeding on to this. So, in a general situation, this could be one amplifier feeding on to this primary amplifier of ours, which can always be represented as a voltage source in series with a resistance; and it could be feeding on to another amplifier, which could be treated as the load; or, it can have an independent source here.

(Refer Slide Time: 07:47)



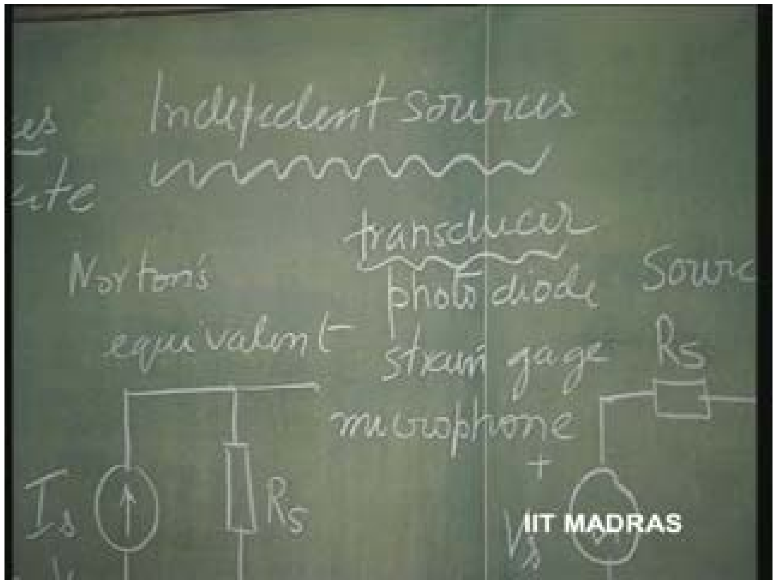
So, let us talk of independent sources. What are independent sources? Independent sources are our signal generators; may be, the sine wave signal generator, or, audio signal generator it is called, or, it could be the transducer, which is converting, let us say, mechanical energy into electrical energy. That also can be represented as a source; or, whatever we had discussed earlier in LED, which is converting light signal into electrical signal. So, that is, the LED output can be used here or we can use also, let us say, solar cells.

The light from the LED can be used to fall on a photo detector and that can be used for further amplification. So, we can convert one form of energy into another energy. We can use the LED as the load here and convert the analog signal, electrical signal, into light signal and again process it further if you want. This light signal can be converted into a source here by using, let us say, photo diode.

So, these days, with the availability of optronics, this kind of conversion commonly takes place, converting electrical signal into light signal and back into electrical signal. So basically, independent sources are all those which can generate electrical signal from some other form, mechanical or otherwise. This could be, let us say, a microphone, which will convert the sound signal into electrical signal; or, this could be a speaker, which will convert the electrical signal into sound signal.

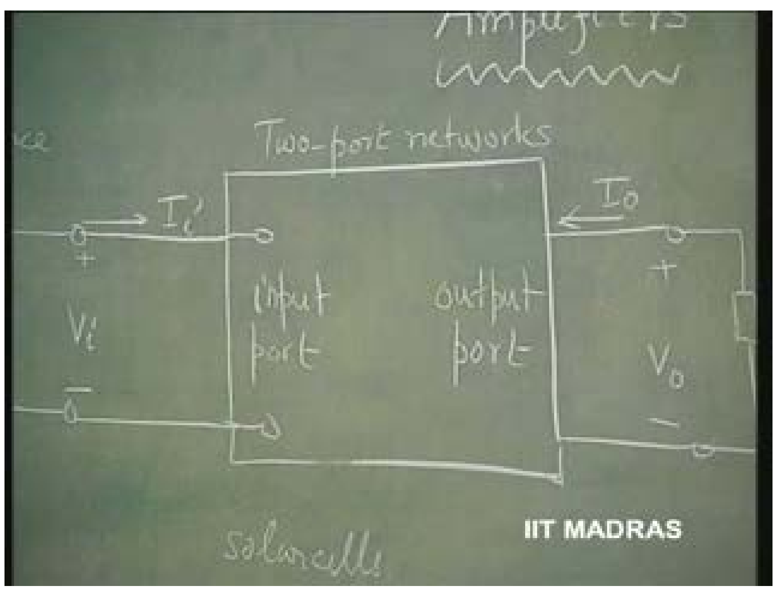
So, we have independent sources. And, the amplifiers are now called dependent sources. This is the distinction between independent source, which could be a transducer, or say, it is a photo diode; and let us say, pressure transducer, strain gauge, microphone; this could be a transducer, independent sources; or, just plain electrical signal generators, test signal, this is the test, these amplifiers, etcetera, we could plainly apply test signals at the input.

(Refer Slide Time: 11:25)



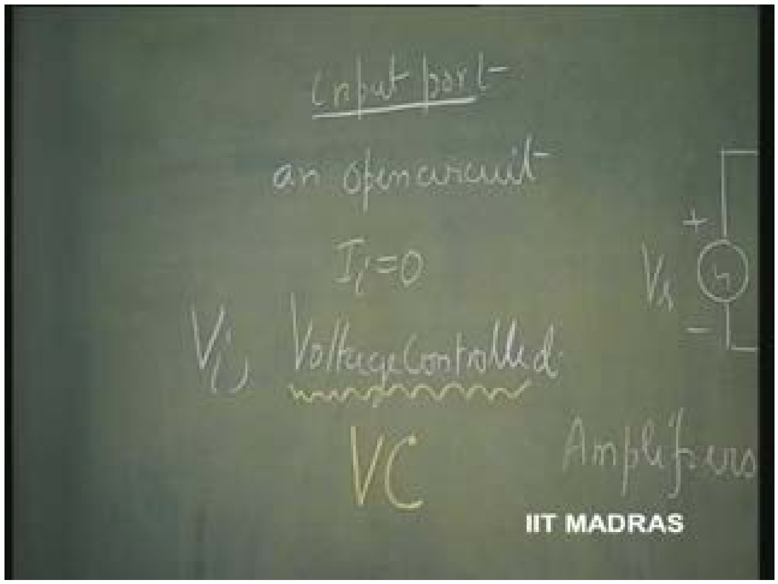
So, amplifiers are dependent sources; this is what we have to understand. That is, the parameters here, V naught or I naught could be dependent upon V i or I i. The output parameter V naught or I naught could be dependent upon V i or I i.

(Refer Slide Time: 12:32)



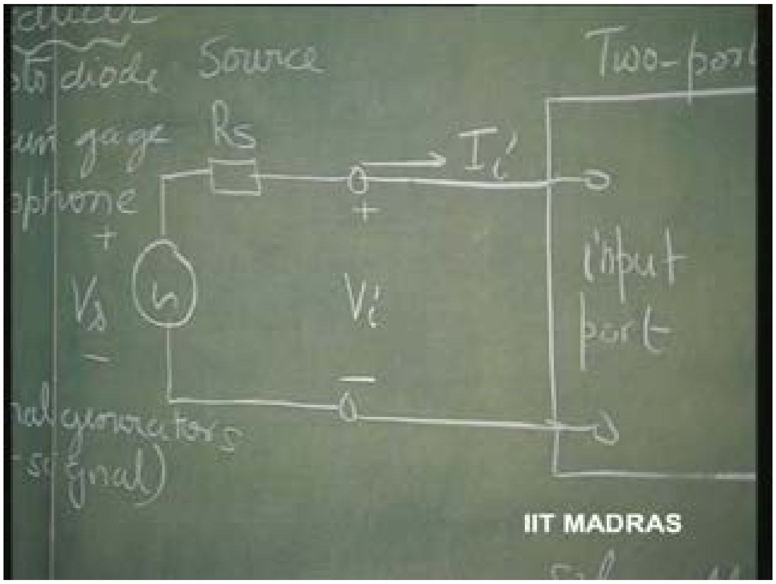
Consider an ideal situation here, that, this is an open circuit. This is an ideal situation now I am talking of. This is an open circuit; in which case, I i is automatically zero. So, if the input port, open circuit, then obviously, I i is zero; which means, this amplifier becomes voltage controlled. We will abbreviate it as VC, voltage control. So, if the input port is an open circuit, then, I i is zero.

(Refer Slide Time: 13:44)



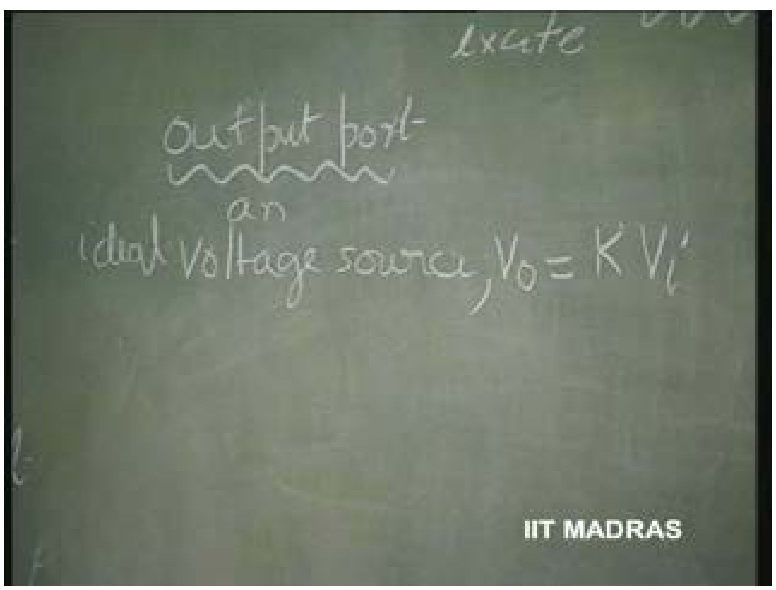
It is controlled by only V i; and because I i is zero, V i is same as V s. Nothing is lost in the sources; whatever be the source voltage, it is going to appear as input voltage to this amplifier. So then, we call it as voltage controlled amplifier. The output can now have its current dependent upon voltage or its output voltage dependent upon input voltage.

(Refer Slide Time: 14:02)



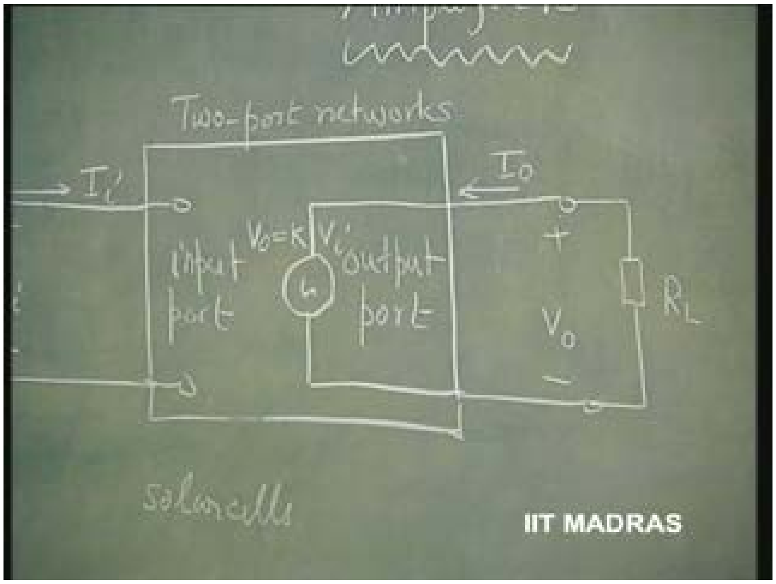
Let us consider again an ideal situation here; one of those, where, output voltage is dependent upon input voltage. So, we will now say that output port is going to be a voltage source, ideal; so output port is going to be an ideal voltage source, whose output voltage is going to be dependent upon the input voltage. So, we will call this as, let us say, K times V i.

(Refer Slide Time: 15:30)



So, if it is therefore the output port, we can now draw a voltage source, ideal voltage source; that means, its source impedance is zero. So, V naught is gong to be K times V i. Because its source impedance is zero, this V naught is going to be the same as this source voltage; so, V naught is equal to K V i.

(Refer Slide Time: 16:07)

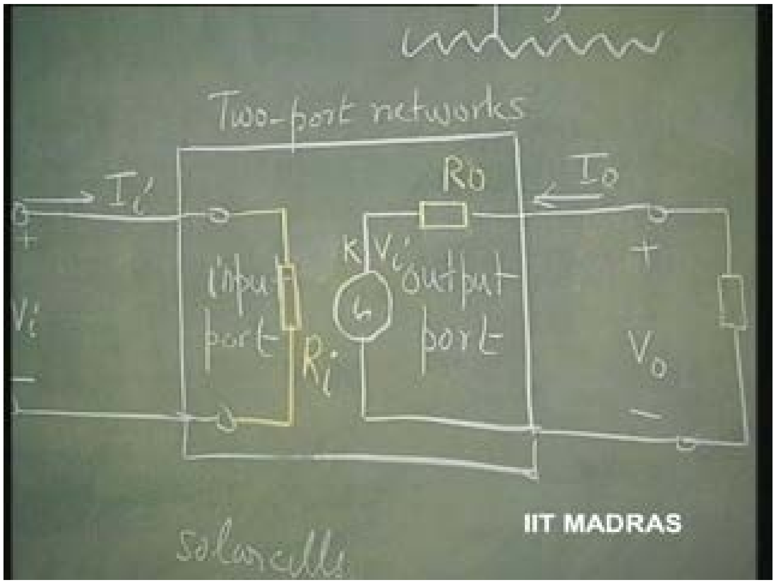


Now, this is therefore called a voltage source. So, what is it? This kind of amplifier is therefore called voltage controlled voltage source; one type of amplifier; voltage controlled voltage source.

(Refer Slide Time: 16:43)

If therefore, I have this as non-ideal obviously; then, I might have a, what is called as an output resistance, which is non-zero for this; this becomes non-ideal. At the output, it becomes non-ideal; then, I might have non infinite input impedance.

(Refer Slide Time: 17:29)

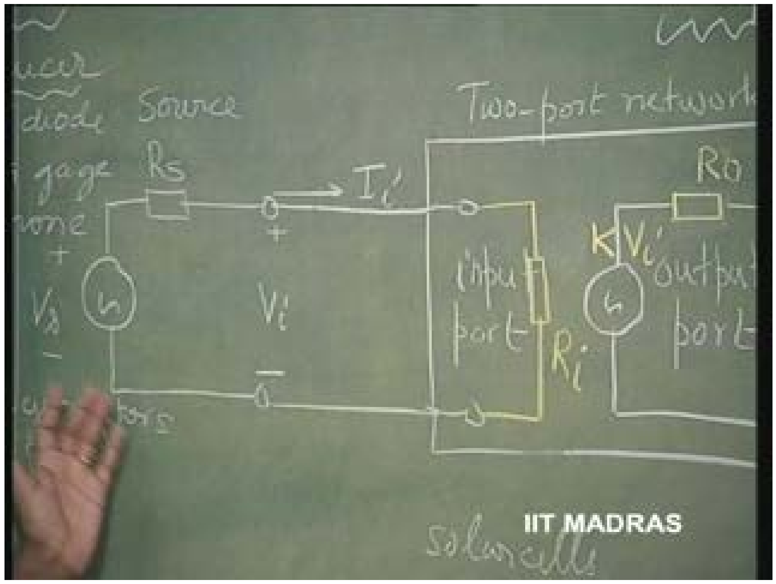


So, in an ideal voltage controlled voltage source, R i is infinity, R naught is zero. Is that clear?

(Refer Slide Time: 18:05)

This is called an ideal voltage controlled voltage source. This is one of the most important amplifiers that is possible ideally, where, input port becomes voltage controlled. Now, this is something that you have to understand. It becomes voltage controlled when I i is zero, going towards zero, that the input current is extremely small. The value of R i should be very large; large compared with what? Now, any comparison here, in practice, should be made with reference to what it is going to get as input. This input voltage here is going to remain undisturbed as V s, as long as I i is zero. That is possible when only R i is very high. Compared with what? Compared with R s.

(Refer Slide Time: 19:06)

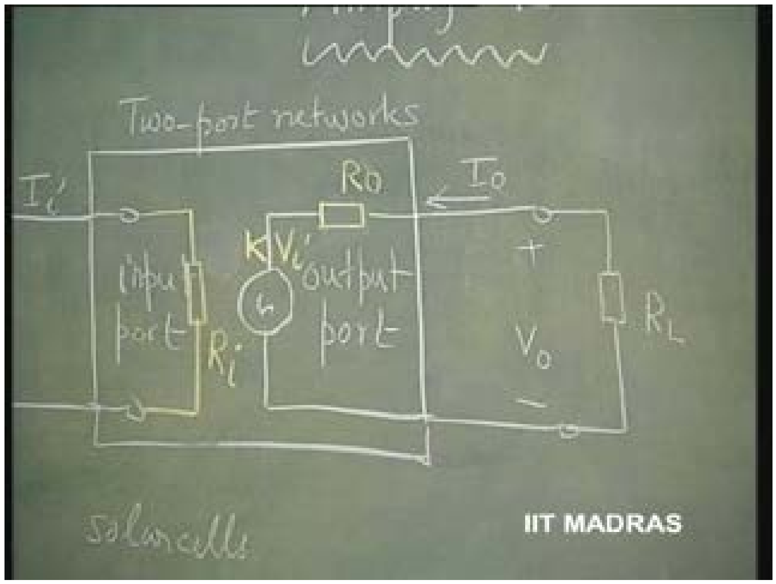


So, this is a voltage source drive, as long as R s is much less than R i. That means, in a practical situation, I can call this system, which is being fed by a non-ideal source into a non-ideal port, as voltage controlled, as long as R s is much less than R i. In such a situation, V i is going to be very close to V s.

(Refer Slide Time: 19:27)

So, this port becomes voltage controlled; so practical VCVS therefore has R s much less than R i. And similarly, here, let us understand it, on the output port, K V i should be very close to V naught.

(Refer Slide Time: 20:16)

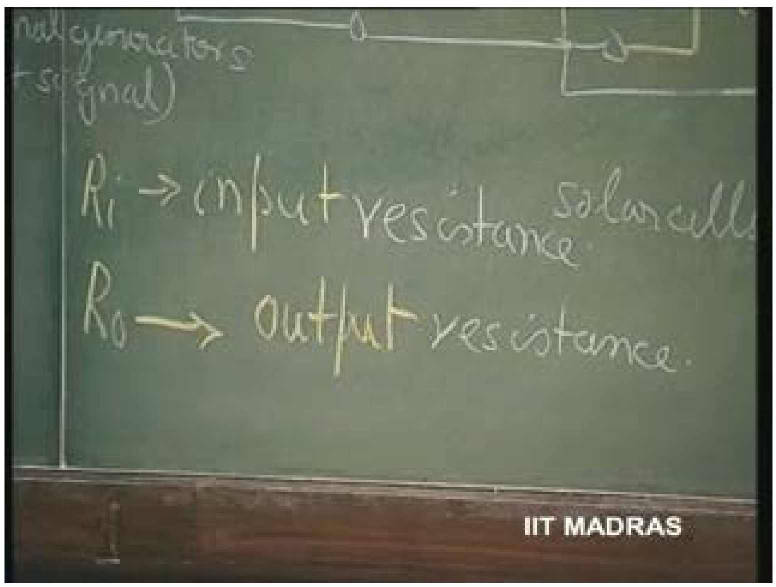


That can happen only when the drop across this is negligibly small; which means, R L has to be much greater than R naught; or, R L has to be much greater than R naught.

(Refer Slide Time: 20:40)

So, in a practical amplifier, we will call this an amplifier which is close to voltage control voltage source, if you know what is the source that is feeding this amplifier and what is the load. So, given the source and the load, I can call this a voltage control voltage source amplifier, only when I have R s, the source resistance, much less than what is called as input resistance of the amplifier. So, R i is called input resistance. Same thing, I can call this really voltage source as the output dependent, independent, that is dependent voltage source, only if R L is much greater than R naught; which means R naught is called the output resistance.

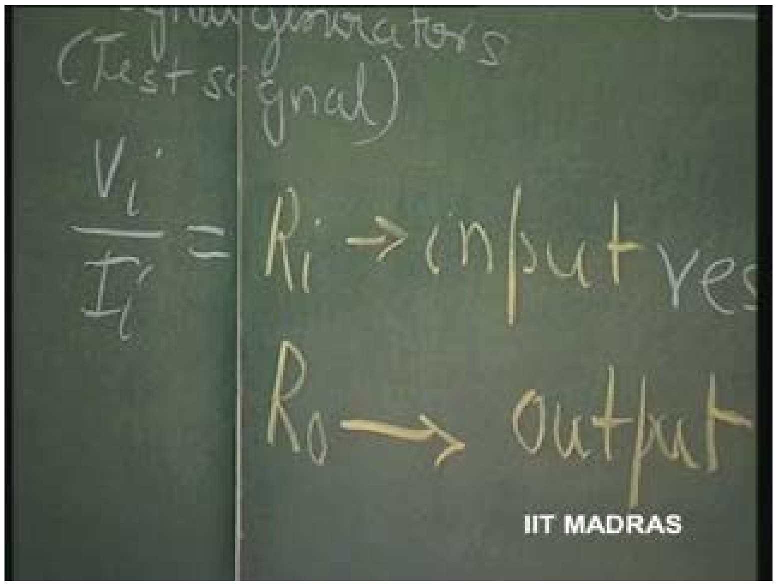
(Refer Slide Time: 22:03)



These are the important parameters of the amplifier. Input resistance. What is input resistance? It is nothing but V i divided by I i. So therefore, I look at it here; voltage across this is V i; that divided by I i is defined as input resistance.

So, this is V i by I i. And at the output, the output resistance is going to be very small compared to R L. Then, we call it a voltage source output. And, how do we measure the output resistance? It is very simple. If V i is zero and I excite this by V naught, then V naught by I naught is going to give me the output resistance. Remember, this dependent voltage has to be made zero. How do you make? Put V i is zero.

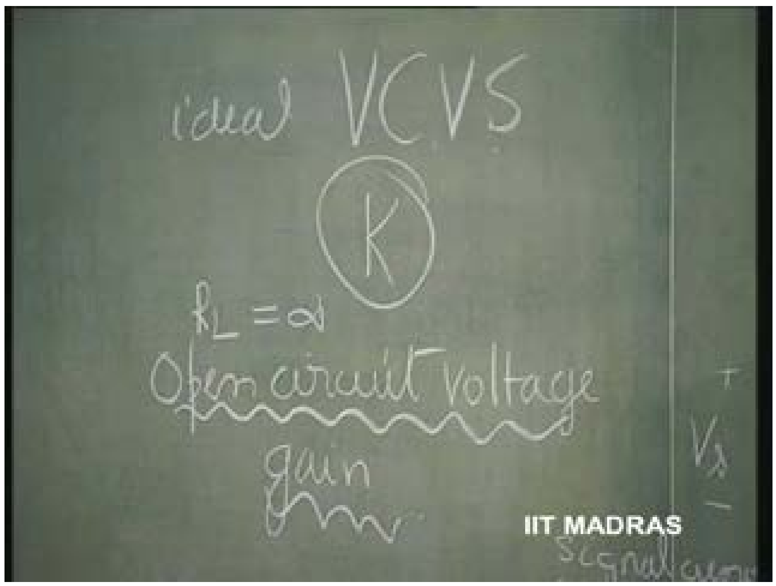
(Refer Slide Time: 22:34)



So this voltage source is going to give zero output and then excite here by means of a voltage, we call it V naught; excite it by V naught, then the current drawn, I naught, is going to give me R naught. So, V naught by I naught, when V i is zero, is defined as the output resistance for this. So, output resistance and input resistance are important parameters of this amplifier which we are calling as voltage controlled voltage source amplifier, in case, these relationships are satisfied.

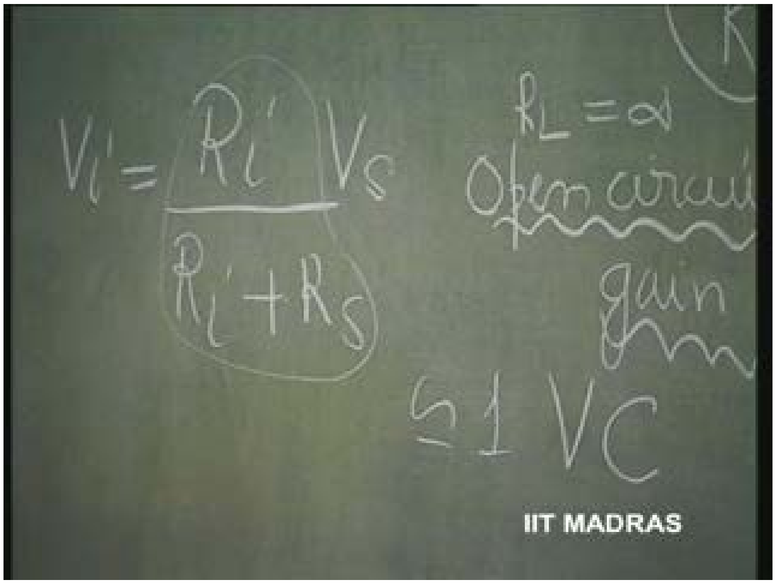
Ideal voltage controlled voltage source on the other hand, has R i equal to infinity and R naught equal to zero. The most important parameter of this voltage controlled voltage source amplifier is K. What is K? K is defined as open circuit voltage gain. What is it? When the load is infinity because it is non-ideal, the load has to be infinity; if the load is infinity, open circuit output it is; open circuit, output is open circuit; then, output voltage is same as K times V i. So, this K is called open circuit voltage gain. That is, what it means is, open circuit means, R L is equal to infinity; or, in the case of ideal voltage controlled voltage source, R naught is zero. So, V naught is going to be equal to K times V i. The only parameter that will exist then, of significance, in the case of an ideal voltage controlled voltage source is K, the voltage gain.

(Refer Slide Time: 25:43)



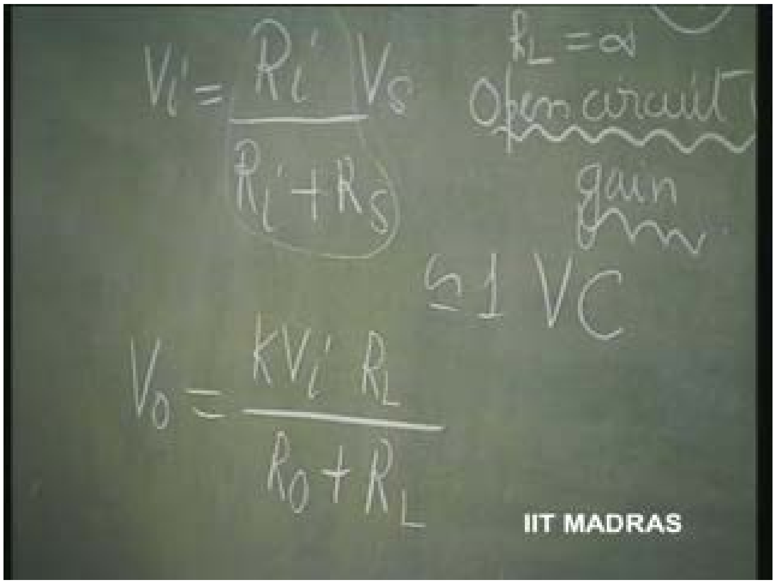
Therefore, this is what is called voltage gain. Now, let us see; let us do the analysis here. V i is going to be equal to R i by R i plus R s in practice, times V s. Look at this. Resistance, this is another resistance. So, it is going to get attenuated here; this signal V s, because of this finite source resistance, is going to get attenuated, and is going to appear as R i by R i plus R s into V s; which means, if it is voltage controlled, this factor of attenuation is going to be very nearly equal to 1, and this is not going to get attenuated at all because, R i is going to be very large compared to R s. Then, we call it as voltage controlled; otherwise, it is going to get attenuated out.

(Refer Slide Time: 26:48)



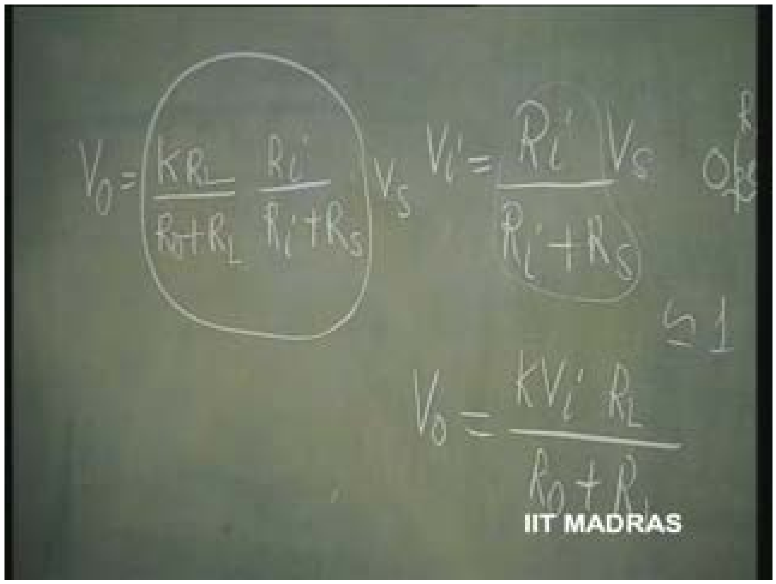
That is not the purpose of a good amplifier. The moment you connect it to the source, drastic reduction in input voltage occurs. So, a voltage controlled amplifier therefore, will be highly suitable for this kind of source, with source resistance which is very small. Now, look at the output circuit. K times V i is going to get divided between R L and R naught. So, the actual voltage, we will call as V naught, is going to be equal to K times V I, that is the source, divided by R naught plus R L into R L.

(Refer Slide Time: 27:40)



So, if you mark this as plus, minus; and this as plus, minus, then, V naught is going to be K times V i into R L by R naught plus R L. Or now, if you want to find out what is the output voltage in terms of the source voltage, then we have here K times R L by R naught plus R L times V i; and V i will substitute from this; which is, R i by R i plus R s.

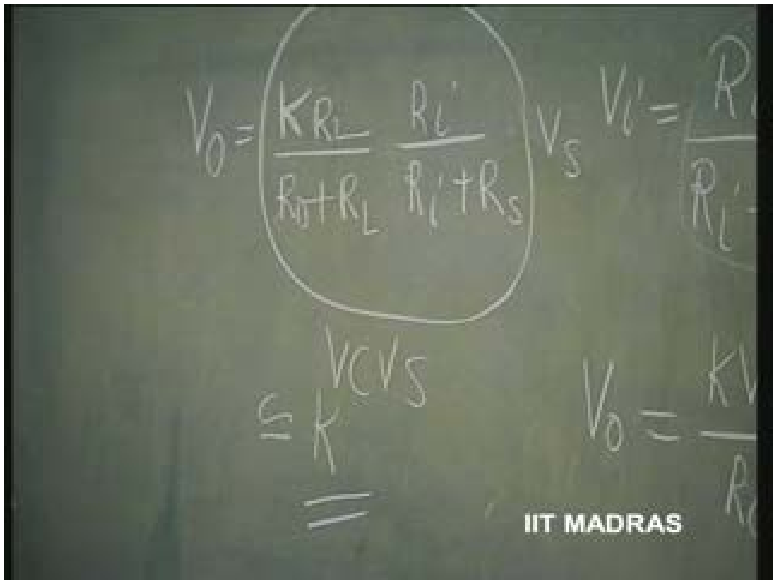
(Refer Slide Time: 28:27)



So, we can see that the actual gain of the amplifier is going to be K, which is the open circuit voltage gain, times the attenuation suffered at the output, which is R L by R naught plus R L. Had it been ideal voltage source at the output, then, R naught would have been very small compared to R L; and this factor also would have been very close to 1; and this factor would have been close to 1; and output voltage is very nearly equal to open circuit voltage gain into V source voltage.

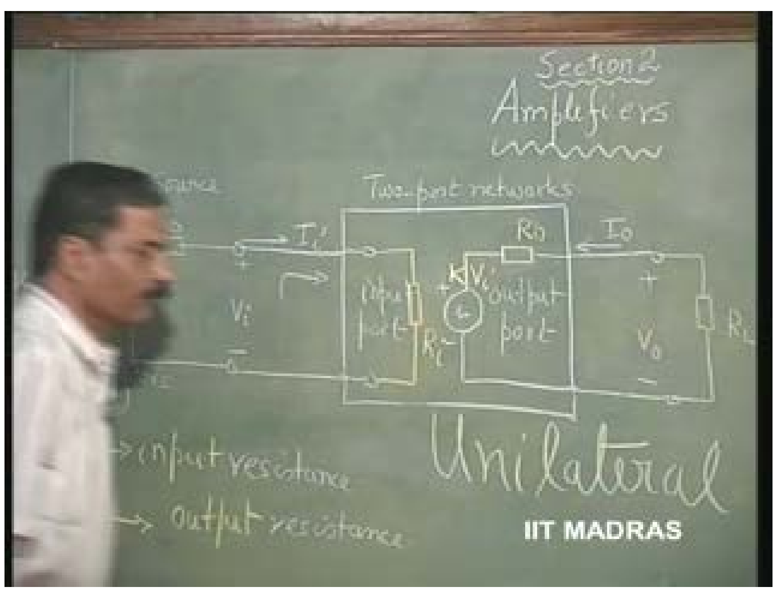
So, if you have a good amplifier which is voltage controlled voltage source, then, this is going to be very close to K, which is the open circuit voltage.

(Refer Slide Time: 29:16)



Now, there are certain terminologies here. This circuit is said to be unilateral.

(Refer Slide Time: 29:41)



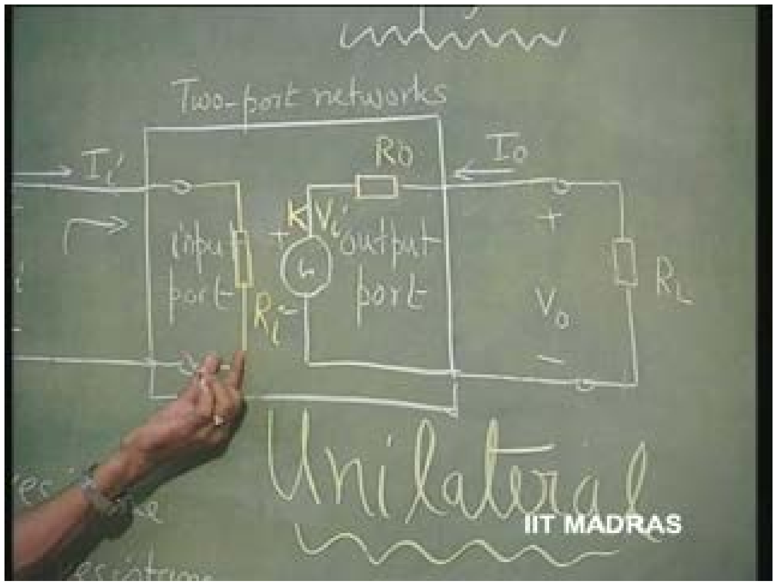
What does it mean? This... something that you have seen bilateral, earlier. That is, whether I apply voltage here and obtain voltage there, and apply voltage here and obtain voltage there; there is transmission in both directions and it almost behaves in identical fashion in both directions, let us say; whereas, in this particular case, when I apply V i here, this V i gets transferred to this side as K times V i; and the effect of that appears here.

So, the transmission is possible only in one direction. In the other direction, when I apply a voltage V naught here, if I apply an independent source here, nothing happens to it on at the input side. That means, input is not influenced by what happens at the output; whereas, output is influenced by what is happening at the input. That is called unilateral; that is, only in what direction, signal is transmitted. In the other direction, no signal is transmitted.

An ideal amplifier therefore is unilateral. The ideal voltage control voltage source is unilateral; and the practical voltage control voltage source that we have now shown, is still unilateral. There is no effect of what happens at the output, at the input side. So, most of the amplifiers that we are going to discuss can be considered unilateral, approximately; very little of transmission that is going to occur. That also, if it occurs, it is going to be occurring to a very small extent, which can be neglected.

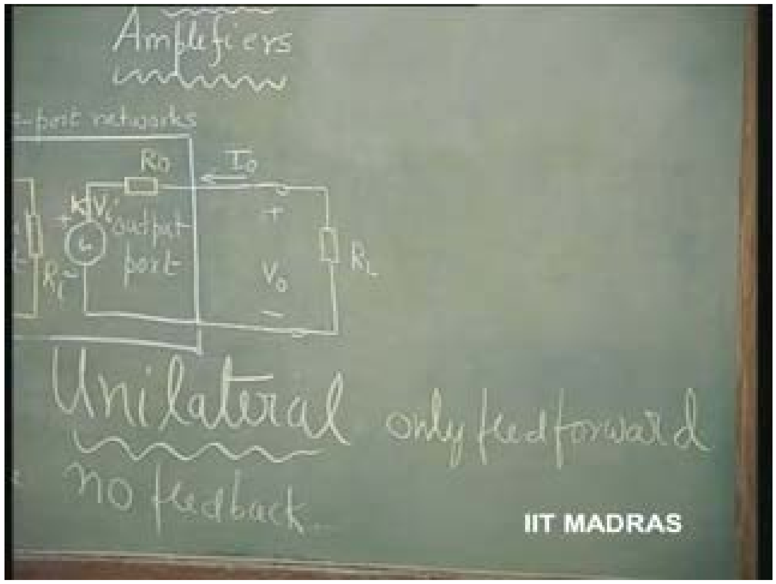
Now, if there is some effect here, from this side to this side, obviously, this V naught or I naught has to be represented as a source here.

(Refer Slide Time: 32:11)



That is called feedback. What is at the output is fed back to the input port; so, if there is some effect due to V naught or I naught at the input port, that has to be represented as a voltage or current source. That is called feedback; and in a unilateral circuit, there is no feedback.

(Refer Slide Time: 33:04)



In a unilateral circuit, there is only feed forward. The signal feed is only in the forward direction. There is no feedback or the feedback factor is zero. So, the feedback factor is zero. That is, there is no interaction of what is happening at the output, at the input port; whereas, what is happening at the input port is getting transmitted to the output port.

Now, this has to be very very clear. Now obviously, we can represent this in the two port parameter. Let us see what is this two port parameter. Before we go to the two port parameter, I would like to also discuss what exactly amplification means. Amplification - this is something that I have... always means, Power amplification. Amplification does not really mean only voltage amplification or current amplification. Amplification always means power amplification.

What is power? Power at the input. There are two ports here. Therefore, we have power fed at the input and power fed at the output; so input power is I i into V I; output power is I naught into V naught. Therefore, power gain is nothing but output power divided by input power; which is, what is it? V naught I naught divided by V i I i, which is a very significant relationship.

(Refer Slide Time: 35:50)

It is this that we want in every amplifier. If we get V naught over V i as a factor greater than 1, then, even if I naught over I i is less than 1, there is still power gain possible.
If V naught over V i is less than 1, as long as I naught over I i is greater than 1, there is still power gain possible. That is why voltage amplifier as well as current amplifiers still are suitable for power amplification. So, this is something that we have. In a passive device, two port network that is, if we take a passive network, comprising of only resistors, capacitors and inductors, then, you can prove that V naught I naught divided by V i I i is always less than or equal to 1.

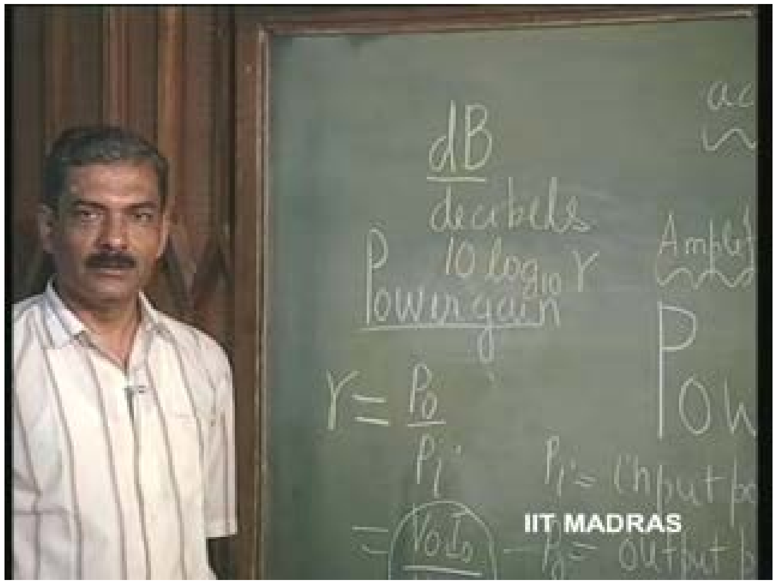
For example, if the network that is put in the black box is made up of only ideal inductors and capacitors, then you can see to it that V naught I naught divided by V i I i is always equal to 1 because, there is no dissipative element in the whole structure. What is inputted will appear as output; this is a classic case of a transformer, for example. We put a transformer, for example. You can get V naught greater than V I; but I naught by I i will be less than 1, by the same factor by which it is greater also, so that, the multiplication becomes equal to 1.

So, in the case of a transformer, ideal transformer, V naught I naught by V i I i is equal to 1; whether it is stepping up voltage or stepping up current. It is of no consequence; it is not an amplifier. An amplifier is one where V naught I naught by V i I i is greater than 1; and therefore, the fact that it is magnifying voltage does not necessarily mean it is amplifying. The fact that it is magnifying current does not necessarily mean it is acting as an amplifier. We should always find out what the power amplification is. Then only, we have this unit becoming an amplifier. Such a thing is possible using what are called as active devices.

(Refer Slide Time: 39:00)

These active devices could be anything that we can think of; the technology can think of. These could be tubes, these could be transistors, bipolar, or, field effect transistors; these could be op amps. So, these active devices are the ones, which if designed properly, which if biased properly, can give you power amplification; not always guaranteed to give. But, if you push them to work for you, by designing them properly, by biasing them properly, they might give you power gain. They might work in a range where amplification exists.

(Refer Slide Time: 40:31)

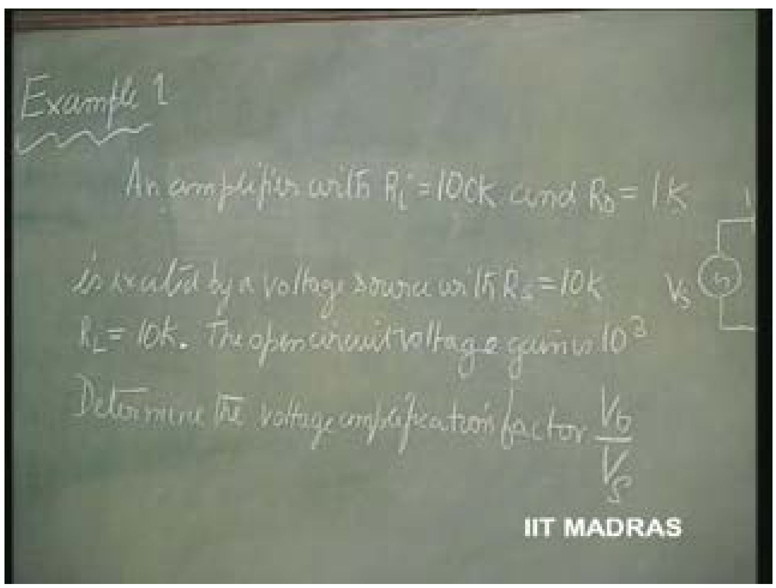


So, this is an important ... this thing; and therefore, you will also know what this unit is. This is a ratio. This is normally expressed in terms of decibels. What is it? This is nothing but 10, deci indicating ten, log to the base 10 of this ratio. So many decibels because, in practice, for example, input port is an open circuit, or, very nearly an open circuit. We know that I i is zero; that means, input power is going to be zero.

So, this is going to be zero; but there will always be output power. So, most of the amplifiers that we are going to discuss will have either I i very close to zero or V i very close to zero. We will consider those options another time. So, we will have these factors going towards zero most of the time, when this is finite. So, this factor is very very high, close to infinity, which means, it is better to express this as a ratio, rather than, I mean, ratio converted to decibels, rather than leave it as a ratio which is going to be huge quantity.

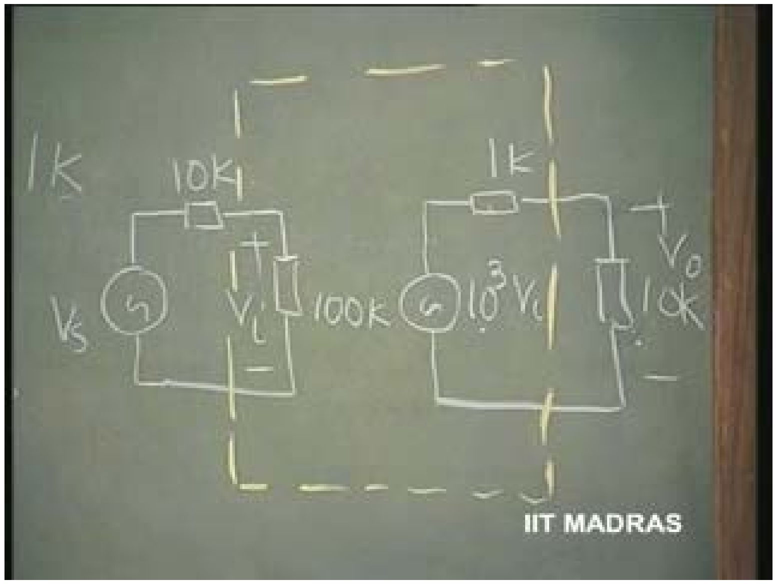
Now, let us try to work out an example. An amplifier; we don't know what type of amplifier it is; we will come to know only after we go through the entire problem; with R i equal to 100 Kilo ohm, R i equal to 100 Kilo ohm and R naught equal to 1 Kilo ohm is excited by a voltage source with source resistance equal to 10 K. So automatically, source resistance is 10 K and R i is 100 K; so it is a voltage controlled block. So, R s equal to 10 K and R L equal to 10 K. Obviously, at the output, the output resistance is 1 K and load resistance is 10 K, it is voltage source. So obviously, the amplifier now can be categorized as belonging to voltage controlled voltage source category. The open circuit voltage gain is 10 to power 3. So, the K value is given as 10 to power 3. Determine the voltage amplification factor, V naught over V s.

(Refer Slide Time: 42:50)



Now, this is a very simple problem, which is normally encountered in any amplifier.

(Refer Slide Time: 43:22)

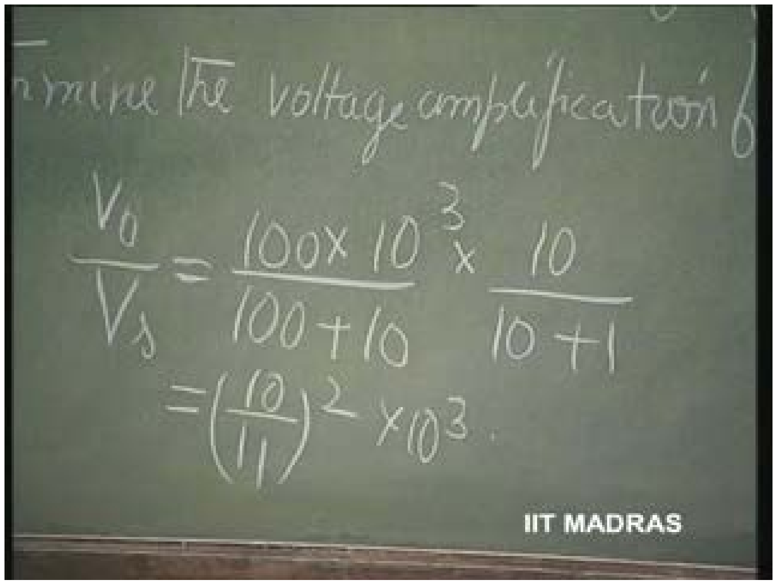


So, V naught over V s, from this diagram; we can now see the diagram, is going to be 100, divided by 100 plus 10, times V s, into 10 to power 3, multiplied by 10, divided by 10 plus 1. So, 100, divided by 100 plus 10, times V s is going to be V i, and that is going to be multiplied by 10 to power 3, appears as the output; and that is going to be further attenuated as 10 divided by 10 plus 1.

(Refer Slide Time: 43:42)

So, the answer is very simple. So, we have it here as 10 by 11 into 10 by 11. So, 10 by 11 square times 10 to power 3, which could be converted into sort of decibels.

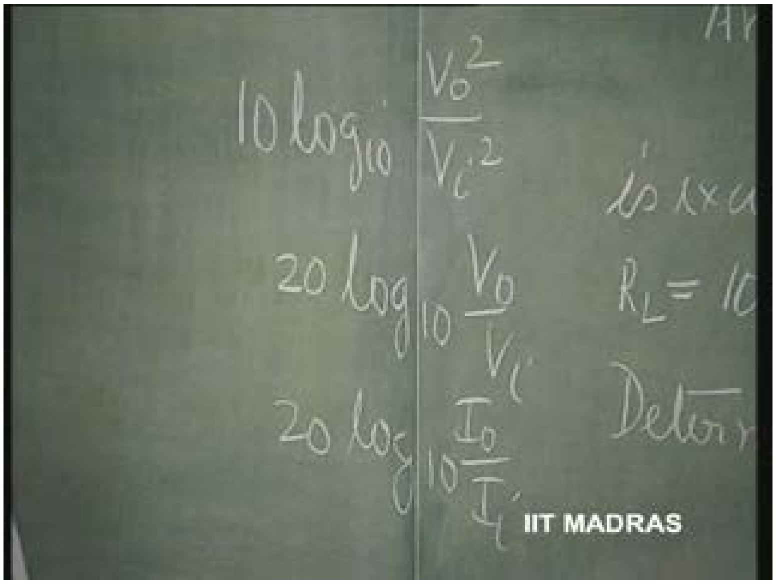
(Refer Slide Time: 44:02)



This is something that we have to be very careful about. We have defined 10 log to the base 10 of power ratio as decibel; whereas, if it is voltage ratio, V naught square divided by V i square, V naught square divided by, let us say, R L, V i square by R i; R L and R i being equal to the same value; that is the definition of voltage ratio; in which case, this becomes equal to 20 log to the base 10 of voltage ratio. Or you can put in the current ratio.

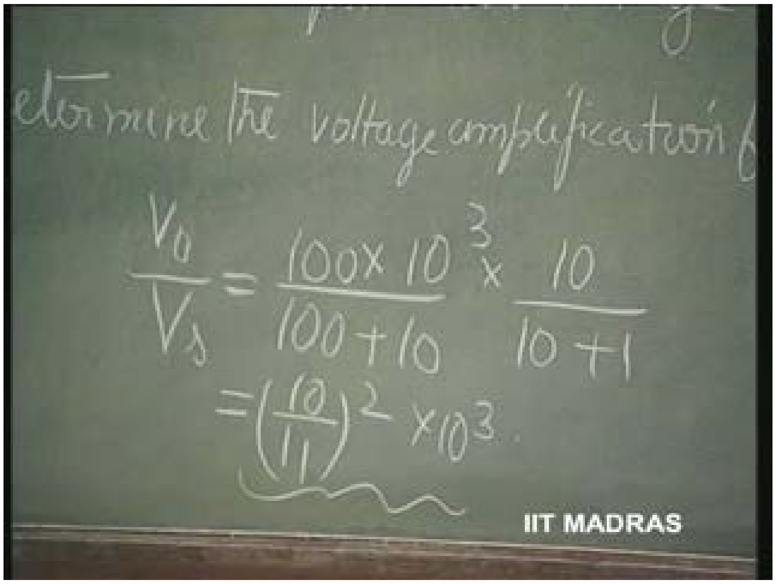
That is, voltage taken across the same load, both in the case of output as well as input, that power expressed in terms of voltage ratio or current ratio will turn out to be 20 log to the base 10 of V naught over V i. If you are expressing therefore, this in terms of voltage ratios, you should put it as 20 log to the base 10 V naught over V i. If it is power, 10 log to ... Similarly, current ratio also is expressed always in terms of 20 log I naught over I i.

(Refer Slide Time: 45:48)



So, if you are going to express voltage ratio in terms of decibel, then, this will be very nearly equal to 60 decibels. This is going to be 20 log of this factor, which is going to be very nearly equal to 60 decibels. You can calculate it exactly as a homework problem. Please do calculate it. It is going to be very nearly 60 decibels.

(Refer Slide Time: 46:22)

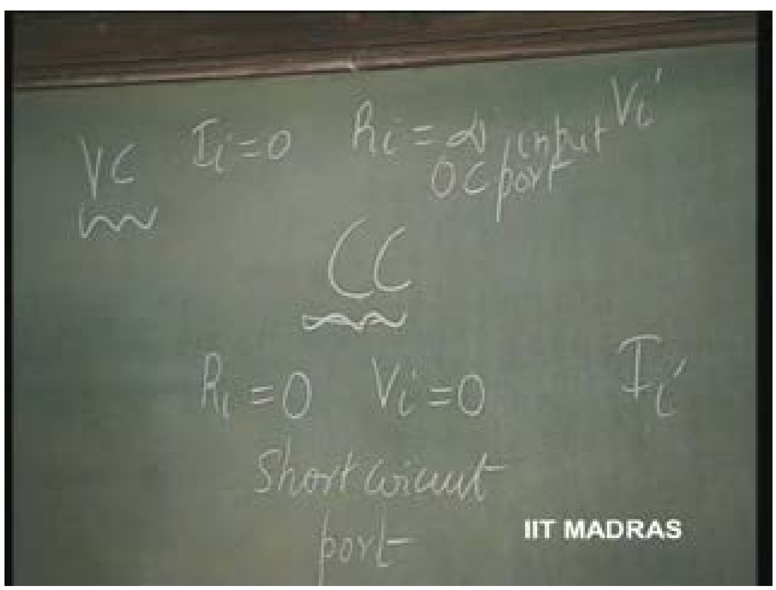


Now, I would like to, at this juncture, introduce you to other types of op amps. This is not the only type of amplifier existing. Obviously, we just said, it could be voltage controlled voltage source. Instead, it could be current controlled. What is the difference between voltage controlled and current controlled? This is something that we have to understand now because, only in the present day electronics, people are coming up with other types of sources which are more important than the so called voltage controlled voltage source which was traditionally in existence as an amplifier.

So, we should learn about other amplifiers equally well. So, current controlled - what does it mean? We just said, in the case of a voltage controlled situation, I i was zero or R i was infinity. In the case of current controlled, obviously, and it is controlled by V i, in the case of current controlled situation, we will have R i equal to zero. It is a short circuit. Here, it was an open circuit. Here, it is a short circuit.

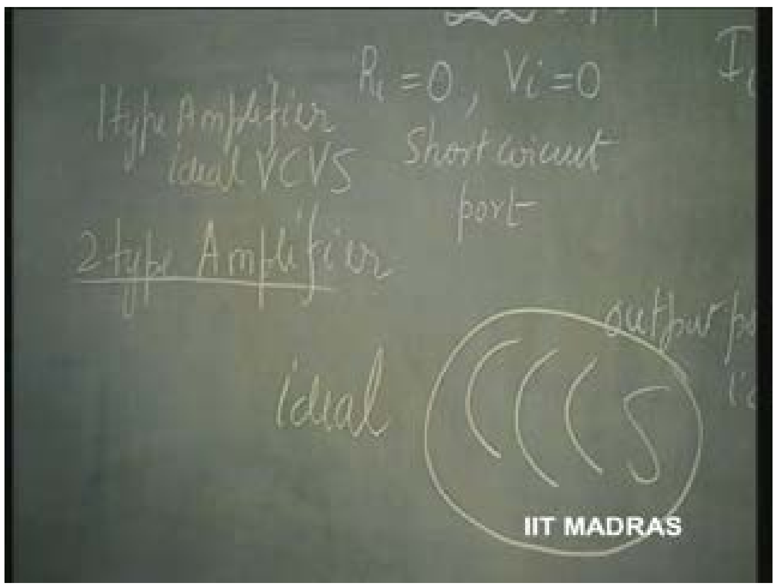
R i is zero. That means, V i is zero; and it is controlled by I i. You see the distinction over here? In the case of a voltage controlled block, I i was zero; for which to happen, R i had to be infinity. You called it open circuit at the input port, open circuit port; and it was getting controlled by V i.

(Refer Slide Time: 48:28)



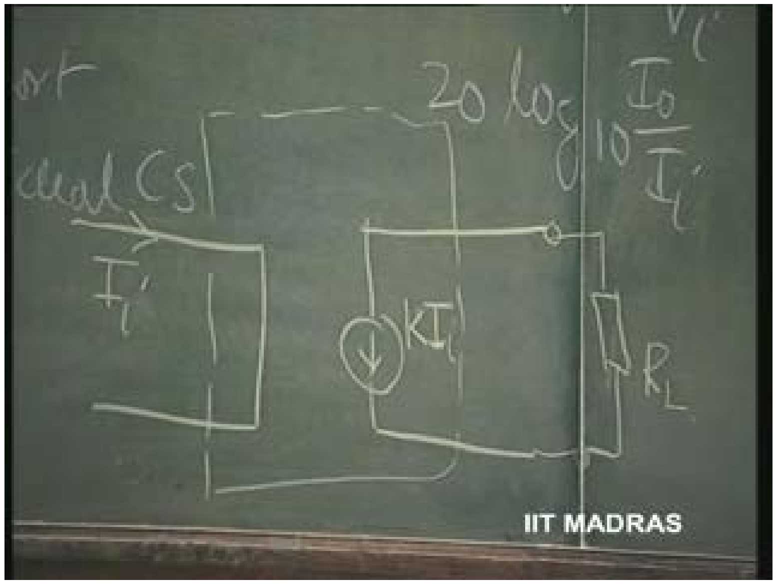
Now, this is a short circuit port. R i is equal to zero. Consequently, V i is equal to zero and it is controlled by I i. And therefore, we have to learn about this amplifier which is current controlled and it could be, instead of a voltage source, it could be a current source. So, output port, this is the case of input port situation; output port could be therefore, an ideal current source. So, we get this block as current controlled current source as a second important block acting as an ideal amplifier.

(Refer Slide Time: 50:00)



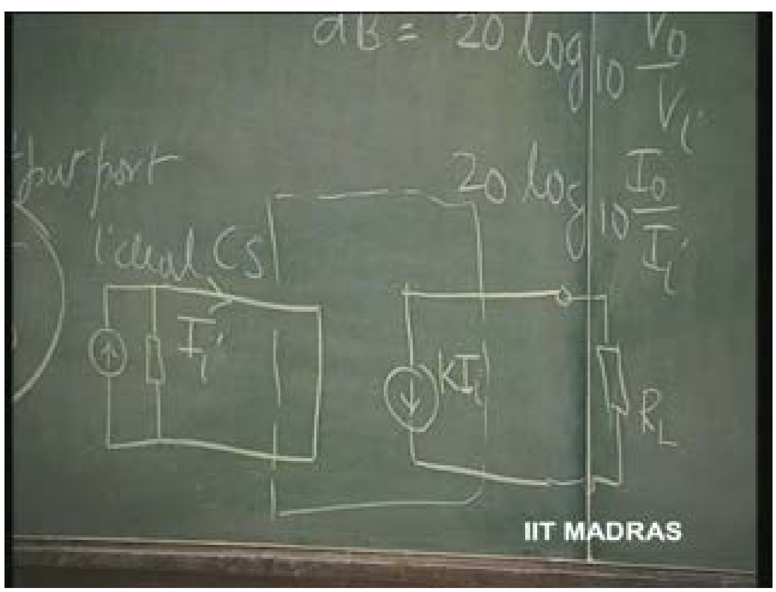
First type was ideal voltage controlled voltage source. So, this is ideal current controlled current source, second type of amplifier. So, how do we represent this? So, this will be a short at the input source and the current source... So, if I i is the input current, V i is zero and output is going to be K times I i. And this is the output port; it is connected to load.

(Refer Slide Time: 50:47)



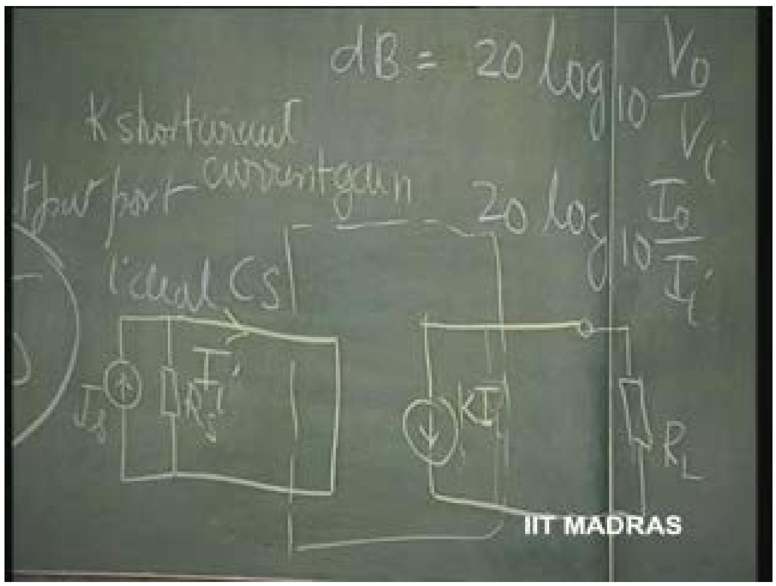
Obviously, we must drive this again by a non-ideal source, whatever it is. So, we would rather drive it using current source, which could be ideal or when it is non-ideal it can have... because, we will not use the other source; it cannot become ideal, because it is a voltage source; it will get shorted. So, we will do the current source which could become ideal with this going to infinity, so R s.

(Refer Slide Time: 51:07)



So, this is the way we are exciting. This is the same non-ideal source, I s shunted by an R s. So, this is called... in fact, this is the other amplifier. This is now called short circuit current gain because in case this also has non-ideality, which is the output impedance here. So, if this has non-ideality which is output impedance, then, this current is going to be the short circuit current.

(Refer Slide Time: 52:11)



So, this is called short circuit current gain. So, K is called short circuit current gain.

This is a current amplifier as against what we had discussed earlier, which is a voltage amplifier. This is called voltage amplifier. This can now be called current amplifier, ideal voltage amplifier, ideal current amplifier. In fact, ideal current amplifier, close to ideal current amplifier, we have, we got devices. We will later see, how the practical devices are close to this.