Analog Electronic Circuits
Prof. Shanthi Pavan
Department of Electronics and Electrical Communication Engineering
Indian Institute of Technology, Madras

Lecture - 07
Nonlinear Two-Ports With incremental Gain

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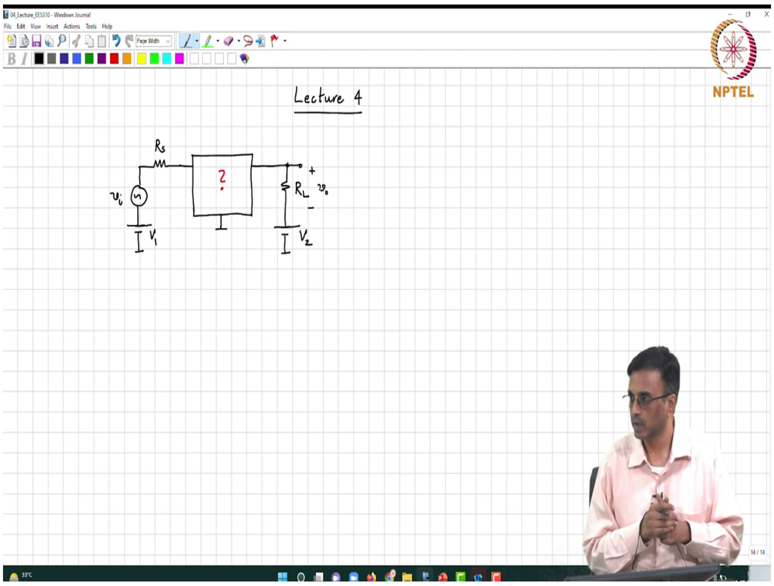

In the last class we were wondering how to make an amplifier. And the aim of the amplifier was to take a small signal v_i with the source having some source resistance R_S and we would like to make an amplifier. In the simplest case the amplifier is a three terminal two port. And across a load we would like to have an output voltage v_o where the power dissipated in R_L is greater than the power drawn from the source, ok.

So, we had and we were wondering how one can make that box there. The first choice was to see if that box could be linear, right? And which basically means, if there were no energy sources inside the box, it basically means it is a network of resistors, right? And we immediately concluded that it cannot be linear. And simply because the power dissipated in R_L is bound to be smaller than that drawn from v_i, because some of it is going to be dissipated inside the resistors inside the box.

Then we said that of course, is you know pretty obvious. Why do not we do something which does not violate the first law of thermodynamics is basically, you have energy sources V_1 and v 2. Now, you cannot say well the power dissipated in R_L cannot be smaller than v_i, because there are two sources which can provide energy. However, if you look at the voltage across R_L, this is clearly a non-linear network because of the presence of the voltage sources. However, if you look at the voltage across R_L it is a superposition of.

Student: Three voltage sources.

Three voltage sources. One due to v_i and one due to V_1 and one due to V_2, it might turn out that for specific values of V_1 and V_2 and for specific values of resistors inside that box. It might turn out that the power dissipated through R_L can be greater than the power drawn from.

Student: From the source.

From the source. However, we are interested in the power dissipated in R_L which is proportional to the input source, right? The power the extra power dissipated in R_L due to V_1 and V_2 are simply DC power. And they basically are useless as far as amplification is concerned, right? Because we want the power at the input frequency corresponding to the input source v_i, we want that to be.

Student: Larger.

Larger, right? I mean does not there is no fun in simply heating up the resistance R_L by going on pumping DC power through it. Does that make sense?

Student: Yes.

The next job is therefore, the box cannot be linear. I mean cannot be a network of resistors. Adding energy sources outside also does not help. Then the next choice is to say the box is non-linear right, and even if the box is non-linear it does not help if there is no.

Student: Outside.

Source of energy outside.

Right, because that simply will violate energy conservation, right? And therefore, the only possible choice is when this box is non-linear and we have these two voltage sources V_1 and V_2, ok.

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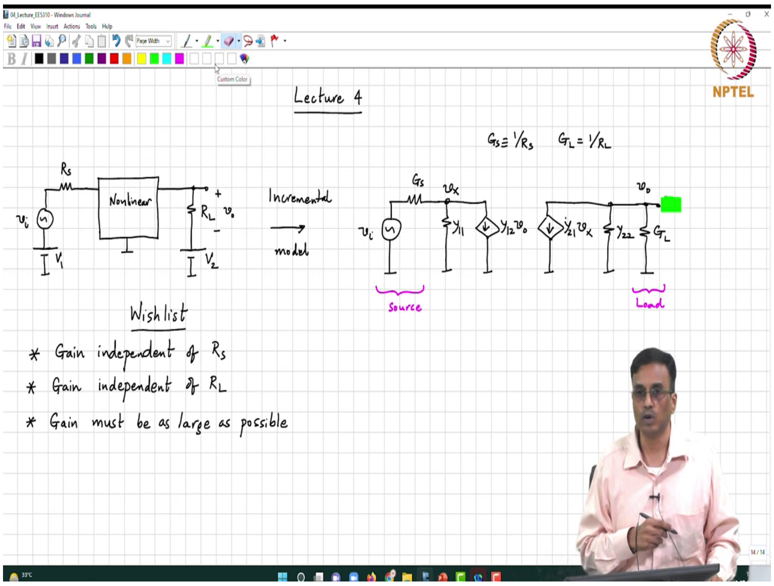

Then please note that this box does not have any energy source inside ok. All the energy sources V_1 and V_2 are.

Student: Outside.

Outside the box. And it is still not clear whether this will still work as an amplifier, but the other three cases will definitely not work alright? So, we are interested therefore, in making sure that the small signal, the power in R_L corresponding to v_i is larger than the power drawn from the source itself, ok. And therefore, we have we are interested in figuring out the incremental voltage across.

Student: R.

Across R, correct. Now we have a non-linear two port and we have two non-linear elements namely V_1 and V_2 which are basically the energy sources, ok. So, to find the incremental equivalent or the incremental voltage across R_L, what we need to do is simply replace every element in this circuit with.

Student: Incremental model.

With this incremental model, right? So, that is easy. We have already done that. What do we do? What happens to V_1 if we go element by element.

Student: Short circuit.

It becomes a short circuit and then of course, what happens to v_i? v_i is as is and this is R_S, and what comment can you make about the box?

Student: Two port linear two port.

It is a linear two port, now the linear two port as yesterday we said that we can model it by its.

Student: Y parameters.

Incremental Y parameters. So, we will replace that by its equivalent network. So, that is v_o what must this be?

Student: conductance.

All these are conductance's mind you. And because all these are conductance's, let us not get confused instead of R_S. I am going to call this as G_S. Where G_S is $1/R_S$ and likewise G_L is $1/R_L$. So, everything in this network on the right correspond to conductance's. Does that make sense people, alright. Now, before we are trying to figure out we know that that box is non-linear, we want to figure out what the characteristics of that non-linear box must be so, that we are able to get amplification, right?

And before, this must be Y_{21}, let me call that v_x alright? And before we get on to the job let us try and figure out what the characteristics of a good amplifier are, ok. I remember that this corresponds to the source, this of course, is the load. For an ideal amplifier you know what comment can we make regarding the gain of the amplifier if the source resistance changes. For a good amplifier we would like to make sure that the gain remains independent of.

Student: Source resistance.

Source resistance. So, this is our wish list independent of R_S, alright. Gain, what about load?

Student: Independent.

Ideally, we would like it to be independent of?

Student: R_L.

R_L, alright, and what else? A gain must be as large as possible, right? And we can add things later if you find additional things that we would like ok. So, basically what are we trying to do? Therefore, what should we try to do now?

Student: Find incremental Y parameters.

Basically, we say well you know this box is modeled by its incremental Y parameters, ok. If the box is modeled by its incremental parameter Y parameters, we will be able to go and calculate find an expression for the gain between v_i and.

Student: v_o.

v_o. That gain will be a function of G_S G_L and all the four Y parameters. We stare at that expression and figure out what those numbers Y_{11}, Y_{12}, Y_{21} and Y_{22} must be. So, they basically are able to satisfy our wish list correct. So, the first step in the whole exercise is therefore, to compute.

Student: Gain.

The expression for gain from v_i to v_o ok. And since everything is what do you call conductance's it is easier to do this using nodal analysis right?

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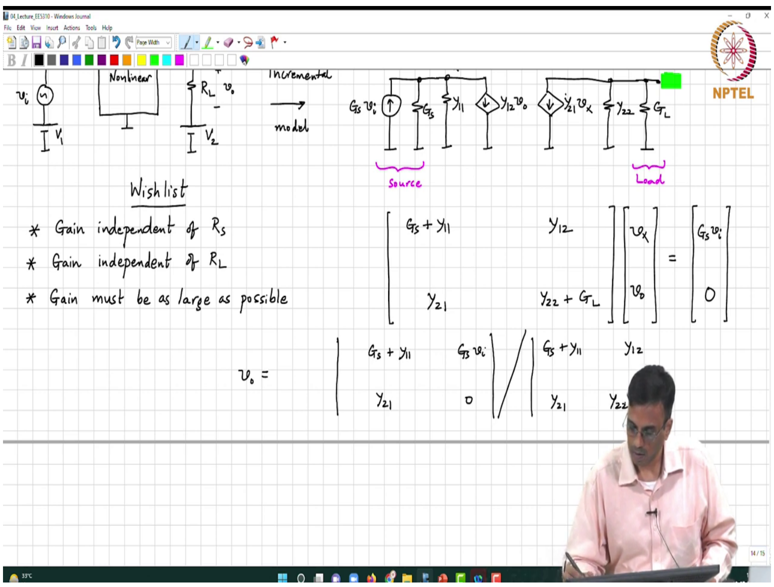

So, we write KCL at every node and we can simplify this as a current source. So, this is G_S times v_i and this is the conductance G_S. This is exactly identical to the Thevenin equivalent that we saw earlier, right? ok. Now, if you want to write the nodal equations for this what will you do, what are the unknowns?

Student: v_i.

What are the unknowns that we are you know in this network?

Student: v_x.

Two unknowns which are the?

Student: v_x and v_0.

The node potentials v_x and.

Student: v_0.

v_0, very good ok. So, we write the nodal equations. So, this is basically G_S plus Y_{11}. This is the node conductance matrix, what should be here? What should be there? How many of you are familiar with writing nodal equations?

Student: v_x.

So, what are the unknowns? It must be v_x.

Student: v_x v_o.

v_o or must be on the right-hand side.

Student: Current.

Yeah, what is the current flowing into the v_x node?

Student: G_S times v_i.

G_S times v_i, and this must be 0. The first term in this matrix must be, first row first column must be $G_S + Y_{11}$ ok.

Student: Y_2.

This must be $Y_{22} + G_L$ that is easy, then what?

Does that make sense, alright. So, what is v_0 therefore, what should we do?

Yes, use Kramer's rule determine replace.

Student: Second column with.

Second column with.

Student: G_S v_i.

G_S v_i, sorry $G_S + Y_{11}$, Y_{21}, $G_S v_i$ and 0 this determinant over.

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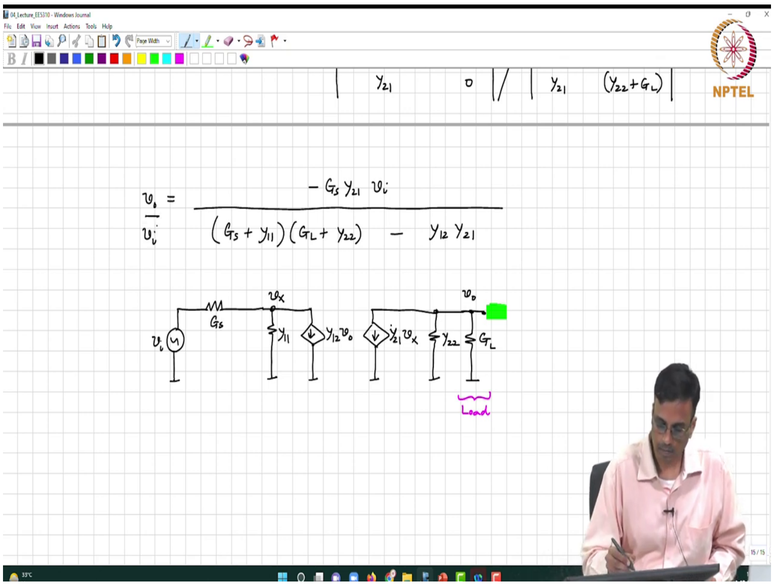

So, what is v_o now?

$v_0 = - G_S \times Y_{21} \times v_i / (G_S + Y_{11}) (G_L + Y_{22}) – (Y_{12} Y_{21})$

Does make sense ok. So, that is the gain of this amplifier. Let me copy that down. I want to revert back to the original and this is v_o/v_i alright? So, after analysis we have found that this is expression for gain between v_i and v_0 alright.

So, now, let us look at our wish list and then figure out what to do. But first thing what are the first thing that strikes you when you look at it.

Student: Function of G_S and G_L.

Of course, it is a function of G_S and G_L alright, what comment can we make when we look at the denominator?

We see that the denominator is formed as a difference of.

Student: Two terms.

Two terms. So, whenever you have a denominator which is of the form a minus b, what happens if a becomes equal to b?

Student: It becomes infinite.

It becomes.

Student: Infinite.

Infinite right ok. So, if the gain is infinite what does it mean?

Gain is infinity that basically means.

Student: Without an input.

Even without an input.

Student: Almost get an output.

You get an output, right? So, this is basically instability right? I mean you basically you want a friend who talks to you nicely, but you do not want a friend who keeps on talking, right ok. So, like that you want an amplifier which has a lot of gain, but not gives you output even without an.

Student: Input.

Input alright? So, but unfortunately as you can see this a term depends on G_S and $G_{L,}$ correct? So, depending on the source and the load resistance it is very likely that somehow this term will become equal to Y_{12} to Y_{21} right? In practice, because you are going to sell this amplifier and for some magical combination of you know G_S and G_L, it may very well turn out that the denominator becomes 0 in which case the amplifier is completely.

Student: Unusable.

Unusable right? And its actually pretty easy to see for this scenario to happen, right? And I will illustrate it in practice. So, this is an acoustic two-port correct?

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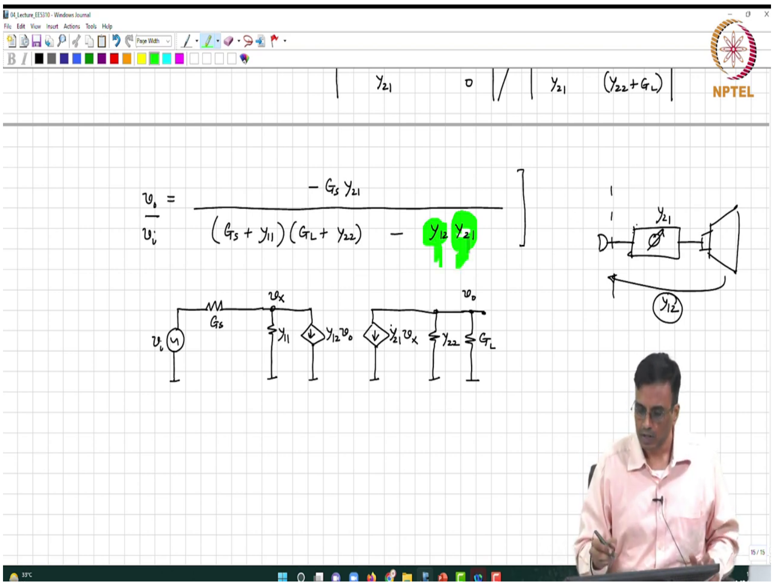

So, this is a mic, and you know there is some amplifier here and this is and there are loud speakers in this room as you can see around you ok. So, remember what is Y_{21}? what is Y_{21} quantify?

Student: Put the effect put the effect of.

The effect of.

Student: Output.

Y_{21}.

The effect of an excitation at the input on.

Student: Output.

On the output ok, what does Y_{12} quantify?

Student: The effect of

The effect of an excitation at the output port on the.

Student: Input.

Input alright. Now so, in this acoustic analogy what quantifies Y_{21} therefore?

What?

Student: that output.

What does Y_{21} you know what determines Y_{21} of this acoustic two port?

Student: volume.

The volume knob of the amplifier, right, which my friend there is controlling ok, alright? And what quantifies Y_{21} of this acoustic system.

Student: Y_{12}.

Y_{12} I understand, but in this room, where is that Y_{12} coming from.

Student: speakers.

There is a direct path from the.

Student: Speaker.

Speaker to the microphone back to the microphone right ok. This is what constitutes the Y_{12} of the acoustic two port alright? Now, this the gain knob here quantifies Y_{21}, right? At this point you can see that is a are we getting an output without an input.

Student: No.

No, right. Mr. Balaji, can you increase the gain, right? So, by increasing the Y_{21} you can see that for some value of Y_{21} in spite of having a really nice room with this being as small as possible, right? I mean why do you think all this fancy wood and you know this absorptive material is there, it is not for the aesthetics ok its not only for the aesthetics the primary reason is for.

Student: To absorb.

To absorb the amount of feedback. I mean basically you know in our two port parlance, it is to make sure that this Y_{12} is as small as possible alright? And I am sure you seen this scenario before, correct? I mean you know you have a public address system and then suddenly it starts singing ok. And what do you do to fix the problem you know instinctively what do you go and do?

Student: Reduce the volume.

You reduce the volume correct why is that working? If you reduce the volume for a given Y_{12} you cannot do anything about the Y_{12}, right? So, if you have a hall with bad acoustics, it basically means that the sound not only comes directly, but also hits walls and then all that and then comes to your microphone through un attenuated after getting reflected through multiple walls.

Now, with all this acoustic padding what is happening, all those paths are getting eliminated largely because the sound is getting absorbed by these walls. So, the Y_{12} becomes much smaller, but still, it is possible to send the system to instability by what did we do?

Student: Increase the Y_{21}.

It simply have increased by Y_{21} alright ok.

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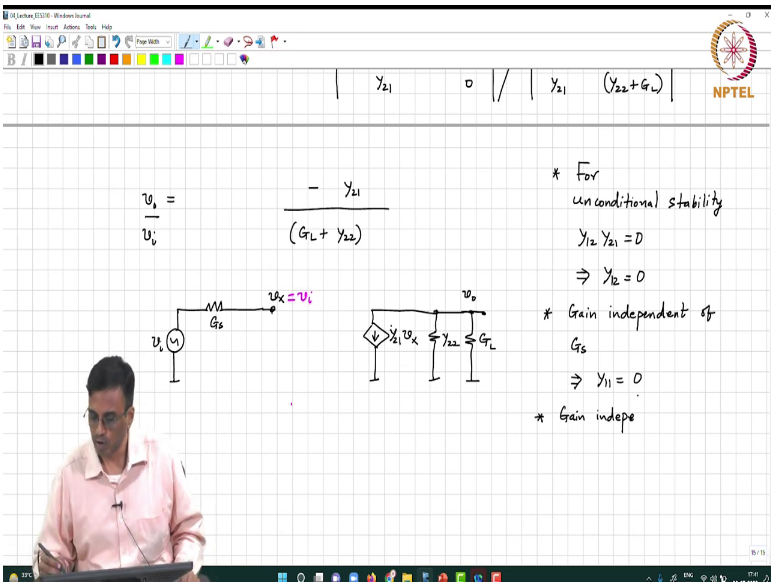

So, to ensure therefore, unconditional stability. So, one of the attributes of a good amplifier therefore, is that it must be unconditionally stable, not merely stable for some magic values of G_S and G_L. It must also be unconditionally stable. You are selling it out correct, the user might put arbitrary values of G_S and G_L. And therefore, the two port must be the amplifier must be unconditionally stable. And the only way that is possible as you can see here is.

Student: Y_{12} 0.

Is if this term does not, you cannot do anything about the first term that is there right, the only thing you can do is that the second term does not exist. So, that at least three ways of making that Y_{12} Y_{21} go away correct. So, for unconditional stability, this Y_{12} Y_{21} must be 0, correct. And this means there are at least three ways of accomplishing this what are they?

Student: Either.

I mean you can make $Y_{12} = 0$ $Y_{21} = 0$ or.

Student: Both 0.

Both 0 ok. So, now, which of these choices is the most appropriate?

Student: Y_{12}.

Y_{12}, why not Y_{21}?

I mean if you make $Y_{21} = 0$, then well there is no instability, but there is no gain, there is no connection between the input and output either correct ok. It is like saying if you are very poor then nobody can rob you right, because you have nothing to lose correct, but that is not hopefully that is not an ideal situation, right?

So, basically you want Y_{12} to be equal to 0. So, if we therefore, now set $Y_{12} = 0$, then this term vanishes alright. We left with this expression does make sense so far alright? So, then we want the gain to be independent of G_S and what comment can you make now. What should we do if we want the gain to be independent of G_S?

Well the expression is telling us that Y_{11} must be.

Student: 0.

0. So, by the way if $Y_{12} = 0$ this goes away ok. So, for gain independent of G_S its very clear that Y_{11} must be 0, right? Intuitively why does that make sense stare at this picture and tell me why that makes sense intuitively? v_x is basically v_i minus the drop across the source resistance R_S, right? The only way the gain can be independent of the source resistance is if v_x is independent of source resistance, right?

So, I mean one way to do that is to say have source resistance equal to 0, but that is not something that is in our hands. The only thing we can do as far as the box is concerned is to make sure that it does not draw any current from the source. So, that is basically saying that the input, this Y_{11} must be 0.

So, that basically means that goes away ok. So, therefore, what is v_x therefore, now.

Student: v_i.

v_i ok. Now if $Y_{11} = 0$ as you can see the gain is indeed independent of Y_S. Now, we want a gain independent of G_L, is that possible? Evidently it is not possible right. What about for a given G_L how do we maximize gain?

Student: Minimize the denominator.

Minimize the denominator and so, therefore, Y_2 to the minimum the denominator can go to is.

Student: 0.

Is 0. Sorry, this minimum Y_{22} can go to is 0.

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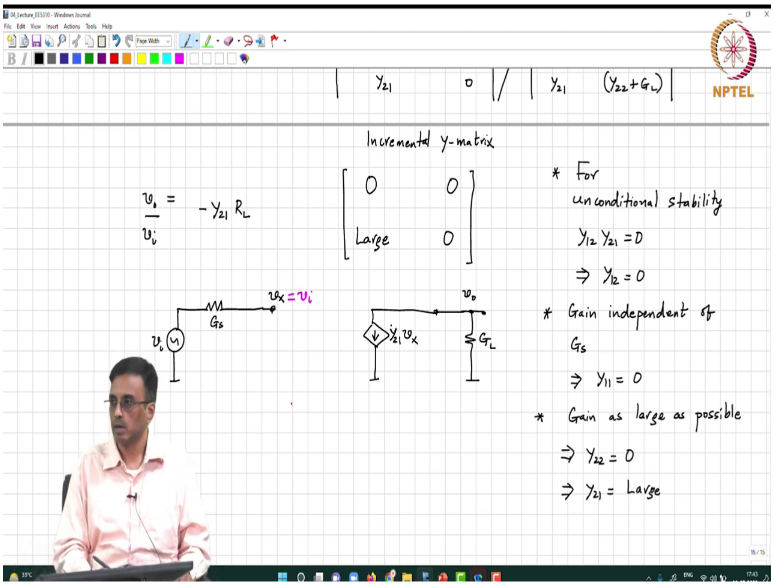

And therefore, gain as possible means Y_{22} must be equal to 0. Why is negative Y_{22} not acceptable? You will again end up with the same kind of instability problems that you.

Student: Some values.

Right for some values of G_L you know this Y_2 negative Y_{22} will cancel with the G_L and then cause an output gain which is infinite ok. And, so, if Y_{22} is 0 then the network this goes away and the gain therefore, becomes - Y_{21} R_L or Y_{21} /$Y_{L,}$ ok. So, alright? And so, now, if you want the gain to be for a given R_L if you want the gain to be as large as possible what should you do? What do you want for Y_{21}?

Student: Large as large as possible.

Yeah, Y_{21} must be as large as possible, does make sense? Therefore, the incremental Y matrix of that non-linear two port must look like this Y_{11} must be 0, and Y_{12} must be?

Student: 0.

0. Y_{21} must be?

Student: Large.

Large, Y_{22} must be?

Student: 0.

0. Ok. So, these must be the incremental parameters of an amplifier.