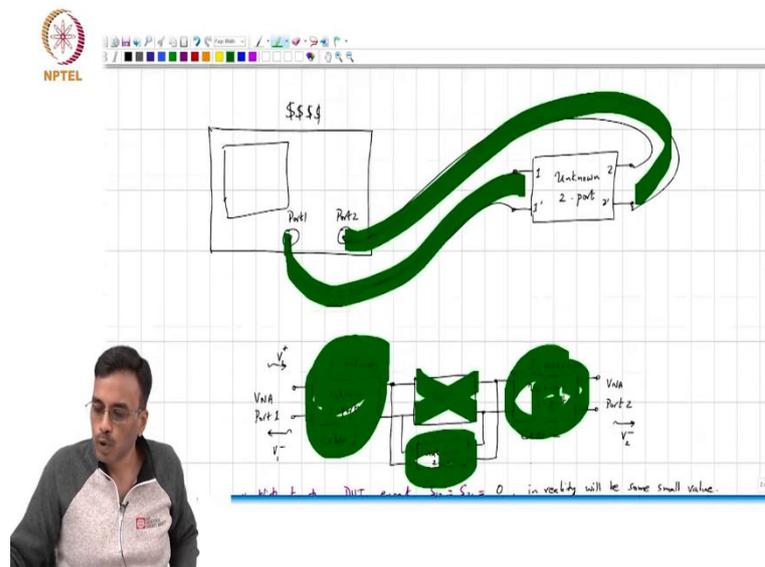


**Circuit Analysis for Analog Designers**  
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**Lecture - 54**  
**The two-port vector network analyzer**

Measuring a one port is nice, but most of the time you are interested in characterizing, interested in characterizing a 2-port network right.

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So, well again you know you have a big box right and then you have a nice-looking screen. And then now, and then you basically have sources for two connectors. So, this is port 1 and port 2 and you know these costs a lot of money right.

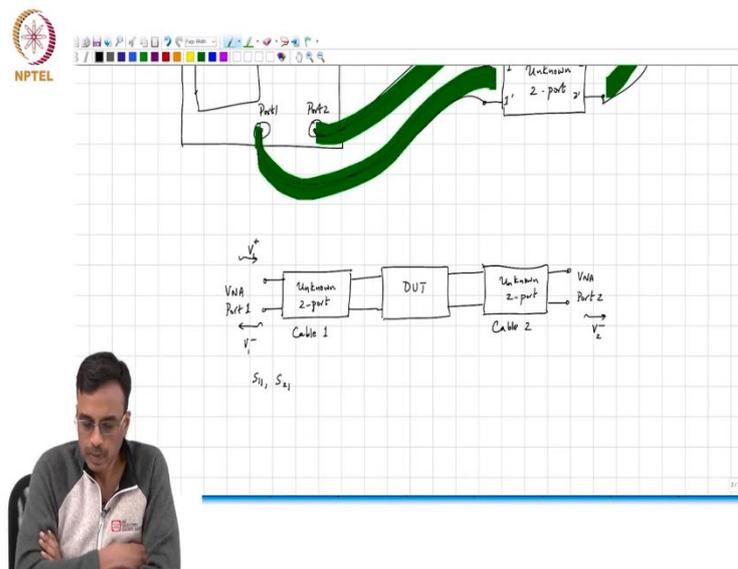
So, now the question is you know and the idea is that you have an unknown 2-port and you would like to measure its s parameters. We have also, we have already seen why it makes sense to measure s parameters rather than you know y and z and so, ok.

So, what do you do? Your well, you connect you know this guy using a cable to port 1 and you connect the 2nd port to this box using cables. So, what do you think we should do now? What all challenges do you anticipate based on your experience with the 1-port network analyzer?

What comment can we make regarding challenges with respect to the 2-port? No, I the question I asked is what challenge, measurement challenges do you anticipate? Well, when ok; well, the I mean if you did not know how you know the exact length and  $z$  naught of one cable, it is not very likely that when you have two cables you suddenly become wise right.

So, the properties of this cable are unknown right, the properties of this guy are unknown.

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So, what you in effect have been, you have an unknown 2-port this is a cable 1, right and then this is the device under test, this is unknown 2-port cable 2 and this is the, so this is the VNA port 1, this is VNA port 2 alright. So, if you want to measure  $s$  parameters of the DUT, what all I mean what all do you need in the inside the VNA? What must be there inside the box? Yes Karthi, what do you think? We need a frequency we need; obviously, a sine wave generator right.

And you know if you wanted to make measurements fast, you probably need two of them right; one pushing current into the I mean, one exciting port 1 and the other one exciting port 2. Or you know you finish making measurements at port 1 and then you know go to switch to port 2 and what do you think. So, in other words what you are measuring at port 1 will be, you are measuring the transmitted and reflected waves at port 1.

And like, likewise you are measuring the transmitted and reflected, the forward and the backward waves at port 2 and you can control which source you want to activate. So, for example, if you only activate the source at port 1 and you measure the. So, in other words you push something here and you measure this and this alright. What comment can you make about, what all measurements will you make be able to make with the by measuring  $V_1$  minus and  $V_2$  minus you will be able to obtain. You know  $S_{11}$  and?  $S_{21}$  and what?  $S_{11}$  and  $S_{21}$  right and likewise when you excite the pole, the source at port 2 you will be getting the other two parameters right ok.

So, but now we have you know we have how many unknowns here? Well, we have three unknowns corresponding to the 2-port response of this cable and here you have you know three unknowns with respect to the output cable correct. So, what do you suggest we do? What do you suggest we do? 6 vice, 6 standard kind of standard devices.

Pardon. Exactly I mean you know the straightforward, I mean the what do you want to do is basically you say get rid of the DUT, you replace you calibrate you calibrate as you assume that the rest of the circuit does not exist, you put in the three standards here right. Open short end and 50 ohms and from that you will be able to calculate these, the properties of that unknown 2-port. And likewise, you do the same thing here and you will be able to get the properties of cabled, correct ok

Now, unfortunately it turns out that that is not all ok. And what do you think might another problem?

Student: the (Refer Time: 06:51) exactly (Refer Time: 06:54). (Refer Time: 06:57) fourth step at the end (Refer Time: 07:00) exactly (Refer Time: 07:02).

No, that is all equivalent to you know I mean basically we are saying that the VNA port is not is not good right, that is equivalent to that is equivalent to adding an impedance here, which is equivalent to adding some something to this unknown 2-port, which is going to get calibrated correct.

So, it turns out that you know in reality, I mean ideally if the DUT was not there right ok, what comment can you make about whatever  $S_{12}$  you measure or  $S_{21}$  you measure? Forget about calibrating you know cable 1 and cable 2.

Let us say without the DUT we should expect  $S_{12}$  and  $S_{21}$  must be equal and what must you expect that measurement to yield? What does  $S_{12}$  and you know in English what is  $S_{12}$  or  $S_{21}$ .

Pardon. Yeah ok. So, forward and you know I mean  $S_{12}$  is the effect of an excitation at port 2 on the response at port 1 and vice versa. So, what do you expect to see ideally the device under test is not there, I mean it is just been removed.

I have removed the there is nothing man. No, do you I mean looks like you guys do not understand the question right, yeah alright. So, what would you expect to see for  $S_{12}$ , I mean you measure  $S_{12}$  and  $S_{21}$  pardon. 0 why is it so difficult is this, is this clear or no? Somebody said  $S_{12}$  times  $S_{21}$  and what how did you get that? What connecting both, there is nothing in the middle I mean you know right. So, ideally if there is you know regardless of how bad the cables are I mean you are simply you know within codes isolated from each other.

The two ports are isolated correct. So, in principle whatever you push into port 1 should have no effect on port 2 and vice versa. So, ideally without the DUT, you must expect  $S_{12}$  is equal to  $S_{21}$  equal to 0. But in practice what happens is that there is always going to be some mechanism through which port 1 talks 2-port 2, it could be you know direct feed through right you know; so here is your, ok.

It turns out that there will be these two ports will talk to each other, no matter what ok. I mean this path ideally will be 0, but actually you know I remember that in the world nothing that supposed to be 0 will be 0 and nothing that supposed to be infinite will be infinite right.

So, here they are the  $S_{21}$  is supposed to be 0, in practice this  $S_{21}$  and  $S_{12}$  even without the DUT will be some small value ok. So, in other words what we have is basically another unknown 2-port ok. Between these two alright.

So, now you have you need to figure out and basically what you are measuring at ports 1 and 2 are, what you are measuring at ports 1 and 2 are? Are the DUT, but now you have you know something here, something here and some port between the input and all. So, this models you know a practical measurement scenario right, if you remove the DUT of

course, you know cable 1 and cable 2 will modify the what you what you are going to measure at the individual ports.

And the two ports will have will have finite isolation, will not have I mean ideally the isolation between the 2 ports must be infinity. In other words when you take the log of the  $S_{12}$  or  $S_{21}$  you used get you know negative infinity dB right. In practice you know again it depends on frequency at low frequencies of course, you know everything is isolated right.

But as frequency becomes higher and higher impedances become, capacitive impedance becomes smaller and you know between any two points there is some capacitance and at sufficiently high frequency, you know the impedance of the capacitance becomes keeps reducing. So, as frequency keeps increasing the isolation between you know two ports which are supposed to be nominally, which are supposed to be isolated will not be I say will not be infinite.

And you can model that as an unknown 2-port in alright. So, what do you think we should do to fix this problem now? Ok. So, there are you know many ways of doing this each with you know progressively what do you call increasing complexities.

You know one thing that he points out is that well the simplest thing to do is to say well, I will first calibrate these 2-port, find these 2-port right. But remember that finding I mean the what do you call if you terminate this part with open short and through.

And 50 ohms you are not only getting information with regard to these 2 ports, but also through this path because port 1 and port 2 are talking to each other. I mean, but that path is actually you know has hopefully a very small strength. So, you know the first cut approximation is say, oh well when I am calibrating port 1 I assume that this paths gain is so small that it does not affect calibration of port 1 right.

Similarly, with port 2 right. So, as soon as I calibrate you know I mean these two ports then I will remove the, I mean the DUT is still not there. And then I will measure the S matrix of the ports without the DUT correct. And that should give me, what is happening with this with the unknown port? Does make sense right, ok.

The more sophisticated way of saying this is of doing I mean clearly there is an error in this approach, in the sense that when you are calibrating the individual ports you assume that the other port is not in the picture at all, right that is you know clearly a problem right.

For most I mean for many low frequency applications of if several gigahertz this probably is ok right, but if I mean if you want to do a more thorough job basically, what you do is basically I mean remove the DUT and just like how we placed impedance standards what do you call to measure or calibrate a 1 port.

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Variable freq sine wave source

Unknown reciprocal two port  $\rightarrow$   $\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$

Impedance Standards: Short, Open, 50  $\Omega$

Obtain  $Z_{11}, Z_{12}, Z_{21}, Z_{22}$  as functions of frequency

$\Gamma_a \rightarrow$  Measured  $\Gamma$  with  $Z_{DUT} = 0$   
 $\Gamma_b \rightarrow$  Measured  $\Gamma$  with  $Z_{DUT} = \infty$   
 $\Gamma_c \rightarrow$  Measured  $\Gamma$  with  $Z_{DUT} = 50 \Omega$   
 $\Gamma_x \rightarrow$  Measured  $\Gamma$  with  $Z_{DUT}$

@ 36GHz

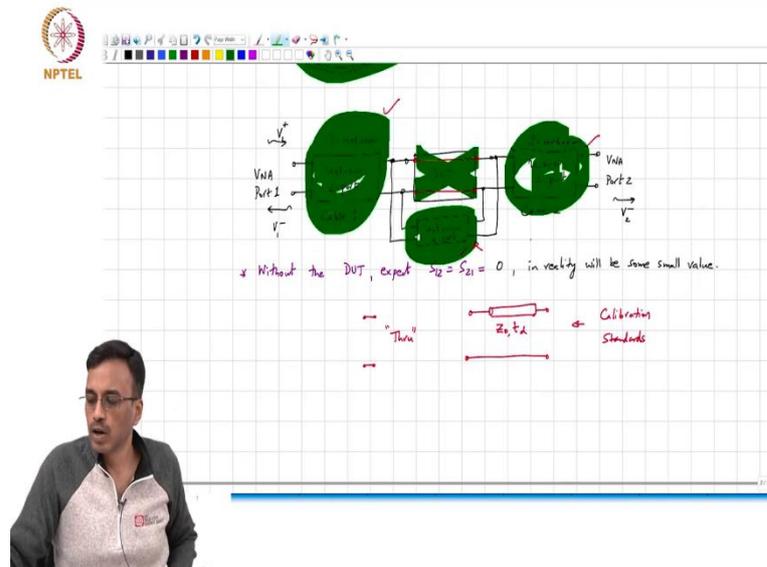
150 ps/ps

20  $\mu\text{m}$

You now have to have a 2-port standard as I mean, remember when we are calibrating a 1-port we said we needed these impedance standards to be able to estimate what that unknown 2-port is.

Now, we need a 2-port calibration standard and the standards that are typically used are basically what is called a through, which is bare which is something which is electrically very short.

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So, this is basically for all practical purposes, this is measuring the S parameters when you short these two ports right ok. So, then the I mean in other words the z DUT is simply replaced by a straight connection between the two ports ok. In other words, you can think of it as a transmission line with 0 length right.

And the other one is you know a 50-ohm transmission line. So, the this is called a through ok and the other one is a transmission line with a very well controlled characteristic impedance  $z_0$  and very well-known time delay  $t$  right. So, these are additional calibration standards needed ok so that the you eliminate the effect of the second of the unknown 2-port which basically exist between port 1 and port 2 right. So, you make all these measurements and then you put the DUT.

And since you know all these the rest of the you know this, you know this, you know this, you know this, you will be able to go and figure out what the 2-port parameters of the DUT are, alright.

And several you know several what do you call standards exist, I mean several I mean as you can imagine you know there are several calibration techniques with the increasing complexity. And therefore, accuracy as you keep going and they are all aimed at you know figuring out you know how to eliminate this unknown 2 port.

And you know the calibration standards and the quality of the through and so on all start to matter and these become very relevant only at you know very high frequencies. Again, the notion of high frequency is dependent on you know wavelength and the frequency of operation alright.

So, with this so this basically; so, over the last lecture and this we have covered the principles of vector network analysis, vector network analysis itself is you know is a is a huge area right.

And you know people still keep writing papers about calibrating a vector network analyzer. And of course, with time there is there is as you can imagine, there is there has been a lot of progress in you know the way this calibration is done.

Earlier you would have to you know physically go and you know connect the cable to the open the short the load and through. And you know as you can imagine people are not careful and then you know they to connect the end of the cable to an impedance standard you know some people would not tighten it all the way right.

Some people would over tighten it and all sorts of errors and then you know the in the calibration standards get spoiled. So, now, there is an electronic box which basically you know has switches inside and this computer control to basically go and go and change all that stuff, do all that stuff for you, alright. So, this vector network analyzer depending on the frequency of interest is you know is as I said a very expensive instrument.

And when I say very expensive, you know it can go to you know several crores without blinking an eye right. And you know this is obviously, a very specialized instrument which requires you know lot of attention to high frequency detail. Mechanical quality of build and so on and ok. So, with this, all that I had to say on about distributed circuits and you know the VNA is done.