Circuit Analysis for Analog Designers
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Lecture - 53
The one-port vector network analyzer

So, in the last class we were talking about the practical issue of you know how these s parameters are measured.

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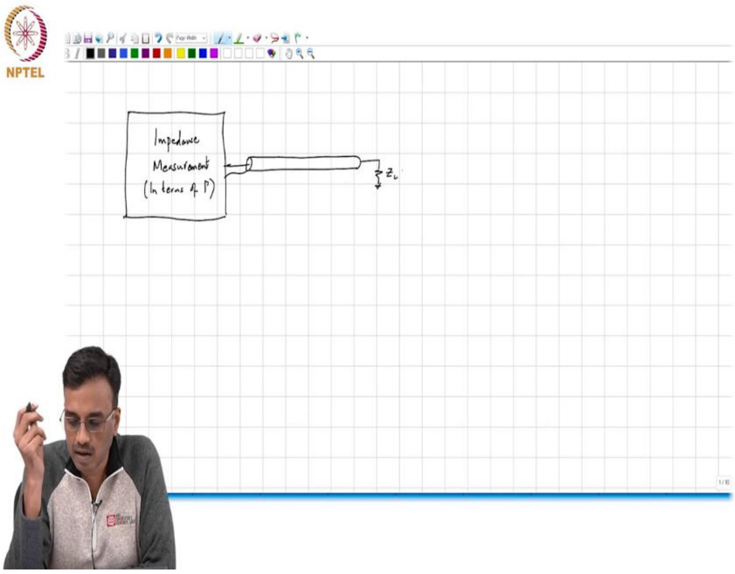

And you know the basic idea is simple we have some sort of cable connecting the measurement equipment, which is basically some box right. And so, basically an impedance measurement unit and what it does is in terms of the reflection coefficient gamma alright. And the transmission line I mean in our idealized analysis we have basically assumed that our transmission line is.

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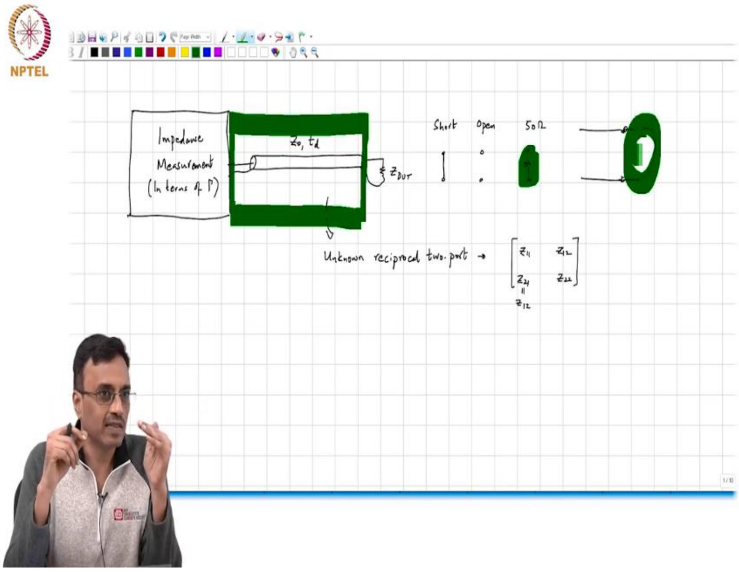

Is it is got some characteristic impedance Z naught and some delay td. And as we were discussing yesterday, the in I mean while in principle Z naught and td can be determined accurately in practice you know as you know users keep changing cables and you know what not. And therefore, we all that we can say is that we have an unknown reciprocal 2 port.

And therefore, there are if you think of its impedance or scattering matrix you basically you know you there are three unknowns namely Z 1, Z 1 2, Z 2 1 and Z 2 and Z 2 1 is known to be the same as Z 1 2. So, the three unknowns that, need to be determined.

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

And obviously, you know you cannot determine these three unknowns without 3 equations. So, the idea is before you put the Z DUT right you put a short circuit, you have an open circuit and you have you know 50 ohms which is a, which is a standard right. And which do you think I mean this; 50 ohms better be very accurate. Because remember that we are measuring reflection coefficient which is dimensionless and our final impedance of Z DUT has got dimensions of ohms.

So, somewhere along the line they must come in you know quantity with dimensions of ohms. If that is messed up then all your measurements will be off by whatever factor that that Z naught is imprecise by, does make sense right. So, if I mean you thought it is 50 ohms, but then you know like you do your home works you basically you know cut corners and then the 50 ohms is 54 ohms right.

Then all the measurements that you make will be off by 4 by 50 right I mean you know simply a scaling error right. Because Z naught will appear somewhere in all those calculations ok. And, so therefore and this notion of you know open and short also needs to be you know when you say a short you know.

Well, the short basically means that the electric field at that point is actually 0 right and open basically means the magnetic field at that you know you just cannot take two wires like this which has played open like this and say it is an open circuit right.

For example, so let us say I claim this is a short circuit I mean I have two wires which are spaced you know whatever 2 inches apart and then I connect these two and claim this is a short circuit. Can somebody comment on whether this is really a short circuit or not. Yes do it.

Yeah, ok yeah. So, basically right I mean as you can see you know if you go and you know connect this transmission line well you have a loop here. And any loop has got inductance, which is equivalent to saying that as frequency keeps increasing, I mean what you thought it is definitely a short circuit for DC. But as the frequency keeps increasing it is no longer a short circuit right.

So, a short circuit is simply not arbitrarily taking you know two points and connecting them with a with a wire it has to be engineered properly. So, that you know it is truly a short circuit. And there is obviously, some art to it is not straightforward right.

And likewise with an open circuit and likewise with the 50 ohms right. These 50 ohms at least you know must be 50 ohms across your frequency range of interest right. So, this box that you buy after paying a lot of money, basically will be designed and so will these three these are what are called impedance standards right.

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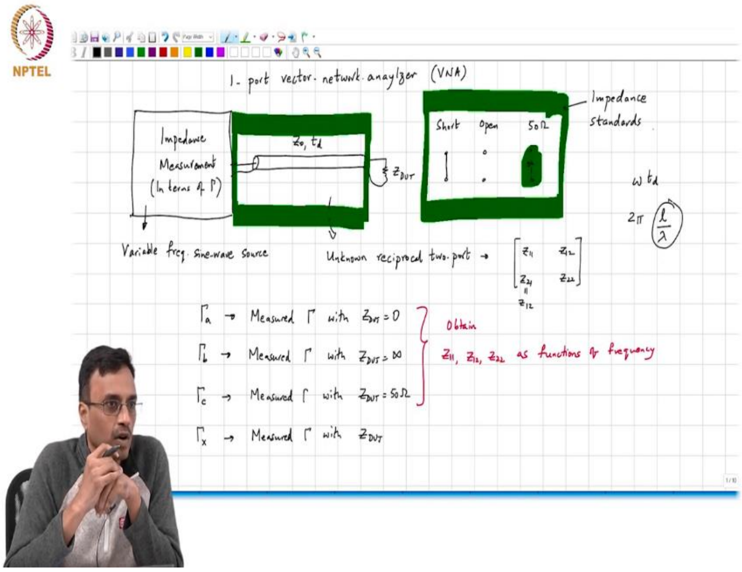

So, these will be very carefully machined and the material will be chosen. So, that you know over the ambient temperature range you know the 50 ohms remains 50 ohms at the open circuit and the short circuit remain, opens and shorts over the frequency range of interest.

You know as you know it is impossible to make an open circuit or a short circuit be open or short for an arbitrarily wide range of frequencies right. So, what when you buy a box like this you will also get you know a jewel case where you put these where the, it also comes with these impedance standards.

And when you make before you make a Z DUT measurement you will first. So, this impedance measurement box basically as we discussed yesterday, you know has got some way of separating the forward going wave from the backward going wave. And is able to therefore measure reflection coefficient as a function of frequency right.

And let us say you want to measure the impedance over a range of frequencies which is what you typically want to do right. Then you must measure the reflection coefficient over a range of frequencies correct. And what do you think you know you will have to what do you think is there inside that box? What all do you think you would need inside that box? To be able to make measurements over a range of frequencies pardon.

I cannot hear you. What is the frequency tuner? Yeah, you basically need a sinusoidal signal source you know whose frequency it can be varied from over the range in which you are interested in making the measurement right. And so, you have inside a variable frequency sine wave source right and so and once you are able to separate out the forward and the backward wave you know you can measure the phase of each of these relative to a standard.

For example, I mean remember that gamma is a complex quantity. So, it is got both magnitude and phase, so you want to be able to measure the phase of the reflected wave in relation to the phase of the incident wave. So, it is not merely enough to measure the power of the reflected wave you also need to measure its phase right. And so, there is some you know sophisticated electronics inside which you know enables you to do this to do this accurately right.

And you know and all this stuff is comes packaged with you know windows operating system and what do you call a nice GUI. So, that you can press button and then it does it does all the stuff that is needed for you. So, it will sweep the so when. So, the measurement process is as follows you turn on the box and then you know you wait for the operating system to boot up and you know after you are done then you connect the short circuit standard there across the cable right.

I mean the cable is there because you know this is a big box you know this size and then you know your impedance is some tiny thing somewhere there right. So, you connect the cable to that between the box and the device under test. But before you do that you must connect it to the short and then you press some button and then the box will basically sweep frequency over the range of interest and measure the reflection coefficient as a function of frequency right.

That is, you know let us call that gamma a, (Γ_a). So, measured gamma with Z DUT equal to 0 ok. Then you press another button you remove the short and then you have the measured and redo the whole thing with Z DUT equal to infinity, (Γ_b), gamma c, (Γ_c) is basically the measured gamma with Z DUT equals 50 ohms. And then gamma x, (Γ_x) which is measured gamma with the actual Z DUT ok.

And as we discussed yesterday the aim of these three experiments is yeah is to basically obtain Z 1, Z 1 2 and Z 22 as functions of frequency right. Once you obtain this these are the functions of frequency well it is a pretty much straightforward you know algebra to go and find. What the true reflection coefficient would be provided these two ports was not there alright. And that is basically you know basically what is done in right.

So, this is what this is a, this instrument is what is called a one port vector network analyzer are often abbreviated as VNA alright. And the VNA is basically what you call just like how you know, if you want to have an electronics lab you know you must have you must have a multimeter and an oscilloscope right.

If you want to do RF and microwave work you know you always want to have you know, VNA is basically as ubiquitous and necessary as a multimeter is or an oscilloscope is in for low frequency work at microwave frequencies at RF and microwave frequency.

And as we discussed yesterday the notion of what constitutes you know RF and what constitutes microwave is a function of this quantity omega times td right. And omega as you know is 2 pi f and td is nothing but, well the distance let us call it the length of the line divided by the velocity of light right and c by f is nothing, but c by f is lambda right.

So, basically this l by lambda is what constitutes. I mean there is nothing which is absolutely high frequency or nothing which is absolutely low frequency correct everything depends on the ratio of distance to two wavelengths right.

So, for example, you know if you are working on a single chip right where let us say your chip dimensions are you know half a millimeter by half a millimeter ok and you are working at 3 gigahertz. Can you comment on whether the circuit is you know can be treated as lumped or you know or can be treated.

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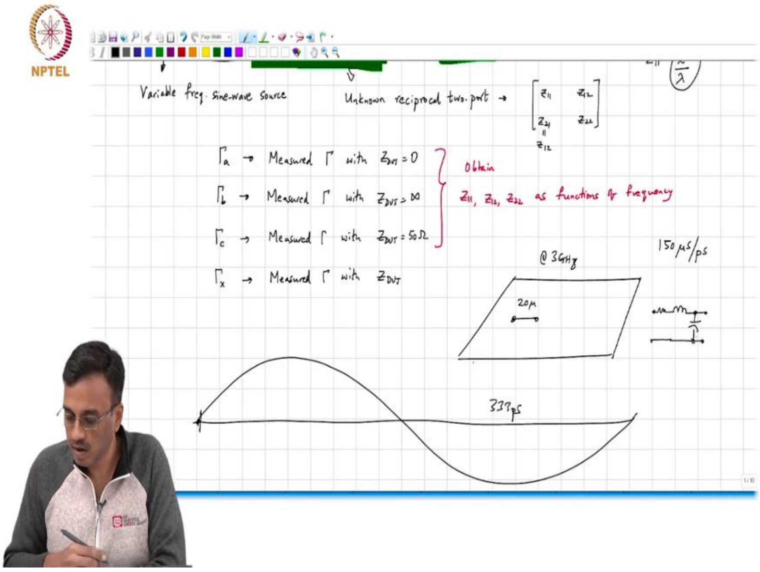

For instance, let us say I have a line which is 20 microns long on a silicon substrate right ok. And the frequency evaporation the maximum frequency evaporation is 3 gigahertz, can we comment on whether this constitutes I mean do we need to use distributed circuit theory or you know we are good enough working with lump circuits.

You have a piece of wire how do you know represent it what would you do. Yes, Ajay Kumar Reddy what do you think? What is the wavelength? Again, if you guys got to get used to the notion that speed of light is 3 into 10 power 8 meters per second only in free space right. On silicon it will be a factor of I mean the dielectric constant of silicon dioxide is roughly about 4, right.

So, it is basically a factor of 2 smaller. So, a good number to remember is that on silicon the speed of light I mean again this 3 into 10 power 4 meters per second right is a number that only makes sense when you know you are dealing with right the sun is you know. So, many billion miles away from the earth ok.

And then 3 into 10 power 8 meters per second you know makes sense you can calculate the sunlight takes 8 minutes to come from you know the sun to earth right. On an IC you are not dealing with seconds you are dealing not dealing with minutes you are not dealing with seconds you are dealing with you know microns and picoseconds. So, it is always you know much easier to express the speed of light in microns per Pico second.

So, 150 microns per Pico second is the speed of light on silicon in free space it is 300 microns per Pico second right. So, if you have a millimeter on silicon is about 6 picoseconds right 6 to 7 picoseconds anyway. So, 20 microns is how many picoseconds? How long will light take to traverse 20 microns? Yes Karthi, what do you think?

Ok right. Something like less than a 10th of I mean about a 10th of a Pico second right. So, and how you know how does it. So, how does that a 10th of a Pico second correspond how does it compare with the frequency evaporation. Let us assume we are working at 3 gigahertz right what is the period corresponding to 3 gigahertz is 330 odd picoseconds right.

So, basically you know the sine wave basically if this is 330 picoseconds right and the what do you call this is a 10th of a less than a 10th of a Pico second right. So, this j omega t d therefore, is you know. So, small that for all practical purposes, you can treat a 20 micro micron wire right if you are working at 3 gigahertz. You can treat it as a lumped element and what kind of lumped element would that be ok. Resistor is you know true at DC if you go slightly at higher frequencies what all you need to do.

So, basically you know you basically treat it as you can treat it as perhaps an LC network many times the l will be so small that l can also be neglected right depending on the rest of the circuit in which this lumped piece of element of metal is embedded right. So, most often times in IC work for example, if you are working at the low gigahertz range you will be you know your layout extraction tools are quite happy modelling a wire as a combination of resistance and capacitors right.

If you have a very long wire, you break it up into small wires and then alright. So, on an IC for example, that matter I mean for example, therefore, you know the absolute frequency 3 gigahertz is of no fundamental consequence right. You know it is as easy or as difficult as you know assembling things on a breadboard right, at a much lower frequency. Because on a breadboard all physical distances are larger or smaller, are much larger and what do you call. Therefore, you know what constitutes a high frequency on a breadboard is in absolute numbers much smaller than much lower than what constitutes high frequency on an IC chip right and those of you taken you know power systems course right what are the frequency evaporation what is the frequency evaporation.

It is 50 hertz right, but now you have a transmission line running from I do not know I mean from you know from Timbuktu to Tamil Nadu right. So, basically these lines are so long right. That there again even though the frequency is 50 hertz and you might think what is 50 hertz is DC right ok.

But the point is not whether 50 hertz is large or small right it is all to do with the physical distance over which you are working in relation to the wavelength of operation right. So, you know 10000 miles of transmission line working at 50 hertz right. Distributed effects become you know just as important and you know crucial as what you call working at 3 gigahertz on, I mean at say 3 gigahertz on a bench top table right.

Whereas the same 3 gigahertz count like you know I mean you do not worry about distributed effects if you are working with 3 gigahertz on a chip does not make sense alright. So, this is an example as I was mentioning this is a, an example of what is called a one port vector network analyzer lets kind of.

The one port that makes sense simply because you are only measuring you know, the impedance of a one port network. And of course, it measures it analyzes a network, so it is a network analyzer why is it called a why do you think it is called a vector network analyzer. And if it is not vector, what would it be? If something is not a vector, what is it.

Ok well. So, there must have been something called a scalar network analyzer before the vector network analyzer right. So, why do you think you have a vector network analyzer yeah. So, basically it is called a vector network analyzer because it measures both the magnitude and phase of the reflection coefficient. So, you know it is it has only become possible to do this over the last maybe 30-40 years or. So, I mean or 50 years right before that they used to have what were called scalar network analyzers which only measured the magnitude and then you know you have to basically you know do something a lot more. I mean involved to be able to infer the phase you know making additional measurements and so on.

Because earlier it you would only be able to measure power right. You not now you have sophisticated electronics which basically is also able to measure the phase in addition to the magnitude. And so, this is why these are called a one port why is this these are called vector network analysis the next thing is a well you know.