CMOS RF Integrated Circuits
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Module - 01
Introduction
Lecture - 02
Transmission Media and Reflection

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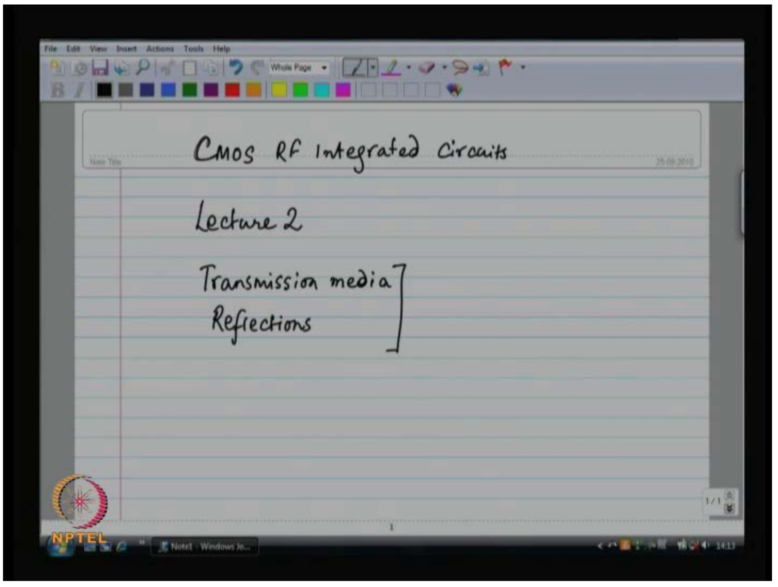

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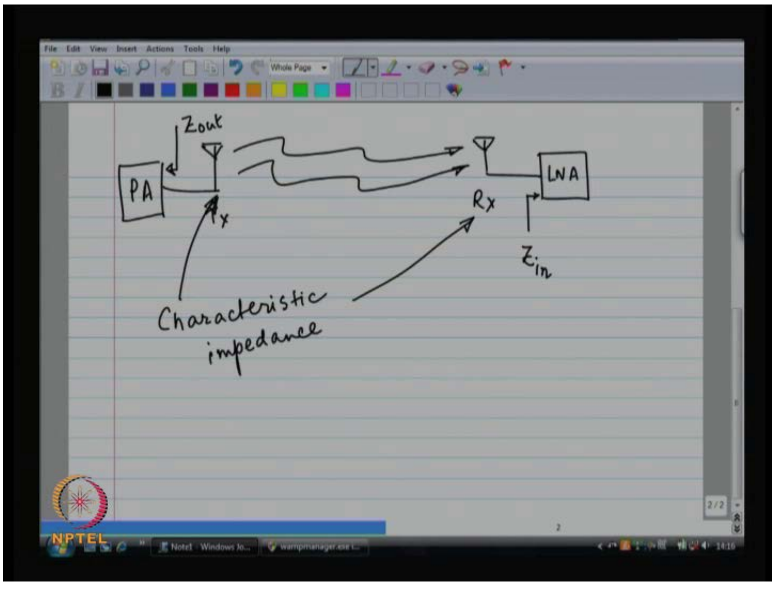

Hello everybody. We are now going to start our second lecture on CMOS RF integrated circuits. And, the lecture is going to briefly cover transmission media and reflections. So, these are the two topics that I am going to try to cover in this particular lecture.

And, in the last lecture, what we were talking about was how there is going to be a transmitter and there is going to be a receiver. At the end of the transmitter, you have a power amplifier – in short, PA. And, at the beginning of the receiver, there is the low noise amplifier – LNA. So, these two are going to be topics of interest. And, we will be designing these two in the subsequent part of this course. But, what we were talking about in the last class was that, between the transmitter and the receiver, the signal is broadcast over the atmosphere.

Now, the transmitter antenna has certain characteristic impedance. So, we are going to talk about this today. What does this mean? So as the receive antenna; it has certain characteristic impedance. The wire connecting the transmit antenna to the power amplifier has certain characteristic impedance; the wire connecting the receive antenna to the low noise amplifier also has certain characteristic impedance. And, the low noise amplifier has certain input impedance; the power amplifier has certain output impedance.

Now, I do not know if you can guess this; but, the reason why we are talking all these is that, all of these need to be equal or more or less equal at the chosen frequency. So, at the chosen frequency, Z out has to be more or less equal to the characteristic impedance of the transmit antenna. At the chosen frequency, the characteristic impedance of the receive antenna should be equal to the input impedance of the low noise amplifier. So, we are going to see why. So, first of all, I am going to jump a little bit ahead of this course and we will discuss this topic later on in much more detail. But, I am going to jump a little bit now, because I want to present to you the reason as to why I am talking about this right now. So, it is like this.

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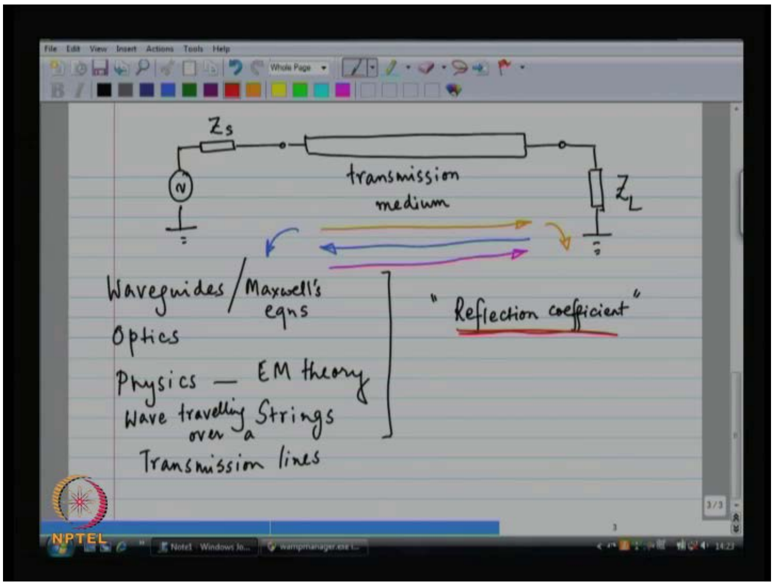

If I have a source… And, always remember that, a source is inseparable from its source resistance; or, rather let us not call it source resistance; let us call it source impedance. It is likely that, this is going to be resistance, but let us not think about it. So, there is a source; source is inseparable from a source resistance or the source impedance. And, I want to transmit something over a medium.

Now, this medium could be air; this medium could be a wire; it could be a coaxial cable; it could be a waveguide; it could be an optic fiber; it could be anything; all right? So, this transmission medium really could be anything. And, on the other side, I plan to receive whatever was transmitted across a load impedance Z L. So, this is the situation; I have a source, which is inseparable from a source impedance; I want to transmit a message across a certain medium all the way to a load impedance; and, in between, there is this transmission medium.

This transmission medium could be a wire; it could be air; it could be an antenna; it could be anything; all right. Now, in such a scenario, what happens is if you have studied waveguides… I do not know if you have studied. If you have studied waveguides or if you have studied optics or if you have studied physics well enough either EM theory or theory, which deals with strings and waves. So, this is not string theory; it is a wave traveling over a string. So, if you have studied any of these or if you have studied transmission lines; so, all of these theories are very similar to each other – all of these theories. And, they all define something that is called a reflection coefficient; all right. So, with this background, I am going to frame the sentence.

The sentence is like this – I am going to launch a wave from the source over a transmission medium and receive this wave over the load. So, I am going to launch the wave over the transmission medium. What is going to happen is when I launch the wave over the transmission medium, the wave propagates over the transmission medium all the way to the receiver. When it hits the receiver; a portion of this wave gets absorbed in the receiver; a portion of the wave is reflected back.

And then, the portion that is reflected back comes all the way back to the source. And now, it hits the source impedance Z S. And, when it hits the source impedance, a portion of this wave gets absorbed by the source impedance and a portion of it gets reflected back even further and so on and so forth. So, these reflections rather echoes; these echoes keep going back and forth, back and forth, back and forth till the sound produced by the echo is very small compared to what has already gone through.

So, this is the basic idea. And, I hope you have followed the way I have framed my sentences. So, a wave has been launched; part of the wave, part of the energy in the wave, is absorbed by the load; part of it is reflected back. Again, it hits the source; part of it is absorbed by the source; part of it is reflected back further. Now, as you can guess, this reflection coefficient that I mentioned earlier is the ratio of what reflects back from the load to what had hit the load to start with.

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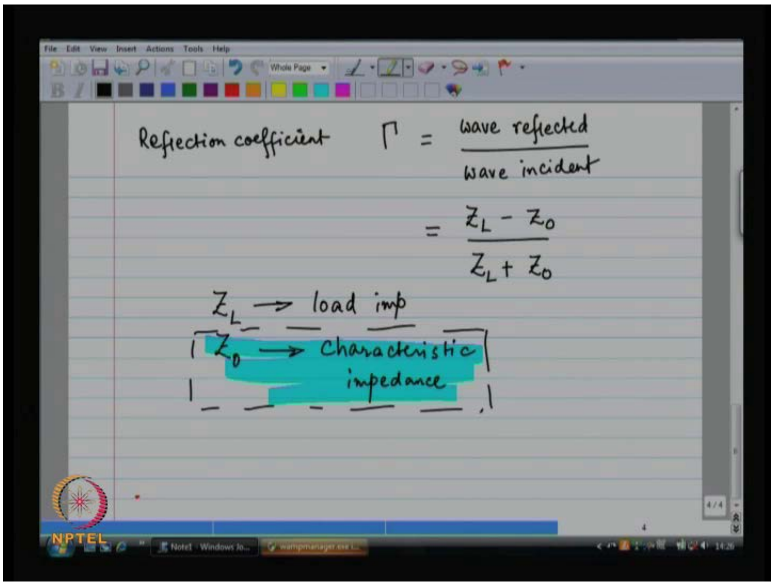

So, the reflection coefficient also called… The symbol for reflection coefficient is gamma. Gamma is the ratio of the wave that gets reflected back to the wave that was incident. And of course, the amount of reflection happening at the load could be different from the amount of reflection happening at the source; it all depends on how heavy or how light the source is. So, these are two different walls.

So, if one wall is more absorbing than the other, then the amount of reflections from the two walls are going to be different. So, you can relate this to sounds and echoes and so on. So, these are like two walls. The two ends of the transmission medium are the two walls; all right. Now, it so happens… This is where I am just going to grab something from future of this course and utilize it right here.

It so happens that, this gamma is going to be equal to Z L minus Z naught by Z L plus Z naught. Here Z L of course, is the load impedance; Z naught is the characteristic impedance of the transmission medium. So, this word came up earlier. So, every transmission medium has the characteristic impedance whether it is a wire, whether it is the atmosphere, whether it is an optic fiber; whatever it is, it has a characteristic impedance. As long as it is transmitting an electromagnetic wave, it has the characteristics impedance.

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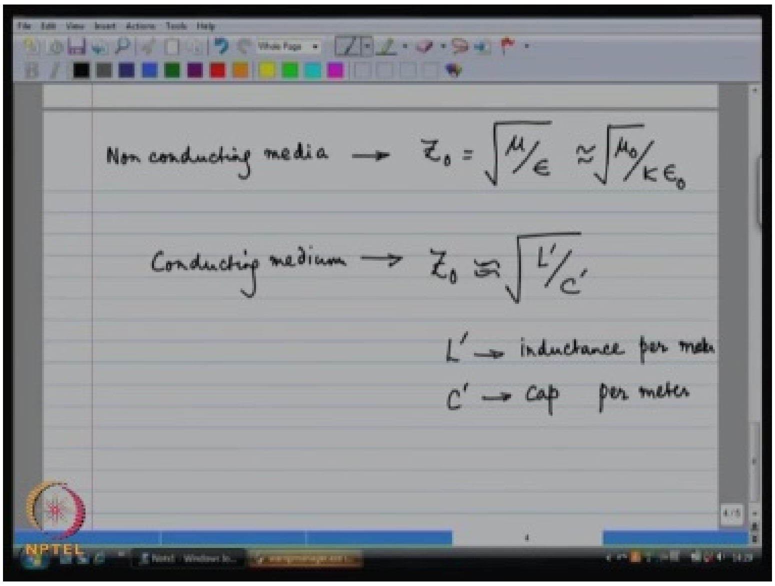

It turns out that if it is a non-conducting medium like the atmosphere, it does not conduct current, charge. Then, the characteristic impedance is square root of mu by epsilon; mu is the permeability; epsilon is the dielectric constant. So, mu is… For typical medium, mu is going to be equal to mu naught unless it is iron or something. And, epsilon is basically the dielectric constant times epsilon naught. So, this is typically what the characteristic impedance is going to be if it is a non-conducting transmission medium. If it is a conducting medium, it is something like this; where, L prime is the inductance per unit length; C prime is the capacitance per unit length of the wire. So, I am talking now about a wire. And, it is something like this.

Now, this formally looks similar under all of these different theories, waveguides, optics, strings, waves traveling over a string. You will get the similar expressions – very similar looking expressions; they might be ((Refer Slide Time: 16:18)) different for mechanical vibrations traveling over strings. For example, it is going to be related to the Young's modulus and mass per unit length, etcetera. So, we do not want to discuss all that right now. The formulation remains very similar in nature, no matter what it is. So, this is the characteristic impedance; and, this is the reflection coefficient. Now, what? So, suppose I know the characteristic impedance; suppose I know the reflection coefficient; so, what?

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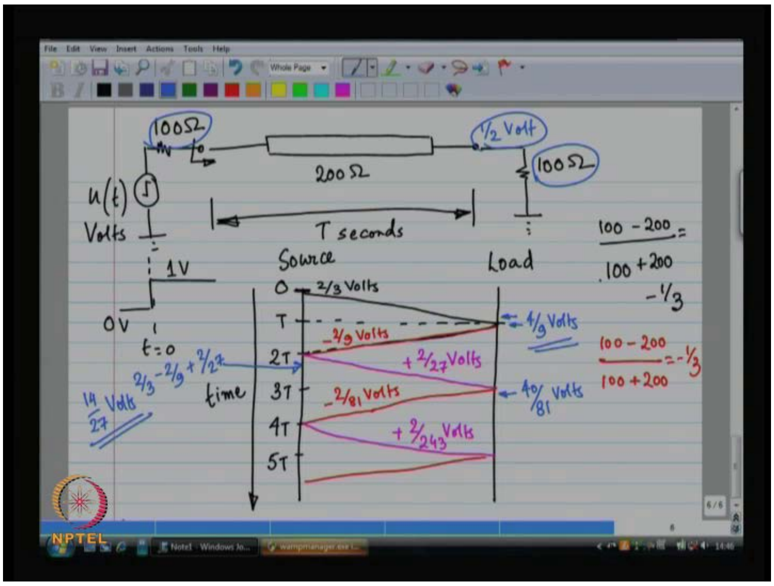

So, this is how it works. Let us say that, I apply a pulse. And, let us say the Z source – the source impedance is let us say 100 ohms. And, I have a transmission medium with the characteristic impedance of let us say 200 ohms. And, let us say the load is 200 ohms. So, this is how it is. And, let us say the distance that the wave has to travel… The wave travel at the speed of light.

So, let us say that the distance that the wave has to travel can be covered in a time capital T – 1 second. It is quite a large distance. If it is 1 second, then it is 3 into 10 power 8 meters. It is a very large distance, but this is just for ease in our calculations or understanding. So, you can choose your time over here. Forget 1 second; let us say it is T seconds. Let us say over here at the input, I apply a wave that looks like u of t volts. I will try to launch a wave of this shape. At time t equal to 0, I want 1 volt. Before time t equal to 0, I want 0 volts. So, this is the wave that I want to launch. And, I am hoping that, a wave of a very similar nature is received at the receiver. So, what is going to happen?

Now, information travels at the speed of light. When you launch the wave over the transmission medium; at that particular instant, the medium does not know or rather the wave does not know what is on the other side of the medium. So, what it is going to see right over here it is going to think that, the medium is an impedance of 200 ohms. So, it is definitely not 200 in series with 200.

Once again I repeat from last class, the characteristic impedance is not to be confused with resistors or impedances and so on. This is not real impedance; this is not real impedance; this is just a number, which has units of ohms. It is just a number, which has units of ohms. As you see, it is probably coming from a formula like this or like mu naught by… mu by epsilon square root or square root of L prime by C prime. One of these formulae is leading to the characteristic impedance. So, we have launched this wave. And, this wave does not know what is coming on the other side of the transmission medium.

To the wave, the transmission medium appears to be an impedance of 200 ohms. So, this is how we do this computation. We put a bar for the source; one side for the load. And, we divide it into… We plot the waveforms as a function of time and distance. So, this wave from 0 to 1 volt is launched initially at the source. The source resistance is 100 ohms; the medium looks like a resistor of 200 ohms.

Therefore, there is going to be voltage division. And, the effective wave that is going to be launched is something which has a value of 2 by 3 volts. And, this 2 by 3 volts is going to reach the load at the time T. At time T, 2 by 3 volt is going to reach the load. And then, when it hits the load, the load is going to reflect something back and absorbs something. How do we compute what it reflects back and what it absorbs? From the reflection coefficient.

So, the reflection coefficient at the load for us… Remember what the reflection coefficient is. It is Z L minus Z naught by Z L plus Z naught. And, this happens to be equal to 200 minus 200 divided by 200 plus 200; which is equal to 0; fantastic. So, nothing reflects back from the load; the entire voltage waveform is absorbed. And, if nothing reflects back from the load, we do not have to worry about subsequent reflections and so on. So, the load looks like a black object. Whatever you transmit, it absorbs it; fantastic.

What if the load is not 200 ohms? What if the load is 100 ohms? If the load is going to be 100 ohms, then I need to modify the computation of the reflection coefficient 100 minus 200 by 100 plus 200. And, that is going to give me minus 1 by 3. Do not be surprised with negative numbers. So, what is going to happen is 2 by 3 volts – this wave is going to hit the load; and, minus 1 by 3 is going to be reflected back from the load. So, a wave – a value minus 1 by 3 is reflected back from the load.

Now, this minus 1 by 3 volts – this wave was reflected back from the load; it hits the source at time 2t. And, at the source, part of it is going to be absorbed by the source resistance; part of it is going to be reflected back. What is going to be reflected back? We have to compute the reflection coefficient at the source. Now, at the source, the reflection coefficient has the same formula. So, it is 100; that is, the resistance minus the characteristic impedance by 100 plus 200. So, it is the same value. And, as a result… I made a mistake; I made a mistake. So, minus 1 by 3 is not what got reflected back. So, one-third of two-third got reflected back.

So, minus 2 by 9 is what got reflected back. Now, when that hits the source, a further one-third minus one-third is reflected. And, what is going to reflect from the source is plus 2 by 27 volts. That goes and hits the load. And, again there is a reflection from the load. What reflects from the load is minus 2 by 81 volts. Subsequently, there is another reflection from the source and so on and so forth. So, this is kind of how we do the computation. This is the way we find out what are these waves going back and forth.

Now, to find out the voltage at a given time at a given location, you have to sum all of these voltage waves. You have to sum, you have to add all of these voltage waves; all right. So, at a given time; let us say at time T, if I observe the load at a time T minus a little bit; if I observe the load, I get nothing. So, at this point of time, at the load, the voltage is 0 volts. Right after the voltage waveform has reached and the reflection has taken place, the voltage at the load is going to be two-third minus 2 by 9. I sum all the waves.

So, the voltage wave that has reached plus the voltage wave that has reflected, and that gives me 4 by 9 volts, now, similarly, on the source side, I had 2 by 3 volts at time t equal to 0; at time t equal to 2T, I would have 2 by 3 minus 2 by 9 plus 2 by 27 – whatever that value is. I do not know; it is too difficult for me to… May be not, so it is 18 minus 6 plus 2, so 14 by 27 volts, this is the value at the source side right after 2T.

And, right after 3T, the voltage on the load side is going to be 2 by 3 minus 2 by 9 plus 2 by 27 minus 2 by 81. So, it is 14 by 27 minus 2 by 81; that is, 40 by 81 volts; all right? What you can show is that, as time progresses to infinity, the voltage at the load is going to be equal to the voltage at the source; and, it is going to be equal to half. It is a resistive divider – 100 ohms, 100 ohms; I have a wire in between; you expect a voltage of half a volt over here. That is what you expect.

That is what you are going to get after a long time. So, if the transit time is important to you, then this half – the voltage half does not really show up instantaneously, it shows up after a few transit times. If the transit time is not important to you; if you are talking about a DC signal for example; or, if you apply the voltage today, measure the voltage tomorrow; transit time is of no sequence to you; then, you will see half right away. So, this is basically the way we work with a transmission medium or a transmission line.

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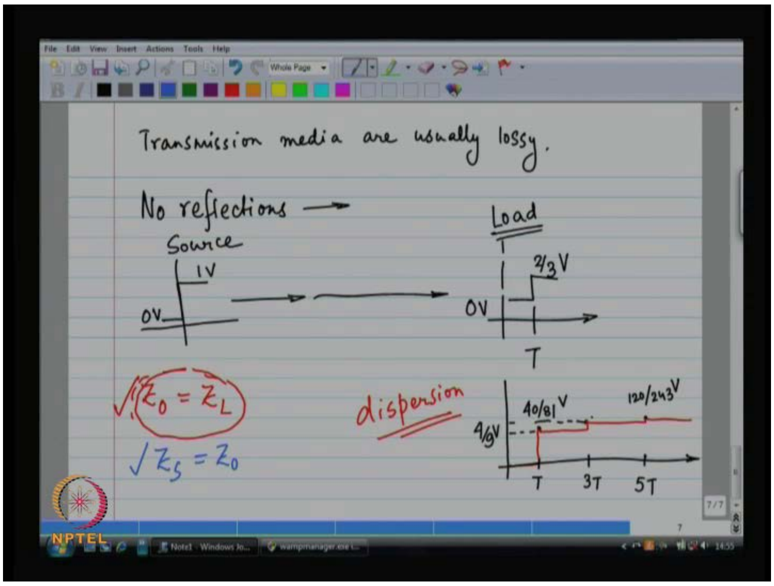

In addition to this, what we have ignored over here is the fact that, transmission media are usually lossy. That is something we have not incorporated in our calculations. We somehow have assumed arbitrarily; and, I assume this without even telling you. We have assumed that, the transmission medium does not attenuate the wave that it is transmitting – the power in the wave. So, I am kind of assuming that, the wire itself does not have resistance. I am assuming that, all the power that you transmit is eventually being received by the receiver. It is not a fair assumption; but, for the sake of this calculation, I had made this assumption.

So, in addition to this, you have to incorporate the fact that, the wave itself – the one that is launched – that wave itself is also attenuated while traveling over the transmission medium. It is natural. I am sitting here; you are sitting there; I can hear myself full blast; you can hear me at a much lesser volume as long as you are sitting far away from me. So, this happens naturally over all transmission media whether it is a wire, whether it is the atmosphere, whether it is a coaxial cable, whether it is waveguide, optic fiber, whatever it is; there is loss. Now, this loss was not modeled in this. You can easily model this loss. If you know how many dB of loss you are having per meter, per kilometer, then it is just a simple addition on top of this.

The other thing that changes when you incorporate loss is the fact that, this parameter Z naught no longer remains a real number. It could very well easily be a complex number. Z L, Z S – these could also be complex numbers; in which case, gamma itself is a complex number; in which case, all of these reflections that we did in the time domain – they become much harder to do, because when the reflection coefficient is a complex number, then what you have to do is you have to break up what you had transmitted; you have to break up the waves in terms of sinusoids; and then, when it is reflected, you add a phase; you multiply it by the reflection coefficient; you add the phase delay of the reflection coefficient, etcetera. And then, you sum up all these waves and you end up with the bigness. Usually, we leave all these for the simulators to do, but you can do simple computations by hand nevertheless.

Now, what else is important over here? Something very important we observed in the very first half example. The fact that when I had the load resistance equal to the characteristic impedance, no reflections took place; and, when no reflections took place, if I transmit a pulse; when there are no reflections, if I transmit a pulse on the source side and it travels over the medium, then all that I am going to receive is a delayed pulse. So, I transmitted the pulse; I got two-third volts; that wave traveled all the wave to the load;

and then, from the load, nothing reflected back. So, at time T, I received two-third volts over here. What you see is that, the shape of the waveform is conserved. This is very important to us that, the shape of the waveform I transmitted a pulse; I got a pulse; it is delayed; it is attenuated. But, I still got a pulse. I did not get a sine wave.

When the load resistance is not matched to the characteristic impedance of the wire, then what have I got? The example that I did… So, at time capital T, I got 4 by 9 volts; at time 3T, I got 40 by 81 volts; and, at time 5T, I did not compute; I probably got 121 by 243 volts; no, 120 by 243 volts. So, the waveform that I received looks somewhat like this. So, I transmitted a pulse; I hope that I would receive a pulse; instead I got an approximation to a pulse. I did not quite get a pulse anymore.

This phenomenon is called dispersion. The fact that I got an approximation to a pulse – no longer a pulse; this is called dispersion. And, this was because the load resistance was not matched to the characteristic impedance of the transmission medium. So, this is not something that is nice. We want the load to be matched to the characteristic impedance of the medium. That is when we get to conserve the shape of the waveform that was transmitted.

Now something else happens when you manage to do so; that is… So, this is something that we like. Now, suppose by some quirk of fate, Z naught is not exactly equal to Z L; I mean you tried your best and you designed Z L; you tried your best to match it to Z naught; but, it is not exactly equal. Then, what do you do? Do you have any other choices? Yes, the next thing that you have to do is to try to make sure that, the reflection at the source is also very small.

So, if it is in your hand; if it is in your hand; it might not be in your hand; but, if it is; then, you can probably work on Z S and try to make sure that, Z S is as close to Z naught as possible. That is going to further minimize reflections from the source side. So, that is the second tear of what you can do. So, first, we would like to have this. Then, we would also like Z S to be equal to Z naught. So, this is also something good; not the most important, the second most important; all right?

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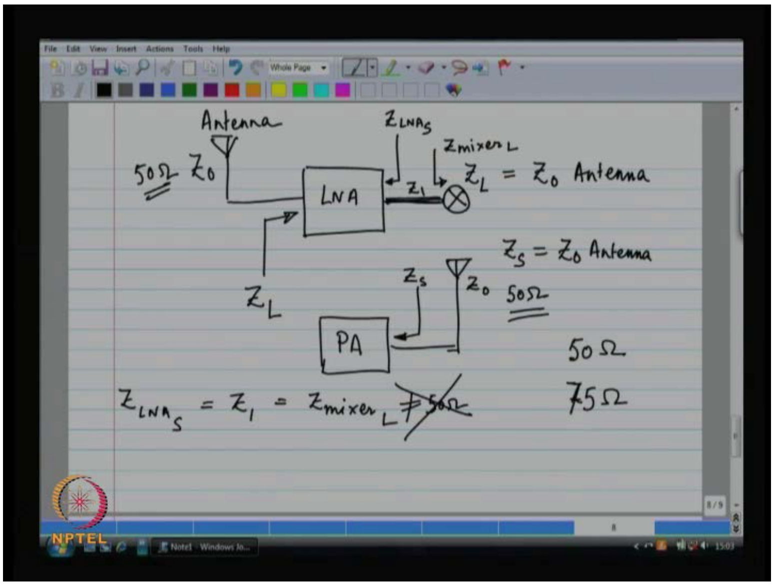

So, what does this mean for us? If I am making a receiver, this is the antenna and this is the low noise amplifier. If I am making this receiver, then what this means for us is that, the characteristic impedance of the antenna has to be the same as the input impedance of the low noise amplifier. We would like this to happen, so that you can conserve the shape of the waveform that you receive.

So, you are talking on the cell phone; someone else is listening on the cell phone; and, the shape – the precise shape of the waveform that is transmitted needs to be receive; otherwise, you have got dispersion. You do not get a faithful representation of what was transmitted. So, you would like Z L to be equal to Z naught of the antenna. So, this is something important for us when we are designing our system. When we designing our system, let us say we are making the transmitter and I am designing the power amplifier; that transmits, that pumps out power through an antenna.

Then, once again the source resistance – now you have control over the source resistance; you would like Z S of the power amplifier; you can model the power amplifier as a Thevenin equivalent voltage source in series with a source resistance. So, that source resistance is what I am talking about – source impedance. You would like to design Z S to be equal to the antenna characteristic impedance; all right? So, this is something very important for us.

What else? Suppose you have made the low noise amplifier; the next block is the mixer. And, between the low noise amplifier and the mixer, there has got to be a wire. What would you want to do? You would want to make sure that, the output impedance of the low noise amplifier is equal to the characteristic impedance of the wire, which is equal to the input impedance of the mixer.

So, this is something that you would like to have, because if you do not have this, then there are going to be reflections going on back and forth between the low noise amplifier and the mixer. So, a typical number that you will hear about from many different people; or, if you have visited the market, you would here about them; a typical number for the characteristic impedance is 50 ohms; and, another typical number for characteristic impedance is 75 ohms. So, these two typical numbers are used for different applications; 75 ohms is used for cable TV, for all kinds of television systems.

Whereas, 50 ohms is used for all kinds of other applications not related to cable TV and television. So, 50 ohms is used everywhere else. 50 ohms is by far the standard number that is used. Where this has come from is it is a very strange and not very clear root way 50 ohms has come from, evolved. So, it turns out that, air as a medium, the atmosphere as a medium, has a maximum power handling capacity at a given characteristic impedance.

And, it has a minimum loss at another given characteristic impedance. So, there exists a characteristic impedance at which air has maximum power handling capacity. There exists another characteristic impedance at which air has the lowest loss. So, an optimization between these two has led to this number – 50 ohms; it is not very… I know I am not being very clear over here; but, hopefully, as the course progresses, we will be able to find out more about these numbers. So, typically, one would design the antenna to be a 50 ohm antenna.

So, the Z naught of the antenna is probably going to be equal to 50 ohms. This means that, the output impedance of the power amplifier has to be matched to 50 ohms. This means that, the input impedance of the low noise amplifier also has to be matched to 50 ohms. This does not mean that, the output impedance of the low noise amplifier and the input impedance of the mixer have to be 50 ohms; it does not mean any such thing. So, this is not true.

You can choose your own characteristic impedance of the transmission line in between the low noise amplifier and the mixer. And accordingly, you figure out and decide what needs to be the output impedance of the low noise amplifier; what needs to be the input impedance of the mixer. So, do not confuse 50… do not bring it inside the IC. 50 ohms is a standard; it is used whenever you have two discrete integrated circuits. Typically, 50 ohms is going to be the standard.

So, suppose you want to put together an LNA and a mixer and an antenna; you buy an off-the-shelf antenna, you buy an off-the-shelf mixer, you buy an off-the-shelf LNA. Typically, all of the input impedances, all of the output impedances of all of the different parts will be 50 ohms. But, if you are making this on an IC, then there is no such golden number called 50 ohms; you decide what needs to be the characteristic impedance; and accordingly, you choose the number. It so happens that 50 ohms is used because the cables that are used to connect these different components transmission lines.

These transmission lines have characteristic impedances of 50 ohms. 75 ohms is the standard that is used for all cable television. So, you go to the market and you want to buy some cables; make sure that what you buy; if you are buying for you lab, make sure that what you are buying is of 50 ohm cable and not 75, because 75 is widely available, very widely available; all right.

So, with this, I am going to start summarizing what we have done in this class. We went about with our… Our objective was to study transmission media and to study reflections. And, we understand that, any transmission medium – whatever it is – an optic fiber, the atmosphere, an antenna, a waveguide, a coaxial cable, a piece of wire – whatever it is, it has a characteristic impedance. Now, this word – characteristic impedance is not to be confused with resistance or impedance.

Characteristic impedance is a number, which has a units of ohms and it is characteristic to a certain cable; that is it. It is not the input impedance seen when you look into the cable. Now, there is also this business of the reflection coefficient; if you transmit something and it hits a wall, part of what you transmitted is going to be absorbed by the wall; part of it is going to be reflected by the wall. The ratio of what gets reflected to what was transmitted is the reflection coefficient. Now, this reflection coefficient may or may not be a real number; it could be a complex number. So, beware over there.

So, typical formulation for refection coefficient is Z L minus Z naught by Z L plus Z naught; Z L is the load impedance; Z naught is the characteristic impedance. As you see, all of these are impedances. And, the result may or may not be a real number. Then, as far as… When we talk about atmosphere as a transmission medium, Z naught happens to be equal to the square root of mu by epsilon; if you have a conducting medium such as a wire, then Z naught happens to be equal to L prime by C prime. L prime is defined as the inductance per unit length; C prime is the capacitance per unit length.

These formulations are very similar. The big catch over here is that, I am assuming that, there is no loss. So, whatever you are transmitting is being received by the receiver; all the energy is actually going through. If it does not, then you add more complex terms for Z naught and it no longer looks exactly like L prime by C prime. It actually becomes R prime plus j omega L prime by G prime plus j omega C prime. This is actually the correct formula accounting for all the losses, etcetera; does not matter for us. We can incorporate the losses by assuming a certain number of DB degradation as the wave progresses over the medium.

We did a quick example of how the wave progresses over the transmission medium. So, you will launch a wave; portion of it actually makes its way over the transmission medium; part of it hits; this wave hits the load; part of it reflects back; what reflects back hits the source. Again, it reflects; what reflects hits the load again. Again part of it reflects back. So, it is like echoes. To say something, it echoes back from the wall; then it echoes from this wall; then, again it goes there, keeps going back and forth. And, we did some quick calculations.

And, we saw that, these echoes are really no good; we do not like echoes. We would like to see the same shape of the waveform being conserved. And, that can be achieved when the characteristic impedance is equal to the load impedance. So, this is the golden condition that you want. Load impedance equal to the characteristic impedance. This is when there are no echoes. When there are echoes, these echoes kind of approximate what you transmitted. And, this phenomenon is called dispersion. So, with this, I am going to summarize today’s lectures.

Thank you.