CMOS RF Integrated Circuit

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Module -03
Passive IC Components
Lecture - 09
Inductors and Wires

Welcome to CMOS RF integrated circuit this is the ninth lecture; we are now in model 3 we were discussing passive components. So, in the last class we were talking about inductors. So, we started from the infinity long solenoid and we did you saw the result what is the inductions of the solenoid?

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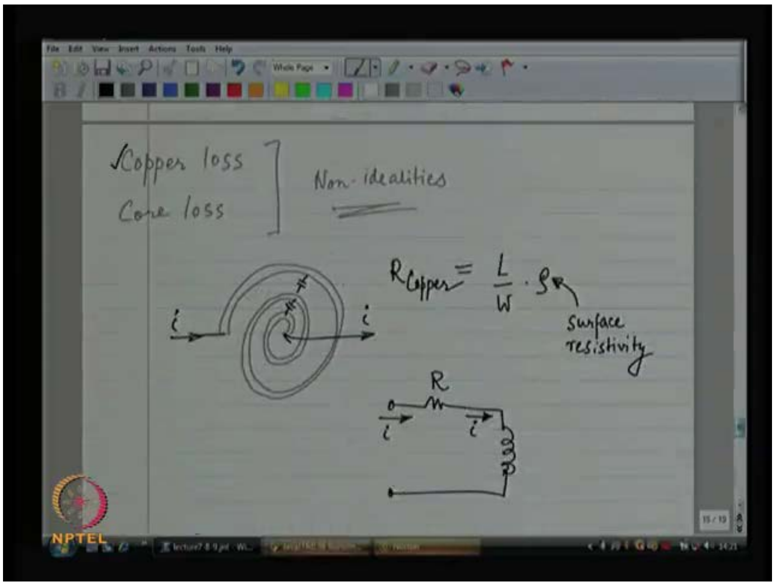

Then, we said that has usual we cannot really make a solenoid IC and we compressed the solenoid like a spring. So, consider along spring and you compressed it into one or one surface right; you compressed the entire thing into one surface, you are going to get something which looks like a spiral. So, this is what you go into get. So, you compressed the whole solenoid which looks like spring into a spiral on one surface. And, like the kind of inductor that we work with on an I C. Then, we further went on and we discussed what are the different non-idealities. So, there is a copper loss and the core loss. So, both of which we discussed because of the serial, series resistance the wire is also resisted.

So, that is why there is copper loss and inductor should be loss less right; should be loss less passive opponents. But instead because the wire is resistive; when a current goes through there is some amount of loss in power consume power. So, that is the copper loss then, there is the core loss the core loss is because of eddy current in the substrate. So, when I have a changing current; because of I got in changing current I will get changing magnetic field. Now, this magnetic field it so, happened will go through the substrate part of the magnetic field will hit the substrate field; whatever magnetic field is hitting the substrate that magnetic field changing.

So, the substrate is going to react in a way to oppose the change in the magnetic field. In a way what it saying is that the substrate is going to react in a way to oppose the change in the current that cause in the magnetic field in the first place; changing magnetic field in the first place. So, that is what I need you to comprehend over hear it is a step by step phenomenal. So, I am pushing, I am applying voltage across an inductor; which is changing as a function of time this changing voltage causes a changing current. Now, I have got a changing current through the inductor it causes the changing magnetic field part of this magnetic field hits the substrate whatever part hits the substrate; the substrate wants to make sure that magnetic field remain constant. So, it opposes the change in that magnetic field.

Now, as it opposes the change in magnetic field what it does is basically it creates a potential across itself; a changing potential is created across itself. Now, the changing E M F that is created; drives the current through the substrate. Now, when I drive a current through the substrate, the substrate is also resistive right; when I drive a current through the resistive thing it creates a loss in terms of power where is this power coming from? Is it coming from the substrate no, it is coming from the original voltage source that you applied across the inductor that is the source of power; it is not coming from nowhere. So, we got a lot of step in this process and it is important to understand this step. Because if we understand this step; then only will able to design better inductor with lesser amount of eddy current loss. So, it is a know ideality.

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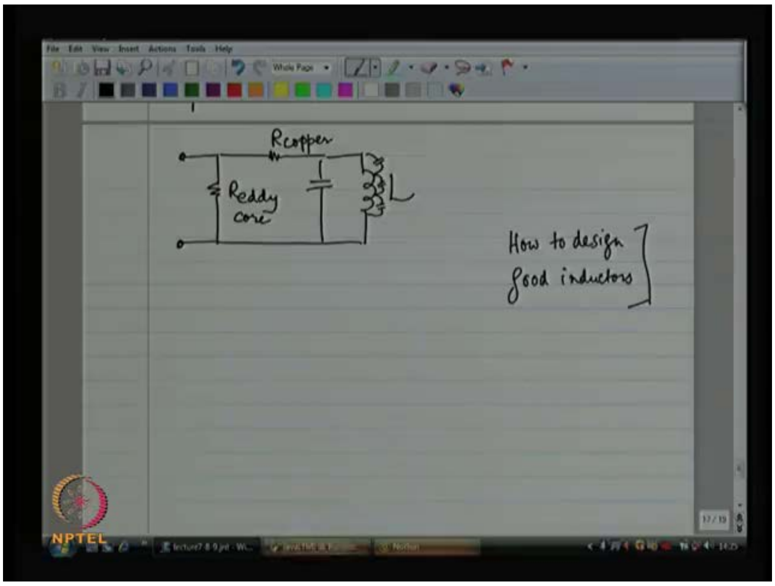

Now, then we went further and we develop the some kind of module for the inductor; we saw the resistance, the series resistance is a series R eddy, the R copper is series resistance; the eddy current create a parallel resistance be with so that is model over there.

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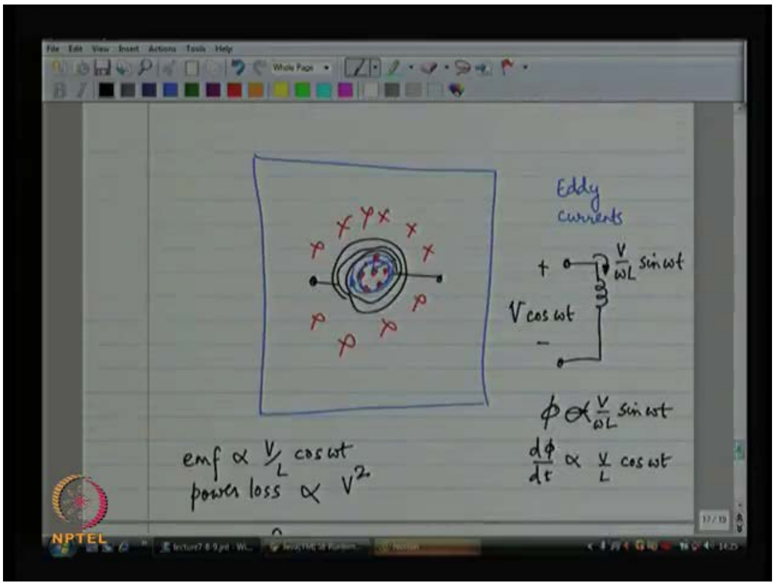

And, in addition what we got is the fact that the inductor is not really appear inductance; you got a piece of wire hanging on top of a substrate. So, it is look like a parallel plate capacitance as usual. So, that is also part of the model; then not only that to make thing towards each turn of the inductor is coupled to every other turn of the inductor through side wall capacitance right.

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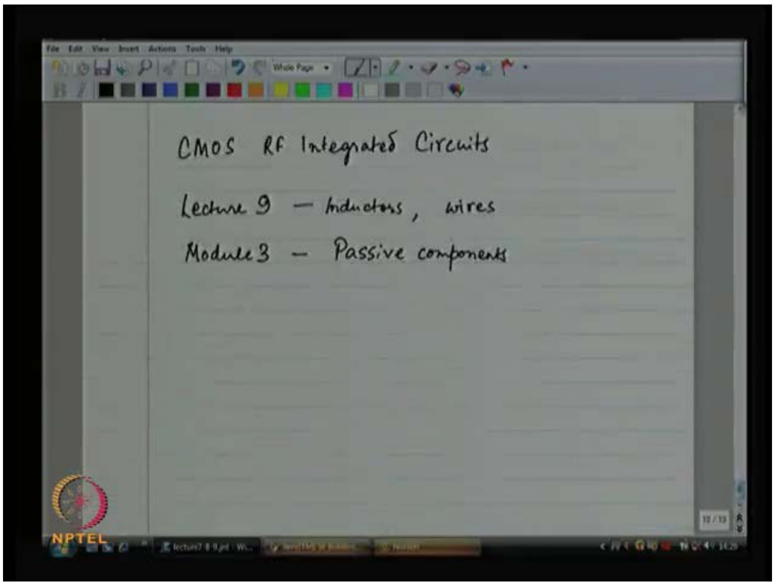

So that also is part of my model and I have a lot of those small capacitor between every 2 terms of the inductor; net result the model is CMOS I am sorry to say that but that is how it is will have to deal with CMOS inductor.

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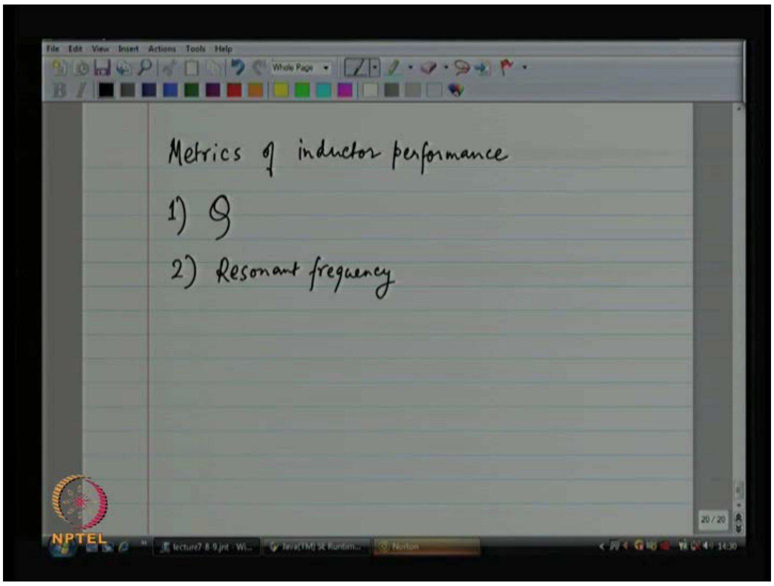

So, now in this class I am going to try to understand or I am trying to present how do we make better inductors ok. So, what are all the difference things that you can change and how is it going to affect your performance? What is the first of all what are the different metric's do we have of the inductor? Number 1; metric is Q thank you, this is something of great importance; Q kind of summarizes is lot of different things, it is summarizes all the different losses in the inductor how? Well, the definition of Q itself is what? Definition of Q is omega times the peek energy that is stored divided by the average power that is dissipated right.

So, average power dissipated means you have summarized all the losses, you lump all the losses together average power dissipated. And, peek energy stored gives you an idea of what is the value of the inductance etcetera. So, the Q is one of the most important probably the only parameters of interest is it; is there anything else that you are interested.

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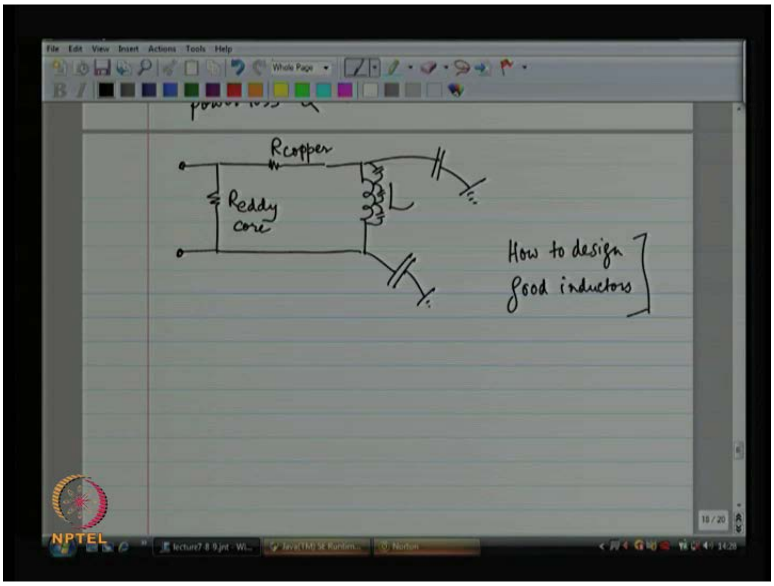

So, let us go back to the model; the Q kind of summarizes the relationship between L and R copper and R eddy and R core all this things that taken together and you get a value for the Q what else is there. The some capacitance there is lot of different capacitance actually turn to turn capacitance, inductor to substrate capacitance; lot of stuff how do model those? Actually, there is something wrong here right; should be inductor to substrate capacitance. How do you put all of those things in your model; you do not want you do not make a capacitance that is excellent in terms of all the losses no losses. But you know the huge capacitance it looks resemble more likely capacitance; then in the inductor you want to make such an inductor no.

So, how do we represent? What is going to be effected if the capacitance is too large? So, I made a statement earlier which kind of gives you a hint; the capacitance is so, large that the entire device looks more like capacitance then like a inductor what you make of that what should be the metrics? Well, you got this think all resonant frequency right you put L and C in parallel will got a resonant frequency. So, below the resonant frequency; the device looks like an inductor, above the resident frequency the device looks like a capacitance right that is how it is. So, what is the highest frequency at which I can still use this contraception as an inductor and does not start behaving like a capacitance; these are my 2 metrics, performance metrics.

So, one way to optimize your inductor is to have a close form expresser; that gives you these metrics and then optimizes the different parameters. Well, you are not going to be kept doing that; to do that you probably need some kind of an electron magnetic simulator or something right or you need to do have lot of jugglery with lot of equation. And, then you can work around your way; it is not my business to all to do all that what I can offer you is an innovative feel as to what needs to be done ok.

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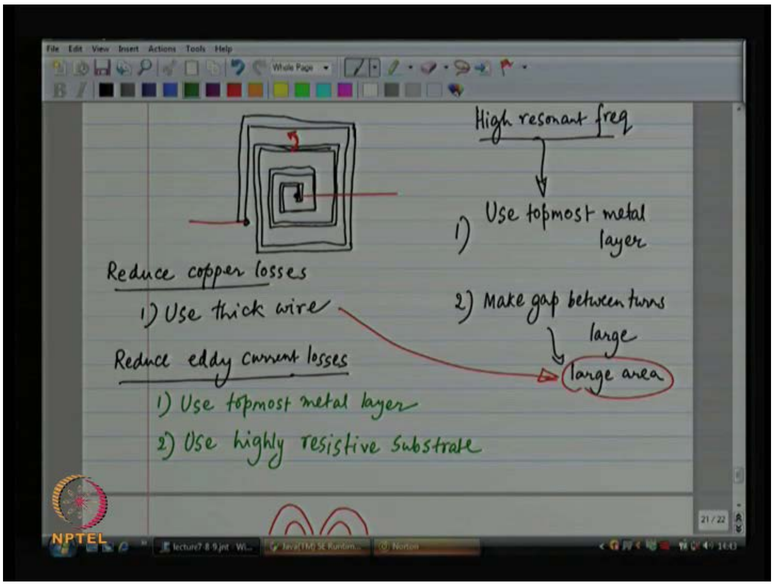

So, let us say that this is my inductor; last class we were working with a spiral, circulars spiral. Today, we are working with square spiral any reason, no reason; what is ever why you might choose one over the other both behave perfectly well as a inductors. One cool need thing about the square spiral is that all the coordinates can now satisfy the greed requirements of your foundry. So, the square is quite popular because of that. There are lots of other varieties of inductor as well hexagonal, octagonal etcetera; you can choose one over the other depending on what are the different angles that are allowed by your foundry in this. For example, you are is taking only 0 degree and 90 degree right perpendicular and horizontal wires.

So, foundry is love this kind of staff as soon as start making things that in angle there is significant risk that your vertices might go of the greed; greed of manufacture ability right. Once, they go of the greed you are not sure; if the mass making going to be correct or not etcetera. So, strange things might happened. So, that is why lot of people preferred this square inductor fine. Now, assume that let us work R way what are the difference things that you need to do to make sure that the resonant frequency of this inductor is very high, what are you going to do?

First of all you have to reduce the parasitic capacitance to ground, ground is the substrate. So, to do that what you need to do, you need to use the top most metal layer; if I use the top most metal layer then the parasitic to ground is going to be minimized fine, can you do anything else to reduce no, that is as far away as can be from the substrate. So, the substrate is here you use the top most metal layer and that is way you can minimize the effective parasitic; what else can I do turn to turn capacitance, how I may going to reduce the turn to turn capacitance your right.

So, basically make the gap between 2 turns as large as possible fine; we understood is easy to understood. So, if I increase the gap between 2 successive turns capacity, capacitance is going to decrease; everyone is the happy, fantastic. Now, if I have increased the gap between 2 capacitance, 2 successive turns; the area of device is going to increase fantastic. So, just keep that in mind that this is consequence of what you are, of your optimization this is the end result that to end up with large amount of area fine.

Now, the next thing that I want to do is I want to reduce the series inductor as far as possible. So, reduce copper losses are you going to achieve that? You have to make the resistance of this wire; the inductor is piece of wire point around if to make the resistance of this wire as low as possible how you will do that? You are going to make the wire as thick possible. Can I change the length of the wire; well, changing the length of the wire amongst to changing the value of conductors you get a I mean if I make less of number of terms then you know what you get different value of the inductors that is not something that would like to do.

So, let us stick to the number terms that you need the inner, radius outer radius; whatever the radius of core. Let us keep that fixed right; we can only use thicker wires what is that result in? That result in same thing large area. Because now I have made the gap is also large and the wire themselves are also thick; as a result the area cover by the inductor also become large fine. Now, let us try to reduce eddy current how you will achieve reducing, how will achieve that? Let us say, let us not reducing eddy current let us say eddy current losses any ideas? So, I have got my inductor, I have got my substrate inductors: is like an electromagnetic ok.

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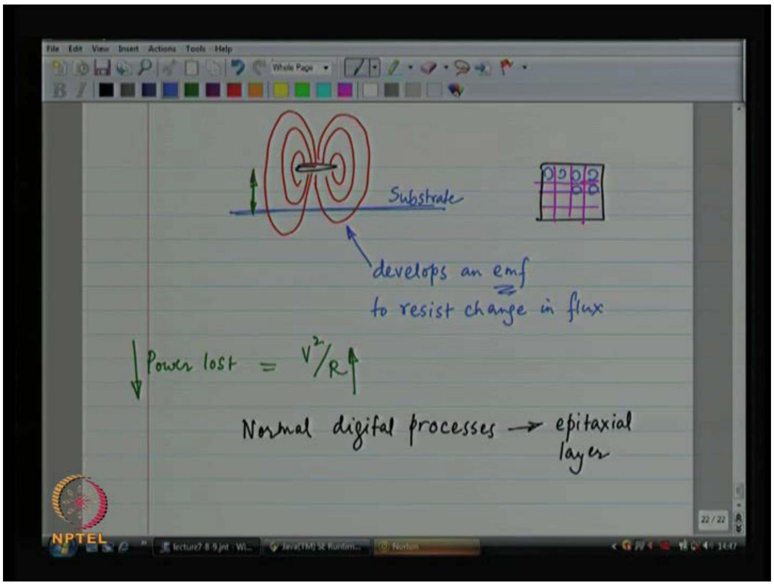

This was the primes of the story and I have got my substrate over here. So, some of this freelance also going through the substrate and the substrate does not want to change in the flux. So, whenever the change freelance there is a change in the flux; the substrate is going to oppose that change and the consequences is going to develop an e m f that is also important. So, just from the diagram what is the first thing that you going to do, where I, how I make to this inductor; such that you can reduce them also eddy currents your right ,what you need to do is place that place the inductor at a height go higher . So, be as far away from the substrate as possible.

Now, suppose you are already using the top most metal layer; what else can you do? So, now take a look the substrate develops an e m f to resist the change in flux. So, suppose it develop, suppose there is a track like this and the substrate has developed an e m f across this track of volts V; what can you do about track such that the amount of power lost is minimum at what will you do to reduce the amount of power lost. The already develops potential V, the power lost is V square by R; suppose, struck from end to end as resistance R power last V square by R which means that as R goes R; the power lost goes down .

So, therefore what we do is; we use highly resistive substrate what is the substrate made up of? The substrate is normally made up of silicon doped with p type material. Now, actually that is not it, if that was it then life would be good but that is not it; what happens is that for our digital circuits there is a phenomenon called latch up have you heard of latch up probably. So, to prevent latch up from happening the substrate is made highly conductive. So, latch up happens because of bad designers; who have to put enough number of contacts in the substrate, close enough right that why latch up happens.

Now, to solve a problem created by bad designers what we normally do is we make a substrate highly conductive. So, there exists designers who are bad; the foundry assumes that all designers are bad and they would not put enough number of contacts. And, therefore they put an extra layer in the substrate and make it highly conductive; this layer is called epitaxial layer. So, let me just write it down. So, if you are working on a normal digital process; then, it is very very likely that be are you going to apply an epitaxial layer on the substrate to make it highly conductive like a metal.

Now, if you are have making an inductor and you have an epitaxial layer it is bad news because they is going to be huge amount of power lost in the substrate. So, typically what we do is; we do a couple of things, we blocked the epitaxial layer. So that underneath a inductor at least; the substrate not conductive. So, this is the done a very routinely to make in better inductors. There are other ideas as well, people dig trenches inside the substrate and separate the substrate into lot of different pieces. So, instead of having one huge conducting plane if I draw the top view of the substrate.

So, instead of having one huge conducting plane under the inductor the dig trenches an isolate portion. Now, each of these isolated portions are conducting themselves. But because of the trenches the whole thing is not conducting. Now, this reduces the length I am sorry, this reduces the area over which the e m f is going to develop. So, now instead of a current going over the entire area of substrate; we have got small small currents over small small portions of area see you still get eddy current.

But the quantum of eddy current is reduced significantly; have you seen this before in any other discussion have you seen this? This is commonly use in transforms you laminate the core of the transformer you slights the core of the transformer it lot of sheets. This power transformer out there you will see that the core is laminated into the lot of sheet. So that one huge eddy current is not going to flow through all of them there laminated isolated from each other.

So, in each of those laminate does going to local eddy current that is still going to contribute to eddy current losses, core losses but this not going to gigantic eddy current going all through. So, what you reduce over is V effectively; if reduce the quantum of V over there each loop as much lesser V, R is also proportion to V but the net result is that the. So, the numerator is with the numerator is go down V goes down to x and R also goes down 2 x what is going to happen in the power lost? power lost is also going to go down by 2 x. So, that is why what happens in this case.

So these are some commonly used techniques; use thick wire, use top most metal there, use highly resistive substrate there, lot of other ideas with respect to inductors see the making good inductors is very very very much an art it is not really is a science any more why is because silicon is expensive. So, every time a designer does something new; you know it is very hard to figure out whether what the new thing that he has the incremental change is done has it really given a benefit or not. It is you do not really want to do a massive experiment and compare lot of different inductor design and so on, so forth.

So, that is what I am saying that inductor designs as become more often hard and you hear about things and do things. And, it is come down to point where it is no longer; the signed behind the designer of inductor is lot of time disregarded. So, lots of people use a ground shield underneath the inductor. For example, I will just give you an example personally, I do not understand why?

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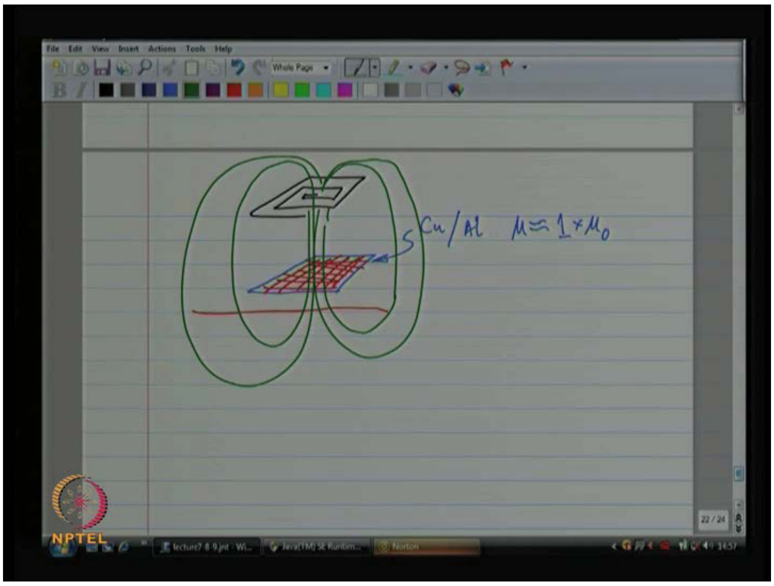

For example, I will just give you an example personally, I do not understand why? Let us see what I am talking about. So, I made in inductor I am trying in 3d. And, I got the substrate underneath the inductor hopefully the substrate is for away. Now, what a lot of people do is they put ground plane underneath on metal 1; underneath the inductor next step was that the figure out that the ground plane conducting huge quantities of eddy current. So, still keep the ground plane; what they started doing was pattering the ground plane why would do such thing? Personally, I am not very clear about why?

The ground plane this particular material is going to be either copper or aluminum or something like that these have a permeability of very close to one most material are permeable relative permeability very very close to 1; relative permeable, 1 is the permeability of vacuum only material that are far off from this relative permeability of 1 are iron cobalt and nickel.

So, as long as you are not using any of these3 materials iron, cobalt and nickel you are in range of 1. So, copper is probably little bit diamagnetic I am not sure. So, anyway it does not matter putting copper underneath the inductor is not really going to shield your magnetic field lines; if you put iron in that is going to shield your magnetic field lines why? All those magnetic field is going to comment they will be going only through the iron and not through anywhere else.

It is like iron likes to conduct magnetic fields a copper brown plane underneath the inductor is not really going to absorb any magnetic field lines. So, the magnetic field will still go just like before; it is going to behave like electromagnetic little exacted to view. But magnetic field lines as still going to be like that no change because of the extra ground plane; what is going to happen now is that you have probably created a lot of plates in between for the capacitance, for the parasite capacitance. So, earlier the parasite capacitance was the capacitance between the inductor and ground plane; you know the substrate inductor and substrate these are the 2 plates.

Now, you have created a new plate closer by. Now, if this new plate is also grounded then, you are actually increased the parasite capacitance of this; if the new plate is not grounded then, you have other reason of concern; you are going to get a lot of different mutual capacitances which I am not very sure of what to do with. So, this is having a pattern ground plane underneath inductor. So, a lot of people do this personally I would not recommend I would not ask you to do make such an inductor because I am not sure what the science behind it.

So, when you read about inductors my request to you is think about the science; do not get the swear by here say, question everything there is a lot of bogus staff out pair. And, lot of people get published every year about newer and better and the with lot of different claims involved; most of this claimed are not substantiated that much maybe, there is some truth, maybe the author of the paper did in did get the performance in improvement by a 0.1 d B, 0.2 d B I do not know. And, it is a really cause for concern and at the same time thought.

So, you have to think about what, why did the author do this? what the science behind it? And, then you have to take the paper with pinch of salt; see what is the experimental set up they have, what kind of experiment comparison have they done and what kind of performance improvement did the author get; is it something that he could have got gotten by fluke, as an you know experiment to experiment things might be different. Now, you are getting today, you are getting 0.2 d B of improvement, maybe if you till the wire little bit it could have become minus 2 d B. So, it is not very clear how I mean;

if someone gives you performance improvement which is very small it is not very clear if that is in improvement at all are not may be measurement in accuracy. So, please take such paper with pinch of salt and my sincere request to you is to think about the science behind and then go for the design. If you think about the science behind you are always going to get the right answer.

So, lot of different inductor design are there in literature pyramidal inductors, circular spiral, octagonal spirals; people have put this ground plane there is lot of stuff with the ground plane, pattern ground plane etcetera. I do not know maybe what they are saying is right, maybe they are not please think about the science when you read it that is as far as I am going to talk about inductors; you will be getting some homework problems with respect to this. And, please try to solve this homework problem as well as you can. And, that will give you further feel and understanding of how to make good inductors.

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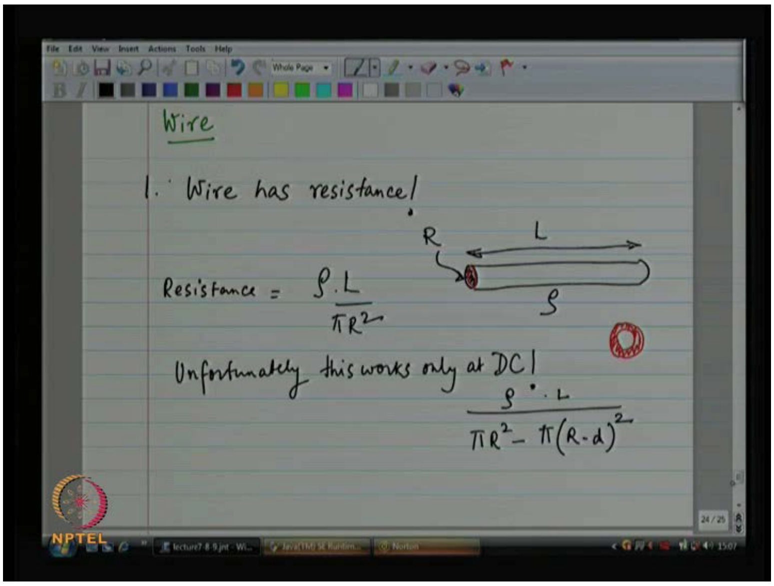

The next important passive component is going to be a wire and really added this been other course wire would have been ignore; wire would have been treated as a short-circuit; we are going to treat a wire as a material through which electromagnetic wave propagates am I right. So, is going to our treatment of a wire. So, we are working with frequency that is very very large gigahertz typical. So, at these large frequencies if you just treat a wire as a short circuit it may or may not work. So, what is the first thing that comes to mind? What is the first non ideality of a wire? A wire as a resistance.

So, let us think about a cable, a wire, solid piece of metal, not necessary metal; any material length L, radius R and resistive of prove a material has a resistivity of rho what is going to be there resistance of this wires? it is the if you take the rho, the resistance is going to proportional to L and it is going to inversely proportional to the cross sectional area; in the what is the cross-sectional area pi R square. Now, this is easy to understand. Now, what you are not told over here is that this resistance typically is a function of frequency why? So, if you study your electromagnetic theory I do not know how profession to your with your E M theory; of course if you do study it anyway.

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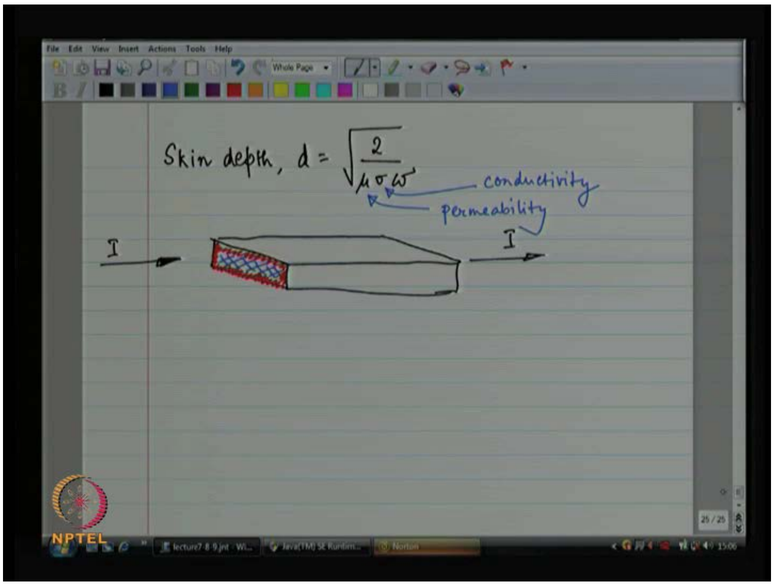

So, I am just going to pick a result out of there, out of the EM theory course; there is something called skin depth what this kind of tells you is as follows like this; if I have a wire, let us talk about wire if I have conducting material let us say a slab of iron, or slab of copper. So, I have slab of copper and I am trying to push a current through this copper. Now, what this skin depth business tells you is as follows; basically tells you that the current is not really going to go through the bulk of the copper, it is going to go through the skin of the copper. So, if the current going to propagate remember the current is at a frequency of omega; sorry, I forgot to tell if the d c current it just goes to through the bulk of copper; the current is going at frequency omega.

So, what this skin depth formulation tells you is that current likes to propagate through the scheme of the material, through the surface of the material. And, the depth up to which the current does propagate is given by that formula actually is not even that it is like this at a depth d; the current is 1 by e times the current at the surface; 1 by e is about one-third. So, at a depth d from the surface; the current that is going is one-third the current that is at the surface that is what this exact formulation is. But never mind for our purposes how we are going to interpret this is all the current really goes through the surface, through the cross-sectional of width depth d and the remaining portion of the bulk of the copper plate is un used.

So, this portion of the copper or whatever material you are using is unused; what are the different things in the formula nu is the permeability and sigma is the conductivity 1 by rho is sigma. So, if you have something is perfectly conductive that is sigma is infinitely large; then, you know all the current goes through entire bulk of the material is used to form is used to from correct propagation. However, sigma is finite fine. So, in the light of this what is going to be the resistance of my wire? Well, now current is going to be conducted only on the surface still a depth d. So, it is like you got an annuals on the surface through which current is going through right.

So, the cross-sectional of this cross-sectional area of this is a pi R squared minus pi R minus d square that is the cross-sectional area and this gives me my new resistance at a given frequency right. So, given omega you can compute the resistance. So, what does is tell you, how are going to make a wires nice wires; it is what it tells you that if you keeping making the wire thick and thicker it is not going to be much benefit to get out of it. Because the wire there current is only going to travel on the surface of the wire. So, what matters as for as current is concerned is larger perimeter.

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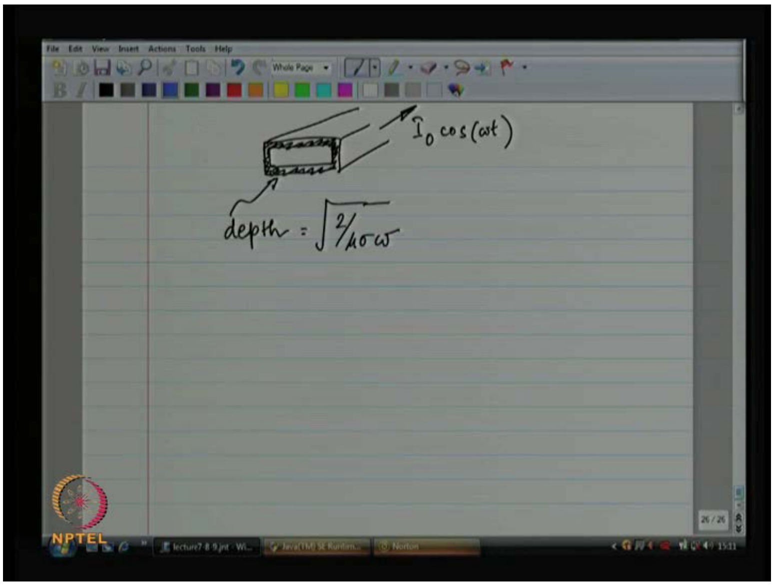

So, if I have a large perimeter; it matters to me because more current can flow, there is more surface area. So, this is the region where the current is going to go through. Now, let us that is what skin depth. Let us go back a couple of steps how does these, what is the implication of this on your register design; well, implication of this an register design is if you did not worry about this up front. Then, you might get much larger resistance than you expected right; also it means right there resistance is no longer linear at different frequency is the value of resistance itself changes; large of the frequency more there resistance. Because you get less area of through which cross-sectional area through which current is conducting.

What does this mean for our inductor design; for our inductor design this is bad news as far as the subjective is concerned, reduce copper losses I wanted to use thick wire. But thick wire is all been all both dimension, both as for as the depth of the wire goes as also as thickness of the wire goes. But this is only so much you can do because you can make the wire higher and higher but you know the current is propagate only on the surface. So, it does not matter.

So, when you work within inductor, when you design in your inductor please make sure that you have worried about skin depth, please make sure that you done some computation; to relate, to find out, figure out exactly how much the depth of your skin is then what is the thickness of the metal that foundry is providing. So, only after this computation sign of your design do not ignore skin depth. So, this skin depth a lot of implication for everybody right. So, a wire has resistance and it not just resistance it varying amount of resistance has function of frequency; at d c the resistance is easy to find out at higher and higher frequencies it becomes more and more resistive fine.

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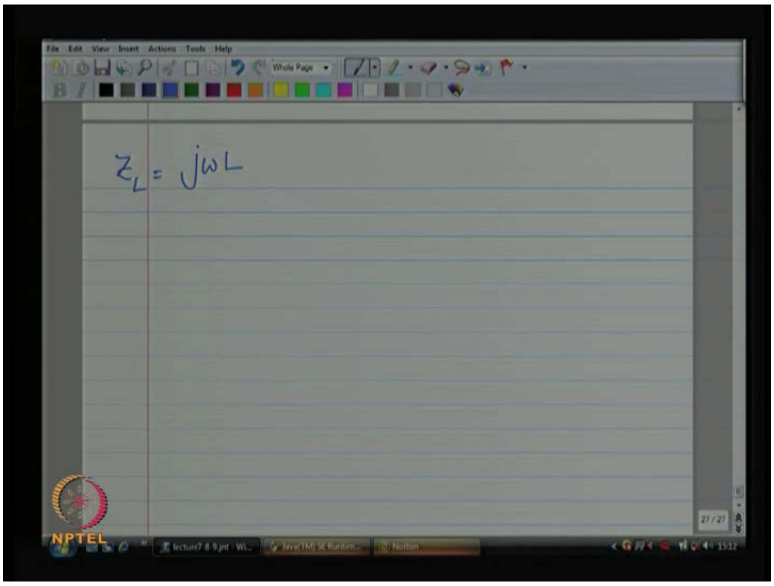

So, these kinds of leads you believe that the wire almost works like an inductor; the inductor impedance increases as frequency increases right; somewhere it rings the bell and we are talking about wire whose resistance increases as frequency increases. So, you know wire is kind of behaving like an inductor.

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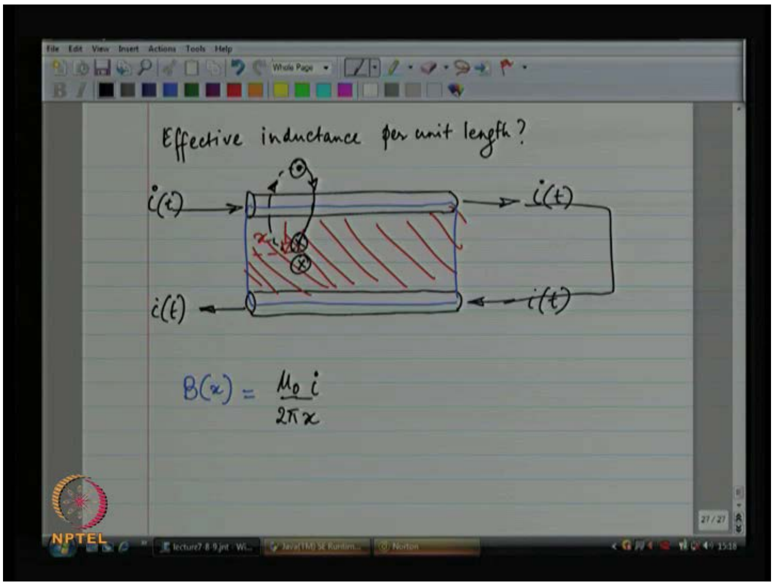

So, the next step for us would be to find out what is the effective inductance per unit length of a wire? And, to do this I am going to model my wire are actually, my system as a combination of 2 wires; one through which current is going go, the other through which current is going to come back. I am pushing this current through this wire and the same current actually going to loop around and come back through the other wire. And, we are going to consider this system were this 2 pieces of wire are parallel to each other and are of equal length etcetera; why I am picking up such specialized system is there any justification behind picking up this.

So, many constraint such a system; well, you remember your refection how you solve the Laplace's equation by means of reflections well slight like this. If you have wire on, if you have charge on top of ground plane did in the last class; you have a plus Q on top of ground plane it looks minus Q beneath the ground plane right. If you have a lot of charges in the ground plane; then, it looks as if you have a lot of equal and opposite negative charges beneath the ground plane. Now, this charges are moving those charges will also move right. So, the bottom wire is actually mirror image of the top wire; why is that? Because I have in my head, I have a ground plane in between where is this ground plane coming from it is a substrate right; the substrate is the ground plane in this case.

So, I am just going to compute the inducting per unit length of this set. And, in my mind there is a reason why I pick this set up; I hope the reason is convening enough. So, how you going to do is as follows; first we are going find out the magnetic field at a distance from the wire. Let us say at a distance x from the wire; what is magnetic field? Then, we are going to find the flux. So, we find out the magnetic field at a distance x, then we find out the flux over that entire area.

Now, you think of a loop that looks like this you know; the total amount of flux through that loop. So, rate of change of flux is going to give you the potential the back e m f that is developed right. So, what is magnetic field at a distance x from a wire that is carrying current i. I am sure you all forgot an appears law; how do you work with appears law? You construct a loop around the wire right; the amount of current cutting through the loop is high. So, mu naught by 2 pi times i. Now, mu naught i divided by 2 pi that is the length of the loop is going to give you the magnetic field i o distance x that is fine.

So that the magnetic field of just 1 wire, the other wire is going to be very similar; we are going to work on the other wire later on. Just remember that the magnetic field if i is going to that way then we got right hand rule. And, as result of that you magnetic field is going to looks something like this. Similarly, for the other wire also the magnetic field is going to point into the page inside. So, we are going stop here. And, we will do the detail calculation in next class; we are going to find out effective inductive per unit length, we are then going to proceed and find out effective capacitance per unit length. And, then we are really go at work on the wire.

Thank you.