CMOS RF Integrated Circuits
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Module - 03
Passive IC Components
Lecture - 08
Inductors

Welcome to CMOS RF integrated circuits; this is a, we are still in the third module that is we are talking about passive components. And, today's lecture we are going to talk about inductors, before that I am going to briefly recapitulate what we studied in the previous lecture on capacitors and registers.

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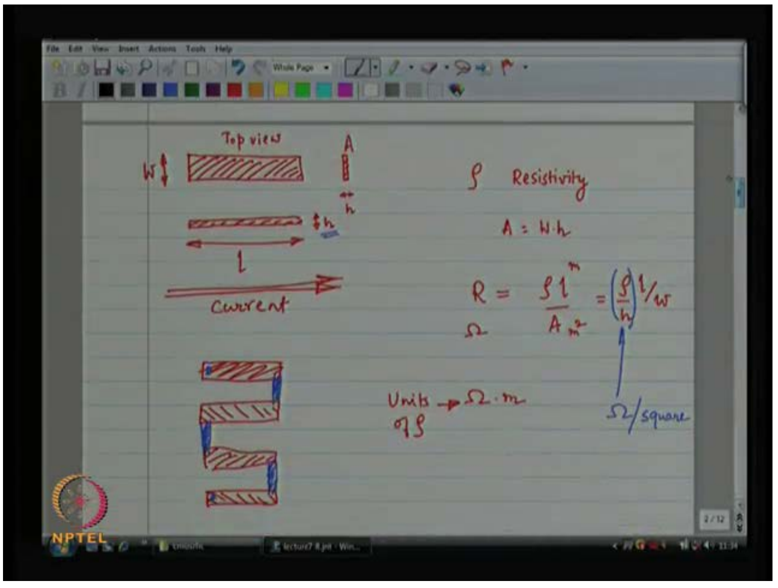

So, registers were easy units are in ohms per square typically that is what the foundry is going to give you, would basically count the numbers squares and that gives you the resistance of the entire track.

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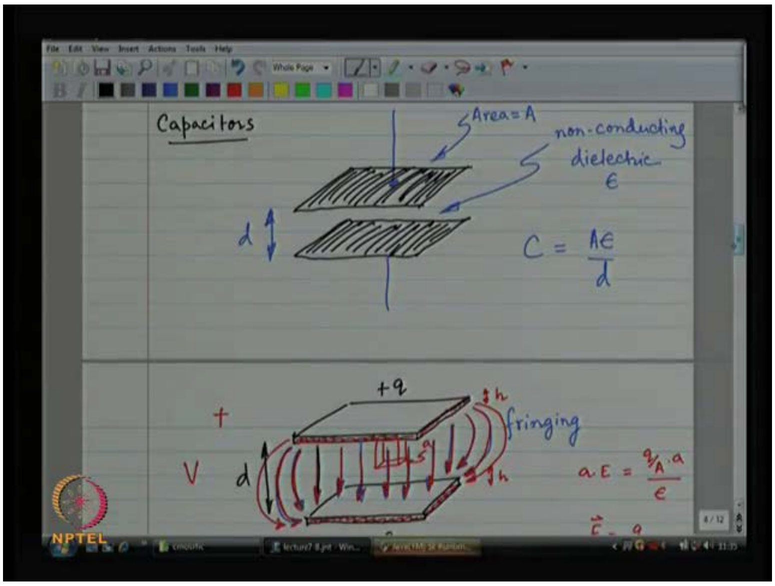

Fine, capacitors whenever you see to parallel plates it founds the capacitor.

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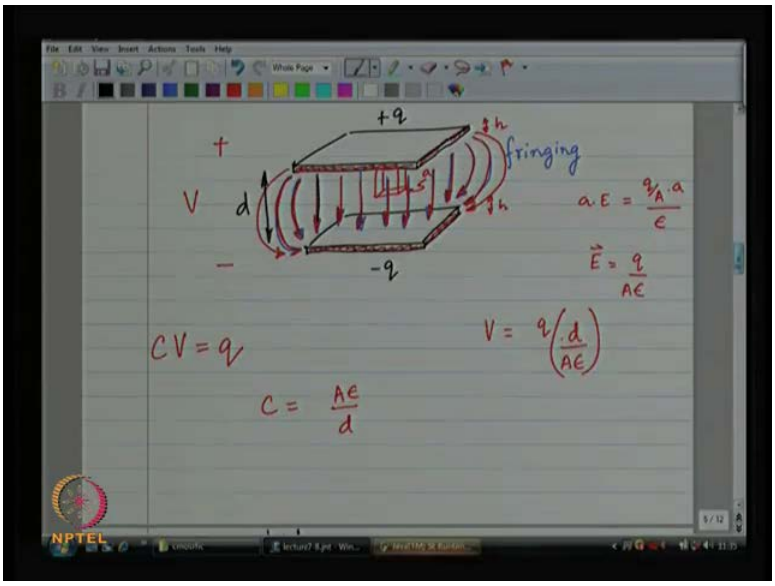

Now, neat ways or you have to remember that the field between the 2 parallel plates; if the plates are infinitely large the field is perfectly vertical, if the plates are limited in size which is the case then, there is going to be fringing along the borders. So, the capacitance, net capacitance is going to be proportional to the area. So, there is going to be A epsilon by d that component is going to be there, and in addition there is going to be a little bit, because; of the parameters that is going to be proportional to the parameter fine.

On an I C how do I make a capacitor? I can take 2 metal layers and build a capacitor between them. That is 1 way of doing things, but; the distance, the separation between this 2 metal layers are quite significant which means; that I do not get very good capacitance density, I usually burn up lot of area to make a small capacitor. Then, I can use the MOSFET itself to make a capacitor, the gate to channel the separation between gate to channel is well controlled and it is quite small. So, I get good capacitance density, but; this comes with k V arts the k V arts are that I get very large parasitic to ground, and I also end up with a capacitor that is required to be biased.

So, the dc voltage between the gate and the channel has been more than a threshold voltage to make this work. Alright, next idea was to use 2 wires, 2 tracks and the separation between the 2 tracks can be made very small that is the size of the resolution of the technology. If you are in a 0.1 micro and technology then, that could be as small as 0.1, the thickness between the gap between the 2 layers is much larger than 0.1 micro in 0.1 micro and technology. So, anyway; so, I can use that thought that idea and I can make a wire to wire kind of capacitance in a sense, there also I will be getting some parasite's, but; if I choose a iron of metal layers then, the parasitic are less.

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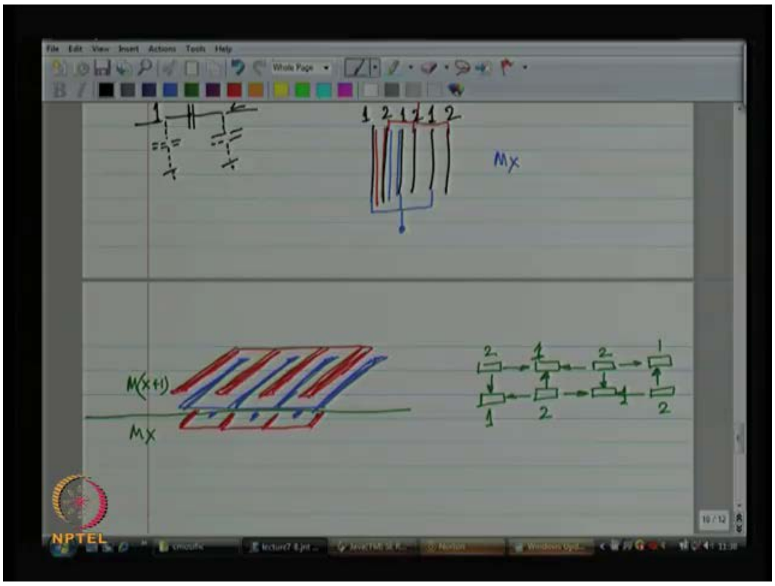

I can basically make something which is fingered, the way I have drawn it; I do not know if the 3 d picture was comprehensible, but; this is more or less what I wanted to show. So, top layers has fingers. So, there are 2 sets of fingers and between every 2 fingers, there is going to be as side to side capacitance. Now, just like I have got 4 hands like this, 2 hands like this, I could put to more hands below this in the opposite configuration.

And, that could give me the vertical capacitance as well, that is what I was trying to show in this diagram over here. This 3 d picture I do not know if it was a very clear are not, but; anyway. So, this is what I wanted to show in this picture alright. So, now, this one more thing, that one smaller thing that you could do basically, the side view the cross section will view is given here.

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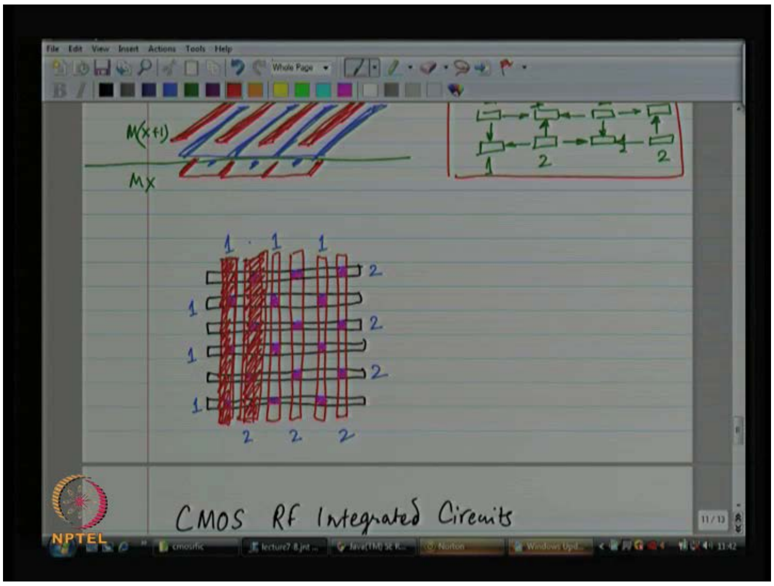

Now, making this connections all the twos need to be sorted together, all the once need to be sorted together, are you achieve this. So, the layout style is something like this, on metal 1 layer or metal x layer, I put horizontal strips. And, on metal x plus 1 I put vertical strips, and I want this wire to be ,1 this is 1, this is 1, I want this to be 2, this to be 2, and this to be 2. And, similarly; I want this to be 1, this to be 1, this to be 1, and this to be 2, 2 and 2. So, I need to make a short between all the twos. So, I am going to put a set of V as over here, over here and over here. Put a set of V as here, here and here, set of V as here, here and here. And, then again I am going to put, I need to shot all the once.

So, I am going to put. So, V as are the connection between the 2 metal layers right. So, this could be my layout. So, now everything is connected now, I get what I wanted. So, I get the side to side capacitance as well as the plate to plate capacitance. Now, of course, my drawing is not particularly nice, what you have to make sure is that this width is large, and the gap between the 2 is small. So, you have to make this width large and the gap small. So, as long as you do that you will get very high capacitance density. You are going to your basically taking advantage of both metal to metal capacitance as well as sidewalls right.

So, these are basically, how we build capacitors on an I c. There are lot of other interesting ways you can make fractals etcetera, and try to compress an infinitely long line segment in a finite amount of area. You can do stuff like that and anyway. So, there are lots of other ways of making very good capacitors as well, just keep that in mind. Now, we move on to the next item on a list of passive, and we are now, going to talk about inductors. Now, what is an inductor, how would you make an inductor, a discrete inductor, how would you make it? You have any suggestions; the very rudimentary inductor is a solenoid right, think of a core.

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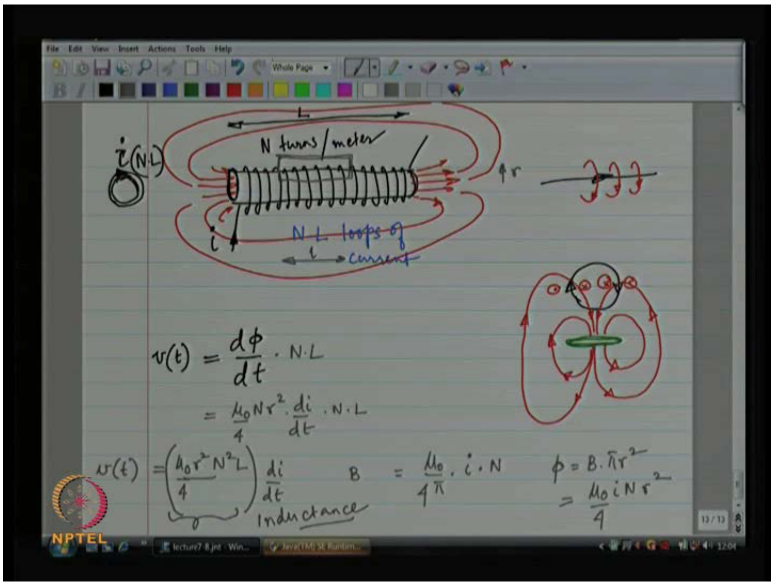

Iron core, let us say and there is winding, copper winding around this core that is your typical discrete inductor. You can also make this core in the shape of a torrid etcetera. So, let us think about this, this is a solenoid. Let us assume that the solenoid is infinitely long, length of the solenoid is huge, and let us say, we have has a result packed in a lot of turns in the solenoid. Let us say there are N turns per meter in the, on the solenoid this is our assumption.

Now, later on we are going to say that the solenoid is of length l, but; from now, let us make the assumption that this length of the solenoid is incredibly long, infinitely large. Now, what happens how does this work as an inductor? So, first of all when you push a current through a wire, it creates a magnetic field. So, if I have a wire current going through a wire it creates a magnetic field around it. How do you know the direction of this magnetic field? By the right-hand rule, right you take your right-hand; the thumb points in the direction of the current then, the curl of the finger corresponds to the direction of the magnetic field.

So, if what I have drawn on this highpoint in the point might thumb in the direction of the current then, basically the curl of my fingers is going to give me the direction of the magnetic field. And, the magnetic field is going to go around the wire, fine. If you make a loop of wire, lope of current. Consider a loop of current; current is going round and round, what is going to happen in this case? The current on the left side is going to create a magnetic field that is going to point into the plane of paper; the current on the right side is also going to do the same thing.

Now, if you draw the side view of this then, you have basically, got a current looping around and the magnetic field will look like this pattern. So, this is your typical dipole magnet has a North Pole and South Pole. So, basically as soon as you have a loop of current, it behaves like an electromagnet. Right, as a North Pole and South Pole and you know magnetic fields are looping around fine, this picture is fine. So, any lope of current basically, works like a magnet. Now, if I have got so many loops of current, how many loops of current have I got in this solenoid? I have got N times L loops of current. All of these are individually magnets, all of these loops of current you can think of each of this as a magnetic dipoles right.

So, as a result when the current is what I have drawn, there is going to be magnetic field going into the core. And, this magnetic field is going to loop around. So this whole thing is now going to behave like an electromagnet. So, far, so good it has flux an electromagnet has flux, magnetic flux through the core. And, Faraday’s law says that whenever, you try to change the magnetic flux a voltage is induced that opposes this change. If you try to change the magnetic flux, I mean the magnet does not like a change in magnetic flux; it would like to keep the magnetic flux constant.

So, whenever there is change in magnetic flux a voltage is developed which would be opposing the change in magnetic flux. In our case if you have an inductor; there will be a potential drop across the inductor. Right, it will generate a negative voltage means; they will be a potential drop across the inductor. This potential drop across the inductor is proportional to d phi by d t not, just proportional it is equal to. Where, phi is the magnetic flux through the solenoid. Why would the flux want to change? The flux would change if the current changes. So, what is the relationship between the current and the flux? Well now, I am going to draw the top view, the cross-section of this solenoid.

So, this is my core and I have got current spinning around the core in this direction. So, when I draw the cross-section of the solenoid it basically, looks like this. And, the current spinning around and I have got N times L such loops, N times L such loops are there. So, each of this loops is going to contribute flux right, each of this loop is going to contribute flux which is proportional to i. Now, what is the exact amount of flux that is going through a core of solenoid? So, to do that you use Ampere’s law, do you remember Ampere’s law, what are you courses Maxwell’s equation, I know you are all scared of Maxwell’s equation, but; his equations are the final word.

So, Ampere’s law is just 1 portions of Maxwell’s equation. So, if you draw a loop like this, to construct a loop like this then, the magnetic field along this lope, the integral of the magnetic field along this loop is mu not by 2 phi times the current enclosed. So, if I construct a loop length L, let us see this is L then, the integral of the magnetic field is going to be twice magnetic field times L. Because this is an infinitely large solenoid is going to be no component on the horizontal sides is only going to be magnetic field along the vertical, the am sorry, the top and bottom edges.

So, 2 be times L is going to be the integral of the magnetic field, and this is going to be equal to the amount of current that is enclosed in the loop mu not by phi times. And, of course, this means; that the magnetic field inside the solenoid is mu not times i times N divided by 4 phi. So, therefore; the flux is the magnetic field over the entire area. So, the entire area of this let us say, this has a radius of r and then, the flux is going to be B times phi r square. Did I do it correctly? Yes. So, this is my flux now, the voltage developed across each of this loops is the rate of change of magnetic flux.

So, the total voltage developed is going to be the voltage developed across each loop is the rate of change of magnetic flux, the total voltage developed is going to be d phi by d t times N times L that is the total number of loops that I have. Now, the inductance times d i by d t, is the potential drop across the inductor. So, what is going to be the inductance over here, this quantity is the inductance. So, that is how the, we come up with the inductance of a solenoid. Now, first thing to understand is that there is a potential drop only when there is a change in the current otherwise, there is no potential drop. The flux through the inductor would like to be a constant. Whenever, there is change in flux the inductor creates the voltage drop which opposes the change in current, the change in flux I am sorry, alright.

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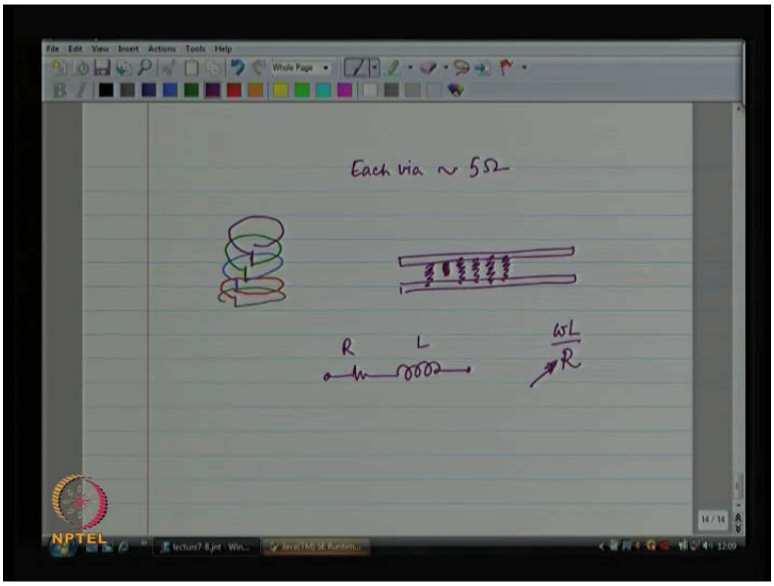

Now, on an I C how would you make this, how would you make this solenoid on an I c? Well, 1 way to conceive of it is you draw your loop in metal 1, and then put via and then, go to metal 2, and draw another loop and then put more via and then, and go to metal 3 and then, do another loop and then put more via go to metal 4 do another loop and then, put more via go to metal 5 do another loop and so on and so forth. It could do it like this; it is conceivable of doing like this. The biggest problem here at the via, each via is highly resistive, each via looks like a register of something like 5 ohms. What is that via?

Anyone who has worked with pc boards, you know what is via is? When you make a 2 layer pc board, you drill a hole and you plate the hole, and that is the via. We do the same thing on an I C’s, while making IC’S.

So, there is metal 1, there is metal 2 in between there is oxide layer. Now, when you want to make a via, you punch a hole over here, you punch a hole, hole has to be of specific depth and specific diameter that is the diameter of via. You punch that hole and then you pore metal inside and then you have got your via, right. It is a very narrow hole that we punch as a result it is highly resistive, typical resistive value is something like it could be as high as 5 ohms. There is also a probability associated with the via, there is a probability non-zero probability that when you are punching the hole, the hole does not go through. So, what if you punch a hole and it does not go through then, no contact is made. In fact, you failed to make contact.

So, that probability is also there, it is a non-zero probability and, because; of this non-zero probability there is going to be distinct possibility that your chip is going fail, because; you failed to make a contact. So, therefore, you put a lot of vias in parallel, right you put hundreds vias in parallel and hopefully some of them have made contact which is going to establish connectivity between the 2 metal layers, alright. If you put hundreds of vias in parallel then, each via is 5 ohms. You have made hundreds vias in parallel then, the total parallel resistance is going to be 0.05 ohms. Hundred vias in parallel right 5 by 100. So, it is good practice to put a lot of vias in parallels.

So, that first of all some of them have to punch through. Secondly, you get much lesser resistance. Why is resistance important for us? Because; you are trying to make an inductor, if you put a series a resistance a resistance in series with an inductor then, what is the q of this? The larger this quantity, the lower the quality of the inductor. So, you want an inductor of high quality, when we are talking about an inductor we want R to be 0, unfortunately it is not possible, but; we would like R to be 0.

So this is one way that we could make an inductor is not usually done, this is not usually the practice because of this via problem. We do not want to put vias in the path of the inductor, because via are resistive. We want to put metal, we want to put high conductive metal all over the place we do not want vias. So, what is done is you have the solenoid which is the spiral you compress it, you have seen a spring think of a spring, and think of compressing the spring onto one plane, what are you going to get? Your going to get a spiral inductor ok.

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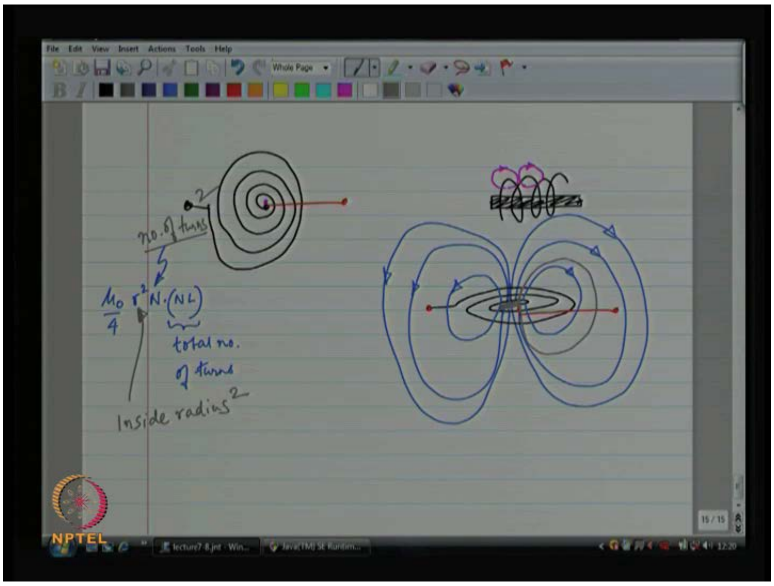

So, this is what we typically make on a chip. We basically treat it treat the solenoid as a spring and flatten it onto one plane. So, we can do the whole thing with just one metal there, and what you have got over here is a spiral inductor. It is a very crude approximation of solenoid, remember the earlier design was also quite crude I mean; no way can you call this as solenoid. Anyway, this is what we do, what is missing? The core is missing. What is the problem with that, why is the core important? The magnetic core you know, when you make a solenoid you put an iron core in inside it. Now, it is missing, we cannot put iron on the chip right.

And, alternatives of iron are cobalt and nickel; we cannot use any of those on a chip. We can we only have axis to copper may be aluminum right. So, the core is missing. So, what, what happens when code is missing? You see what the code does, what iron does is it likes to capture all the field lines the magnetic field, magnetic field would rather travel through iron then through air. As a result when you have your solenoid and you have an iron core inside it, the magnetic field lines would rather travel through the iron I supposed to the air. So, as a result no magnetic field travels to air, as a result you get the entire magnetic field travelling through the iron core. So, there is no magnetic field that leaks out through these gaps, no magnetic field leaks out ok.

In our case everything is air. So, as a result there is going to be leakage. So, there is going to be individual magnetic field also around each wire. So, those field lines are actually going to leak out, they are not going to the travel through centre. We would like this thing; we would like this entire structure to work like a magnet like an electromagnet, right.

We would like the magnetic field to come out and go in a circle, right. This is the plane of the inductor, we would like the magnetic field to come out to the centre and go around and come back that is how we would like it to be. Unfortunately there is considerable amount of leakage each of the peripheral loops will have their own small amount of magnetic field going around them. And, as a result there is leakage flux leakage.

So the quality of the inductor is not, that great I mean the equations do not precisely apply as before fine, so far so good. So, basically the idea is this; that this structure is a plain the inductor is a plain and we are trying to make an electromagnet, the magnetic field lines are going to come out and go through the substrate comeback like this that is the idea. So, let me draw in 3 d; these are the 2 nodes of the inductor, and this is how we want the magnetic field lines to look like. Depending on the direction of the current right and the inductor opposes the change in this flux, the magnetic flux that goes to the core agreed.

So, this is what we are working with, alright. What do you think are going to be the non idealities of this? First of all let us come up with some approximate idea of what the value of this inductance is going to be, is the value of the inductance going to be proportional to the number of turns. Look when we talked about a solenoid the value of the inductance was mu naught by 4 r squared N squared L. What is L over here? You have really compressed everything.

So, really L was not really the thing we had N turns per meter and N times L total number of turns. So, if I have some total number of turns that is what I have got here, I do not really have any length any more inductor has been compressed to one plane. So, I have got the total number of turns. So, it is definitely going to be proportional to the total number of turns.

Next term N also reflects the total number of turns. Does it reflect total number of turns, where did it come from? It came from the, we constructed loop; we wanted to find out the magnetic flux. So, first we wanted to find out the magnetic field, we constructed a loop and used Ampere’s law we did the integral of the magnetic field along that loop right. And, found that was proportional to the current going through that loop. So, here probably that loop is going to look like this, something like this or let us say that loop is like this right. So, there the total current flowing is proportional to the number of turns not, the number of turns per unit length any more fine, and that length part is gone now.

So, the integral of this is going to be the size of the loop times, the field. Basically, the length of the path times the field that is going to be the integral loop. And, then you figure out what is basically, the magnetic field you have got at that radius and then, you compute for different radia in magnetic field then, you have to integrate the magnetic field that will give you the total flux fine, this is how it is. So, the inductance should be proportional to the square of the number of turns, roughly speaking; what is this r square doing here, where did this come from? This came from the flux phi r squared we multiplied by the area right. So, here what is this radius, the inside radius there radius of the core and then, mu naught by 4 is just a proportionality constant.

So, this is what we basically expect. We expect our inductances value to be proportional to the square of the inside radius should be proportional to the square of the number of turns and besides these 2 there should be a proportionality constant, some factor agreed this is the total value of the inductance, fantastic. If I have got your agreement on this then, let us proceed to the next step; what are the non idealities of this inductor? You have studied power systems, magnetic circuits long back maybe, in your first year as an undergraduate or a second year as an and a graduate. So, there is a magnetic core and there is a transformer you put a primary winding you put a secondary winding what are the different non idealities, do you remember? Anyone core loss and copper loss.

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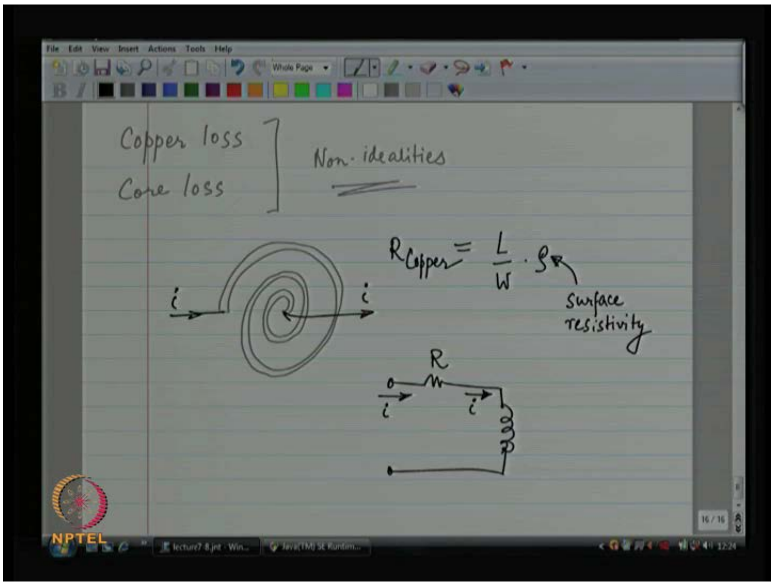

So, the same 2 things are going to apply over here. So, first let us do the copper loss, because it is easy to do it. I have got an inductor; the wire has resistance unavoidable wire has resistance. What is the resistance of this wire? You basically count the number of squares that is inside this track and multiplied by the ohms per squared that the foundry has given. So, the surface resistivity times the number of square that are in this that gives you. So, that gives you the copper loss.

So, the model for copper loss is basically, something like this, you have your inductor. And, the copper loss; if you are pushing the current i through the inductor then, the amount of the power lost in the inductor is going to be i times r squared, I am sorry, I square times i that is the amount of power lost in the inductor, which basically means; it is also associated with a voltage drop, right. It is as if this copper loss contributes a register which is in series with the inductor, it is easy to individually see that. The next item which is much more involved is core loss. What is core loss, what do you think is core loss? Not, everyone remembers what is core loss?

Now, let us go back to this 3 d picture. So, first of all how does this inductor work? I push a current through the inductor, when I have a current through the inductor it creates a magnetic field, magnetic field creates a flux through the inductor when I have a changing magnetic flux it induces an e m f or it induces of voltage to oppose the change of magnetic flux that is how the inductor works right. So, it does not like a change in e m f, change in flux. So, it generates an e m f which opposes the change in magnetic flux. Now, this change in magnetic flux is everywhere, it does not have to be just a change in magnetic flux through the inductor, magnetic flux does not like to change anywhere. So, let us say this is the inductor, the inductor itself does not like a change in the magnetic flux through it, but; other objects also do not like change in magnetic flux through them.

Say this is the inductor and this is my table over here. So, the inductor does not like change in magnetic flux, the table also does not like change in magnetic flux and both of them are going to create e m f that oppose any change in magnetic flux, right this is Faraday's law of induction. Now, let us look at the 3 d picture when I have this inductor, it is going to be over a ground plane.

So, I have got a ground plane that I had not drawn in this diagram, but; it exists. So, there is a ground plane underneath the inductor. What the ground plane are we talking about? We are talking about the substrate the p type substrate is hanging on underneath the inductor. The I C, the base of the I C is the p type substrate on top of it, somewhere on top of it, you are making your inductor constructing your inductor.

But the base of the I C is the p type substrate p type substrate is conductive material am I right. So, and also you are going to connect it to ground presumably. May or may not connected to ground does not matter, there is a plane. For now, this let us not worry about the ground business, there exist the plane underneath the inductor. And, this particular plane also does not like a changing magnetic flux through it whenever, there is changing magnetic flux is going to oppose it right.

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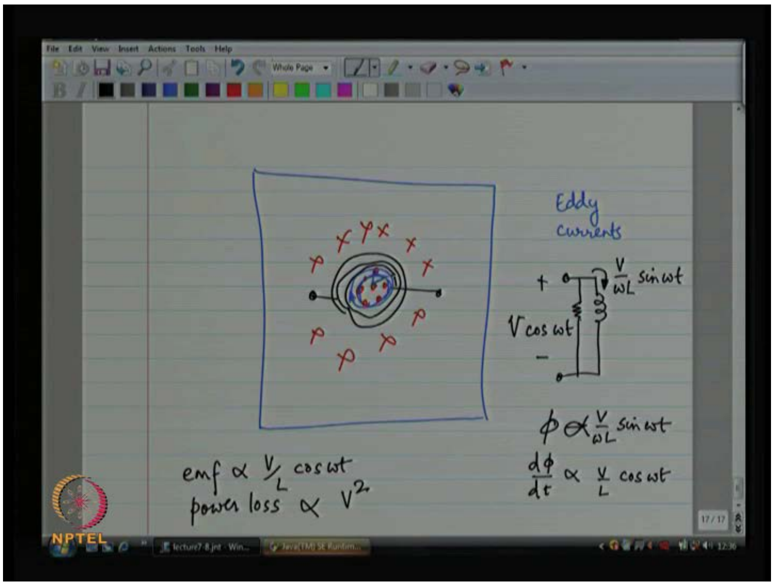

So, let us draw it in a different way; let us say this is my plane and this is my inductor. I am just going to draw 1 circle or think of it like a solenoid. And, the field there is some magnetic field inside and magnetic field outside. So, this is like an electromagnet and all of this field lines go right through the inductor hit the ground plane and then, come out and again go, it is like can electromagnet right.

So, now that we have this, what do you think is going to happen when I tried to change the magnetic field? When I change the current, magnetic field is going to change, when the magnetic field changes there is going to be a changing flux on the ground plane on the plane beneath there is going to be a changing flux. What is going to happen as a result of the changing flux, whenever you have a changing flux there is going to be an e m f, a potential that is developed as a result of the changing flux, right. You can kind of think of this as if.

So, let us say there is a look like this on the ground plane as changing flux through that loop right, and when there is changing flux through that loop there is going to be e m f developed across the boundaries of the loop. And, what is going to happen as a result of that there is going to be a current flowing around the edge of the loop. So, I am going to try to make this a little larger in size. So, this is the ground plane, and every time I have a changing flux I have a changing magnetic sorry, I have an e m f developed in the loop on the ground plane. And, when I have an e m f developed loop on the ground plane was going to happen, there is going to be a current on the ground plane. If there is a current on the ground plane, because of no reason I mean I did not want a current on the ground plane looping around like that.

But now, there is a current looping around like that on the ground plane these currents are called eddy currents. So, the currents looping around in the ground plane beneath the inductor. When there is current looping around on the ground plane that is going to be a loss in terms of power, think of it this way; you push you apply a voltage across the inductor. Let us say it is a cosine wearing at frequency omega radians per second. So, you apply this changing voltage across the inductor as results of this you are going to get a changing current.

What is the magnitude of the current? Now, the magnetic flux is proportional to the current right. Now, I think I am going to work with the sines and cosines, because; I like them something like this is going to be the current flowing through the inductor. Now, the current flowing through the inductor which is changing at the rate V by omega L no, there is a current V by omega L find omega t. So, the flux is going to be proportional to the current, the flux hitting the plane beneath is also going to be proportional that current. Now, d phi by d t is going to be proportional to V by L cos omega t right, that is your d phi by d t. Now, d phi by d t proportional to the V by L cos omega t then the e m f developed is proportional to d phi by d t e m f developed across that particularly is proportional to V by L cos omega t.

And if you have an e m f that you developed across a loop then you are going to have a current through a loop which is the e m f divided by the resistance of that loop. And, therefore; there is going to be power loss which is equal to e m f times the current fine. So, you are going to have power loss which is proportional to the square of the voltage that you applied across the inductor. So, effectively this is going to look as if, there is some sort a register over here, although it is not really taking out some current. It is actually taking out some current, because of leakage, flux leakage. So, almost there like there is a register which it is some of your current and creates a loss.

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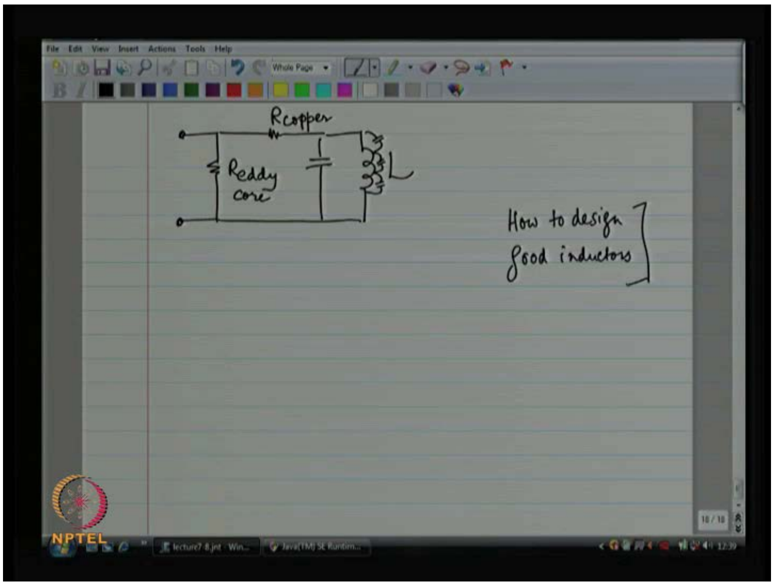

So, in your model for the inductor; you will have because of the core losses it will look like a resistance in parallel, because of the copper losses it look like the resistance in series. So, this says more or less some sort of model for inductor. What else are there any non idealities? Well this one obvious non ideality, if we talk about a plane now, beneath the inductor then, there is an inductor to plane capacitance, right. Is one more thing between every turn there is a capacitance, wall to wall capacitance right. So, all of this capacitance are really going to come inside this.

So, the final model for the inductor is going to be pretty complicated, depending on how well you want to simulate your inductor or how well, how accurately you want to model the behavior of the inductor. Your model is going to be very complicated. The copper loss and the core loss; copper loss in response to the series resistance that you see, core loss is going to appear as a parallel resistance it is just a loss is not a physically connected the loss associated with core loss is not physically connected to the system, but it still going to heat up your power right. And, then there are going to be parasitic capacitance of all over the place. So, this is my final model for the inductor, we are going to stop here. In the next class we are going to see how we can design good inductor and then, we going to move on to next topic.

Thanks.