Electro Magnetic Field

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Lecture - 36
Skin Effect (Continued)

Good morning. Last lecture was a somewhat in coherent 1 where else I am trying to bridge from 1 set of concept to another. So, let me remind you what we discussed and go on to the important phenomenon of skin effect, we have started with the pointing theorem.

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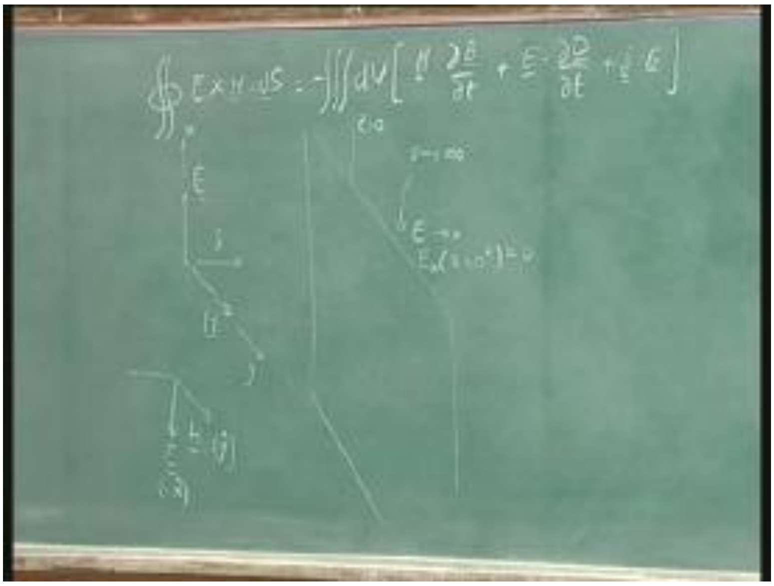

So, we had surface integral E cross H dot ds was equal to the various circuit losses or gains namely H dot del B del t plus E dot del D del t plus j dot E the minus sign. And as I have been saying for the last 2 lectures this is circuit theory this is waves. So, last lectures I looked at how a wave could interact with a circuit. So, what I gave as an example was you have your wave the electric field the magnetic field let say this is x this is y. So, x cross y is z and this wave we do not know how it got created, but we are going to see it see how it going to get destroyed where there it meets to the plate. And this plate initially I said sigma is very high tending to infinity, well sigma tend to infinity I must have electric field 0 inside the material. So, E goes to 0 which meant that Ex and let call this points z is equal to 0, at z is equal to 0 plus meaning just after entering the material must be 0. But at z is equal to 0 minus just outside the plate I have a wave and the wave definitely has non 0 electric field.

So, how can we do that? Well, I gave you the construction namely you can have a second wave which satisfies the same equations which is of this type the electric field up magnetic field the other wave in which case E cross x goes along minus z. This does not actually help us, but it tells us you can have 2 ways the forward wave and the backward wave. So, I am going to use this idea and I am going to try and achieve E is equal to 0 at the plate namely. I will take an electric field down which will cancel the electric field up and I want E cross H this way which means I have my magnetic field along the y direction. So, E is along minus x H is along y, where as for this E is along plus x H is along plus y. So, the electric field cancel magnetic field adds. Now, we will come back to this, what will look like away from this plate in a very short while, but let us look at the condition I would require at the plate of itself at the plate.

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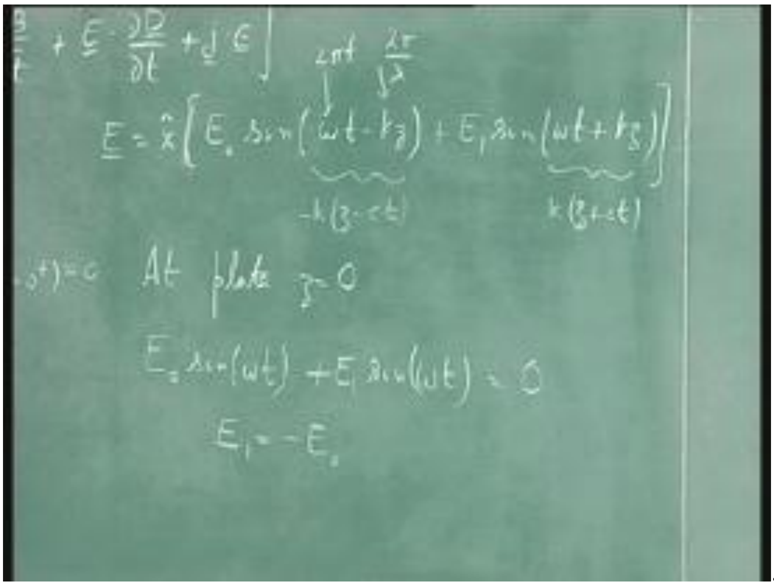

My total wave electric field is along the x direction it is some E naught and I am going to assume a sinusoidal wave. So, let say sin of omega t minus kz omega is nothing, but 2 pi f and k is nothing but 2 pi over lambda. So, we stick those in you find that this is nothing, but k times z minus ct, and you have a second wave plus an E 1 sin omega t plus kz which is k time z plus c. So, this is actually minus k this is the minus sign. So, you can see that the same wave solution have come out z plus ct and y minus ct, but I have made it. So, that z is equal to 0 I have only a function of time. Now, what happen at the plate at plate z is equal to 0. So, I can drop the kz and both this things and I need that the electric field goes to 0. So, I require that E naught sin omega t plus E 1 sin omega t equals 0; obviously, it only can happen if E 1 is equal to minus E naught. So, that is exactly that is what I have shown here, I have a reflected electric field a reflected wave. A wave go in a backward direction whose amplitude is exactly equal to the original wave, but in a opposite direction that is what the minus sign means. So, this is along plus x and this is along minus x this phenomenon where all the energy come and bounces is called reflection.

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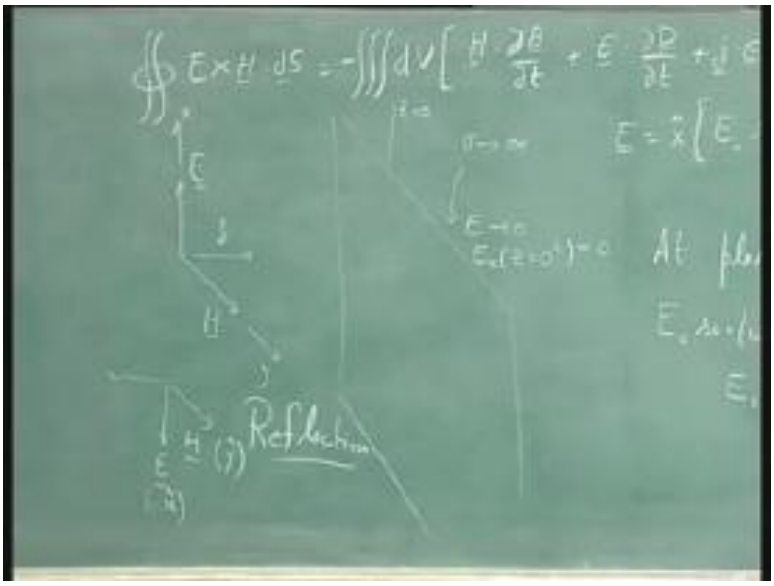

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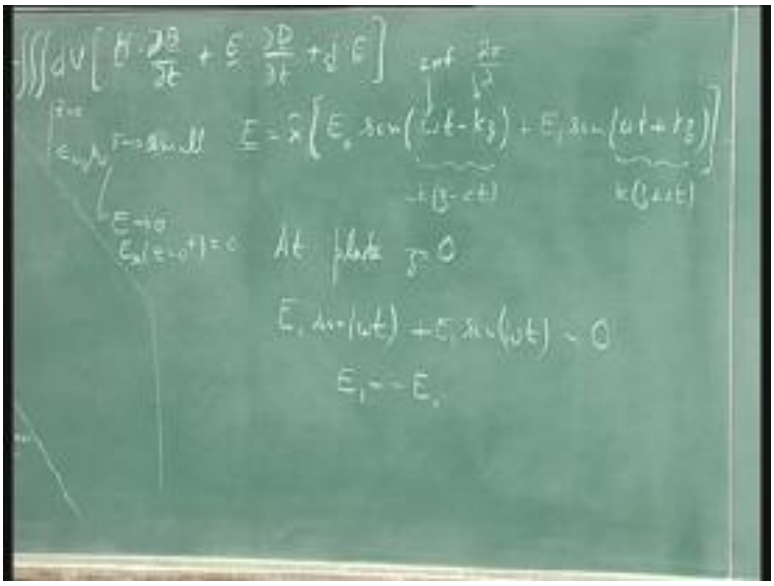

Now, let us take a second case, where sigma is not infinity. In fact, it is small and let us assume that we have epsilon naught and mu naught on the other side that is the this is the metal whose electronic and magnetic properties. Electric and magnetic properties are similar to vacuum, but which has the small conductivity. So, what is going to happen is that because sigma is small I can have an electric field inside this matter. And I know that the electric field is continues and I know that the magnetic field is continues except for a surface current. Now, because as the small sigma whatever electric field can come here can sustain only a small j because sigma e is j.

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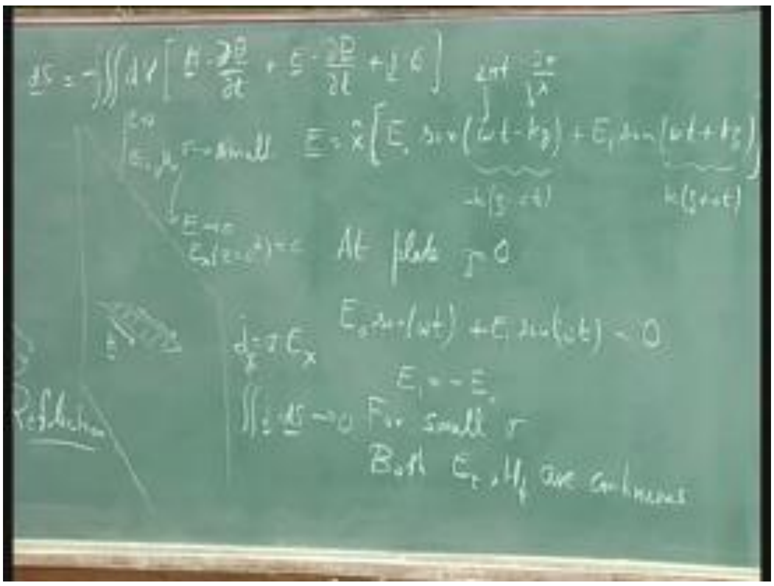

So, the amount of magnetic field let just inside the plate and just outside the plate has to do with this is the vacuum magnetic field, this is the magnetic field just inside the conductor. These 2 are related by the amount of current let us coming through this loop, but because j is limited to jy where thus look like jx is equal to sigma Ex. Since sigma is small and E is limited to whatever it is according to the wave jx is small. So, as I make this loop very small the total current surface integral j dot ds goes to 0 which means magnetic field is the same just inside the material as it is outside the material. So, I have both the electric field and the magnetic field are continues, for small sigma both E tangential and H tangential are continues. What does that mean? It means if I am now looking at it side waves my electric field is pointing upwards magnetic field is out of the board.

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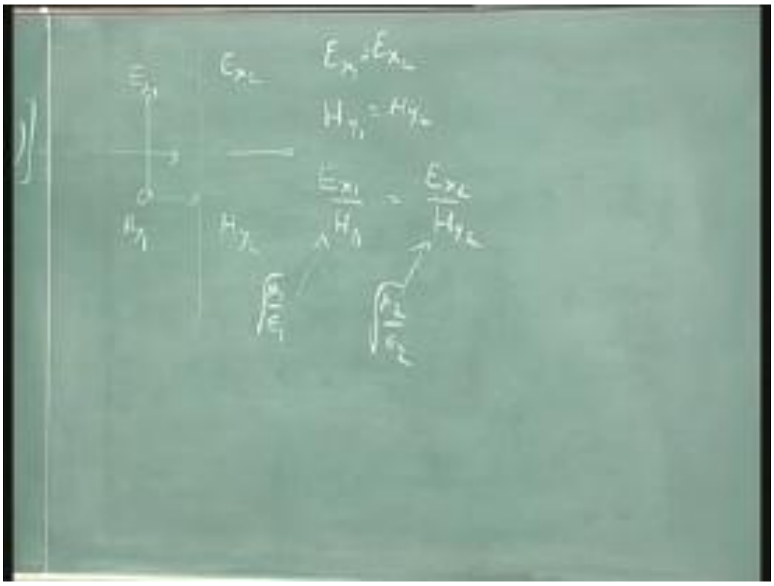

It has arrived at this plate I have that let say the electric field here is Ex 1 Hy 1 and inside the material it isEx 2 and Hy 2. Continuity of the electricfield means Ex 1 equals Ex 2 continuity of the magnetic field implies Hy 1 equals Hy 2. Now, this would not be possible unless Ex 1 over Hy 1 is equal to Ex 2 over Hy 2. Now, Ex 1 and Hy 2 Hy 1 are related we know that from the wave equation, because curl of E is related to del B del t. So, when we put that down we find that Ex 1 over Hy 1 is square root of mu over epsilon. So, in this case it will be mu 1 over epsilon 1 in this case it ismu 2 over epsilon 2. But in our case we have assume that the electric and magnetic properties are same in both sides which means this 2 ratios are the same. If you had the material where the electric and the magnetic properties changed abruptly this would not be possible. And we have come back to that case when we go back more detail to the problem of reflection. In that case what happen is not only to be have a wave coming in and getting into the material we also have a wave reflected alright. So, we now know that the electric field and the magnetic field are the same on the other side of this interface.

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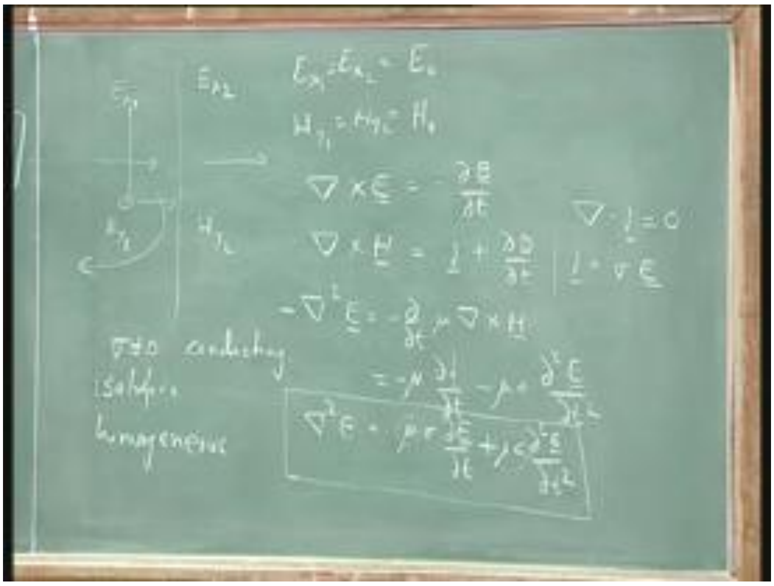

So, we know that the electric field here is mu naught magnetic field here is H naught derive from the wave equation. Now, what happen inside this material we gave to go back to the wave equation? And what we have is paradise law curl of E is equal to minus del b del t amperes law curl of H equals j plus del b del t and when we combine this 2 and as I told you last time we discard the charge density. We assume along with this that divergence of j is equal to 0 what that really saying is the wave is propagating in this direction to the right. The electric field is producing current in the x direction. So, if the current is in the x direction j is jx, but the variation is in the z direction as the function of z then divergence of j is equal to 0.

Therefore, there is no charge built due to this current it isa purely inductive current. It does not create any coulombs law effects, substituting we get minus del squared E is equal to curl curl E which is minus del del t of mu curl H, which is minus mu del j del t minus mu epsilon del squared E del t squared. Now, here is where simplify some more j is not only divergence free j is derived from E. So, j is equal to sigma E that because it isa conductor and in a conductor we know that the conductance current is related to the applied electric field. So, we can substitute that here and we get minus mu sigma del E del t minus mu epsilon del squared E del t squared. So, I can take all the minus sign out. So, you get del squared E is equal to del E del t plus mu epsilon del squared E del t squared.

So, this is the generalization of the wave equation in an isotropic conducting medium, I say that because first j sigma is not equal to 0. So, conductive and I say isotropic because otherwise you get funny effects when you write down mu and epsilon it is inside a medium. If the properties of the mediums are different in different direction it does not behave like vacuum. Then you can have strange effects and finally, you also pulled it out of a del del t and we pull the mu out of the curl of H. So, it is also homogeneous isotropic and homogeneous. So, we have all this conditions this is the kind of wave equation you get. Now, what I am going to do is I am now going to look for a solution that looks exactly like what we already solved. I am going to guess that the same solution will work even here.

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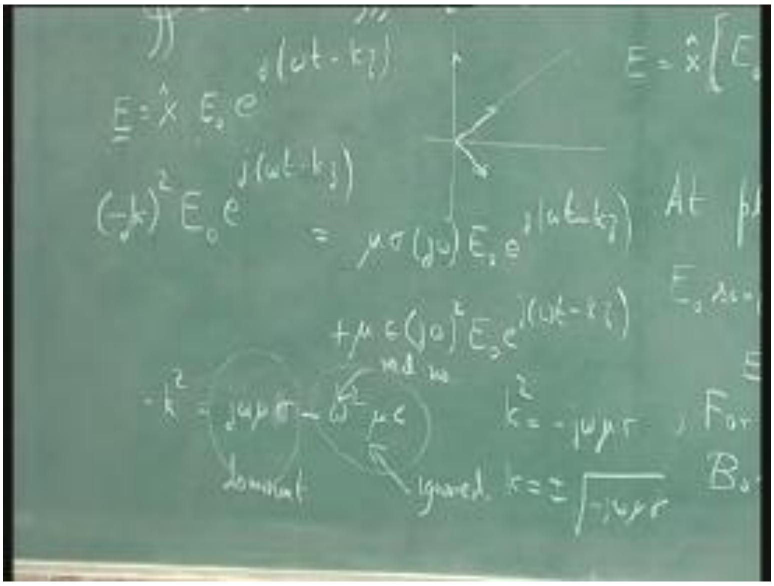

I am keeping the pointing wave theorem about because it is have guide to everything that in this part of the course. So, I am going to assume that the electric field is still x hat times E naught sin omega t minus kz I do not need the brackets I do not have any written field. So, I am not keeping the plus kz I am keeping only the minus kz. Now, it is it turn out to be much easier to deal with complex exponential rather than sines and cosines we saw this last time. So, instead of talking about sin and cosine I am going to do I am going to work with phasers e to the j omega t minus kz and the real electric field is the real part of this. So, it will are the imaginary part of this is we want sin. Now, I will substitute that in to that equation. So, del squared will give me minus k squared this is the left hand side. The right hand side is first mu sigma del del t is going to give me a j omega and E naught e to the j omega t minus kz and then plus mu epsilon del squared del t squared is going to give me a j omega squared. As you can see the electric field and it isspace and time dependence are common to all that terms in the equation.

So, I can remove them if I remove them if E naught is 0 I do not have a wave and the exponential can never be 0. So, I divide by through E naught E to the j omega t minus kz, I get looking at j minus k squared is equal to j omega mu epsilon sorry mu sigma that is this terms minus omega squared mu epsilon. So, I facted out the E naught e to the j omega t minus kz out of this equation. So, what left is minus jk whole squared that minus k squared j omega mu sigma that is here j omega whole squared is minus omega squared. So, minus omega squared mu epsilon. So, if you assume that I have real wave coming that omega that omega is given omega is the real number for this given omega. I can now solve for k and k is in general a complex quantity now there are different cases, but the case we will be interested in right. Now, is one where this term is much, much greater than this term is not the only interesting case, but it is one of the more important cases.

So, this is dominant and can be ignored it is good for decent conductors and very good conductors of electricity. If we instate we looking at the dielectric which is lossy then it will be the reverse the wave would be dominating again over the currents. But we are going to look at the case where the currents are dominating over the wave time. So, in that case we have a big simplification we can write k squared is equal to minus j omega mu sigma. I hope I have all my terms correct if there are any sin errors you can catch that. So, now, after solve for k and solving for k means taking the square root namely k is equal to plus or minus square root of minus j omega mu sigma. So, now I get an answer that gives me both real and a imaginary part. Because you can see that if I have a pure real imaginary quantity and I want to take it is square root it is in this state’s if it, where a pure negative imaginary quantity and I want to take it is square root in this direction. So, there is both equal amount of real and imaginary part respectively. Now, what does that mean? It means that this wave continues to be a wave there is a part which is real k. So, we write this in here what you will get the electric field E which is the function of z a.

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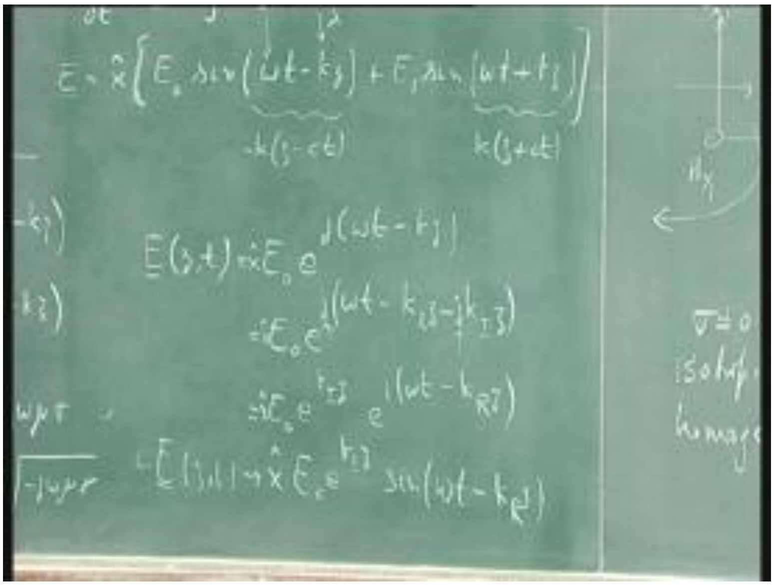

And t is equal to E naught e to the j omega t minus kz which can be written as E naught e to the power of j omega t minus k real z minus k imaginary times j z. So, if you now look at this expression we can see that there is a j here and a j here you combine the 2 j s j squared is minus 1. So, this become E naught times e to the power of k. Imaginary z times e to the power of j omega t minus k real z take the imaginary part of this, because we started off by with sins and cosines. So, since I started with sin I must take the imaginary part of this equation. So, the real electric field is call x direction the real electric field which is the function of z and t is x hat E naught e to the k imaginary z sin omega t minus k real sin.

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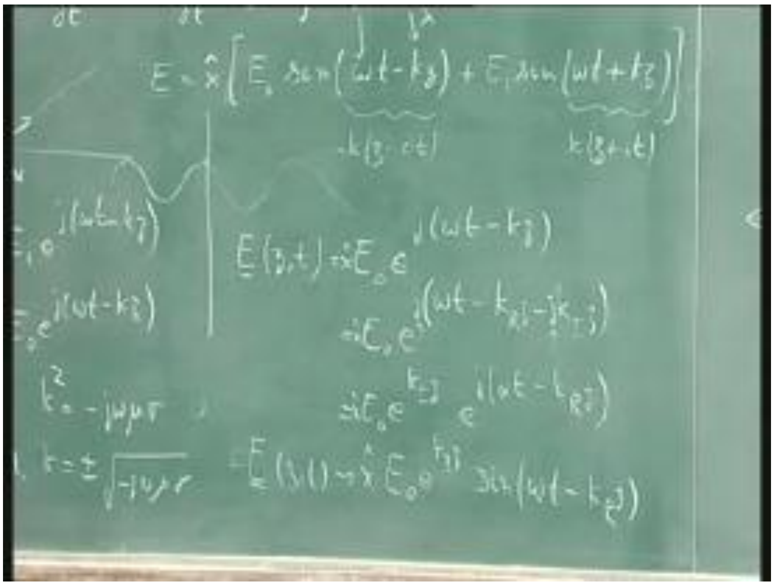

So, the sin omega t minus k real z is still there this wave which came to this interface continues to go through the beyond the interface, the value of k real is not the original value it has changed. So, this wave length is different from this wave length, but there is new term here there is the term which is e to the k imaginary z. Now, if you look at what k real and k imaginary are well according to this you have that it is going to be in this direction which means that I have a k real which is equal to square root of omega mu sigma. And a k imaginary is equal to negative of square root of omega mu sigma.

The real and the imaginary parts are equal because this is 90 degrees when you take the square root it will become 45 degrees or this equal amount of real and imaginary part. How much of each well you will get the magnitude is this, so you have a 1 over root 2 in each direction omega is 2 pi f. So, we were combine both those quantities I can write down the final answer, it is equal to the square root of 2 pi f over 2 mu sigma. And this is the negative of square root of 2 pi f over 2 mu sigma the 2 is cancel. And so you get this very important expressions, which is pi f mu sigma square root of, if you look at it here this expression is saying exponential of minus z times square root of pi f mu sigma.

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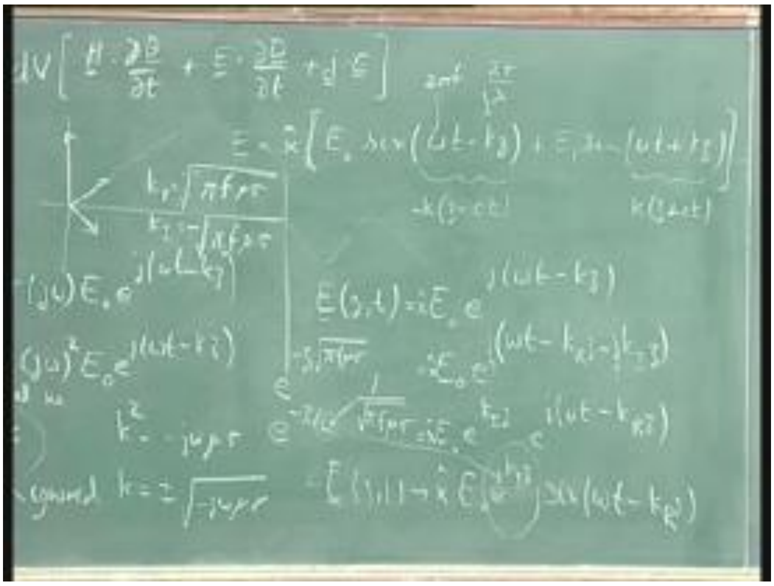

So, it is a decaying function e to the power of minus anything is a decaying function the amount by which the scale length on which it decays is 1 over this quantity. Because usually if you want to know the scale length of decaying exponential you will write it as e to the minus z over l and l would be the scale length. So, in that sense this l is 1 over square root of pi f mu sigma and this l has a name it is called a skin depth. Now, let us draw a picture and understand what this skin depth is saying.

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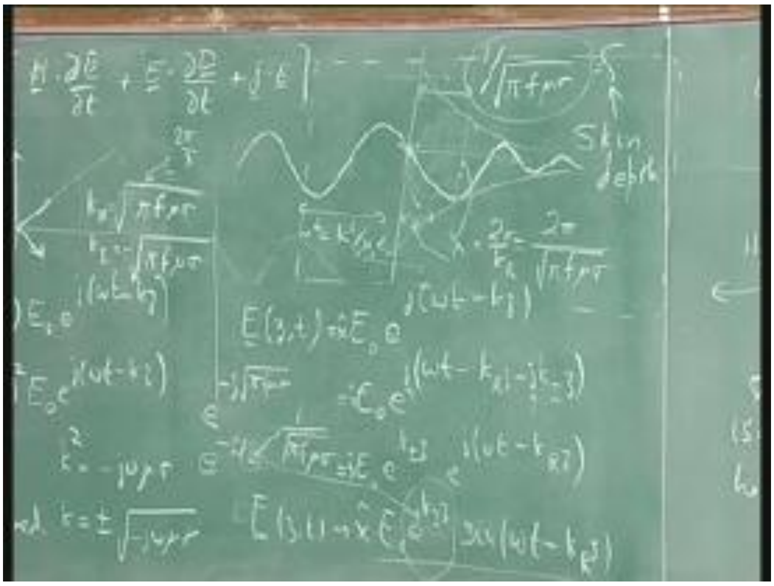

This is our solution and what it is saying is I have a wave that reach the plate once it reach the plate this wave length had in free space. This lambda was related to omega squared is equal to k squared c squared or k squared over mu mu naught epsilon naught. So, it is wave length has nothing to do with the material inside the material there is still a wave length, but this wave length is a different wave length, that is what it does. It has very short wave length comparatively speaking it is wave length in the material has to do with the, this k real because k real is nothing but 2 pi over lambda. So, lambda is if you take the lambda to that side and k to this side lambda is 2 pi over k real which is 2 pi over square root of pi f mu sigma. So, you can see that epsilon is vanished from this expression here the value of the epsilon was controlling the wave length.

It was this is speed of light the speed of light divided by frequency was wave length suddenly here the sigma that determines the wavelength and not epsilon. That is because we have assume that the wave part of the wave equation the omega squared mu epsilon is not important we only kept this time. So, naturally the wave you get out of it is not going to see epsilon at all it is only going to see sigma. The wave also decays and decays exponentially that comes from the e to the ki z, and it is decay on a length and what length is that that length is 1 over square root of pi f mu sigma. The same pi f mu sigma that you get coming into lambda the only difference is lambda is actually I have drawn it not correctly it decays faster than the wave length. So, I drew it properly it would not look like this it will look like the wave length is longer than the scale length it look like that. So, wave length would be this much, this would be my lambda and this is the scale length on which the amplitude drops to 1 over E of its value. But they are both related to this same quantity pi f mu sigma square root.

And, so it is this quantity which completely describes what is happening inside the materials and this is called delta which is the name given for the skin depth. Now, this delta has many important things about it and let us take them 1 by 1 probably the most important thing from our point of view is I have a wave of the form E cross H. That is transverse electric field transverse magnetic field moving in the third direction. We do not know what kind of object it is, but we do know that when it is hits a conductor it loses it amplitude. So, what it means is if I take a surface of this type I know that E cross H is always in the z direction. So, the sloping sides of the cylinders wont contribute out here the amplitude has gone down to 0 or gone down to a negligible value. So, this part does not contribute to either. So, this entire E cross H term is purely due to this surface.

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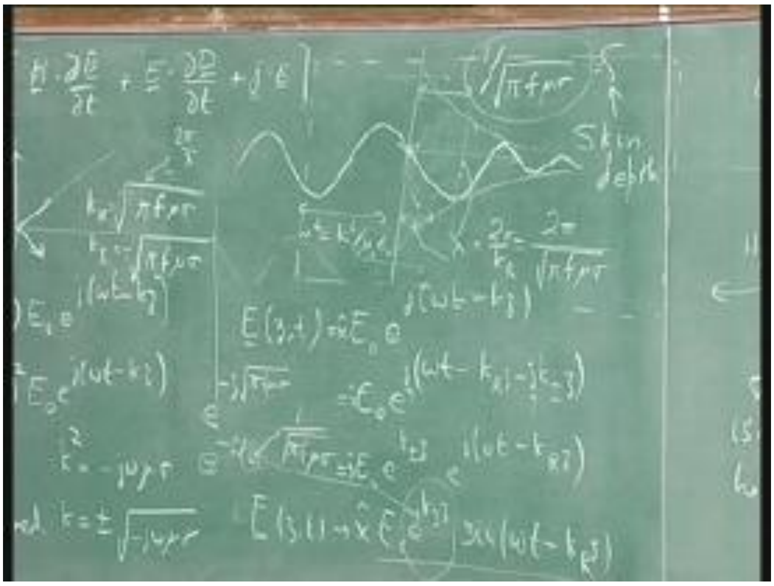

So, the E cross H term for our case will become surface integral.

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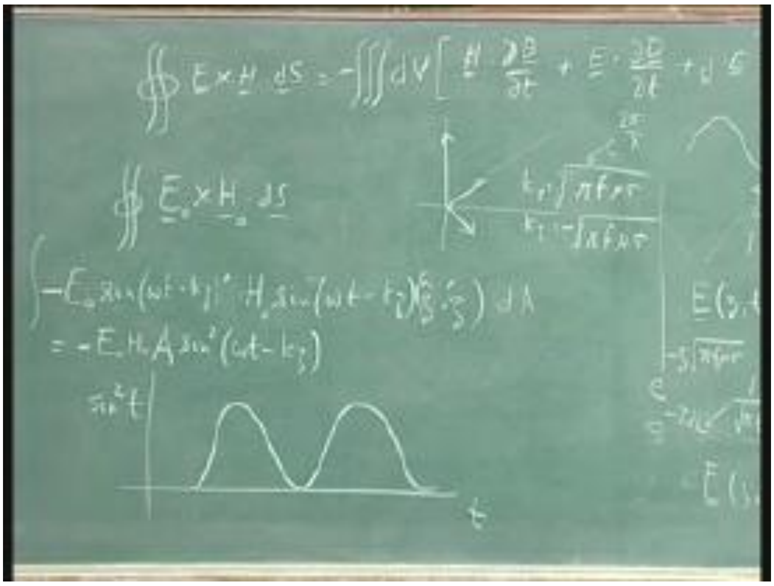

E naught cross H naught dot ds the incoming vacuum wave E naught cross H naught dot ds, because on the other side wave has gone to 0. This is some quantity we can work out what it is it is going to be E naught times sin omega t minus kz this is along the x direction times cross H naught we know that the function is the same type for H and E.

So, it is again sin omega t minus kz x cross y x cross y is z. So, we can pull the x cross and make it z hat dot ds ds is in the z direction, but there is a minus sign because the energy is entering the cylinder. Whereas, E cross H dot ds is talking about leaving the cylinder. So, there is overall minus sign. So, the, this is integrated over the area. So, what does that give me, gives me minus E naught H naught integral over the area.

So, there is an area times sin squared of omega t minus k z sin into sin, so sin squared. If I average this sin squared you know what you get that is just phasers let us plot sin squared this is the in time I am doing it. Because I fixed z z is where ever i put the surface this is what sin squared will look like. So, if I average sin squared omega t regardless of the frequency I know that my average is going to be half, because this piece is identical to this piece. So, whatever I loss on this part again on this part, so regardless of the frequency the average of sin squared is always half. So, if average over 1 time period this will go to minus 1 half E naught H naught times area. So, well known result to you I am sure because you know all about averaging of power.

But it is in important result it saying that if I have a plain wave energy is continuously entering this dotted line it is not averaging to 0. In fact, it is averaging to a constant value where is that energy going is not going out. So, this is energy that must be spend inside the volume integral namely inside my circuit here is just this plate. And the energy is vanishing into the material of the plate where could it vanish well my H dot del B del t is it is oscillating, but it is not growing or decaying. So, if that H dot dB dt is taking up any of this power it must continuously grow. So, it cannot be this E dot del t del t can be thrown out for the same reason. So, it has to be j dot E and j dot E is. In fact, what we have been doing because when we solve the wave equation.

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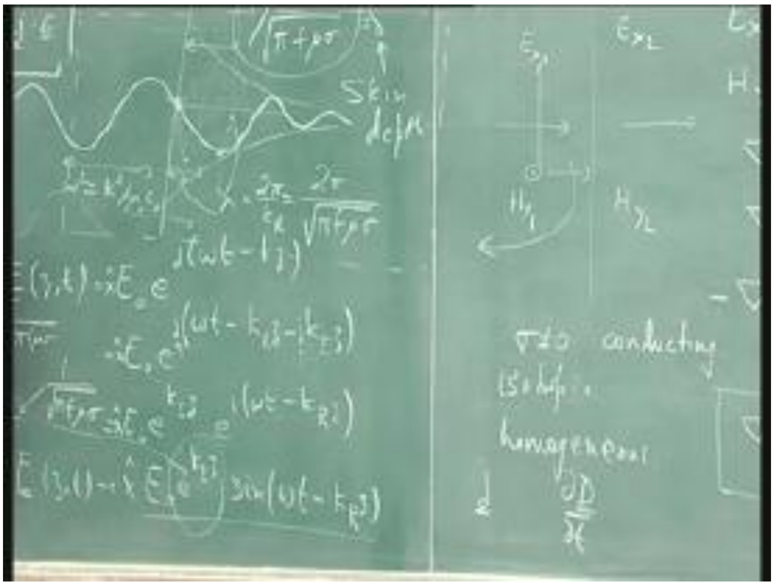

We were keeping the j term I supposed to keeping the del D del t term in curl of H it was the j term we kept and. So, definitely the current is the term that is dominating in this material. So, j dot E must be taking up all the energy where I am putting into this cylinder. So, it is represents the fact that this type of solutions we have been working on the 1 dimensional wave equations solutions carry energy. They deliver uniform power 1 half E naught H naught and integrated over area gives me total amount of power I am giving and that power is continuously dissipated inside this slap of metal. So, waves can interacts with circuits which means actually you think about it.

Circuit can generate waves because everything we have set we can reverse the phasers and instead I have j dot E be the source of the wave. So, if wave can decaying in metal the metal can also create a wave both are possible. So, this is what tell us that possible to have broadcast systems which possible to have an antenna that radiates waves and an antenna that observes waves. So, that is the most important thing that comes out of skin depth, but there is another thing which is equally important from point of view of a electrical engineering of circuits. And that has to do with how big is this number the skin depth we call it skin depth because it is some finite distance over which the wave is present. Now, the wave is present over a finite region it means this electric field is present over that region.

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And we know that j is nothing but sigma E which means current is also present only over that region. Let us try and look at some of the numbers for different material. I am first going to put down at table of conductivities it is in your own text book. But it is instructive to look at the numbers so that you can check them for yourself.

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The range of sigma is quite large; obviously, for vacuum at 0 now let us look at something which is the total insulator quartz. That silicon dioxide basically it is an excellent insulator it is units are more per meter or these days we call it us siemens per meter. Conductivity is the inverse of resistivity resistance in ohms resistivity is has a ohm meter it has a ohm meter in it and conductivity will be mow per meter. So, what do we get for quartz the number is 10 to the minus 17 siemens per meter. If you come to something more reasonable we look at distilled water it is a very good insulator actually distilled water is 10 to the minus four siemens per meter. It is very hot to get electrocuted by distilled water it would not happen. If you look at sea water 5 siemens per meter you can definitely get the strong sock if a your current flows and your touching sea water.

Now, let us look at some other more common conductors steal I am taking stainless steel here it is around 0.1 into 10 to the 7 siemens per meter iron I suppose rod iron is 1; 1 into 10 to the 7 siemens per meter a 1. If I take aluminum it is a very good conductor it is3.8 into 10 to the 7 siemens per meter and silver is 6.2 into 10 to the 7 siemens per meter. So, that is the range and the 1 hand you have excellent insulator that have 10 to the minus 17 siemens per meter and the other end silver which is 6.2 into 10 to the 7 siemens per meter. So, that is a range of 10 to the 24 in conductivity here is a very important point and is a point made in your text book, which is that if you look at magnetic material. And you ask what is the range by which a magnetic permeability varies you find that the magnetic permeability varies a lot.

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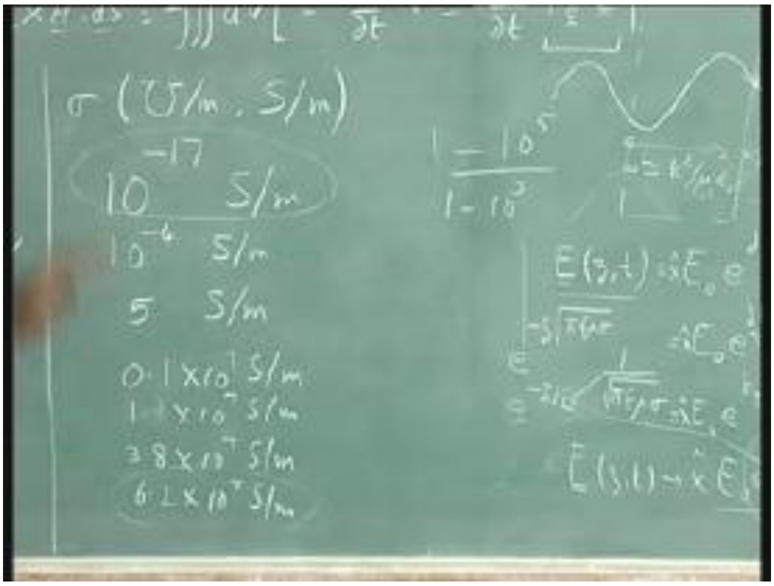

1 to the 10 to the 5 and the in useful range for cheap material is 1 to 1000, whereas here the range is of order of 10 to the 24 and this is the reason I mean this is the very

commonly use material quartz silicon dioxide it is part of all our chips is a part of all our circuit board on the other hand silver, silver is again part of all our electronic circuits. So, for practical materials we have the range of 10 to the 24 in conductivity for practical magnetic materials we have 1000 to 10,000. That is what we are actually able to talk about electric circuit kvl kcl and have it agree with experiment. Whereas, when we talk about magnetic circuits we have to continuously keep in mind that is always something you will call leakage plex. The reason is magnetic circuit are not as good circuits as electric circuits are good circuits. Now, what is this mean for your skin depth? Skin depth is in meters.

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Now, we can easily work out the numbers because for almost all this materials mu is mu naught. So, this is equal to 1 over square root of pi f mu sigma where mu can be replaced by mu naught, but otherwise mu is basically mu naught. So, when you work out these numbers for you have to choose the frequency. So, I will give you the formulas that are there in your text book there is no point calculating these things you will not learn anything tremendously from them. So, for a frequency of this for sea water at 1 mega Hertz the skin depth at you, come up with is 25 centimeters at 10 Hertz, the skin depth is 80 meters this is in sea water it has to 10 over square root of f. So, you can see that if 10 Hertz it is 80 meters 1 Hertz is 80 times square root of 10 meters. Now, the same number if you do for copper I have not got it got copper here copper is about 3 it is between aluminum and gold and silver.

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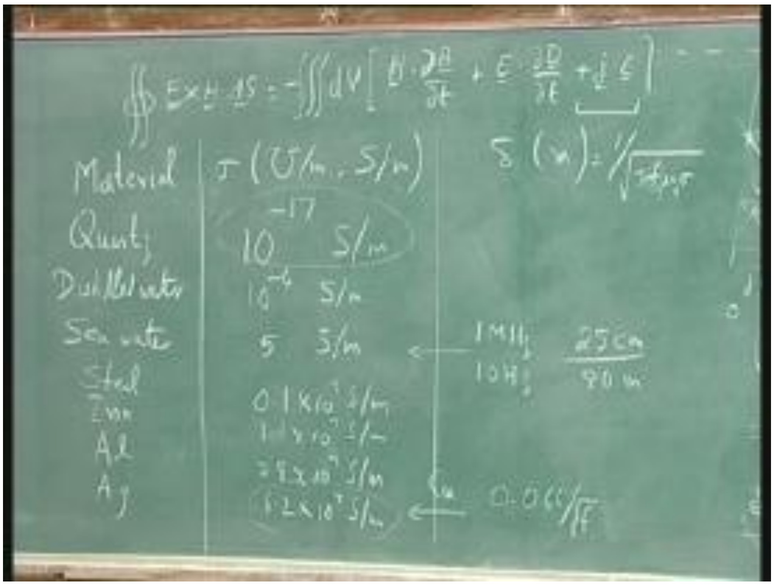

So, for copper the number is 0.066 divided by square root of f as you can see that is all you need to keep all this number can be worked out sigma itself is 5.8 into 10 to the 7. So, it is essentially that of silver. Now, what is this number mean in practice? Well there are important cases. So, let us put those important cases down for 50 Hertz actually the number equals for 60 Hertz does not matter at 60 Hertz.

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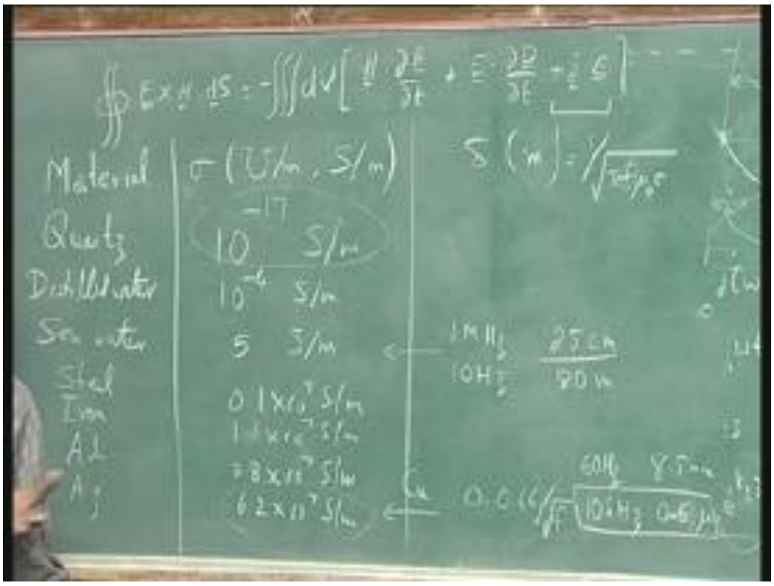

The number you get is delta equal to 8.5 mille meters at 50 Hertz it is slightly larger, but not much larger. So, the skin depth in copper at 60 Hertz is less than 1 centimeter at 1 megahertz well at 10 gigahertz is the number is given the number is 0.06 microns sorry 0.6 microns. So, these 2 numbers should tell you quite a bit. So, let look at this 4 number and see what we can learn from them first of all if you look at this number. This is where we are talking about rf circuits when you talk about satellite transmission we talk about high speed circuits gigahertz is the ring. And look at the skin depth at gigahertz it is less than 1 micrometer since the skin depth is less than 1 micrometer.

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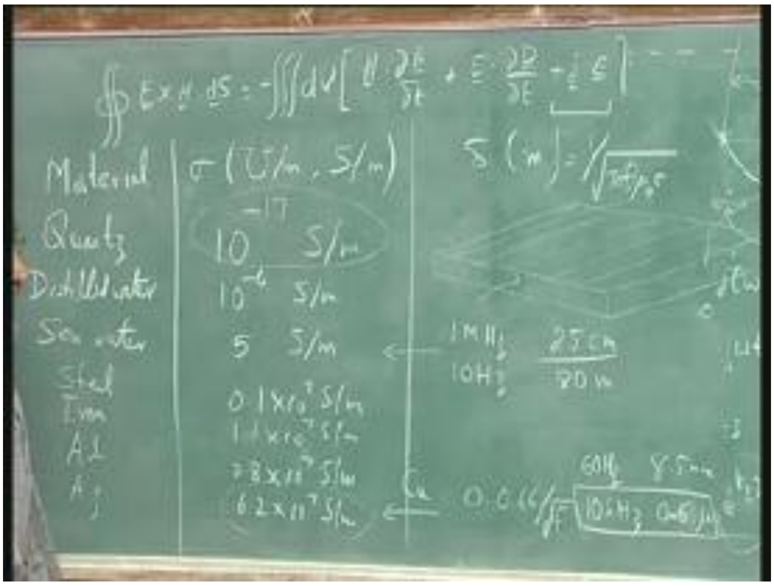

When you make a pcb for rf purposes it is mainly a dielectric it is somewhat high epsilon on top of which you have coated silver or copper. This coating does not have to be very thick, because you know that all the current is going to set at essentially the top micron of that coating. So, that coating can be very very thin. So, this frequency and the amount of skin depth at that frequency defines the kind of size of your pcb are your chip when you look at this number 60 Hertz 8.5 mille meters. That is talking about something different you look at your power conductors you know that usually.

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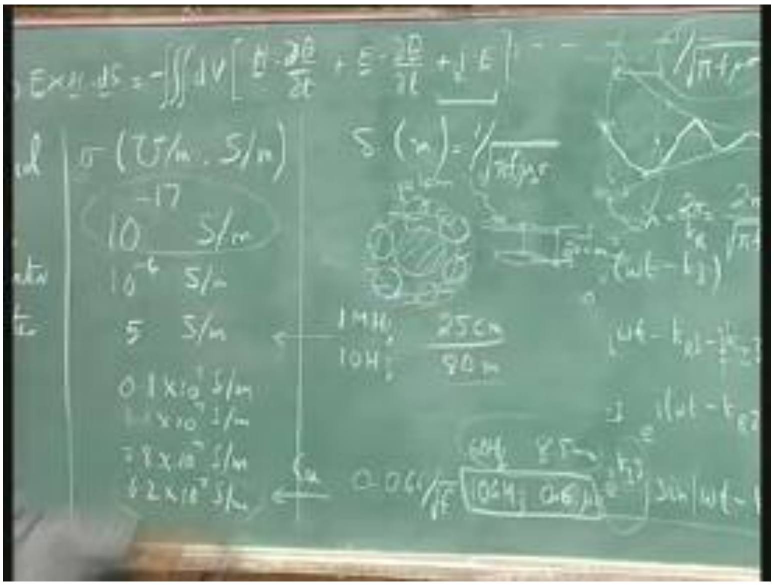

You have a central strength member and you put your current carrying copper around it. Now, why do we do that? Because when you have current flow through all this copper wires they share the electromagnetic field so much. So, that the total current flow through all of this together create the magnetic field and the combined charges that the magnetic field in turns creates the electric field that threads all of this cables together. So, we can actually consider this entire structure has an electromagnetic wave and electromagnetic field does not see individual cables. It sees this entire cylinder as it surface and what this result tells us is that only a region of about somewhat less than 1 centimeter of out of portion of this structure carries current. So, this current carrying current region is of the order of 1 centimeter the rest of it is not carrying very much current.

Therefore, there is no point having full lot of expansive copper in a middle of this cable. Instead what we do is we put a strength member there a steel rod which gives the cable it is strength. And we just pack copper cables all round it also comes from the same theory that gave us the skin depth of 10 gigahertz or if circuits. And this should tell you something about the universality of this theory. It applies to 10 gigahertz it applies to 60 Hertz it will apply to 10 Hertz. Now, let us look at this other 2 numbers. Now, see what is the very good conductor is not good as metals, but you can see that in comparison to insulators it isa very good conductor. But consequence of being a very good conductor is that at 1 megahertz the skin depth is only 25 centimeter which is 1 foot. Now, if you have see and you have a submarine traveling under the sea. The height is certainly more than 25 centimeters, which means that any kind of broad cast coming towards the submarine which going to get observed in the first meter or, so of the sea water, no signal is going to reach the submarine this is the big problem.

And in fact, it is 1 of the biggest problem of submarine communication. And the way they solve it is that they use very low frequency signal to communicate with the submarine. As the frequency drops the skin depth increases and if you happen to be within a few skin depth of 80 meter which means if this distance is within let say 200 meters then the signal will reach the submarine. The problem of course, is at 10 Hertz the amount of information that you can transmit for second is very low that is alright. Usually if you need to communicate with that submarine, what you want to tell it is listen to me. I have something important to tell you and then the submarines comes close to the surface and then you can use one megahertz transmission to give it to the actual information. So, it is all of this concepts whether it is wave propagation in the sea or wave propagation in copper they are all talking about the same effect namely when a signal enters the materials.

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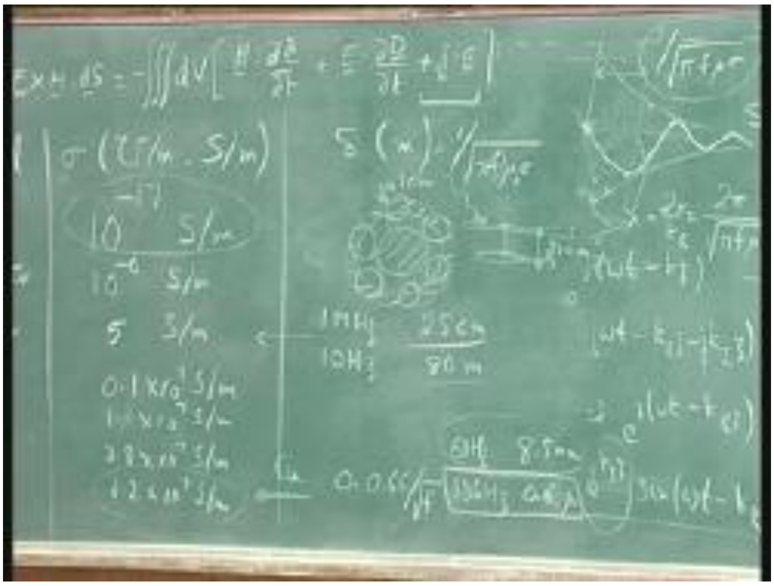

It does not attenuate completely instate it becomes partially transmitting and partially attenuating. The kind of signals that you will see is this right the amplitude is exponentially decaying, but it have a wavelength. The only useful region over which the signal can be detected is what is called the skin depth and this skin depth depends strongly on sigma, because it has 1 over pi f mu sigma. Now, if you look at the sigma values for different materials it varies from extra ordinarily small numbers to very high numbers. And as a result this values we call skin depth also varies you can imagine that if at 5 more for meter at 1 mega Hertz is 25 centimeters. What it is in silicon and that is why in fact, if you use silicon as your optical fiber communication in which goes 1000s of kilometers without getting attenuation. It is all the same subject and is important to realize that once we have completed Maxwell's equations and have all 4 equations is in the full form. All these ideas apply equally well, to core electrical engineering as well as to communication it is not like this. There is 1 electromagnetic for communication engineers and 1 electromagnetic for machine engineers it is the same electromagnetic it is the same electromagnetic. That talk about power systems and it is same electromagnetic that talks about rf circuits.