Plasma Physics

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Module No. # 01
Lecture No. # 40
Surface Plasma Wave

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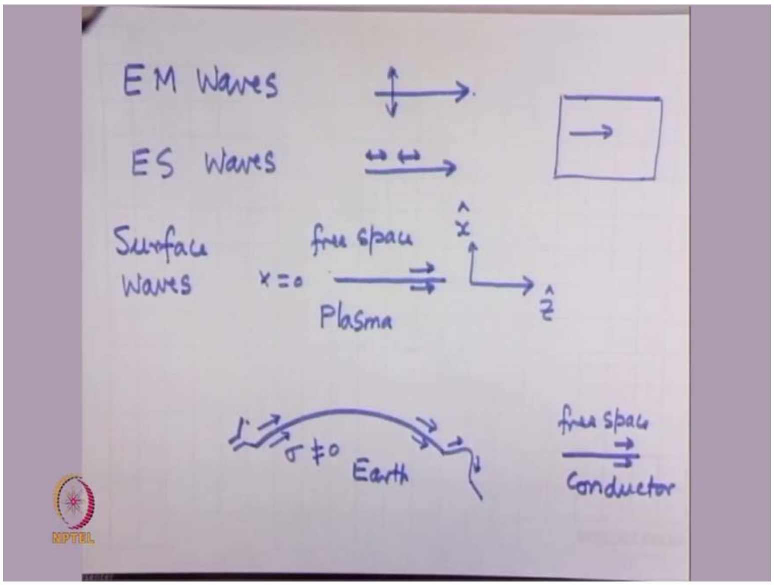

Today, I would like to talk to you something different than in our earlier lectures. In our earlier lectures we have been talking about waves that have been promoting through the volume of a plasma and these could be electromagnetic waves, which are transverse waves like this, this is the direction of propagation the electric field is transverse or electrostatic waves, which could be longitudinal so, they are traveling in this direction then the electric field oscillates like this.

But these waves are traveling inside a plasma, which is the bulk of the plasma so, these waves travel in these region, well they are also influenced by the boundaries and the boundaries are closer to the wave propagation.

However, the effect of boundary is not that significant on the character of these waves. Plasmas also support a particular kind of mode that travels from surface suppose, I consider a boundary between a plasma, and free space, and let me call the direction here as z, and this direction as normal direction is x.

Then, there is a possibility of a wave propagation along the surface, and this wave is sort of an electromagnetic wave but, it is a little complex structure. That the electric field of the wave has a component in the direction of propagation as well as in the normal direction, and the amplitude of both components are maximum on the interface, on the surface separating the two media, let me call this surface is x equal to zero.

So, this is a very particular kind of wave, which influences or which is influenced by the properties of the medium near the surface. And what happens to the near, far away from the surfaces is not that significant, obviously this requires sharp boundaries. Such sharp boundary plasmas are difficult to form, to create in laboratory but, with (()) ionization one can certainly create plasmas with very well define boundaries.

However, from the perspective of plasma physics one can treat conductors, semiconductors and even the soil as sort of a conducting medium so, any conducting medium which has finite electrical conductivity can support this kind of wave. Traditionally, it was during may be 30s, 40s, 40s rather, when people were thinking of radio communication at medium frequency waves, people recognize that if earth is a curvature like this, then there an, earth is a finite conductivity, which is non zero, then medium frequency waves can travel as surface waves and they can be guided by the curvature of the earth so, as the earth bends they will also bend.

And if there is a mountain somewhere here on the surface of the earth then, these waves will climb the mountain and get down from the mountain. These are very special kind of waves, which are primarily guided by the surface of the material, surface of the conductor may be earth in this case.

And they could be very useful for radio communication, the reason is that if I have a antenna placed here suppose, I have an antenna placed here, if there were no earth this these waves will be traveling in this direction they will not bend so, they will travel as a sky waves and they will hardly bend, but if there is a conductor here (( )) are excited as a surface wave, then as the earth bends they can bend and their propagation has been recorded up to a distances of several thousand kilometers, and the attenuation is also not very large. So, that is a beautiful example of surface wave being employed for communication, these waves are called surface waves in communication jargon but, in plasma physics they are known as surface plasma waves.

In last thirty years lot of interest has been generated on these waves, especially the waves propagating over the surface of a conductor like gold or silver and free space. So, these waves are guided along the surface, they penetrate just very little a fraction of a micron inside the conductor, and they expand a few microns in free space, and they are so much influenced by the presence of any contamination placed on the surface of the material that, their propagation constant is influenced and these can act as very good censors so, there is a great advantage of employing these waves for censor applications.

I think, before I delved into the applications, I would like to talk to you in some detail about the nature of these waves, how do they propagate? What is the phase velocity? What is their model structure? And so on.

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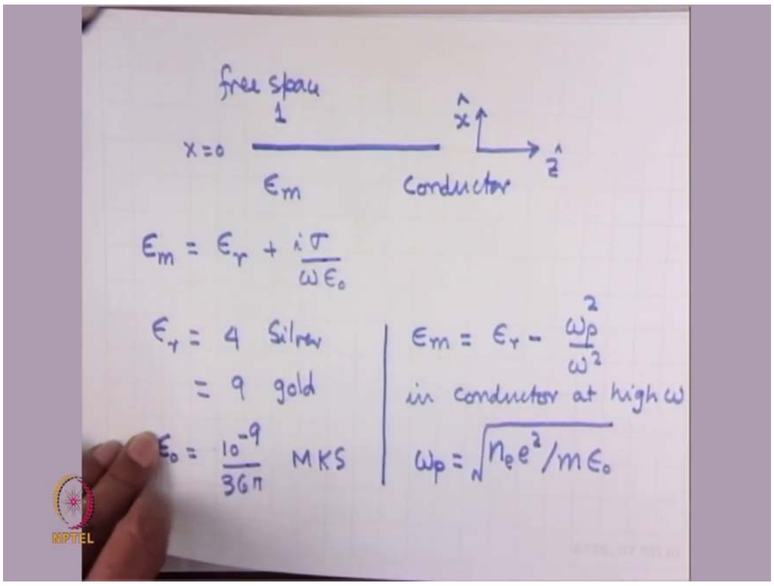

So, let me address the issue of surface wave is a guided wave. I am considering a conductor here it could be a plasma, it could be a soil or it could be a metal. I will call this as conductor or semiconductor, and characterize this by effective permittivity epsilon m, and this is free space here on top, and I will be characterizing this by a effective plasma conductivity permittivity like unity. And I will be using a coordinate system with this as my z axis, and vertical direction as x axis, this is my x equal to zero plane.

You know, if I am taking of propagation of a wave of frequency omega then, conductor permittivity, effective permittivity is epsilon r plus i sigma upon omega epsilon 0, where epsilon is called the relative permittivity of the material, of the conductor, for instance epsilon r is 4 for silver, epsilon r is 9 for gold, 4 for silver, 9 for gold and so on.

Sigma is the conductivity, electrical conductivity, for earth sigma is typically of the order of 1 unit in M K S unit one. Epsilon 0 is free space permittivity, which is 10 to the power minus 9 upon 36 pi in M K S units, sigma is the electrical conductivity.

Now, in case of plasmas this expression simplifies, even conductors that simplifies if I put the expression for conductivity and ignore collisions then, epsilon m is equal to epsilon r minus omega p square over omega square in conductor at high frequency.

If collisions are ignored one includes collisions then, there is a factor here that can be multiplied but, lot of interesting physics can be understood if I take this real expression for epsilon m.

Now, first of all let me develop a formalism then, we will put this actual expressions for epsilon m, one might certainly recognize that, this quantity depends on frequency, omega p is the plasma frequency which is related to the density of the conductor, if it is there are free electrons there then, omega p is related to free electron density as n e, e square upon m, epsilon 0 under the root this is called the plasma frequency.

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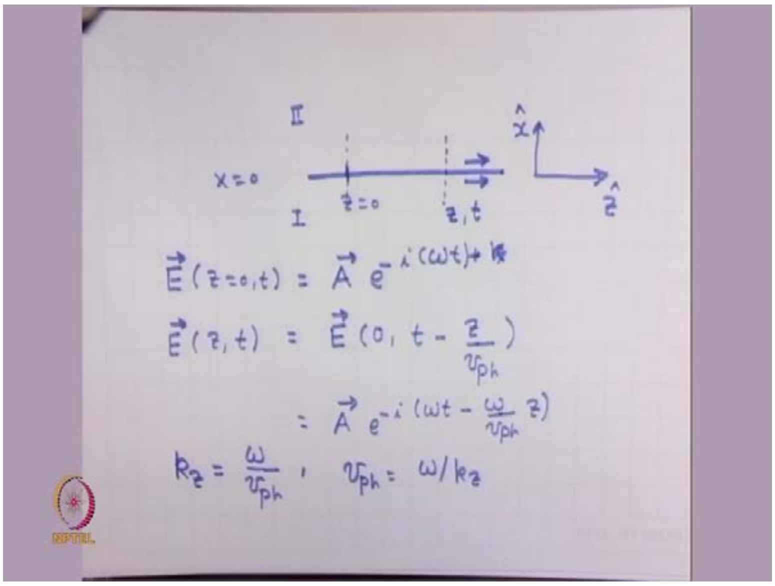

Now, let me consider the propagation of the wave. This is my interface with z axis here, x axis there, x equal to 0 is the dividing plane, I will call this medium one, medium number two, and suppose this is my point z equal to 0 rather, I will consider this z equal to 0 plane then, I look for wave propagation, I say that the electric field of this wave which is traveling as a z direction. Whatever is the field here at z equal to 0 at time t suppose, I choose that my electric field at z is equal to 0, at time t is sinusoidal of this form a exponential minus i, omega t minus k sorry, omega t this is the sort of variation I am presuming.

Suppose, I consider the electric field of this wave to be having time dependence of this form actually, electric field is the real part of this means a cos omega t, and I say that the same field is appearing here at z position at a later time. My issue is that the field at z, at time t, I would except to with the same at E as E at z equal to 0, at a earlier time t minus that time signal takes to travel from z equal to 0, to z equal to z, and that is z by v phase, where v phase is the velocity of signal propagation.

So, if I put this in this expression this becomes is equal to a, exponential minus i, omega t minus omega upon v p h into z. I use a symbol omega by p h, v p h as k z. Conversely, I can say that the phase velocity of the wave is omega by k z so, if I use this signal then I say that a, for a wave that propagates without distortion, because this field will have a r dependence also, x y dependence also, same x y dependence is it here, if it is same as reproduced here at a later time.

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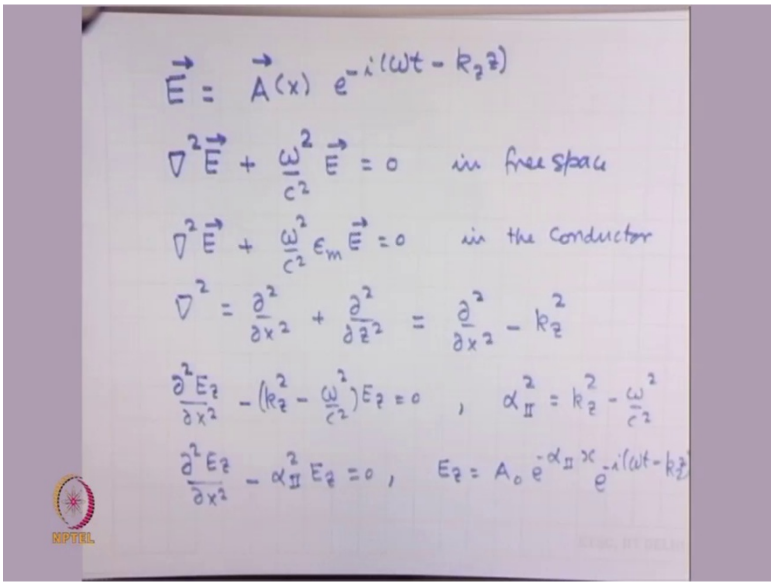

Then the field must have this sort of delayed response, and hence we assume that my electric field of this wave is written as some amplitude, which is a function of x, y dependence i neglect saying that the field is uniform in y direction, exponential minus i omega t minus k z z, this sort of t z dependences guaranties that the wave is maintaining its x profile as it travels.

The issue is that, if my electric field depends on a, on X, amplitude depends on X then, it must satisfies wave equation. Wave equation for the electromagnetic wave is del square E, plus omega square by c square E equal to 0, in free space and inside a medium, conductor medium is del square E, plus omega square by c square, epsilon m into e is equal to 0 in the conductor.

This equation is true for x component of electric field as well as z component of electric field, let me write down this for z component of electric field, and when I say that del square is d 2 d x square, plus d 2 d z square but, we have already taken z dependence of the field whether in free space or in the conductor to apply this form so, I will replace this delta delta z by I k z and this becomes d 2 d x square minus k z square.

Because this as to operate over the electro field, which has a z dependence of this form so, this will become like this. So, let we write the field inside in the free space it would be like d square, E z by delta x square, minus k z square, minus omega square by c square, E z is equal to 0, in free space and this is a constant quantity so, I would define this as alpha 2 square is equal to k z square minus omega square by c square.

Then, this equation can be written as d 2 E z by delta x square, minus alpha 2 square, E z is equal to 0, and the solution I can write down as E z is equal to some constant say a 0, exponential of minus alpha 2 x and this dependence is explicit so, I have to write it exponential minus i, omega t minus k z z.

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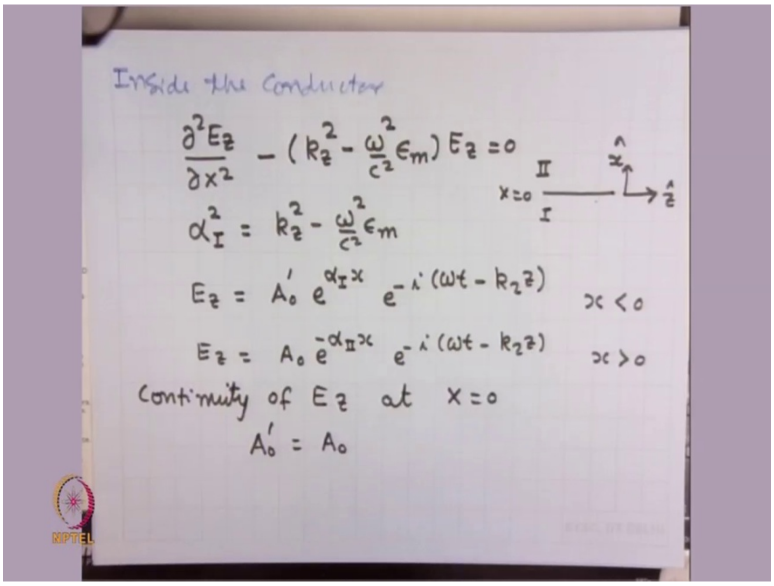

So, this is my electric field of this surface plasma wave in free space, its similar excise I will do to solve this equation, again replace here del square by this quantity like this, then my equation for E z in the lower medium would be, inside the conductor I would have del square E z by delta x square, minus k z square, minus omega square by c square epsilon m, into E z is equal to 0, I will call this quantity as alpha 2 square, alpha 1 square in the lower medium as k z square minus omega square by c square epsilon m, please recognize that I am talking of this geometry this my z axis, x axis, x equal to 0, and this is medium number one, this is medium number two, free space is have up metal or conductor is underneath.

Solution of this equation can be written as, which behaves well, correctly for x tend into minus infinity, the field should not got to infinity it should be well behaved solution then, this would be A 0 dash some constant, exponential of alpha 1 x, exponential minus i omega t minus k z z.

Please recognize this is for x less than 0, for x bigger than 0 my solution was E z is equal to A 0 exponential of minus alpha 2 x, exponential minus i, omega t minus k z z, this was for x bigger than 0, minus sign is written purposely so that, when x goes to plus infinity have up then the field should not go to infinity, should go to 0, this is the well get solution.

Continuity demands that E z is tangential, E z is the resistive component of electric field, this should be continuous at this interface so, continuity of E z at x equal to 0, this is the interface, it demand says that a 0 dash should be equal to a 0, put x equal to 0 here both everything is same except this term this is the quantity.

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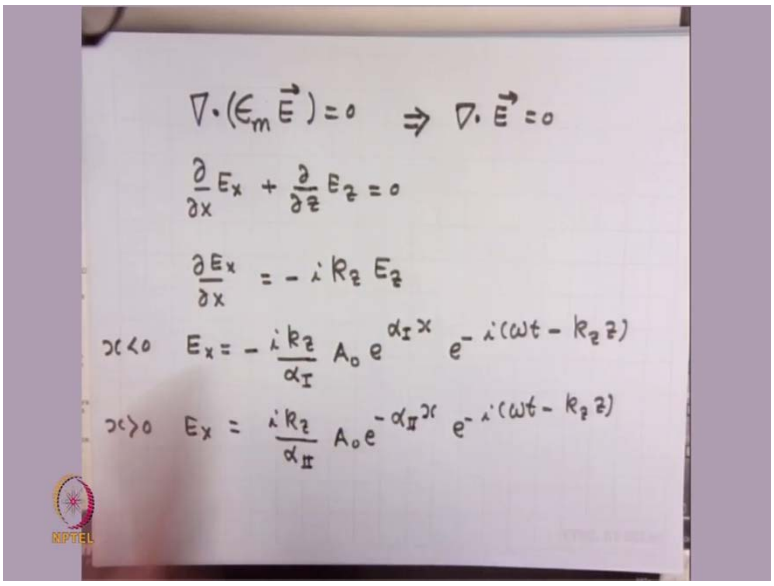

However, to obtain E x either, we solve the equation for E x or a easier ways that go to first maxwell equation, which says that divergence of epsilon m into E is zero, where epsilon is the effective material permittivity for free space this is unity, this is the important condition, del operator we are taking to have only x and z components so, this equation tells me and epsilon m is a constant in a particular medium, whether you are considering free space or conductor this is a constant so take it out.

So, this is we will satisfied when divergence of E is 0, this equation implies delta, delta x of E x, plus delta, delta z of E z equal to 0, delta, delta z I have already written as i minus as i k z so, this tells you that delta e x upon delta x, is equal to minus i k z, E z. One can integrate this equation and because x dependence of this is exponential, this gives you straight way E x is equal to in the lower medium, this will give you minus i k z upon alpha one, and then this will be a 0 exponential of alpha 1 x, exponential minus I, omega t minus k z z, and this is for x less than 0.

For x bigger than zero the same thing will integrate to give you, for x bigger than zero this is equal to, E x is equal to i k z upon alpha 2, A 0 exponential of minus alpha 2 x, exponential minus i, omega t minus k z z, interesting part here is that at x equal to zero this E x is different then this E x, they are not equal E x and the signs are also different there is a phase difference of pi.

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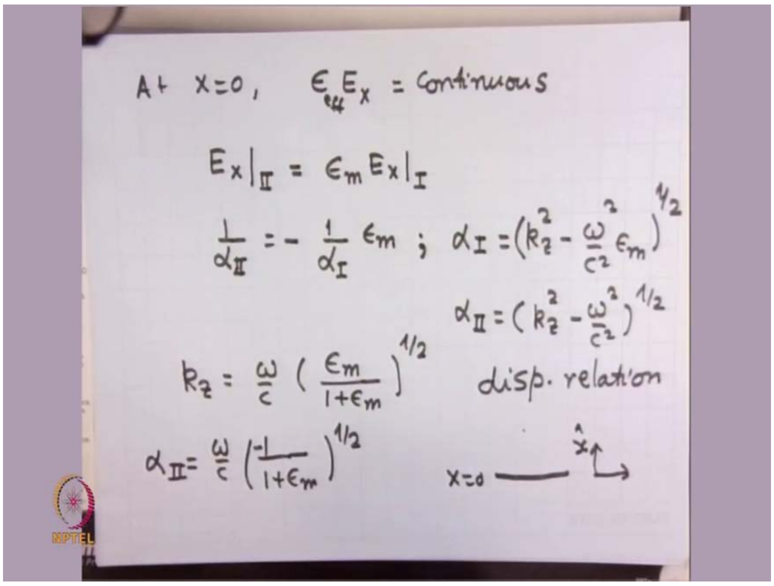

Another important thing is that at the boundary normal component of effective dispersant vector should be continuous, at the boundary which is X equal to 0. Epsilon into E x should be continuous, this is the effective relative permittivity of the medium multiplied by E x, which is called the normal component of the displacement vector, should be continuous in free space the value is unity so, I would say that E x in the second medium should be equal to the first medium or lower medium the value of this quantity is epsilon m into E x in the first medium.

If I use the earlier expression, I will find that every at X equal to 0 every term is cancels out, except you will get one upon alpha 2 here is equal to minus, 1 upon alpha 1 into epsilon m. Now, what we can do and recognizing that alpha 1 is k z square, minus omega square by c square epsilon m, and alpha 2, well under root of this quantity and alpha 2 is k z square minus omega square by c square under root.

Recognizing this v square both sides so that, under root signs are removed and this equation can be solved, and this give you k z is equal to omega by c, into epsilon m upon 1 plus epsilon m to the power half, this is the dispersant relation for the surface plasma wave.

What we recognize, that if the field amplitude has to decay above from the interface recognize that, this is my interface x equal to 0, and this is my x direction vertical direction. If my want by field amplitude to follow of, with x either in the upward direction or downward direction then alpha 1 and alpha 2 should be real or should have a large real part, this will happen only when k z is bigger than this quantity, and k z is bigger than omega by c also.

So, what we are looking for that k z is bigger than this quantity, if I put the value k z in this expression alpha 1 turns out to be equal to omega by c square this, and you will get simply 1 upon 1 plus epsilon m to the power half, this is epsilon, sorry two, I am substituting this back here and we will got this expression.

This tells you, if this quantity has to be real, sorry minus one upon this quantity this is minus here, just substitute this value of k z here in this expression and this turns out to be minus 1 upon this quantity in this expression, and how about k z 1 alpha 1, alpha 1 turns out to be also similar expression that I can write here.

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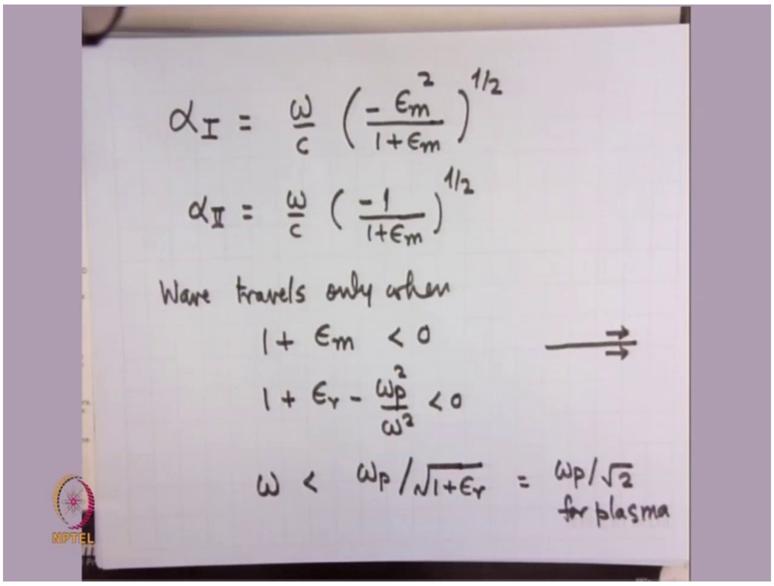

Alpha 1 the field decay in the conductor is omega by c, and its turns out to minus epsilon m square upon 1 plus epsilon m to the power half.

It is a very strange kind of thing, if I want alpha one to be real I must have this quantity to be positive, epsilon m even if it is negative square of this quantity will be positive so, there is already negative sign in the numerator and hence 1 plus epsilon m has to be negative, only then alpha 1 will be real and similarly, alpha 2 let me rewrite this alpha 2 which is equal to omega by c minus 1 upon 1 plus epsilon m to the power half this is a very important thing that, this wave will travel along the surface only when wave travels. Only when 1 plus epsilon m is less than 1, less than 0, if I use the expression for epsilon m, which is equal to 1 plus epsilon r, minus omega p square upon omega square has to be less than 0, this tells you that omega has to be less than omega p divided by under root of 1 plus epsilon r.

For a gaseous plasma epsilon r, the relative permittivity is unity so, 1 plus 1 is 2 so, this becomes omega p upon root 2 for plasma, for conductor epsilon r is different than one so, this could be less than omega p by root 2.

So, there is a limitation that the wave is which has to travel on a surface waves along the interface between two media their frequency has to be below certain quantity, and this quantity is called surface plasma on resonance frequency.

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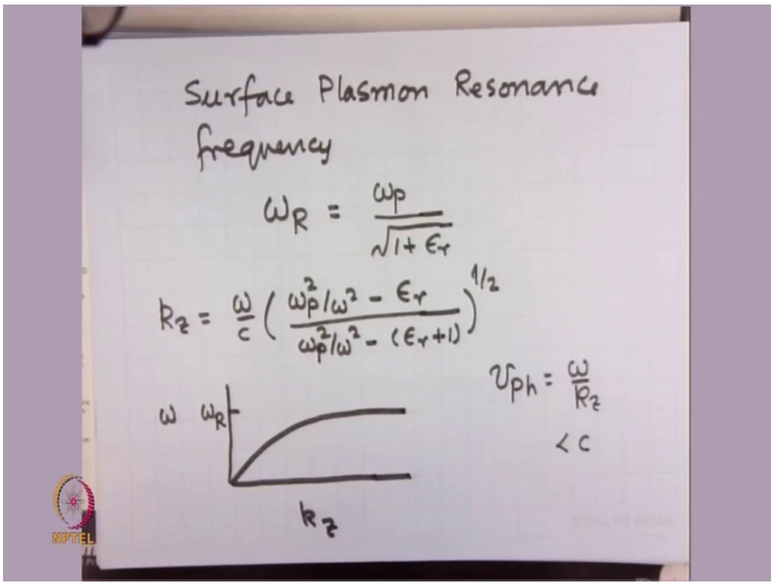

So, let me define this surface plasma on resonance frequency. Resonance denoted by a quantity omega R is equal to omega p upon under root of 1 plus epsilon r. If I plot k z versus omega using this expression then, please recognize k z, I can explicitly write as omega by c and this can be written as omega p square upon omega square, minus epsilon r, divided by omega p square upon omega square, minus epsilon r, plus 1 to the power half and let me plot this.

Normally people plot k z here and omega here, then at omega equal to omega R, which is this frequency, what do I get? When this becomes equal to this, denominator becomes infinity is 0 and k z goes to infinity so, the plot is n like this, this becomes linear here and then goes like this.

So, this is a wave where k z this quantity is bigger than one, and k z could be quite large so, the phase velocity of this wave, which is omega by k z is always less than c and could be much less than c.

Now, that makes this wave very, very interesting. Very important thing is about this wave is the diffraction, you know diffraction of a wave is dependent on the wave length of the wave, longer the wave length stronger the diffraction, divergence of the wave but, this wave has a shorter, larger k and hence shorter wave length for a given frequency and hence suffers very little diffraction.

You can focus this wave to a size much less than the wave length in free space, that is the advantage of this wave and that is why from device applications point of view this wave is getting more and more attractive.

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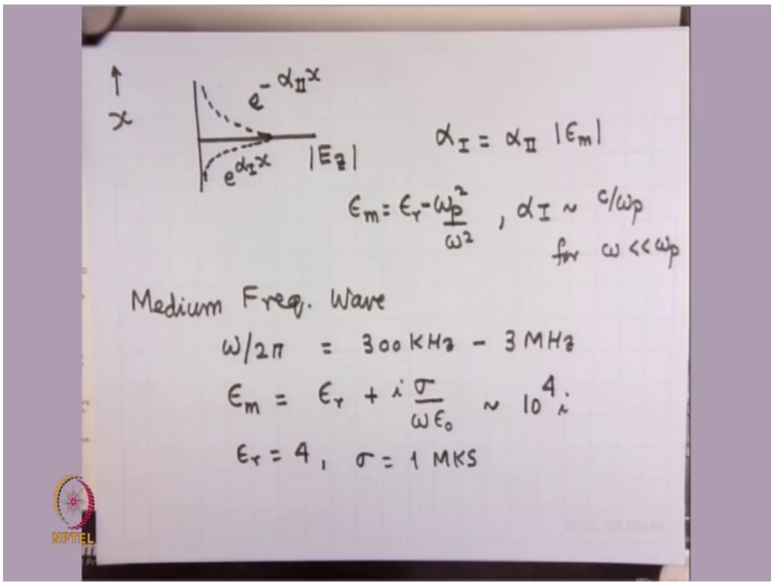

Now, let me let you a few interesting thing about this wave. First of all this wave if I plot electric field of the wave which E z for instance, modulus of this quantity as a function of x, if I plot x I am plotting here, this is above the surface, this is below the surface of the boundary between conductor and free space.

So, the E z is continuous so, this will fall of like this, exponentially fall off, in the conductor this will fall off like this, this will fall off like this, that exponential fall off here is exponential minus alpha 2 x, and here is like alpha 1 x. Alpha 1 is equal to alpha 2 modulus of epsilon m. So, epsilon m please recognize is the conductivity, epsilon m sorry, effective permittivity which is epsilon r minus omega p square upon omega square.

So, depending on the value of omega, if omega is very small as compare to omega p, epsilon m could be very large, and in at those frequency, low frequencies the field will decay very rapidly inside the conductor, and what you can see here is that alpha 1 could be of the order of c upon omega p for omega much less than omega p.

So, the wave is really localized inside the conductor very close to the surface but, it can have a broader width in free space, this one important aspect of this E x e one can similarly, deduce and see the corrector. Now, if applications, I like to mention three very important applications of this wave, one was obviously for medium frequency communication.

Earth is not really a conductor of the form like gold or silver, it contains soils but, when you are talking of frequencies like medium frequency waves or medium waves, we are talking about frequencies omega upon 2 pi, in the range 300 kilohertz to three megahertz.

So, those are soil, has soil particles separated from each other soil grains, separated from each other by certain distance or may be connected to each other but, the wave length of this wave is very large, and consequently one can treat this to be continuous medium so, there may be pebbles, there may be clay, there may be water molecules, etcetera, but, you can average out the properties of the earth.

Typically, earth epsilon m for the earth, at these frequencies is epsilon r, plus i sigma upon omega epsilon 0, you may recognize that sigma epsilon r is like four for the soil, and conductivity is like one in M K S units, for wet soil this can go up to 10 so, it vary review 1 and 10.

But omega we are talking about 3 into 10 to the power 7 or 10 to of the order of 10 to 7 radian per second, epsilon 0 is about 10 to minus 11 now, we can recognize that, this quantity is 10 to minus 11, this is like 10 to the power 7 so, still this product is of the order of 10 to minus 4 and hence this was of the order of 10 to the power 4 times i.

Means the imaginary part is much bigger than the real part and you can ignore this part, and that helps you simplify the expression for propagation constant a great deal.

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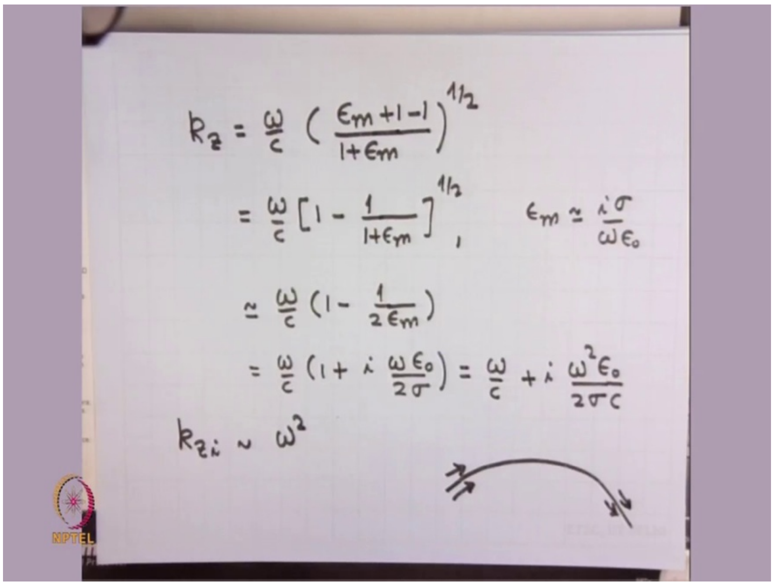

So, when we are talking of medium frequency communication over the earth, k z of this wave is equal to omega by c and it was epsilon m upon 1 plus epsilon m, my suggestion is take plus 1 here and subtract minus 1 here. And then divide this quantity by one plus epsilon m so, you will get omega by c into 1, for this ratio minus 1 upon 1 plus epsilon m to the half but, epsilon is very large magnitude wise as compare to unity so, you can ignore this one.

So, this is approximately equal to omega by c into 1, minus 1 upon 2 epsilon m, and if I put the value of epsilon m that I have derived, just in the last sheet as i sigma, upon omega epsilon 0, then this becomes is equal to omega by c, 1 plus i, omega epsilon 0 upon 2 sigma.

Please recognize that k z is a real part, which is equal to omega by c, plus a imaginary part, which is omega square epsilon 0 upon 2 sigma c so, this is a strongly dependent on frequency the absorption coefficient, imaginary part of k z is called absorption coefficient, and this is scales as so k z imaginary part, it goes as omega square.

That is why above 3 megahertz frequency, when short wave regime is starts the damping becomes so severe that, these waves cannot be, the surface waves cannot travel long distances and hence surface waves are not preferred or not excited in at that frequency band.

But for medium frequency communication when omega, these waves can travel k z i turns out to be of the order of a 1000 kilometers, and hence these waves can be used for communication from Delhi to Bombay, Delhi to even farther distances, even soviet union people have recorded these waves.

So, that is a very interesting aspect of it, and as I mention to you these waves can travel along this surface of the earth, even if the earth surface is curved so, they can go beyond the line of sight, geometrical line of sight, and that is the beauty of these waves, they also suffer little diffraction divergence.

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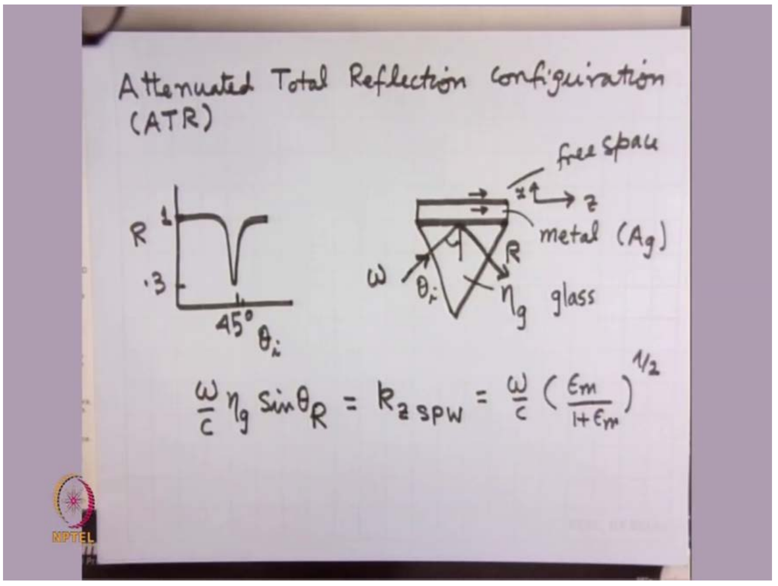

Second application that I wanted to mention is, censor application, for which excitation of surface waves over silver interface, silver vacuum interface is consider to be very useful but, a very geometry is used called A T R configuration, called attenuated total reflection configuration, let me tell you what is this.

One chooses a prism, and you deposit a silver film over this, like this, this is the glass prism of refractive index eta. G glass, this is metal typically silver, sometimes if it used gold also and you want to generate a surface, this is free space here.

If any fascinating experiment was conducted, that you launch laser here at some angle say theta i, this is a metal with plasma frequency bigger than the laser frequency omega, you are launching a laser, simple laser and then this will be reflected wave here that is coming out, because this is a medium which is over dense for the laser and this is like over dense plasma, it does not penetrate that much but, there will be some tunneling a little bit of energy goes from here to here but, very little.

And what happens suddenly, if I plot the reflectivity, means the amplitude of the reflected wave as compare to the amplitude of the incident wave the square of that so, intensity reflectivity if I plot as a function of theta I, what I find?

When this is launch a different angle of incidence, the reflectivity suppose this is reflectivity of silver for the laser is nearly in 95 percent or so, very close to the one but, suddenly what you find here that, there is a (( )) at about 45 degrees angle of incidence, well depending on the material, for for gold it is 45 degrees, for silver is just close a few degrees away.

But this is very sharp and this reflectivity reduction could be like 70 percent reduction or so, this could be like 0.3. That is something very interesting over here, and when does it occur, people wanted to match that, what is the propagation constant of this wave in the glass, if omega is the frequency, omega by c eta g is the propagation constant of laser in glass, if you resolve its components, vertical component of this propagation constant and a horizontal component. So, then horizontal component would be sin theta i, this is the propagation constant of laser in glass, its horizontal component, I am choosing this is my z direction, this is my x direction and x equal to 0 is the top surface of the metal.

And what we have been found that, the value of theta i for which this occurs this resonance occurs, let me call this angle theta R, this occurs when this is equal to k z of the surface wave, surface plasma wave, which was equal to omega by c, epsilon m, upon 1 plus epsilon m to the power half.

Something very spectacle occurs, when the horizontal component of laser wave vector in the glass equals the wave vector of the surface plasma wave then, this there is a severe reduction it means there is a conversion of laser energy into surface plasma wave energy, and the wave propagates near the upper surface of the thin foil.

That is the called attenuated total reflection configuration in brief this is called A T R configuration, otherwise you are expecting total inter reflection of waves but, suddenly you found that, there is a penetration of energy from here to this upper layer and at the upper layer is surface plasma wave sighted.

Now, if you put little bit of material on the top surface like d n a molecule or a small layer of some dielectric material, then people found there is a significant shift in the resonant frequency and that depends on the permittivity of the material that you put over here.

So, just by observing the shifting frequency one can deduce the permittivity of the material used, and their the permittivity is a characteristic of a material, and hence you can characterize what material it was was there, whether is a d n a molecule or whatever.

So, the properties of dielectric properties, are at optical frequencies can be gazed by this technique with great sensitivity, this has been one of the most sensitive techniques for diagnostics of d n a or diagnostics of undesirable gases in air so, for sense this is essentially a censor application, very useful censor application.

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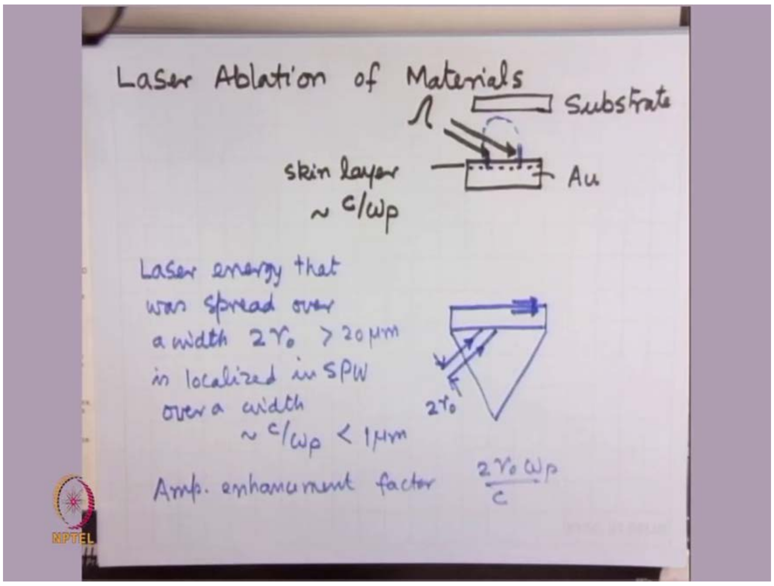

Let me also tell you something, one more application of this, which is in laser ablation of materials, before I tell you something about the role of surface plasma wave in ablation of materials, let me tell you something about direct ablation of material by a laser.

Suppose, I choose a material say gold, I want to deposit on some material here, suppose this is my glass substrate called substrate, this is my gold I want to deposit, suppose gold film over glass what do I do, I shine laser light here directly here, what the laser will do?

If the plasma frequency of the material is bigger than the laser frequency, the laser will not penetrate much, it will penetrate only up to a skin layer, this called a skin layer of width c upon omega p, very little.

But the advantage of the laser that is, if suppose I sent a pulse wave laser of one pico second duration, what will it do? Quickly it will heat a skin layer, the material in the skin, the electrons are heated by the laser and then, they collide with the lattice and transfer their energy to the lattice atoms, and the lattice melts evaporates, sometimes plasma is formed, a plume is formed and that plume rises and the plasma moves like this, a plume is created here they goes up and it strikes the substrate, which is kept at a low temperature so, this is cools down there and a gold film is deposit on the top.

Now, the thing is that, if you are shining a laser you are primarily utilizing or using the heating only in this region where the laser is spot is there so, your heating is very localized in the horizontal plane of the gold surface.

And secondly, the heating rate depends on the laser intensity so, its limited by the laser intensity. If you do not have a very, very powerful laser then the heating rate is slow and it may not, the heat that is generated here can be thermally conducted out downwards so, either you should choose a very large intensity laser, and you should choose a larger cross sectional area of the laser shining the gold surface then, you can deposit a large surface area film.

However, what the surface wave does? It does a interesting thing, if I choose a material like this in the A T R configuration then, laser light that you are shining is only of this cross sectional, this is the cross section of the laser, suppose the radius is r 0 so 2 r 0 is the width of the laser.

But when this laser gets convert into surface plasma wave then the width becomes very narrow, this width is very narrow. The width of a surface plasma wave is less than a micron, this size of the laser is about 100 micron so, you are sending a 100 micron laser over a surface and the surface wave is traveling over a very large distance but, localized in a very small region.

So, the laser energy that was a spread over a width 2 r 0, that was a spread over a width 2 r 0 means of the order of 100 micron or so, is localized in the S P W surface plasma over a width of those c by omega p, and that is the advantage, this is of the order of less than 1 micron, this is bigger than say 20 micron or may be 200 micron or something.

So, there is a sharp reduction in the extent over which the laser energy is localized and that leads to enhancement in amplitude. So, there is a amplitude enhancement of this order, divide this divided by this. So, amplitude enhancement factor is 2 r 0 divided by c upon omega p, and this could be like hundred fifty, hundred or whatever means equivalently you will gain the same effect here as if the laser intensity were to be enhanced in this case by square of this quantity.

So, you have got orders of magnitude in reduction in laser intensity to gain the same heating effect, and more over this is traveling a long wave so, this is, this laser energy though localize in the transverse direction but, horizontally it traveling a long way.

So, it can illuminate or heat the surface area several times more, like here it was like 20 micron or so, or 100 micron, this can spread over distance of the order of 1000 micron or more, and hence a much bigger area is exposed, and heating will take, ablation will take place so, this is much more effective that is the great advantage of this technique.

Means convert the laser into a surface plasma wave and let the surface plasma wave do the heating in ablation of material, I think that is a very interesting application of surface plasma wave.

Finally, I would like to tell you one more application of this in material processing by plasma processing of materials.

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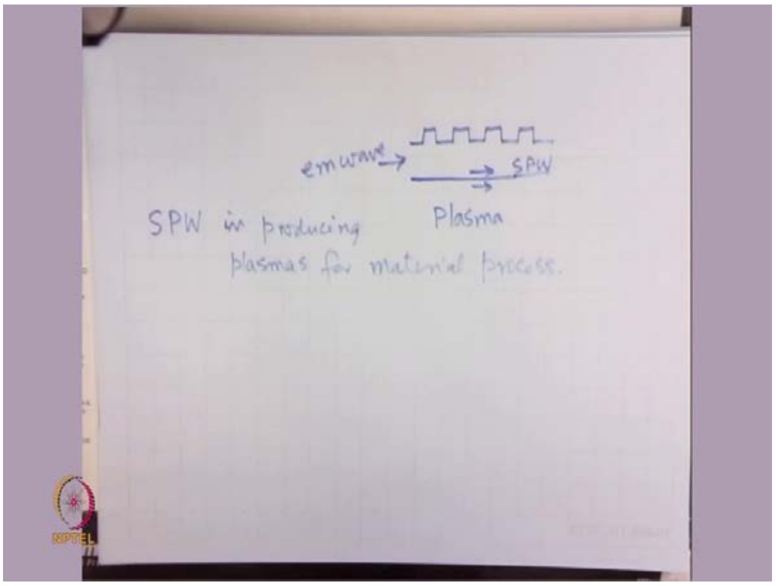

What people in taiwan have done, they take here a gas, where they want to form a plasma and then, they create a surface a structure, a slow wave structure here. And they launch an electromagnetic wave here, what they find that, if you, if some plasma is created here then, this is this sort of slower wave structure excise a surface wave here and that can sustain the hot plasma here.

Means, this electromagnetic wave field will initially cause the initial ionization but, that ionization as it is develops, there is a sharp boundary between plasma in free space and then he will produce a surface wave so, when the electromagnetic waves gets convert into surface plasma wave it becomes more effective in heating and sustain in the plasma.

So, this is utilized, SPW is utilized in producing plasmas for material processing. And I think that is a great advantage so, surface plasma waves really emerging as a strong can/contender contender or a strong candidate for material processing, either via plasma route or through laser ablation technique, and it is also finding many device applications, I think, I like to stop at this point, thank you very much.