Millimeter Wave Technology.
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Lecture-05.
Introduction to Millimetre-Wave Technology (Contd.)

So next let us discuss about the mat material properties at millimetre wave frequencies. So first of all we need to measure these material properties at different frequencies to characterise them there are some popular methods at microwave, millimetre or terahertz or infrared frequencies and these methods are different at different frequencies. For example at low RF or microwave frequencies we use parallel plate method.

We place dielectric material between two parallel plates or characterisation or sometime we design some sort of resonators and then we measure the resonance frequency and other effect to measure the dielectric constant of any given material so we can still use that resonance method at millimetre wave frequency also.

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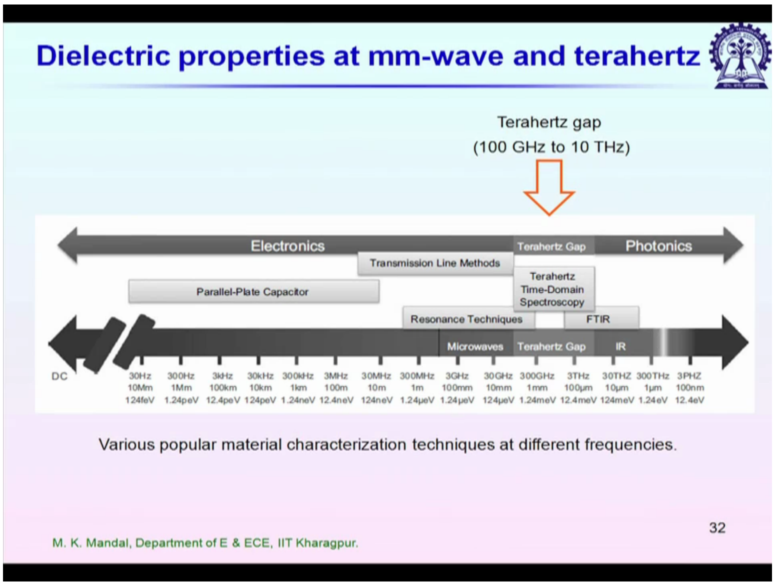

Dielectric properties at mm-wave and terahertz

Various popular material characterization techniques at different frequencies.

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So other techniques are transmission line methods so for transmission line methods what we do? We fabricate different lanes of transmission line it can be let us say micro strip line which uses which supports quasi TEM up to different length and then we simply measure the S parameters or scattering parameters of this two different lengths by using may be some vector network analyser. So from the measurement of this complex scattering parameters then we can determine what is the alpha or beta or that given transmission line or what is the dielectric constant of the given substrate. Actually if we further increase the frequency to sub millimetre wave or to terahertz frequency this transmission line method or that resonance method is not very accurate.

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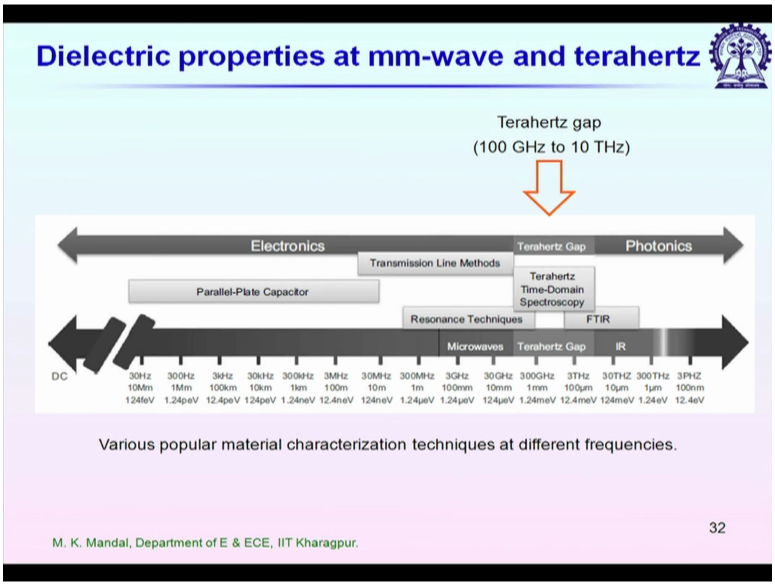

Dielectric properties at mm-wave and terahertz

Terahertz gap
(100 GHz to 10 THz)

Various popular material characterization techniques at different frequencies.

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There are some other methods which we use so that is terahertz time domain spectroscopy but unfortunately its not again very accurate method so we can determine the material characteristics at lower frequencies as well as at higher frequencies. For example infrared or optical wave length very accurately but we have a problem from 100 gigahertz to 10 terahertz we don’t have any methods which can give us very accurate sigma tan delta and epsilon R values of any given material so that is why sometimes we call it a terahertz cap. So whatever values I am going to show here these are the approximate values that is why.

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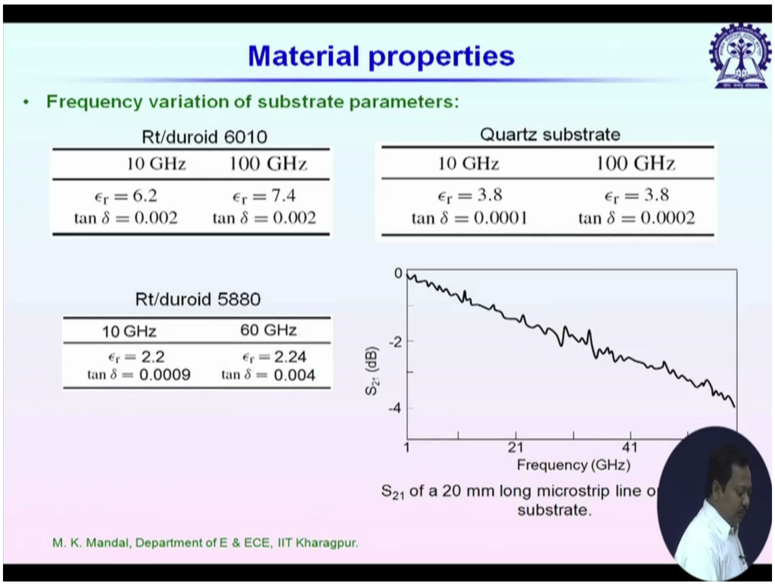

Material properties

- Frequency variation of substrate parameters:

Rt/duroid 6010

10 GHz	100 GHz
$\epsilon_r = 6.2$ $\tan\delta = 0.002$	$\epsilon_r = 7.4$ $\tan\delta = 0.002$

Quartz substrate

10 GHz	100 GHz
$\epsilon_r = 3.8$ $\tan\delta = 0.0001$	$\epsilon_r = 3.8$ $\tan\delta = 0.0002$

Rt/duroid 5880

10 GHz	60 GHz
$\epsilon_r = 2.2$ $\tan\delta = 0.0009$	$\epsilon_r = 2.24$ $\tan\delta = 0.004$

S_{21} of a 20 mm long microstrip line o
substrate.

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So let us take some popular substrate material first for example the first substrate it is RT duroid 6010 so Roger suggests its dielectric constant at 10 gigahertz epsilon R is equal to 6.2 and loss tangent that is equal to point 002 but some other groups already used the same material at high frequency as high as 100 gigahertz.

And they report it that the measured dielectric constant at 100 gigahertz of this same material is 7.4 and they also obtained similar loss tangent value point 002 now another popular material RT duroid5880 so already we have seen the measured value given by Rogers corporation at 10 gigahertz epsilon R is 2.2 and tan delta is point triple not nine so another group measured its performance at 60 gigahertz for that they got epsilon R equal to 2.24.

So almost no difference and tan delta it actually increases to point 004. So another popular material its quartz substrate so its actually low loss substrate and very popular at millimetre wave frequencies but the only problem is that its fragile. At 10 gigahertz epsilon R equal to 3.8 even at 100 gigahertz no change look at the loss tangent value its just point triple not 1 it increases to just point triple not 2 at 100 gigahertz.

So it shows why quartz is so less lossy substrate. Now we are doing a one experiment what we are doing? We are fabricating let us say one 20 millimetre long micro strip line which is basically a form of transmission line on a 35 NQ substrate and then what we are doing? We are measuring is to one and plotting it over the frequency range. So look at the variation of loss at 1 gigahertz this loss is just point 1 or point 2 DB.

And at let us say 20 gigahertz it increases to 1.2 to 1.3 DB but for the same micro strip line at 60 gigahertz loss increases to almost 4 DB. What is the source of these losses? Then as such whatever material properties we have seen in comparison to 10 and 10 gigahertz and 100 gigahertz that tan delta value or epsilon R its not changing as such but if I measure loss, loss is increasing very rapidly with frequency.

So at millimetre wave frequency you see if the loss is 3 db that means half of the power is already wasted. you are receiving only half of the insuring power. Then there might be some other sources of losses so that we have to learn very carefully. So the main point is at conductor loss, it increases with frequency not only that we will see there is one more type of loss which we call the surface wave loss.

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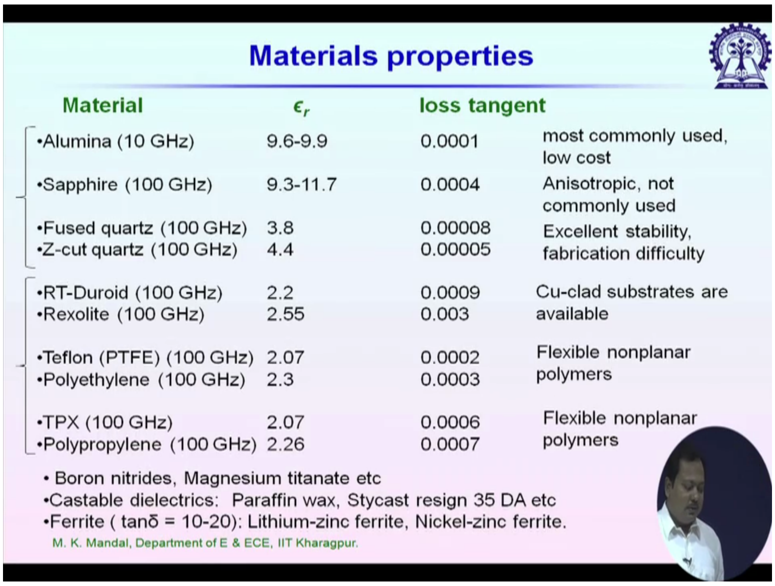

Materials properties

Material	ϵ_r	loss tangent	
•Alumina (10 GHz)	9.6-9.9	0.0001	most commonly used, low cost
•Sapphire (100 GHz)	9.3-11.7	0.0004	Anisotropic, not commonly used
•Fused quartz (100 GHz)	3.8	0.00008	Excellent stability, fabrication difficulty
•Z-cut quartz (100 GHz)	4.4	0.00005	
•RT-Duroid (100 GHz)	2.2	0.0009	Cu-clad substrates are available
•Rexolite (100 GHz)	2.55	0.003	
•Teflon (PTFE) (100 GHz)	2.07	0.0002	Flexible nonplanar polymers
•Polyethylene (100 GHz)	2.3	0.0003	
•TPX (100 GHz)	2.07	0.0006	Flexible nonplanar polymers
•Polypropylene (100 GHz)	2.26	0.0007	

- Boron nitrides, Magnesium titanate etc
- Castable dielectrics: Paraffin wax, Stycast resign 35 DA etc
- Ferrite (tanδ = 10-20): Lithium-zinc ferrite, Nickel-zinc ferrite.

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So before that let us go through some other materials, popular materials one of them is alumina so for alumina depending on its purity epsilon R it can varies in between 9.6 to 9.9. I will show you the values of alumina even at terahertz its being used and typically its lon loss tangent value is point triple not one this is most commonly used material for a low cost fabrication at millimetre wave frequencies.

Sapphire typically at 100 gigahertz again depending on its purity and composition epsilon R 9.3 to 11.7 loss tangent point triple not four so its one type of an isotropic material and not very popular then the fused quartz so its main advantage it is excellent stability so quartz with different cut its called Z cut quartz so for this one epsilon R is 4.4.

And look at their loss tangent values its very small in fact in this chart this quartz material they provide lowest loss then the popular RT duroid substrate it is RT duroid 5880 so typical epsilon R 2.2 so this rexolite substrate 2.55 and for this 2 types copper clad substrates are available so that means the dielectric slap with top and bottom metallisation then the PTFE substrate Teflon as commonly called typical dielectric constant 2.07 at 100 gigahertz.

Polythene polyethylene its dielectric constant 2.3 and its a polymer we have also some other TPX so TPX material is flexible material and polypropylene its dielectric constant 2.26 it is again another polymer so among there are many more. Among these if you say which is the most popular material at millimetre wave frequency it is alumina because its cost is very low.

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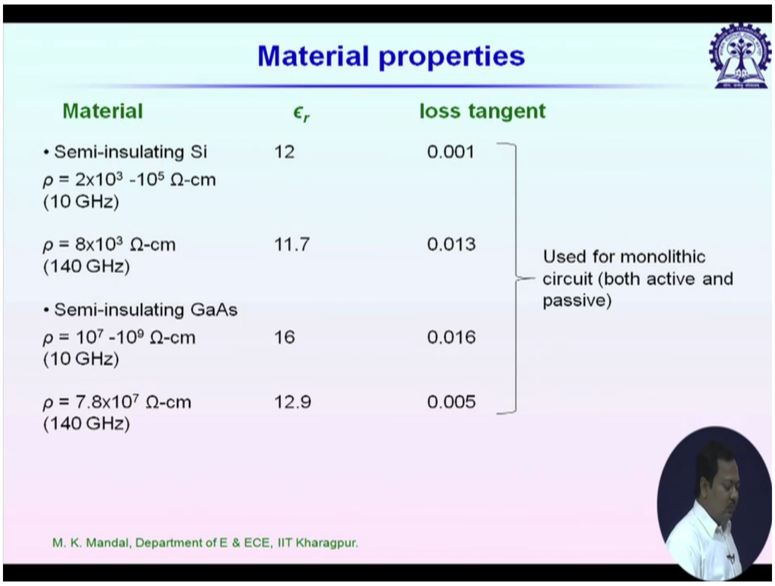

Material properties

Material	ϵ_r	loss tangent
• Semi-insulating Si		
$\rho = 2\text{x}10^3$ -10^5 Ω-cm (10 GHz)	12	0.001
$\rho = 8\text{x}10^3$ Ω-cm (140 GHz)	11.7	0.013
• Semi-insulating GaAs		
$\rho = 10^7$ -10^9 Ω-cm (10 GHz)	16	0.016
$\rho = 7.8\text{x}10^7$ Ω-cm (140 GHz)	12.9	0.005

Used for monolithic circuit (both active and passive)

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Now in the previous one when we are going through different dielectric so that means we were considering mainly circuit design in printed circuit board technology but we can design also circuit on chip in that case we have to use silicon, germanium or group 3 group 5 material. So then let us see how this material they behave at millimetre wave frequencies?

So first of all silicon or germanium and typically when we consider N type or P type material its a semi conductor material. So it comes with a finite sigma value so its very lossy so we cant use this semiconductor materials as metal or even we cant use this semiconductor material as dielectric. Because if we treat the semiconductor material as dielectric it will be very lossy already at millimetre wave frequency .

We have many sources of loss we don’t want to increase the loss further. So then what is the option? How we can utilize the silicon, germanium or other group 3 group 5 materials? So one thing is that we can use pure silicon, intrinsic silicon or germanium so in that case we don't have any doping so its resistance will be high and we can use that type of silicon or germanium as dielectric material to design our component how we do for PCB.

So with that silicon only thing is that we have to act some metallisation so this silicon or germanium which is very close to intrinsic material we call it high resistive silicon or high resistive germanium. So let us see their material properties.

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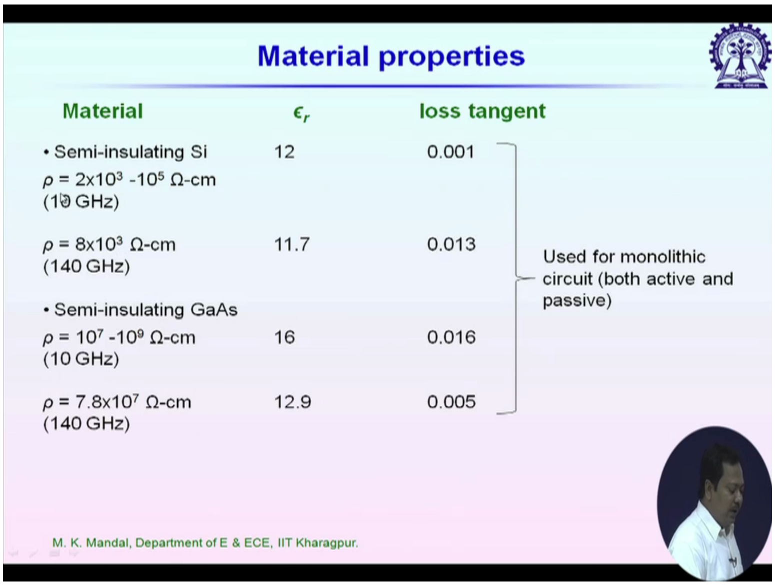

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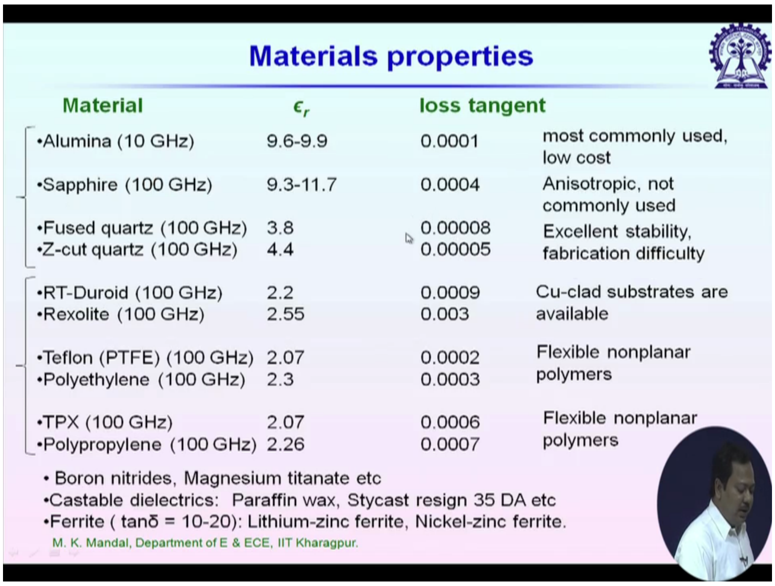

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So semi insulating silicon typical rho 2 into 10 to the power 3 to 10 to the power 5 ohm centimetre so this value is given 10 gigahertz an its epsilon R is 12. Loss tangent is point 001 not bad. So if I consider a typical value for which measurement result is available rho is 8 into 10 to the power 3 ohm centimetre and the measured value is at 140 gigahertz epsilon R is 11.7.

And loss tangent point 013 its high but still we can use it for circuit realisation. You can compare this point 013 value with the previous table for all this dielectric its at least we have let us say point 003 we have a point 00 factor and here its point 013. Next semi insulating gallium arsenide so remember whenever we are using this word semi insulating so that means it is more like intrinsic doping concentration is negligibly small.

And we have to use special fabrication process to fabricate them conventional fab labs they don’t support this fabrication. So semi insulating gallium arsenide rho typically 10 to the power 7 to 10 to the power 9 ohm centimetre and epsilon R is quiet high 16 and if I consider a typical value rho 7.8 into 10 to the power 7 ohm centimetre for which the measured value is of epsilon R is 12.9 at 140 gigahertz.

And the loss tangent is point 005 so if I compare the loss tangent value with silicon obviously its a very good substrate almost like dielectric but the problem is that its very expensive compare to silicon. So we can use for monolithic circuit fabrication for both active and passive device fabrication so you see dielectric constant let us say its already 12 or more than 12 now what about the com passive component size?

Let us say antenna dimension and antenna its length typically is lambda g by 2. So if I consider is 60 gigahertz design wavelength free space wavelength is 5 millimetre at if I fabricate this antenna on gallium arsenide so this is it comes then 5 millimetre 5 divided by root of 12 point something divided by 2 because its lambda by 2 so their dimension of this resonating antenna is so small that we can integrate this antenna on chip itself.

And we can think of on chip antenna not only that on chip antennas arrays that is also possible at millimetre wave frequency. Some other passive components which we learnt later like couplers, filters. Which uses the properties of transmission line and whose dimension again is determine by lambda g sometimes lambda g by 2 sometimes lambda g by 4 so those passive components also we can design on chip.

Because size reduces it becomes fraction of millimetre. So in the same chip then we can design active components as well as those passive components like filter, couplers and we can integrate in a single chip.

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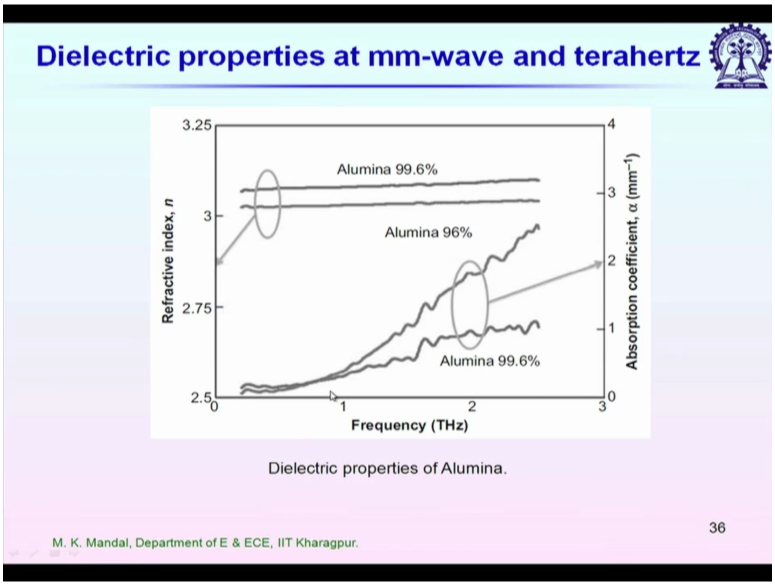

Dielectric properties at mm-wave and terahertz

Dielectric properties of Alumina.

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So next let us see how the properties of alumina is varies with frequency. So alumina its being used noly not only at millimetre wave frequencies as you see look at the frequency scale so starting from microwave to almost 2.5 terahertz its being used. And the refractive index which is related to dielectric constant of this material so moral is it remains constant over this wide spectrum of frequency.

So we have their comparing two values one for case 1 its almost very pure alumina 99.6 percent alumina and the second one is 96 percent alumina so if I look at the epsilon R values so it is more or less constant over this frequency range and absorption coefficient which represent actually the loss tangent so it increases but not that bad particularly if I typically if I consider below 1 terahertz. So that is why this alumina is very popular substrate at millimetre wave frequencies.

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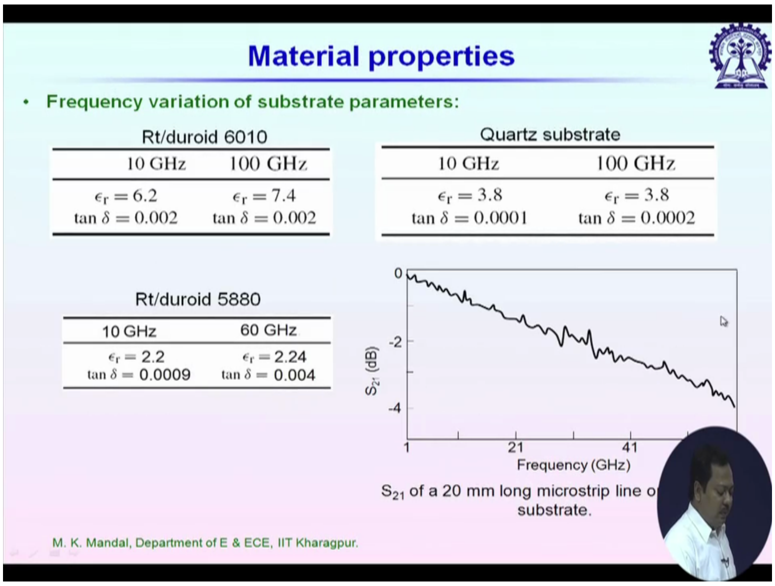

Material properties

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S_{21} of a 20 mm long microstrip line o
substrate.

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So now let us go back to the micro strip line example. So after studying this material properties at millimetre wave frequencies we see that in comparison to microwave frequency range or a RF frequency range loss tangent value or other properties is does not change they do not change drastically. There is a change there is an increment of loss tangent value but its really small.

So then if I look at the measured is to 1 of transmission of a micro strip line but what we see? We see that loss it increases rapidly with frequencies so then there might be some other sources of losses. And this loss is a function of frequency which obviously is more at higher millimetre wave frequencies.

So sometimes this loss is so high let us say at sub millimetre wave frequency that we even cant use printed lines. For sub millimetre wave frequency range near 300 gigahertz so then what are these sources of losses? We will see one by one.

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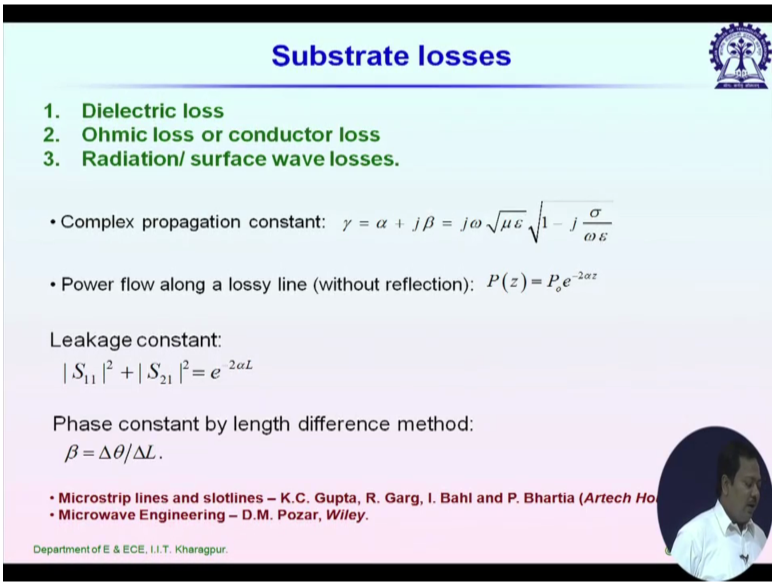

Substrate losses

1. Dielectric loss
2. Ohmic loss or conductor loss
3. Radiation/ surface wave losses.

- Complex propagation constant: $\gamma = \alpha + j\beta = j\omega\sqrt{\mu\varepsilon}\sqrt{1 - j\frac{\sigma}{\omega\varepsilon}}$
- Power flow along a lossy line (without reflection): $P(z) = P_o e^{-2\alpha z}$

Leakage constant:

$|S_{11}|^2 + |S_{21}|^2 = e^{-2\alpha L}$

Phase constant by length difference method:

$\beta = \Delta\theta / \Delta L.$

- Microstrip lines and slotlines – K.C. Gupta, R. Garg, I. Bahl and P. Bhartia (*Artech Ho*
- Microwave Engineering – D.M. Pozar, *Wiley*.

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So the first one is conductor loss sorry here it shows dielectric loss so the dielectric loss ohmic loss or conductor loss and then the radiation and surface wave losses. So if we design any wave guiding structure at millimetre wave frequencies then obviously we have to use the complex propagation constant.

We cant use the approximation of lossless line we have to consider both alpha and beta. Alpha it represents the attenuation and beta it is the phase constant. So which is given by approximately twice pie by lambda g. So for a any given medium if we know the Mu, epsilon and sigma value then we can easily calculate what is the alpha value and beta value of any given medium.

Now the power flow along a lossy line let us say around the line we don't have any reflection P Z this is P nought into E to the power minus twice alpha Z. We have a factor of 2 since we are considering a power and not the electric field. So this alpha and beta we can actually measure it by fabricating 2 different lengths of lines.

So the loss whatever we have it is then included in alpha and if there is any phase variation for if there is any dispersion effect that we can determine from the beta variation so then we see that alpha and beta both are very important parameters for any wave guiding structures so how to measure them. So you see we have a relationship here the leakage constant alpha it can be represented in terms of this scattering parameter.

If we have a section of wave guiding structure then if we can measure the S parameters let us say the S11 and S21 then from that S11 square plus S21 square this is equal to E to the power minus twice alpha L. So we can determine experimentally what is the alpha for any given guiding structure similarly we can determine what is the phase constant beta by length difference method. So what we have to do?

We know that the theta due to a given physical length L that is equal to theta equal to beta into L. So now if we fabricate 2 diferent lengths let us say L1 and L2 and the length difference is delta L. Then the angle difference we can easily measure from S parameters because angle of S21 that is nothing but the angle experienced by the signal from port 1 to port 2. So from that then experimentally beta that is equal to delta theta by delta L.

So we see that we can measure experimentally both alpha and beta and it will give you some idea about the alpha and beta. Now obviously for any design what we expect that alpha should be as small as possible and what should be the variation of beta? Beta is twice pie by lambda g. So if I consider the frequency variation of beta so this is twice Pie into C by F okay let us do in graph.

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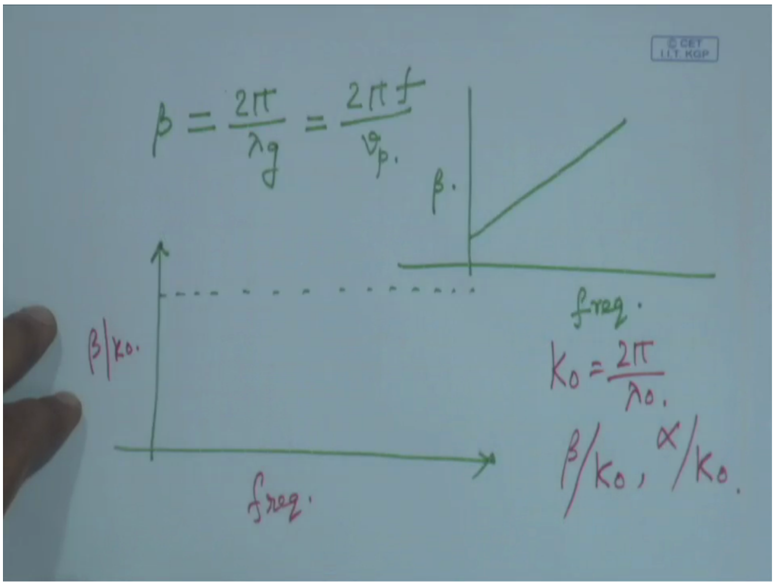

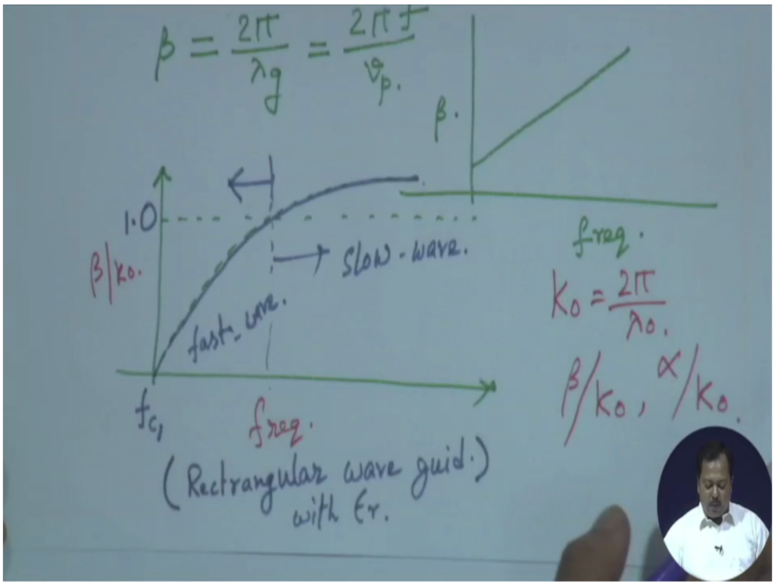

So beta this is equal to twice pie by lambda g this is the guided wave length so twice pie we can write down the velocity of wave inside the medium into F. So then we see ideally if I plot beta versus frequency so it should increase linearly and if there is any deviation from the straight line so that means we have velocity as a function of frequency we have dispersion effect. So practically we deal with 2 important parameters.

We usually plot beta by K nought instad instead of beta so K nought this is equal to twice pie by lambda not so it is nothing but beta in free space. And then we plot what is the value of beta by K nought. And what is the value of alpha by k nought. So if I plot beta by k nought versus frequency ideally it should be constant. But for any wave guiding structure it actually varies with frequency so already we know what is fast wave?

What is slow wave? So let us say we have a rectangular wave guide filled with dielectric material and for that we are plotting beta by K nought versus frequency so I am considering one example a rectangular wave guide with filled with dielectric material of dielectric constant epsilon R.

So if I plot beta by K nought for this given material beta by K nought plot is somewhat like this this dotted line it shows the value where beta by K nought equal to 1.0 this diagram beta by K nought versus frequency is called the dispersion (())(28:50) dispersion diagram. And it provides many important information for example you see at this particular frequency let us say FC 1 its starting from let us say 30 gigahertz beta by K nought equal to zero that means we don't have any propagation below this frequency this is the cut off frequency of that wave guide.

Now as frequency increases beta by K nought increases now at a frequency point here we have a crossing where beta by K nought is equal to 1 so below this beta by K nought is less than 1. What that means? Beta by K nought is less than 1 so that means we have VP Phase velocity higher than C or we can call this left hand side part this is the fast wave region and the right hand side part for which beta by K nought is more than 1 or phase velocity this is less than C we call it the slow wave region.

So in this region then my lambda g is smaller compare to lambda nought. So component notarization is possible for the right hand side while for the left hand side we can design on leaky wave antenna very easily. So ideally it should be a straight line but since it changing with frequency so that means it dispersive so how dispersive this line is we can understand it from that beta by K nought plot.

So you see then why this dispersion diagram is so important we have so many information that what is the cut of frequency for this given guiding structure? Which range over what is the frequency range? Over which it behaves as the fast wave. What is the frequency range over which it behaves as a slow wave structure? Then how dispersive this line is?

Similarly we may have another plot of alpha by K nought versus frequency from which we will have idea of how lossy the line is? If for a rectangular wave guide if I plot alpha by K nought versus frequencies it will be highest at cut off frequencies and actually its infinity and if I increase frequency alpha by K nought it decreases with frequency. So today we will stop here. So in next class we will discuss the different sources of losses in details. Thank you!