Millimeter Wave Technology.
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Lecture-03.
Introduction to Millimetre-Wave Technology (Contd.)

So now we learn some term because we are going to use this term frequently throughout this class. So first among these are phase velocities and group velocities. So when one electromagnetic wave is propagating through free space or to on medium or it can also propagating propagate through array umm guiding structures we are associated with two different types of velocities.

The first one we call phase velocity it represents the velocity at which the phase of the signal propagates and its a function of omega and beta we will see and another one is group velocity. So its sometimes we simply call it a signal velocity so if any given envelope is there represents the velocity of that envelope through the medium or through the guiding structure.

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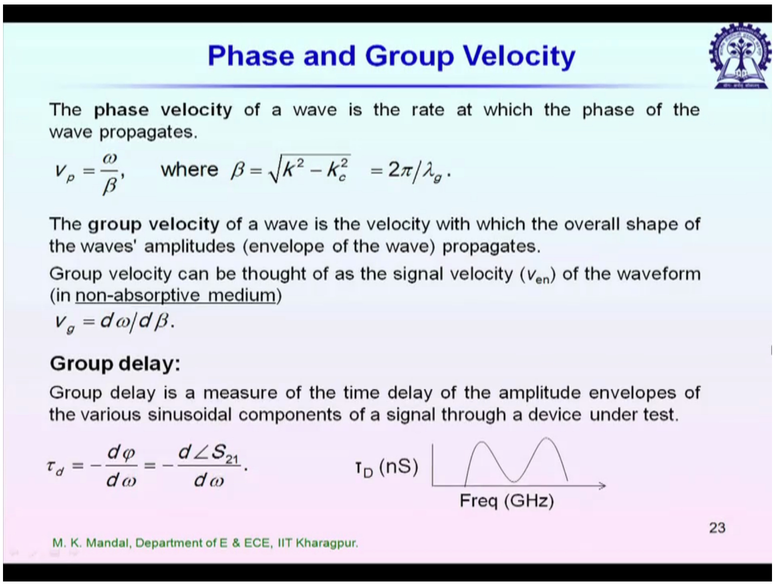

Phase and Group Velocity

The **phase velocity** of a wave is the rate at which the phase of the wave propagates.

$$v_p = \frac{\omega}{\beta}, \quad \text{where } \beta = \sqrt{k^2 - k_c^2} \;= 2\pi/\lambda_g .$$

The **group velocity** of a wave is the velocity with which the overall shape of the waves' amplitudes (envelope of the wave) propagates.

Group velocity can be thought of as the signal velocity (v_{en}) of the waveform (in non-absorptive medium)

$$v_g = d\omega/d\beta.$$

Group delay:

Group delay is a measure of the time delay of the amplitude envelopes of the various sinusoidal components of a signal through a device under test.

$$\tau_d = -\frac{d\varphi}{d\omega} = -\frac{d\angle S_{21}}{d\omega}.$$

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So let us see the first phase velocity so as I said phase velocity of a wave is the rate at which the phase of the wave propagates. It can be given by omega by beta. So where beta is equal to square root of K square by Kc square so Kc it represents the cut of wave number so some of for some wave guiding structure we will see that it has some finite Kc value and for some other wave guiding structure it does not have any Kc value.

Kc equal to zero so beta approximately this equal to two pie by lambda g. Where lambda g it represent the guided wavelength so that means in free space the wave length is lambda not at

60 gigahertz let us say in free space the wavelength is 5 millimetre but when the signal is propagates through any medium or through any wave guiding structure its wavelength changes.

So if it propagates through any dielectric medium of dielectric constant epsilon r then approximately lambda g this is equal to lambda not by square root of epsilon r. So that means its become a function of a dielectric constant and not only that if I plot beta versus frequency so beta is twice pie by lambda g so as I increase frequency then lambda g it decreases so then beta it should varies with frequency linearly.

So if beta does not have any linear variation so that means the phase fellow city it will be different at different frequencies. Next one is the group velocity. So the group velocity of a wave is the velocity with which the overall shape of the waves or wave's amplitude or we can call the envelope of the wave it propagates.

And umm it can be thought og as the signal velocity of the waveform but if there is no loss only in that case and vg this is del del beta of omega so group velocity again it should be constant and with a frequency so we can define one term we call it group delay. So it can be define for any given channel or it can be define for any two port network.

So let us say we have a two port network we are transmitting any signal from port 1 to port 2 so my receiver side is placed at port 2 then I am measuring the time delay taken by different frequency component to reach my port 2. So if I plot these time delay versus frequency ideally it should be constant. This is the desired thing. But practically for any channel or for any component if I plot group delay versus frequency it becomes actually a variable quantity it varies.

Then we face problem due to the group delay variation with frequency what is that problem if I send a pulse. A pulse it will have many frequency components. Now this defined frequency components will travel with difference velocities and it will take different times to reach my port 2. So then at the receiving side if I plot the pulse again the shape will change so these effect called as dispersion and for wide band system its a problem.

So we can avoid dispersion by avoiding group delay variation but for any given components we can actually avoid this group delay variation. So what we can do we can minimize the group delay variation by choosing a proper designing architecture or if this variation is too much in that case we have to use some equalization technique which will minimize this group delay variation and minimize the (())(6:02) effect as a (())(6:04).

Now if I measure How to measure this group delay? This is related to the angle of transmission so you know scattering parameters so the angle of umm transmission that means is to one if I umm plot the variation of this angle with respect to omega that will give you the group delay.

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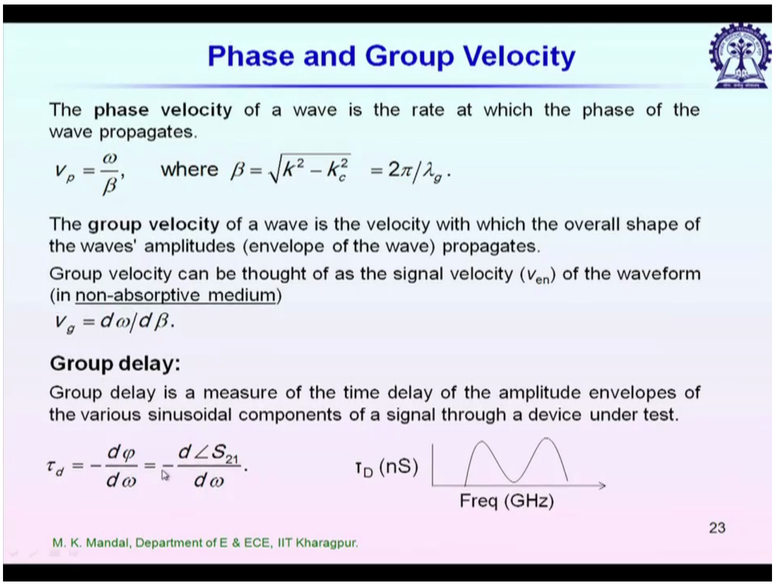

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So mathematically group delay tau d this is equal to minus del del omega of angle of S21. So by using any pectro network analyser or by any means. If we can measure the total angle from port 1 to port 2 so then we can easily calculate the group delay (())(6:54). So this is a typical group delay plot versus frequency for passive components so usually for passive components.

So usually for passive components we face a concave type group delay profile so at mid band frequency the group delay is minimum and at band edge left hand side and right hand side group delay is maximum so all the components it has a finite bandwidth it can operate over all the millimetre wave frequency or all over the electromagnetic spectrum so it will be higher at the left and right band edge of any given two port network.

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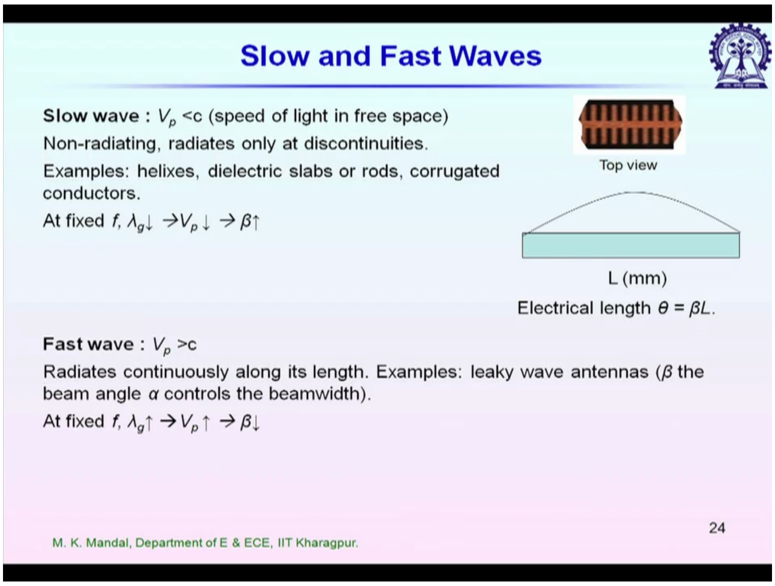

Slow and Fast Waves

Slow wave : V_p <c (speed of light in free space)

Non-radiating, radiates only at discontinuities.

Examples: helixes, dielectric slabs or rods, corrugated conductors.

At fixed f, $\lambda_g\downarrow \rightarrow V_p\downarrow \rightarrow \beta\uparrow$

Top view

L (mm)

Electrical length $\theta = \beta L$.

Fast wave : V_p >c

Radiates continuously along its length. Examples: leaky wave antennas (β the beam angle α controls the beamwidth).

At fixed f, $\lambda_g\uparrow \rightarrow V_p\uparrow \rightarrow \beta\downarrow$

Then the second term slow and fast waves. So how we define slow wave if VP the phase velocity is less than C that means the speed of light in free space we call it slow wave. So at fixed frequency that means for slow wave lambda g should be smaller than lambda not so VP then only VP decreases and beta increases so we represent actually another important at one TT beta by K not so K not this is 2 pie by lambda not increased space and beta this is 2 pie by lambda g any for any given medium or for any wave guiding structure.

So then if we plot beta by K not umm it should be actually it should not vary with frequency so if any wave guiding structure its supports slow wave then usually its non radiating mode so it will guide that transmission mode through the structure and its radiates only at discontinuities. So whenever we are going to design any wave guiding structure like micro strip line or CPW line what we will expect?

We expect that there should be some slow wave inside so that their wont be any radiation from the structure. So we have to keep this thing in mind also when we are going to design any components at millimetre wave frequency as well as at microwave and RF frequencies. So just opposite to this is the first wave where the phase velocity is more than that umm of light in free space the disadvantage of fast wave is that it radiates continuously along its length if its a semi open structure.

So we will see later that rectangular wave guide it supports fast wave but since rectangular wave guide its a close structure it does not radiate along its length. But if we have some semi open structure like micro strip line it will radiate continuously along its length. So we cannot use it as a wave guiding structure then.

But another application it has that we can design antenna actually there is a category of antenna which utilizes this continuous radiation along its length we call it the leaky wave antenna and for this leaky wave antenna the beam direction its a function of beta or frequency. So if I change frequency then beam direction will change so continuous scanning is possible by frequency swipe.

And in that case the attenuation constant alpha of that wave it will determine the beam with of the signal. So we can control the beam with of such antenna as well as the propagation direction or beam angle of the antenna. So in this case so lambda g should be higher since VP is higher and beta is lower than K not.

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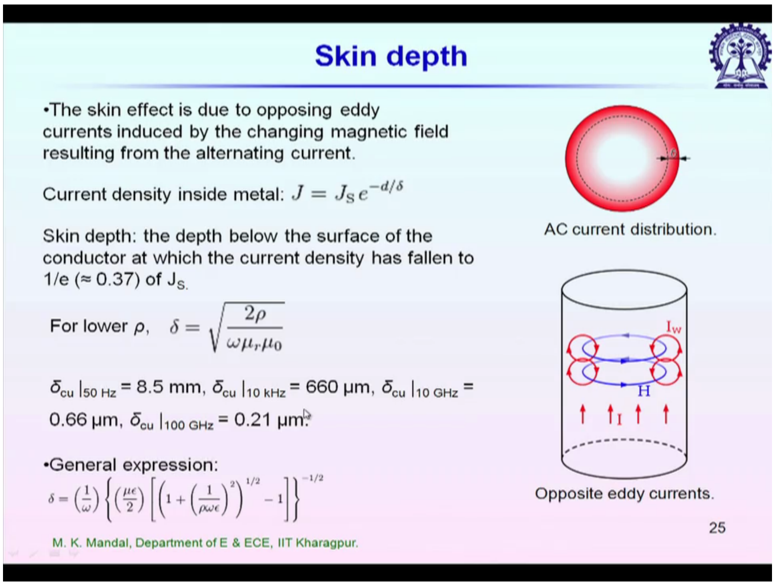

Skin depth

- The skin effect is due to opposing eddy currents induced by the changing magnetic field resulting from the alternating current.

Current density inside metal: $J = J_S e^{-d/\delta}$

Skin depth: the depth below the surface of the conductor at which the current density has fallen to 1/e (≈ 0.37) of J_S.

For lower ρ, $\delta = \sqrt{\dfrac{2\rho}{\omega\mu_r\mu_0}}$

$\delta_{cu}|_{50\ \text{Hz}} = 8.5$ mm, $\delta_{cu}|_{10\ \text{kHz}} = 660$ μm, $\delta_{cu}|_{10\ \text{GHz}} = 0.66$ μm, $\delta_{cu}|_{100\ \text{GHz}} = 0.21$ μm.

- General expression:

$$\delta = \left(\frac{1}{\omega}\right)\left\{\left(\frac{\mu\epsilon}{2}\right)\left[\left(1+\left(\frac{1}{\rho\omega\epsilon}\right)^2\right)^{1/2} - 1\right]\right\}^{-1/2}$$

AC current distribution.

Opposite eddy currents.

25

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Another important term is skin depth. So this term actually explain why at millimetre wave frequencies we cannot use metals for wave propagation. So how we define skin depth? This is the depth below the surface of given conductor at which the current density has fallen to 1 by e times of JS where JS is the surface current density value.

So now look at this top right picture so we are sending some electromagnetic signal through some metallic wire now we are plotting the current density over the cross section of this wire. So you as you can see this current density is highest on the surface of the wire and if we go inside further inside the current density decreases it decrease exponentially given by this relationship J equal to JS into e to the power minus d by delta.

So if we so what is this delta? This is the skin depth it is given by square root of twice rho divided by omega Mu R into Mu not. Rho is the resistivity of this material so this is approximate relationship and it holds good for metals or lower resistivity you can replace rho by sigma then it will be twice by omega sigma Mu R Mu not. So if I look at this expression one important thing we observed that its function of omega.

If I increase frequency skin depth will decrease. So that means at millimetre wave frequency this current will be mostly surface current component it will flow through a th thin layer of metal just situated on the surface of this wire. So since its utilizing a very thin layer surface resistance will be very high at millimetre wave frequency the surface resistance is so high the metal it will be very lossy.

In fact at optical wavelength the frequency is so high we cannot use any metal at all that is why we use in optical fibre always the dielectric material now let us calculate the skin depth value for at some give at some frequencies let us say for copper so if I calculate skin depth at 50 hertz for copper its 8.5 millimetre and at 10 kilohertz it decreases to 660 micrometer at 10 gigahertz its point 66 micrometer if I further increase the frequency to 100 gigahertz it is just point 21 micrometer.

So inside the metal we don't have any current component in other way we can say that the metal thickness we need at millimetre wave frequencies it very small. The thumb rule is that you just take the thickness five times than the skin depth value. So for example at 100 gigahertz if I take a metal thickness of 1 micro meter so it is sufficient to attenuate or to support your current density. We don't have anything beyond one one micrometer inside the wire. So this is the general expression of skin depth about for metal we use this simplified one.

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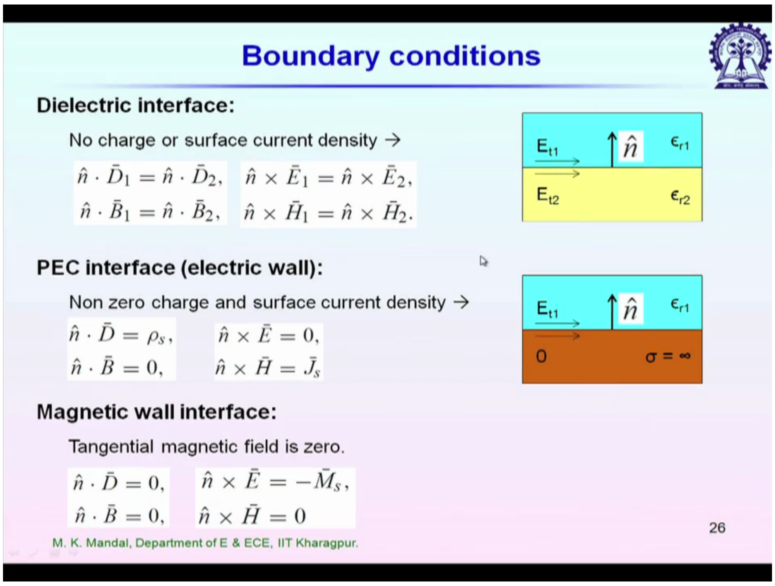

Boundary conditions

Dielectric interface:

No charge or surface current density →

$$\hat{n}\cdot\bar{D}_1=\hat{n}\cdot\bar{D}_2,\quad \hat{n}\times\bar{E}_1=\hat{n}\times\bar{E}_2,$$
$$\hat{n}\cdot\bar{B}_1=\hat{n}\cdot\bar{B}_2,\quad \hat{n}\times\bar{H}_1=\hat{n}\times\bar{H}_2.$$

PEC interface (electric wall):

Non zero charge and surface current density →

$$\hat{n}\cdot\bar{D}=\rho_s,\quad \hat{n}\times\bar{E}=0,$$
$$\hat{n}\cdot\bar{B}=0,\quad \hat{n}\times\bar{H}=\bar{J}_s$$

Magnetic wall interface:

Tangential magnetic field is zero.

$$\hat{n}\cdot\bar{D}=0,\quad \hat{n}\times\bar{E}=-\bar{M}_s,$$
$$\hat{n}\cdot\bar{B}=0,\quad \hat{n}\times\bar{H}=0$$

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Next boundary conditions so let us first consider a dielectric dielectric boundary. The first medium it has a dielectric constant of epsilon R1 and the second medium it has a dielectric constant of epsilon R2 and n cap it represent the surface vector and interface then from the boundary conditions.

We know that if we assume that no charge or surface current density is there on the interference then the normal component of displacement factor is continuous across the boundary and the normal component of B is continuous across the boundary so that means whatever we have due one inside epsilon R2 so if I take the perpendicular component it is equal to umm D2 sorry D2 whatever we have in epsilon R2 it is equal to D1 in epsilon R1 if I consider just the normal component.

So similarly it can be shown that the tangential component of electric field it is continuous across the boundary so the tangential component ET1 that is equal to ET2 so just inside medium 1 and just inside medium 2 is parallel electric field component they are equal. Similarly for the magnetic field H1 and H2 tangential component they are continuous.

Now if we have a dielectric metal boundary so second example let us consider a PEC so how we define perfectly electrical conductor so for that sigma is infinite if sigma is infinite then we don’t umm we don’t have any charge inside this PEC so in that case all the charge it will appear only on the metal surface or PEC surface.

So then the normal component of D it is discontinues by the charge density rho is normal component of B is zero normal and the tangential component of electric field is zero so this is one important observation for PEC or sometimes we call it electric valve tangential electric field component is zero. So if there is any electric field on PEC it might be then perpendicular and the tangential component of H is discontinuous by the surface current density JS.

Similarly we may have magnetic wall interface so sometimes we call it umm open circuit condition. So for magnetic wall interface we have tangential magnetic field zero and the relationships are given here normal component of D is zero normal component of B is zero and tangential component of electric field it is discontinuous by an imaginary magnetic surface current density and the tangential component of H is also zero.

So two important observations from this last two electric wall and magnetic wall interface for the electric wall then we have only the normal component of electric field or tangential electric field component zero and for the magnetic wall we have tangential umm magnetic field zero so we have only the normal component of magnetic field so this first one electric wall sometimes we call the short circuit condition and the second one magnetic wall sometimes we call the open circuit condition.

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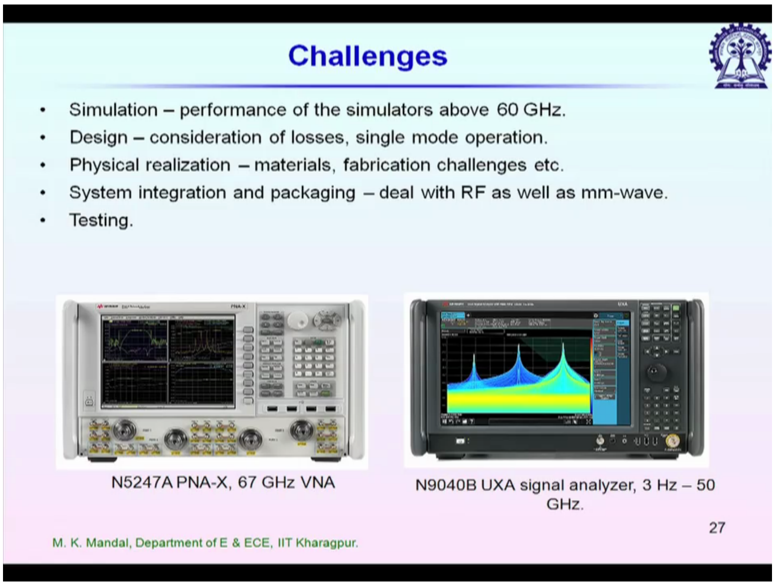

Challenges

- Simulation – performance of the simulators above 60 GHz.
- Design – consideration of losses, single mode operation.
- Physical realization – materials, fabrication challenges etc.
- System integration and packaging – deal with RF as well as mm-wave.
- Testing.

N5247A PNA-X, 67 GHz VNA

N9040B UXA signal analyzer, 3 Hz – 50 GHz.

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So now with this terms so let us see what are the different challenges we face at millimetre wave frequency and then we learn how to overcome them so whenever we are going to design any millimetre wave systems or any millimetre wave component we have to deal with this challenges. So let us start with this first one. Simulation how we design any components? We use different types of EM silver we call it electromagnetic silver.

So what it does? It basically solves Maxwell's equation umm over the structure so we have to first define the physical structure and then the silver automatically it discretised that physical structure and solve Maxwell's equations and now umm so that discretisation number it depends on the wavelength and if I increase the size with respect to wave length so in that case we have to use more number of cells we call.

So that means the overall computational volume it will increase so for example if we simulate any structure at very low frequency and the same on at very high frequency let us say 60 gigahertz and above so it will consume more computational resources so if we simulate let us say any components like a filter at 6 gigahertz it can take let us say a 10 to 15 minutes umm in a 3 gigahertz processor with 8gb ram.

But if I want to design a filter for 60 gigahertz application in the same computer it can take a few hours. So next is design challenge, we will see later there are different sources of losses and this loss is much higher at millimetre wave frequency. So how to minimize this loss when we go for any millimetre wave system design? Thats really a challenge and the second point is single mode operation.

So for any given umm wave guiding structure we prefer that there will be only one type of mode present in that structure and there is no excitation of any higher RADAR modes otherwise this high RADAR modes they will increase the loss of the system and also dispersion so we have to avoid this high RADAR modes then next is physical realization.

So we have to choose or we have to use some materials which will give you lower loss at millimetre wave frequency and we also have to face the fabrication challenges because we will see that many of the millimetre wave as well as microwave components are based on transmission line theory and in transmission line umm following this transmission line theory then this components length will be given in terms of wavelength.

So for example you can consider a radiating umm patch antenna whose length should be lambda g by 2 at the radiating frequency now let us see we are designing at 60 gigahertz free space wavelength is 5 millimetre and in your umm substrate it will be 5 by root epsilon R so already the antenna dimension is very small now due to the fabrication tolerance if it changes by fac even a fraction of millimetre.

So obviously now the operating frequency will change so you are designing some antenna for 60 gigahertz applications but due to fabrication tolerance it can operate let us say 55 gigahertz or at 65 gigahertz which is not desired at microwave frequency sense the antenna length is quiet big so we don't face usually this type of problems. So fabrication tolerance that is another major important issue at millimetre wave frequency range.

So next is system integration and packaging so finally we have to package this millimetre wave components to protect it from different severe weather conditions so then what type of materials we should use for packaging and how to package this millimetre wave components without changing their characteristics so it again another problem.

So we have to take into account all this issues when we are going for any design and whenever we are going for integration for any system then in that system as we have seen in the first picture that we don't have only the millimetre wave components we have also the RF and low frequency components so in the same module how to integrate the millimetre wave system with the RF and low frequency system that is another challenge.

And we have to consider all this effects so next is testing once I design my component obviously I would like to taste the components its working at all or not. Or it is giving the desired performance or not so we need some instruments and that millimetre wave frequency the instruments are very expensive how expensive?

Let us say we want to buy one vector network analyser which let us say will support till 110 gigahertz it can cost 2 crore so testing that is another important factor and its very expensive only a few labs in our country has this millimetre wave facilities.

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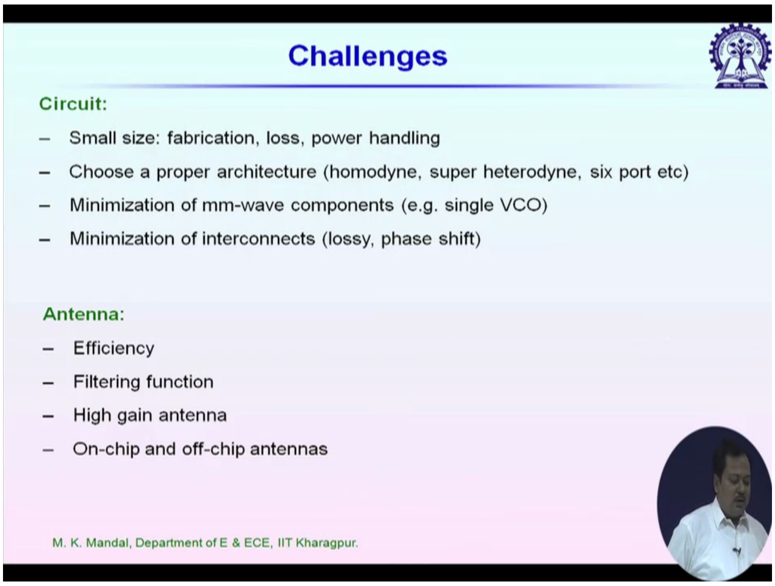

Challenges

Circuit:

- Small size: fabrication, loss, power handling
- Choose a proper architecture (homodyne, super heterodyne, six port etc)
- Minimization of mm-wave components (e.g. single VCO)
- Minimization of interconnects (lossy, phase shift)

Antenna:

- Efficiency
- Filtering function
- High gain antenna
- On-chip and off-chip antennas

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Next circuit realization, so at as how we discussed that the millimetre wave frequency the circuit size is already very small so fabrication is a problem, loss is a problem so if the circuit size become small in that case its power handling capability will decrease. So if possible use a proper architecture for a receiver so not only for receiver for any given system there are different architectures possible so for example let us say we are going to design a receiver.

So it can be homodyne receiver, it can be super heterodyne receive, or it can be a six port receiver. So for a six port receiver we have many passive components parked inside the receiver. For super heterodyne receiver we have to many components, to many active components, to many filters so if we really want to use it for handle device it becomes a problem so for handle device that is why homodyne receiver is preferred or zero.

IF receiver is preferred so then depending on applications we have to choose a proper architecture not only for receiver for any other millimetre wave system. So some system uses many VCO so we have to minimize the mil millimetre wave components to minimize the cost of the circuit.

So if possible just use a single receiver for your whole millimetre wave system so again losses due to minimization of interconnects so interconnects why do we need in the system millimetre wave system will be having many components of (())(28:25) starting from antenna we have amplifier, we have mixer, we have other passive components like coupler, filter. Now we have to use some interconnects to connect them.

So it can be any wave guiding structure or it can be simple wire bounding or (())(28:47) chip attachment but whenever we are going to use them we have to keep in mind that already my wavelength is very small so for a guiding structure let us say if it physical length is L so in that case total phase shipped umm from that wave guiding structure theta it is given by beta into L.

So beta its a function of frequency so if I increase the frequency for a given length L so this theta it will increase so then this at millimetre wave frequencies the wavelength already so small that if the interconnect even its length is 1 millimetre it can provide substantial phase ship fellow. So we have to take into account this phase ship as well as loss, signal loss when its going through that interconnects. So we have many more challenges, or I will take a short break again and then we will continue. Thanking You!