Millimeter Wave Technology.
Professor Mrinal Kanti Mandal.
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Indian Institute of Technology, Kharagpur.
Lecture-13.
Guiding Structures (Contd.)

Okay so we will come back. We are continuing with that ground backed CPW line. So let us come back here.

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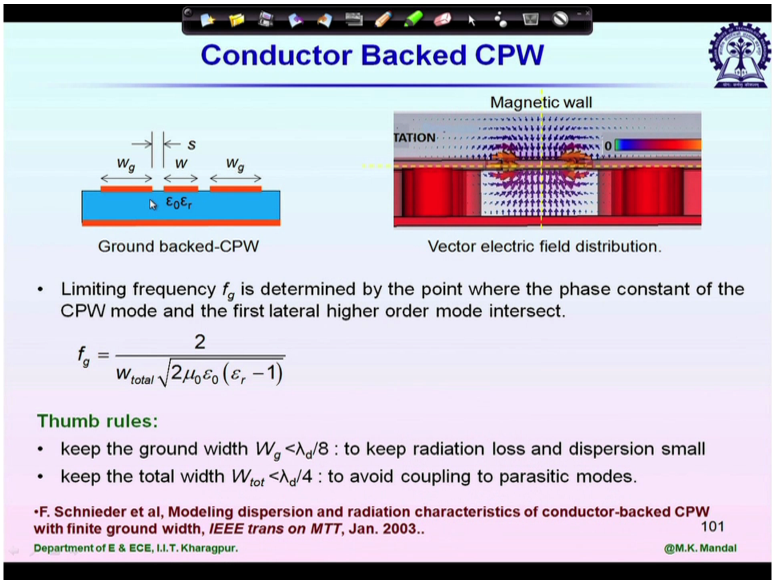

Conductor Backed CPW

Ground backed-CPW

Vector electric field distribution.

- Limiting frequency f_g is determined by the point where the phase constant of the CPW mode and the first lateral higher order mode intersect.

$$f_g = \frac{2}{W_{total}\sqrt{2\mu_0\varepsilon_0(\varepsilon_r - 1)}}$$

Thumb rules:

- keep the ground width $W_g < \lambda_d/8$: to keep radiation loss and dispersion small
- keep the total width $W_{tot} < \lambda_d/4$: to avoid coupling to parasitic modes.

•F. Schnieder et al, Modeling dispersion and radiation characteristics of conductor-backed CPW with finite ground width, *IEEE trans on MTT*, Jan. 2003..

So in ground backed CPW line, we have one additional ground plane. If I now plot the electric field inside the structure. You see we have the CPW basic CPW line and the central part we can consider it looks like a microstrip line. Right? Because we have now this additional ground plane. So in this case what we see practically?

We have the CPW mode so electric field parallel to the dielectric air interface. In addition to that we have microstrip line mode which will be perpendicular to this bottom ground. So you can see from the right hand side figure. We have CPW mode inside the slot as well as we have microstrip line mode. Both together and these two modes have almost similar velocities.

So the dispersion effect usually we neglect it but we may have higher radar modes and that is associated with different velocities phase velocities. So if somehow those higher radar modes are excited then phase velocities will be different and we will be facing dispersion effect. So to avoid that what we do? So the limiting frequency we define one limiting frequency which is Fg here.

It is determined by the point where the phase constant of the CPW mode and the first lateral higher radar mode , they intersects. So this is the next higher mode and approximately it can be given as Fg equal to two by w total square root of twice mew nought epsilon nought into epsilon r minus 1. So it depends on the total width. What is w total? This is from left most point to right most point.

So twice WG plus w plus twice s and its also depends on epsilon r. So in this case you see we have one problem. What problem it is? The problem is that surface wave generation. What type of surface wave we may have here? TE wave already we discussed. Now since we have microstrip line mode we may have TM wave as well.

Not only that if we have thicker WG too wide in that case we may have also parallel plate mode. So all these three surface wave can be generated and the line will be very lossy. To we can avoid the surface wave to some extent by using periodic via so what we do? Let me draw the top view of this modified grounded ground back CPW line.

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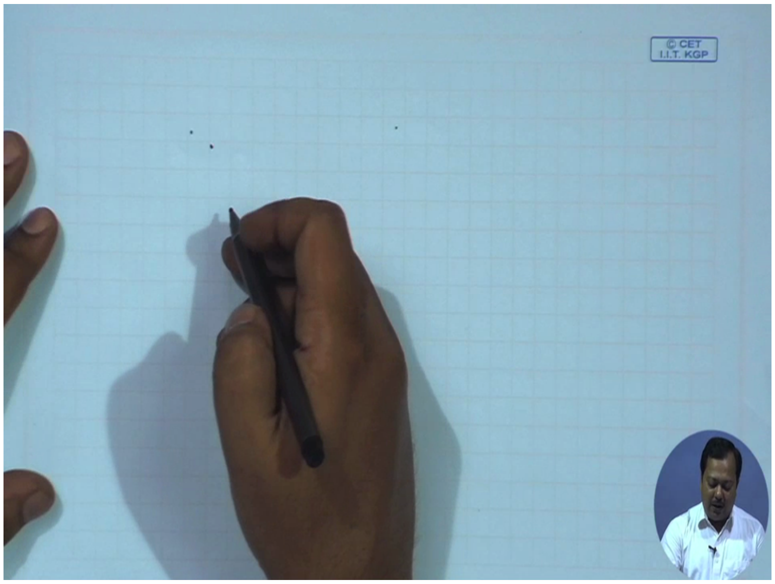

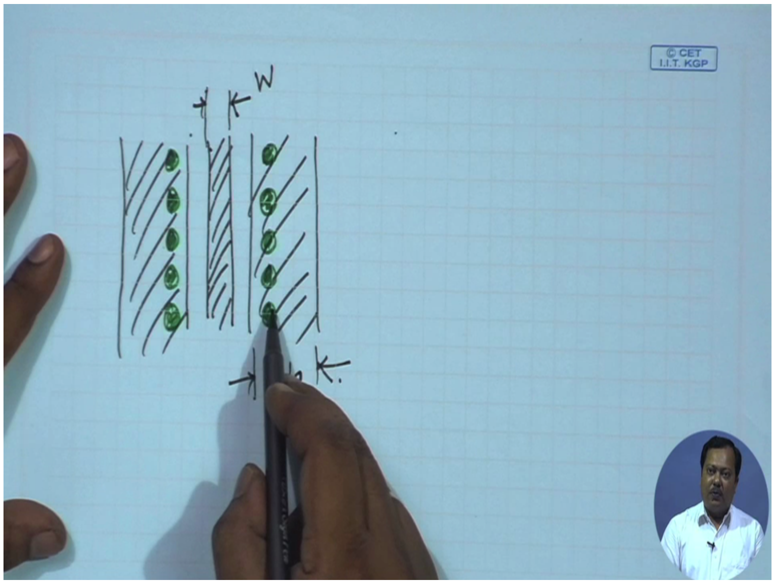

So this is the signal line let's say, and I am drawing the ground line here. So it shows the top view. So this is my signal line its width I am showing by w and this is the ground plane ground ((4:08)) ground line the width is given as WG and then we deal periodic via which connects this top ground to bottom ground and you see what is the advantage of this periodic via which are metallic via. It will suppressed TM mode as well as parallel plate modes. So the resultant structure you can see here.

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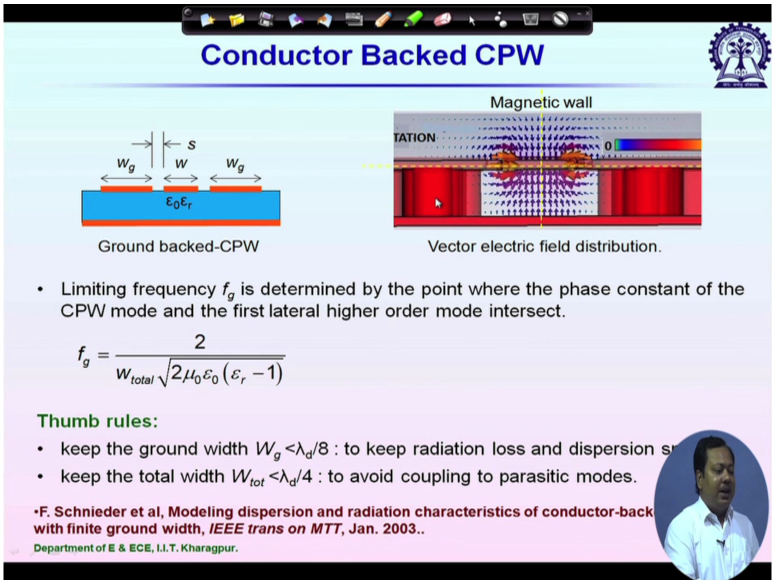

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This red lines it shows those periodic metallic via those connects these top and bottom ground plane and we can avoid leakage to surface wave in that way to some extent. Now in semiconductor fabrication procedure it's not easy to create periodic via.

So in those cases mostly people will use either a conventional CPW line without any ground backing or a ground back CPW line without periodic via. In that case we have to follow some thumb rules. If we don't use that periodic via to keep surface wave mode generation minimum and those rules are listed here.

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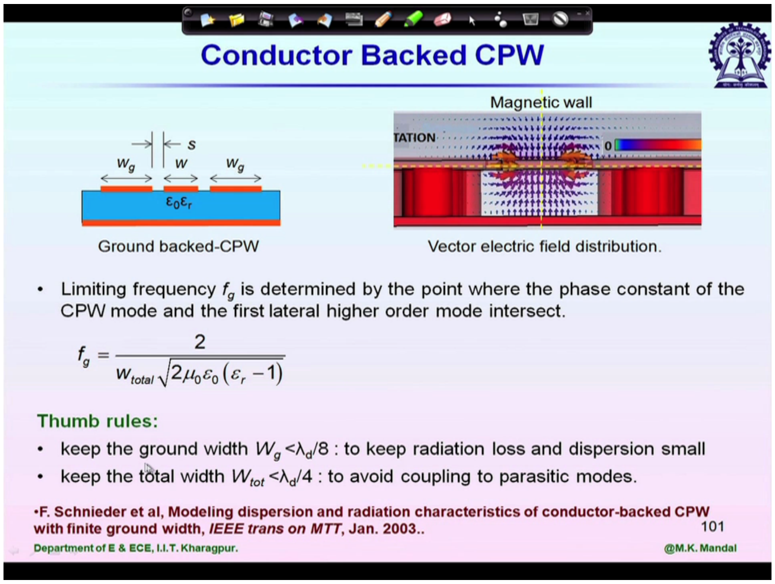

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Keep the ground width WG less than lambda d by 8 so this is to keep radiation loss and dispersion small and keep total width W total less than lambda d by 4 to avoid coupling to parasitic mode other higher radar higher radar modes. So lambda d this is the guided wavelength in ground back CPW lines.

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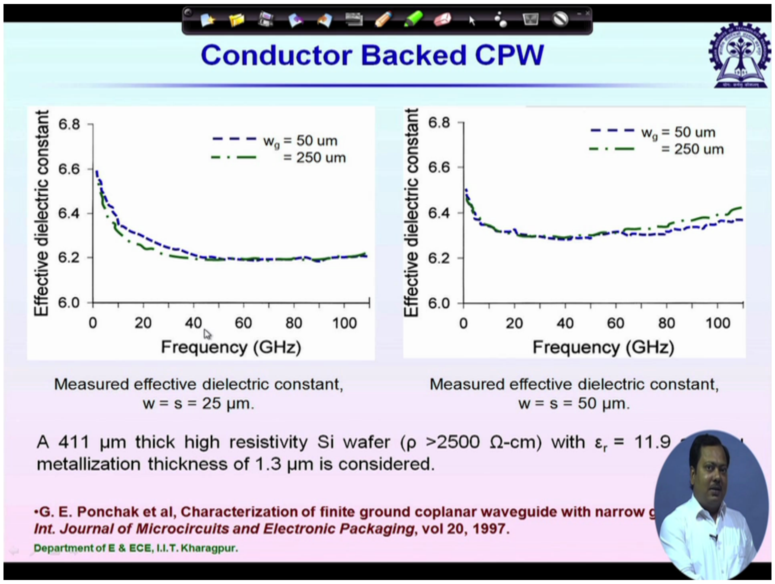

Conductor Backed CPW

Measured effective dielectric constant, w = s = 25 μm.

Measured effective dielectric constant, w = s = 50 μm.

A 411 μm thick high resistivity Si wafer (ρ >2500 Ω-cm) with ε_r = 11.9 metallization thickness of 1.3 μm is considered.

•G. E. Ponchak et al, Characterization of finite ground coplanar waveguide with narrow *Int. Journal of Microcircuits and Electronic Packaging*, vol 20, 1997.

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Now to give you some ideas about loss variation and beta variation so once we have the variation of effective epsilon from that we can estimate what is the variation of beta versus frequencies. So we are considering a silicon substrate semiconductor technology. The thickness is 411 micrometre high resistivity silicon rho more than 2500 ohm centimetre.

So you remember what is high resistivity silicon, it is more pure silicon. So doping concentration is negligibly small and epsilon r its 11.9 and the metal we are using gold of thickness 1.3 micrometre and this shows the major effective dielectric constant versus frequency for two different scenario WG.

The width of top ground plane in one case 50 micrometer and in second case we are increasing it to 250 micrometre and in left figure we are considering the width of the signal line and that is equal to the slot line is 25 micrometer and for the right figure the values are 50 micrometre and look at the variation at very low frequencies its having higher effective dielectric constant.

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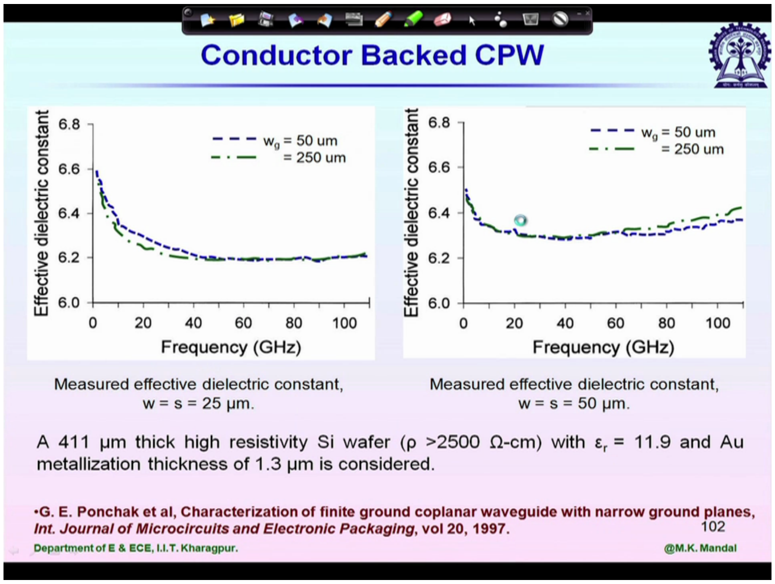

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•G. E. Ponchak et al, Characterization of finite ground coplanar waveguide with narrow ground planes, *Int. Journal of Microcircuits and Electronic Packaging*, vol 20, 1997.

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What that means? That means if I go back to this field plots so we have microstrip line field as well as CPW field.

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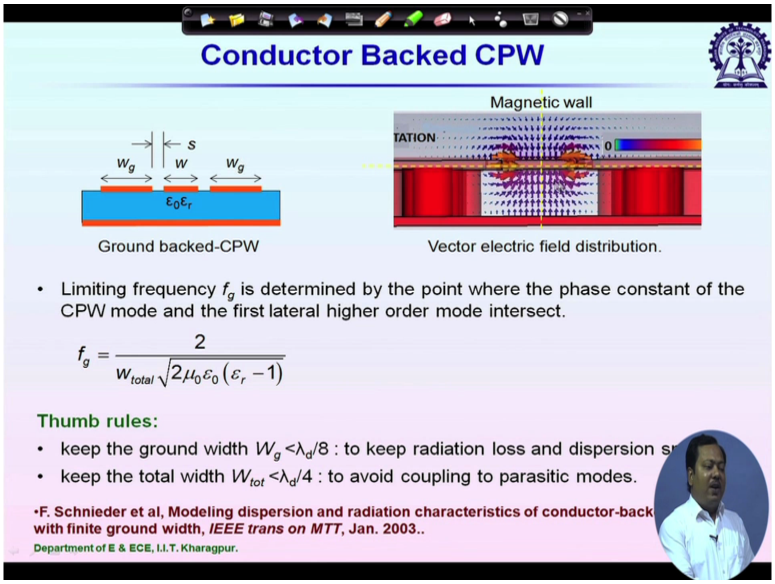

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Now if we have more fields confined inside epsilon r or dielectric layer so effective dielectric constant will be higher.

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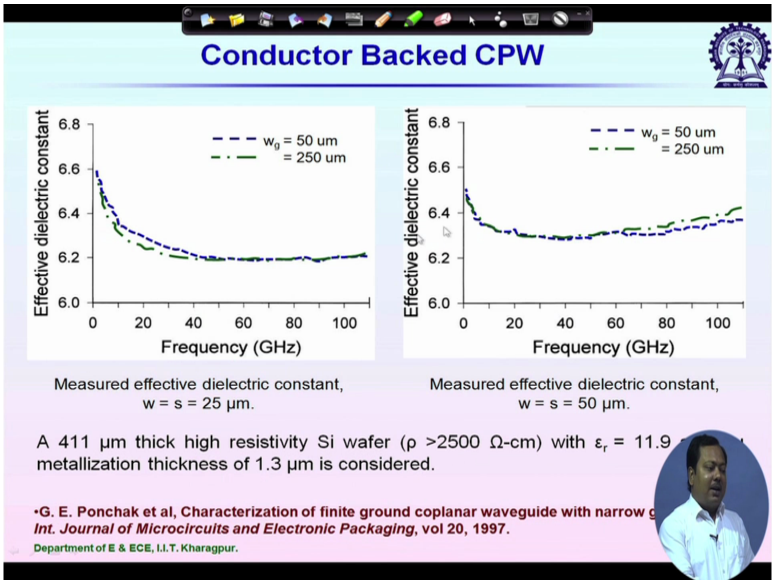

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***Int. Journal of Microcircuits and Electronic Packaging*, vol 20, 1997.**

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So at lower frequencies then we can say that we have less flanging field in air but as the frequency increases, the flanging field in air it first initially increases and then more or less it remains constant. So at millimetre wave frequencies you see we don't face any problem of beta variation as such, since epsilon e is more always constant.

Now the same substrate but we change w and s so in this case slot width is thicker. Its now 50 micrometer previously it was 25 micrometer. So because of that change in epsilon E its slight. Previously it was almost 6.2 and now it is increased to 6.3. So because of the increment of this increased W.

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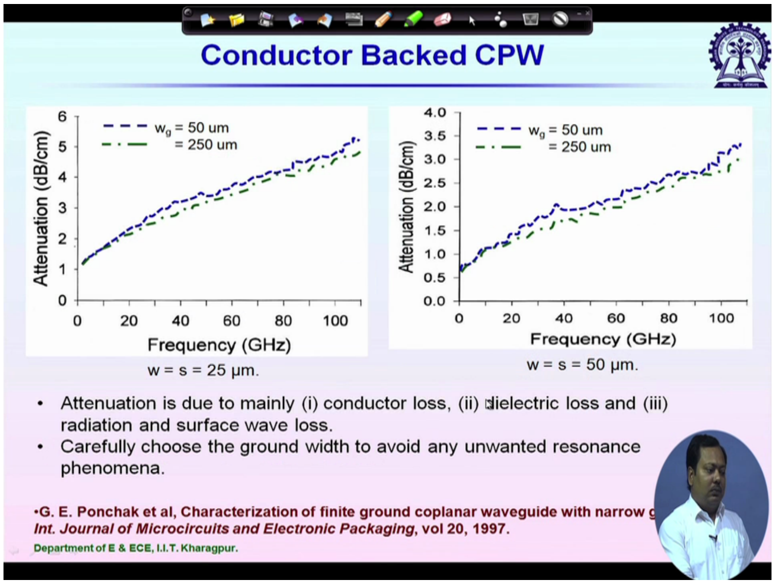

Conductor Backed CPW

w = s = 25 µm.

w = s = 50 µm.

- Attenuation is due to mainly (i) conductor loss, (ii) dielectric loss and (iii) radiation and surface wave loss.
- Carefully choose the ground width to avoid any unwanted resonance phenomena.

•G. E. Ponchak et al, Characterization of finite ground coplanar waveguide with narrow g *Int. Journal of Microcircuits and Electronic Packaging*, vol 20, 1997.

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Now loss variation. Again for the same substrate silicon substrate this is the attenuation in db per centimetre versus frequency measured attenuation we are considering again WG 50 and 250 micrometer. So loss what we expect? it should increase with frequency. This is the major loss. So it will increase.

It will include everything that means it will it will include the conductor loss, dielectric loss and as well as radiation and surface wave loss. And these plots are for the CPW line ground backed CPW line like this one.

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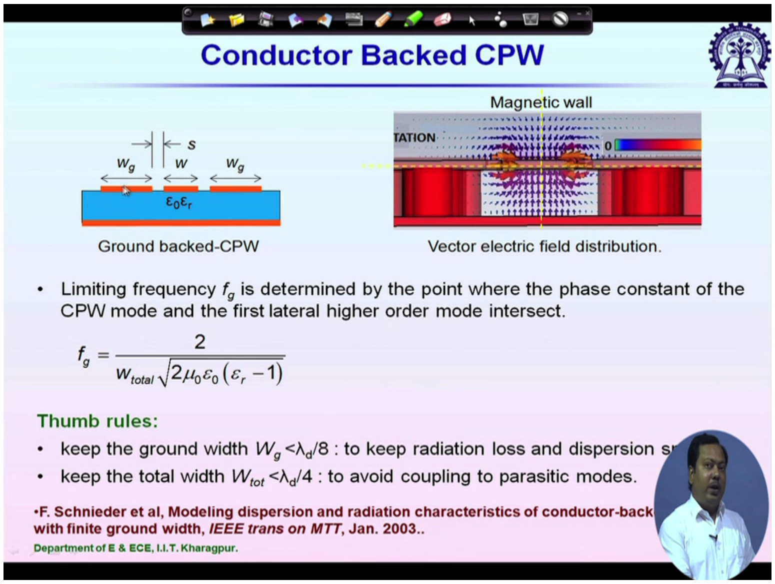

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But without any periodic metallic via.

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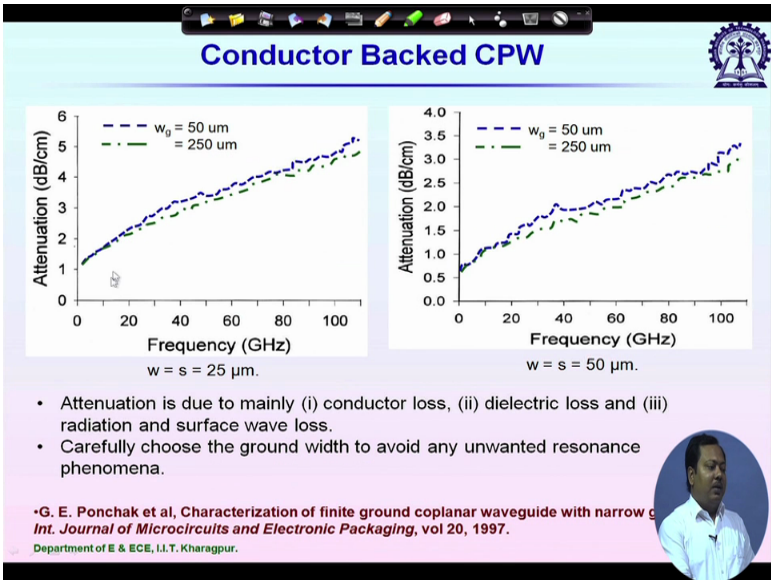

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So mainly due to conductor loss total loss increases so at lower frequencies let's say at 10 gigahertz on the same substrate this loss is typically 1.5 db per centimetre and it increases to 5 db per centimetre at 100 gigahertz so again it shows why we can't use CPW line for long distance wave propagation. We can use CPW line only for interconnects or only for chip to chip connection. Right?

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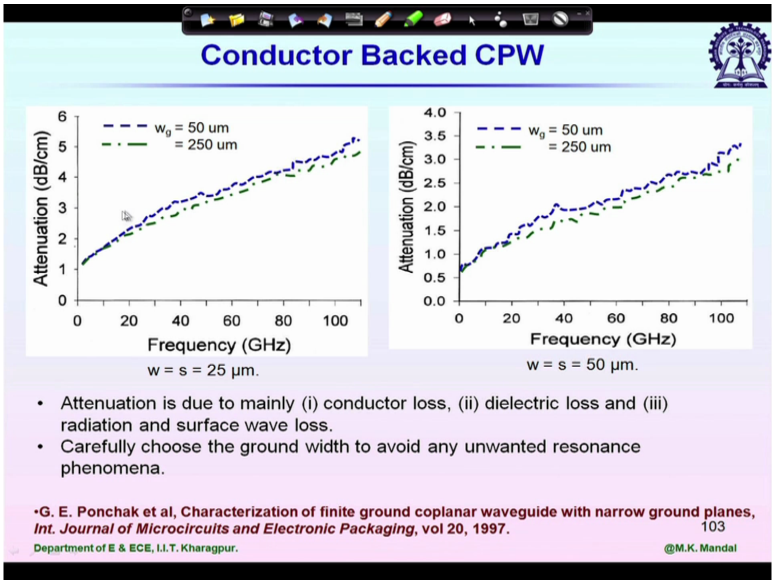

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So 3 db loss that means already power is high 50 percent is wasted. So similarly for the right figure we have similar variation. So the only thing is that since we are using wider W its now 50 micrometer. Loss is little smaller compare to the previous one. So now till now we are discussing about different types of printed lines.

The most popular printed lines are microstrip and CPW line which we already learnt. There are many more like coplanar strip line and others but coplanar strip lines usually we don’t use in PCB form its an example of a balanced line which supports all the odd mode not the even mode.

So coplanar strip line similar example is two wave transmission line two wave parallel line which we use to connect antennas for television applications or umm for telephone telephone cables. But the problem mainly we face with this printed lines is higher loss. If we want to keep the loss minimum then the only solution till now we know is the rectangular waveguide.

But for rectangular waveguide we have some other problems. What are those problems? Its very bulky and fabrication its also very difficult, expensive. Now for some applications let’s say we need some we are umm we want some guiding structure which won’t be as lossy as this printed lines like microstrip or CPW and at the same time we don’t want the rectangular waveguide.

We don’t need that lower loss. Do we have any solution in between that will give some sort of compromization in between the printed lines and rectangular waveguide so there is one waveguide system and it is the planar form of rectangular waveguide we call it synthesized rectangular waveguide in printed circuit board technology or other terms are (())(13:41) waveguide. Also it knows as substrate integrated waveguide. So let's let me show you the pictures.

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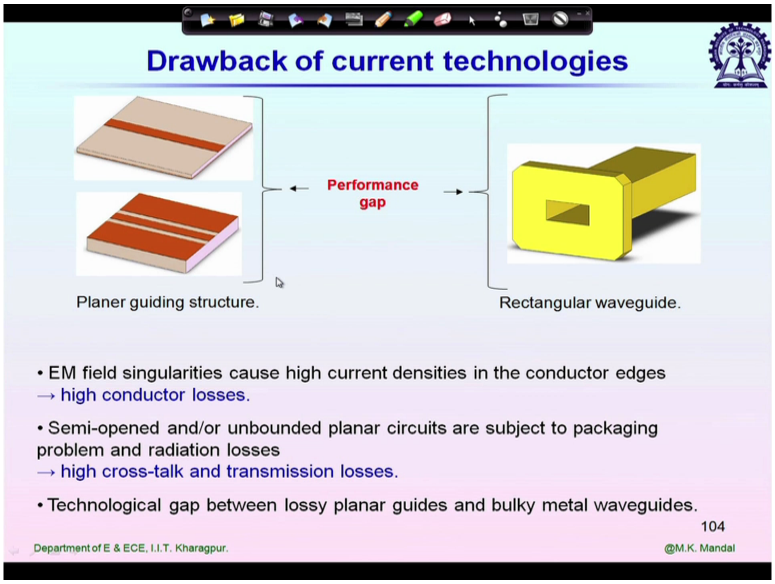

Drawback of current technologies

Planer guiding structure.

Rectangular waveguide.

- EM field singularities cause high current densities in the conductor edges → high conductor losses.
- Semi-opened and/or unbounded planar circuits are subject to packaging problem and radiation losses → high cross-talk and transmission losses.
- Technological gap between lossy planar guides and bulky metal waveguides.

So before going to that the problem what we have seen with the printed lines is that higher conductor loss and mainly this conductor loss it comes from the edges from the strips both for the CPW and microstrip line and not only that it is semi opened structure so we need packaging and it's a problem.

And if we use two parallel lines then there will be high cross talk between these two lines but for rectangular waveguide we have the advantage that it's a closed structure so there won't be cross talk between two side by side rectangular waveguides but the problem is its size and its volume and also the fabrication cost. So we have a performance gap between these two and that is where this is substrate indicated waveguide or a SIW comes.

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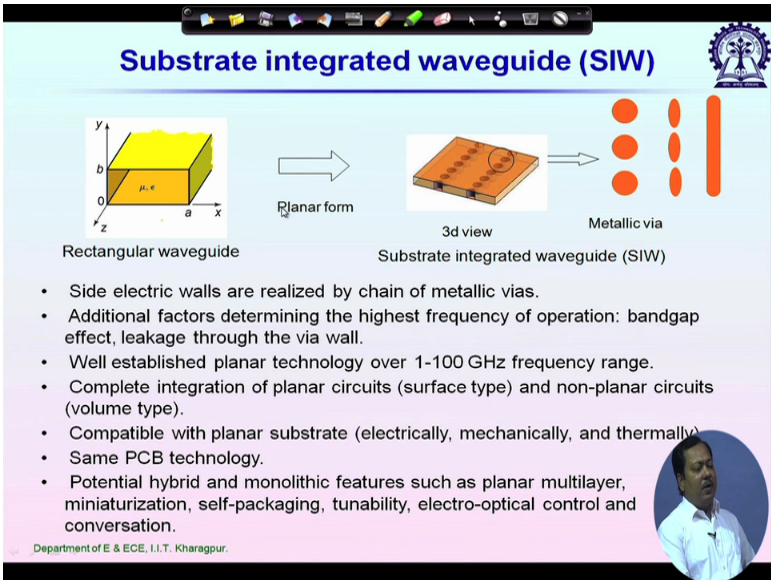

Substrate integrated waveguide (SIW)

Rectangular waveguide

Substrate integrated waveguide (SIW)

- Side electric walls are realized by chain of metallic vias.
- Additional factors determining the highest frequency of operation: bandgap effect, leakage through the via wall.
- Well established planar technology over 1-100 GHz frequency range.
- Complete integration of planar circuits (surface type) and non-planar circuits (volume type).
- Compatible with planar substrate (electrically, mechanically, and thermally).
- Same PCB technology.
- Potential hybrid and monolithic features such as planar multilayer, miniaturization, self-packaging, tunability, electro-optical control and conversation.

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It performance and cost wise it is in between this printed lines and rectangular waveguide. How we design SIW? You see this is the rectangular waveguide we are going to obtain similar characteristics but in printed circuit board technology. The advantage is that we can easily use that cheaper fabrication procedure used in PCB.

Now for a rectangular waveguide it supports TE10 mode and the synthesized waveguide what we are going to design we are expecting that will also support TE10 mode so we have to obtain a similar structure in PCB technology. Now the broad walls top and bottom metal walls we can easily realize in PCB form. How?

Because if we buy any laminate or printed circuit boards it comes with top and bottom metallization. So we can utilize those metals as our broad walls of the rectangular waveguide. So next job is to realize the side walls (())(16:12). But in PCB technology how we can do it? What we do?

We drill periodic via and then metallised them so it becomes change of metallic via and now if the separation between these two metallic via is small in that case any electromagnetic wave propagating through its channel it can't understand the separation and to that electromagnetic wave confined inside this channel.

Its it it behaves like a continuous side wall but provided the separation between these two metallic via it should be very small compare to the wavelength of the guide. So there are some limitations so now one by one we are going to see then what should be the designed steps and how these steps are derived for SIW technology.

Now there are different fabrication procedure we can drill this via laser laser beam that basically bond the substrate and for laser beam by changing the focus we can actually obtain different shape of vias. So we will see one by one what are the advantages of different shapes?

How we can fabricate it? So now this SIW it became a standard form of MM IC in last 10 years and its been used from 1 to 100 gigahertz. Some people also used even at 140 gigahertz. And performance wise you remember it seats in between printed lines and rectangular waveguide.

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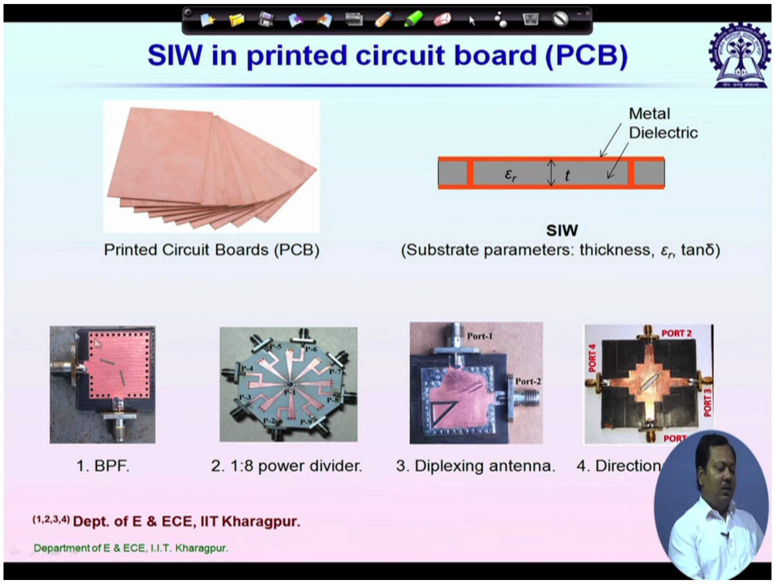

SIW in printed circuit board (PCB)

Printed Circuit Boards (PCB)

SIW
(Substrate parameters: thickness, ε_r, tanδ)

1. BPF.
2. 1:8 power divider.
3. Diplexing antenna.
4. Direction

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So we start from a PCB. You can see there are several laminates here. So we have the top and bottom metals already. Only thing is that we need to add this periodic vias. So here we are showing some components realized in SIW technology. All of these components were designed and fabricated in IIT Kharagpur. So this left one this is showing one bandpass filter.

So you can identify left and right side port. We are using semi connectors and it operates till 18 GIGAHERTZ. So its actually not in millimetre wave frequencies but we can design similar thing at millimetre wave frequencies. So you can identify the vias. The side walls of this cavity and it showing the copper and black colour its showing the dielectric.

And we have used actually one microstrip line to cavity transition and this inner conductor of the SMA it is soldered to this microstrip line. So we discuss why we need transition? Next example its showing one one is to 8 power divider. The input port actually its below its at centre and the SMA connector its seating below the substrate and these are the output ports. And the third example is diplexing antenna.

So this antenna can radiate at two frequencies and not only that these two frequency signals in receiving mode it can actually separate. The first signal it will send to port one and second signal it will send to port2. We don't need additional filter for that and the fourth example this a directional coupler. So if you feed at let us say port one it will basically divide a power between port one and port two and port three with a 90 degree phase difference.

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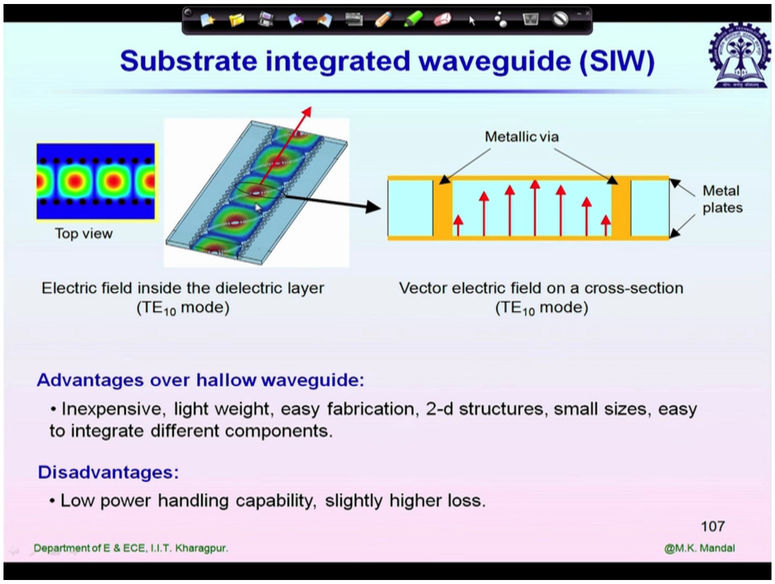

Substrate integrated waveguide (SIW)

Electric field inside the dielectric layer (TE_{10} mode)

Vector electric field on a cross-section (TE_{10} mode)

Advantages over hallow waveguide:

- Inexpensive, light weight, easy fabrication, 2-d structures, small sizes, easy to integrate different components.

Disadvantages:

- Low power handling capability, slightly higher loss.

Now let us see what is the direction of electric field inside SIW. Since its a synthesized function of rectangular waveguide in PCB form we are expecting TE 10 mode. So you look at the electric field strength variation, it looks like a TE10 mode. We have maximum at the centre point and then the minimum on the side walls as we expect for the TE10 mode.

So look at the vector electric field plot on a cross sectional plane so we have maximum on the central plane and on the side walls electric tangential electric field is zero. So the advantage is over hallow waveguide already we discussed. The fabrication procedure is inexpensive. We are using laminates to implement it. So it is a low profile structure.

Almost two dimensional so if I design any components it will be of small size and it will be really easy to integrate different components in same laminate or same PCB structure but of course it comes with some disadvantages. What are those? It has lower power handling capability compare to rectangular waveguide.

But it is higher than the printed lines and it is having somewhat higher loss compare to rectangular waveguide. Since we are decreasing the cross sectional area but this loss is lower compare to printed lines.

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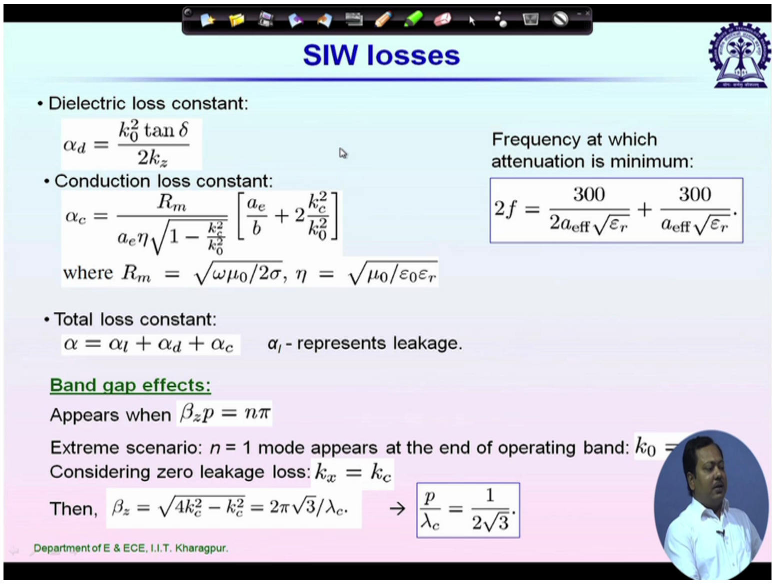

SIW losses

- Dielectric loss constant:

$$\alpha_d = \frac{k_0^2 \tan\delta}{2k_z}$$

- Conduction loss constant:

$$\alpha_c = \frac{R_m}{a_e \eta \sqrt{1 - \frac{k_c^2}{k_0^2}}} \left[\frac{a_e}{b} + 2\frac{k_c^2}{k_0^2} \right]$$

where $R_m = \sqrt{\omega\mu_0/2\sigma}$, $\eta = \sqrt{\mu_0/\varepsilon_0\varepsilon_r}$

- Total loss constant:

$\alpha = \alpha_l + \alpha_d + \alpha_c$ α_l - represents leakage.

Frequency at which attenuation is minimum:

$$\boxed{2f = \frac{300}{2a_{\text{eff}}\sqrt{\varepsilon_r}} + \frac{300}{a_{\text{eff}}\sqrt{\varepsilon_r}}.}$$

Band gap effects:

Appears when $\beta_z p = n\pi$

Extreme scenario: $n = 1$ mode appears at the end of operating band: $k_0 =$

Considering zero leakage loss: $k_x = k_c$

Then, $\beta_z = \sqrt{4k_c^2 - k_c^2} = 2\pi\sqrt{3}/\lambda_c$. → $\boxed{\frac{p}{\lambda_c} = \frac{1}{2\sqrt{3}}.}$

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Next. So first let us study the losses. So we have almost similar formula like rectangular waveguide. Now inside we have dielectric so we are expecting both dielectric loss and the conductor loss. Dielectric loss again its a function of frequency and approximately K nought square tan delta by twice KZ and the conductor loss similar to rectangular waveguide.

It depends on frequency again and at cut off loss will be infinity and it depends on Rm surface resistance. So with frequency surface resistance will increase. And we have one more additional reason. We are using periodic vias to realize the side walls. We don't have continuous side walls.

So if the separation between the side walls is more compare to lambda g what we expect leakage from the side walls. So we have one more source of loss which was absent for rectangular waveguide with continuous side walls. That is the leakage loss. And we represent it by leakage constant alpha l.

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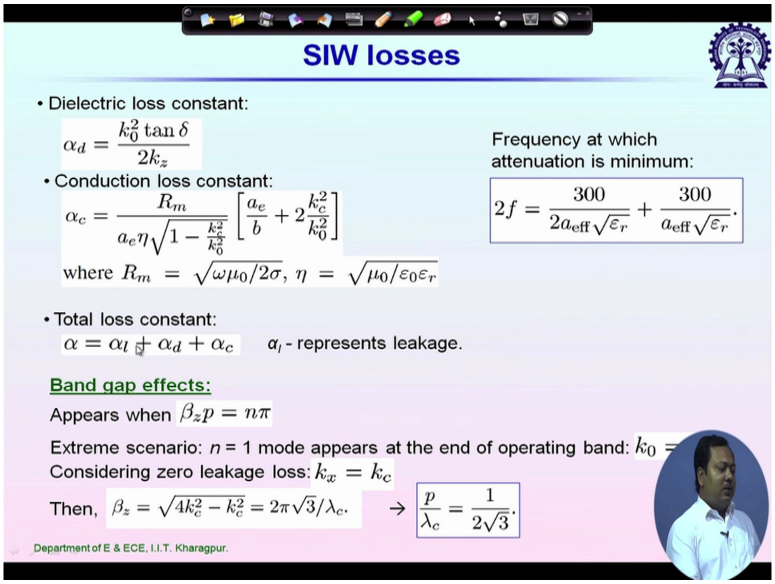

SIW losses

- Dielectric loss constant:

$$\alpha_d = \frac{k_0^2 \tan\delta}{2k_z}$$

- Conduction loss constant:

$$\alpha_c = \frac{R_m}{a_e \eta \sqrt{1 - \frac{k_c^2}{k_0^2}}} \left[\frac{a_e}{b} + 2\frac{k_c^2}{k_0^2} \right]$$

where $R_m = \sqrt{\omega\mu_0/2\sigma}$, $\eta = \sqrt{\mu_0/\varepsilon_0\varepsilon_r}$

- Total loss constant:

$\alpha = \alpha_l + \alpha_d + \alpha_c$ α_l - represents leakage.

Frequency at which attenuation is minimum:

$$\boxed{2f = \frac{300}{2a_{\mathrm{eff}}\sqrt{\varepsilon_r}} + \frac{300}{a_{\mathrm{eff}}\sqrt{\varepsilon_r}}.}$$

Band gap effects:

Appears when $\beta_z p = n\pi$

Extreme scenario: $n = 1$ mode appears at the end of operating band: $k_0 =$

Considering zero leakage loss: $k_x = k_c$

Then, $\beta_z = \sqrt{4k_c^2 - k_c^2} = 2\pi\sqrt{3}/\lambda_c$. → $\boxed{\frac{p}{\lambda_c} = \frac{1}{2\sqrt{3}}.}$

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So then together total loss alpha this is equal to alpha l due to leakage plus alpha d this is due to dielectric and alpha c this is due to conductor and it can be shown we have a thumb rule. Frequency at which attenuation is minimum approximately can be given by this closed form expression. A effective it represents the effective wall separation side wall separation for SIW.

Now we have one more problem here that limits high frequency operation of SIW. We know back scattering and band gap effect for any periodic structure. Now as the side walls already we are using periodic chain of metallic via. So we will face similar problem for this case also. So we have to avoid then that back scattering here. So how to do that?

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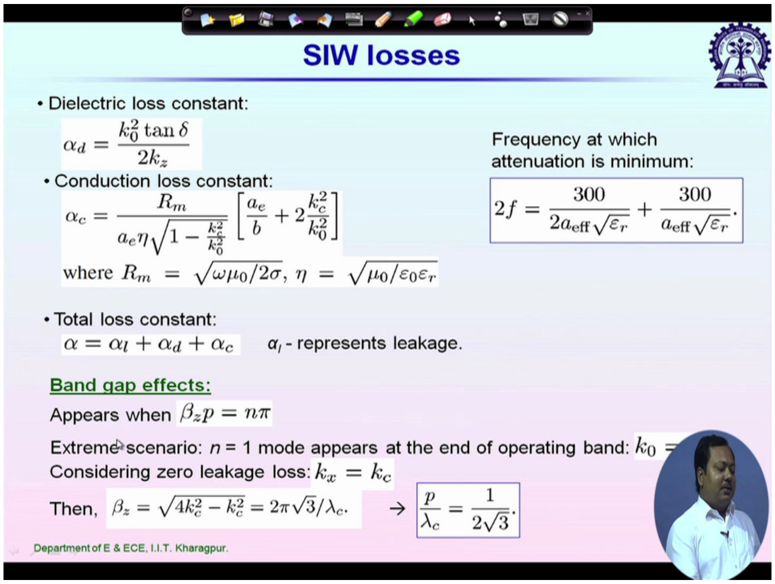

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Band gap effect we say. So it appears for any periodic structure when beta z this is the phase constant multiplied by periodicity p this is equal to n into pi. N is any integer. Let us consider the lowest order mode. We don’t want any bandgap effect in over our band gap operation. So we are considering the lowest order mode n equal to 1 and if I consider a rectangular waveguide.

Let us say operating the cut off frequency 6.5 gigahertz then the given rectangular waveguide we operate over 1.25 times Fc to 1.9 Fc looking at the alpha value. We have similar bandwidth definition also for SIW structure since its also nothing but a synthesized function of rectangular waveguide.

So for a given band then the upper cut off frequency it is determined by next higher radar mode which is TE20. So for 6.5 gigahertz cutoff frequency next the cut off frequency for TE20 mode is 13 Gigahertz. So to avoid any bandgap effect over these bands 6.5 Gigahertz to 13Gigahertz what we have to consider that n equal to one that relationship it should not appear below 13 Gigahertz. So we are doing same thing here.

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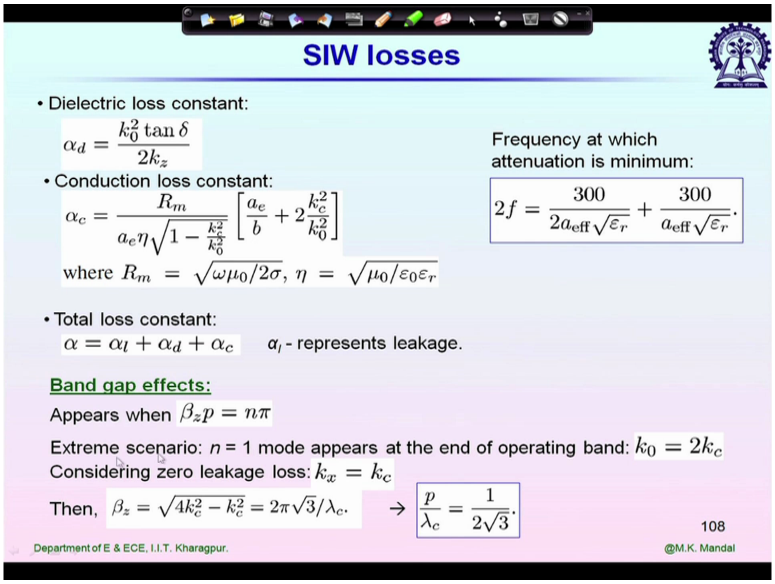

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@M.K. Mandal

So we are considering the end of operating band K nought equal to twice KC. Where KC it represents the cut off wave number and the perpendicular direction to propagation is KX. So considering zero leakage loss KX equal to KC then beta z from this relationship putting n equal to one this is square root of k square minus KC square. So we are just putting K nought equal to twice KC here.

So it comes twice pi root three by lambda c. So p by lambda c equal to one by twice root three. This is the limiting condition to avoid band gap effect. Over this band we have to keep the periodicity smaller than this value. We define a margin better. So to make sure that the band gap effect will not appear over the operating band.

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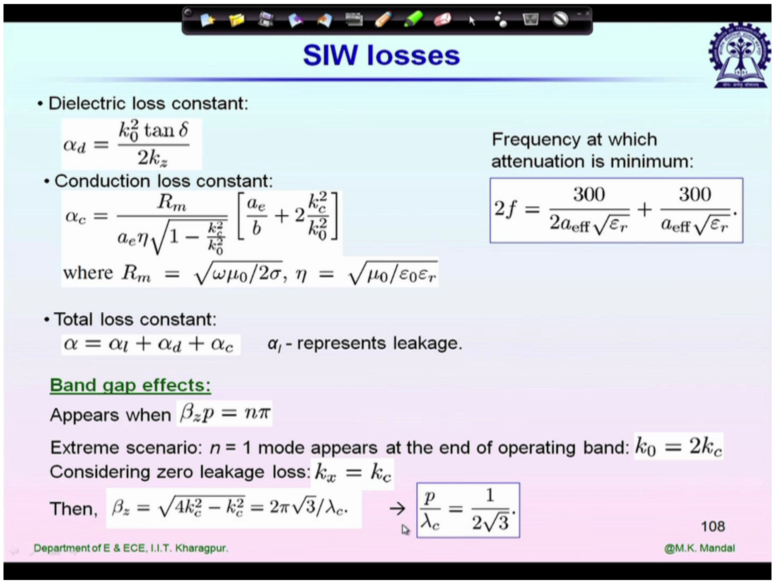

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We take p by lambda c at least 0.25 or one by four. So we have a limitation from here.

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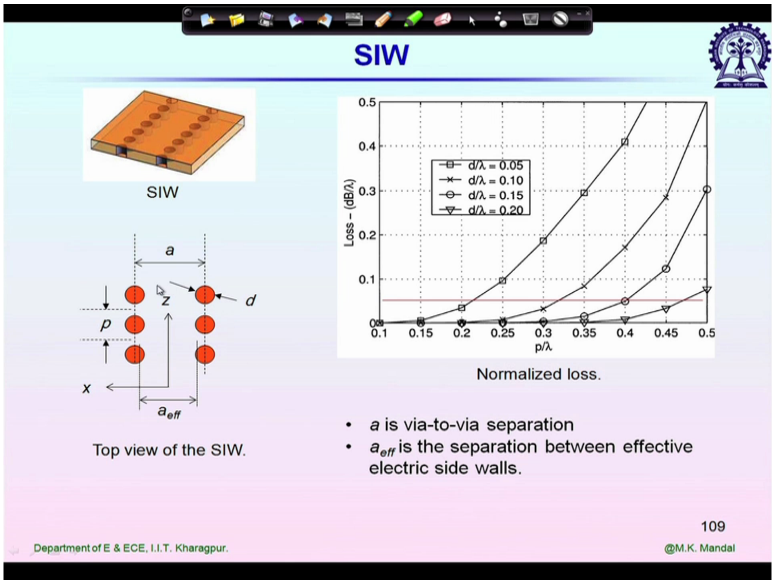

SIW

SIW

Top view of the SIW.

Normalized loss.

- *a* is via-to-via separation
- a_{eff} is the separation between effective electric side walls.

Now let us consider the leakage loss. So we have periodic structure and the periodicity is given as p and the diameter of this via is d. Now from mid point to midpoint separation that is the physical dimension is given by a. So what we are going to do? If I want to use the rectangular waveguide theorems whatever we learned we have to first determine what is the effective separation between these two side walls?

Because finally we are going to realize a continuous side walls by this periodic via. And now that effective separation between those two side walls will be what? Should we take midpoint to mid point? Or from inner edge to inner edge? Or from outer edge to outer edge? There is a thumb rule for that. This a effective is different than and let me show the thumb rule first.

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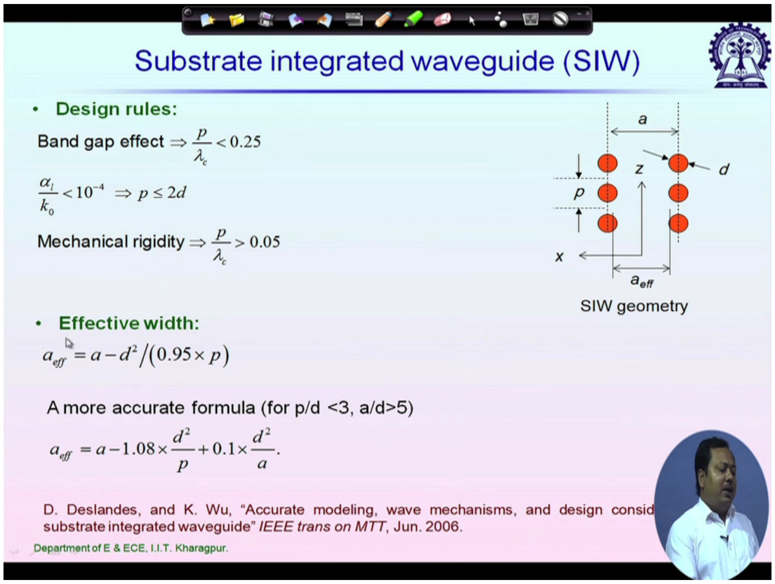

Substrate integrated waveguide (SIW)

- **Design rules:**

Band gap effect $\Rightarrow \frac{p}{\lambda_c} < 0.25$

$\frac{\alpha_l}{k_0} < 10^{-4} \Rightarrow p \leq 2d$

Mechanical rigidity $\Rightarrow \frac{p}{\lambda_c} > 0.05$

SIW geometry

- **Effective width:**

$$a_{eff} = a - d^2/(0.95 \times p)$$

A more accurate formula (for p/d <3, a/d>5)

$$a_{eff} = a - 1.08 \times \frac{d^2}{p} + 0.1 \times \frac{d^2}{a}.$$

D. Deslandes, and K. Wu, "Accurate modeling, wave mechanisms, and design consid substrate integrated waveguide" *IEEE trans on MTT*, Jun. 2006.

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So this a effective it is usually always less than the physical dimension a. This is equal to a minus D square by 0.95 into P. And we have one more accurate formula when P by D is less than three an D a by D is more than five. Then you can calculate what is the effective a effective for this.

So what a effective represents instead of periodic metal via we are replacing it by an effective electric wall and a effective it represents this separation between these two electric walls. So once we have a formula for a effective then we will be replacing the SIW by an equivalent rectangular waveguide. The thickness of that rectangular waveguide is the thickness of the substrate and the broad side dimension of that equivalent rectangular waveguide is a effective and inside we have a epsilon R.

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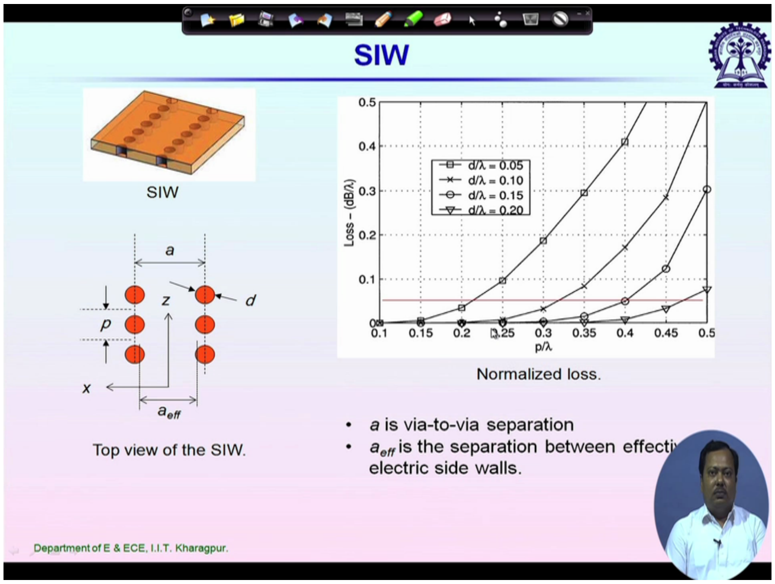

SIW

Top view of the SIW.

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Now okay so we will come back to this leakage loss before that let us take a 5 minute break. Thank you!