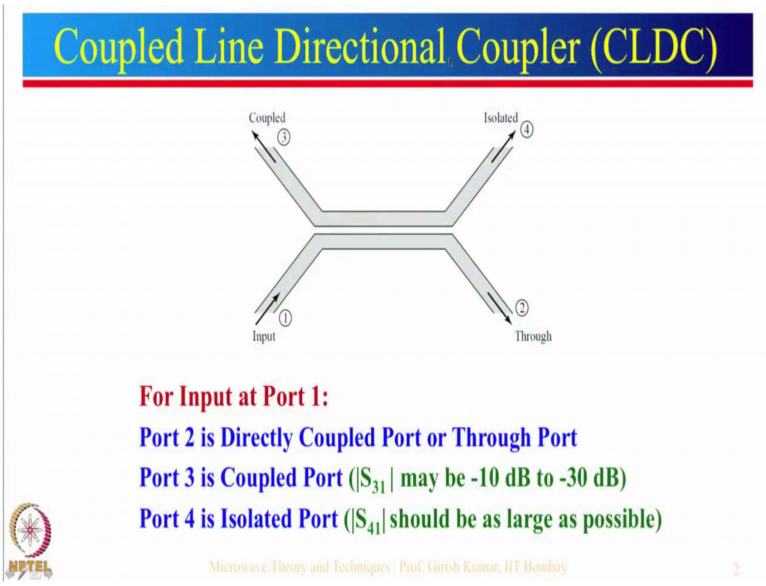
Microwave Theory and Techniques

Prof. Girish Kumar
Electrical Engineering Department
Indian Institute of Technology, Bombay

Module - 04
Lecture - 18
Microwave Couplers - I: Coupled Line Directional Couplers

Hello everyone in the last few lectures we talked about microwave power dividers where we had seen 2 way, 3 way, 4 way power divider. And we had also seen an equal power divider today we are going to talk about Microwave Couplers. So, let us start with first one which is a Coupled Line Directional Coupler.

(Refer Slide Time: 00:39)



So, first of all what is really a directional coupler let me just explain that part. So, let us think about that there is a one micro strip line which is going here let us say we are giving a input here and the output is taken from here. And let us think about one of the application that a power amplifier is connected to an antenna and antenna is transmitting.

Now supposing that if you look at a telecom sector application where they are transmit about 20 watt of power. And that is transmitting through the antenna now how do we ensure that it is exactly 20 watt or it is less or more. So, what we do we can use something like this which is known as a directional coupler, the concept is simple that if you have a current carrying conductor and if you put a another wire next to that so what will happen. The current is flowing through this in this direction and there will be induced EMF which will be coming through this one here.

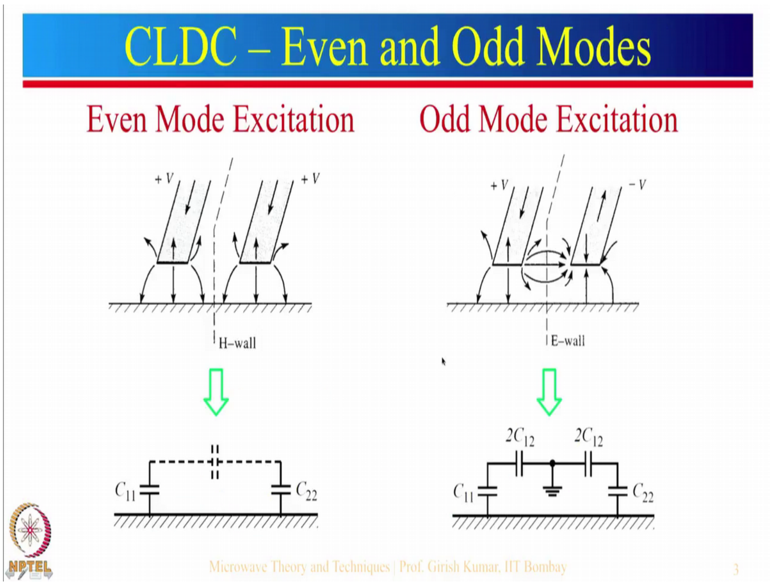
So, the same thing let us see over here. So, we had giving a input here this is known as port 2 which is a through put or also known as coupled port. So, this is where the directly coupled port is there, now because of this particular flow there will be an induced EMF which will be like this. So, this is known as coupled port and generally this particular coupled line directional coupler is good for typical range is minus 10 dB to about minus 30 dB of course, minus 40 dB is possible and also minus 6 dB or minus 5 dB or minus 8 dB is possible. But generally we do not assign this particular coupler for less than minus 10 dB. The reasons will be obvious after we cover the basic concept of this.

So, again so if you are feeding it over here this is the coupled power which is going through here or this is known as isolated port which is port number 4. And generally what we want is that S 4 1 should be as large as possible. So, let us look at the basic concept, but however, to do the analysis of this particular thing you can see that this is a 4 port problem. So, this 4 port problem can be divided into 2 2 ports problem what we do here is that think about if we draw line over here we can say that with respect to this line this particular configuration is symmetrical. So, we say that this one here is 1 so this will be 1 port, 2 port and this is a symmetrical port, so we can apply the concept of the symmetry.

So, what we do in that so just to give you little bit of an idea. So, what we want to do here let us say input is 1 and the input at all these other ports is 0. So, now, applying only input of 1 suppose we say that we apply input of half here and half here. So, plus half plus half actually gives us a even mode symmetry, then we do the second time plus half apply here minus half apply here. So, now, that is known as odd symmetry and then the final analysis is done that you take the sum of these two things. So, we had taken plus half plus half, so that will be equal to 1 and here we had taken plus half and minus half the sum of that will be equal to 0.

However many a times when we talk about S parameter we generally talk about input as 1. So, we give a plus 1 here plus 1 here then this will be even mode, in the second case we give plus 1 we give a minus 1 that is a odd symmetry and then we take the average of the 2. So, plus 1 plus 1 divided by 2 and then plus 1 minus 1 divided by 2, so that will be 0 this will become 1. So, let us look at what are these odd mode and even mode things.

(Refer Slide Time: 04:37)



So, here the same coupled lines are shown slightly different way now. So, coupled lines are actually shown here, so this is the one micro strip line and there is another micro strip line kept next to that. So, now, as I said even mode excitation its assuming that this is plus 1 fed here plus 1 fed here, and for odd mode excitation what we are going to do we will say plus 1 here and minus 1 over here.

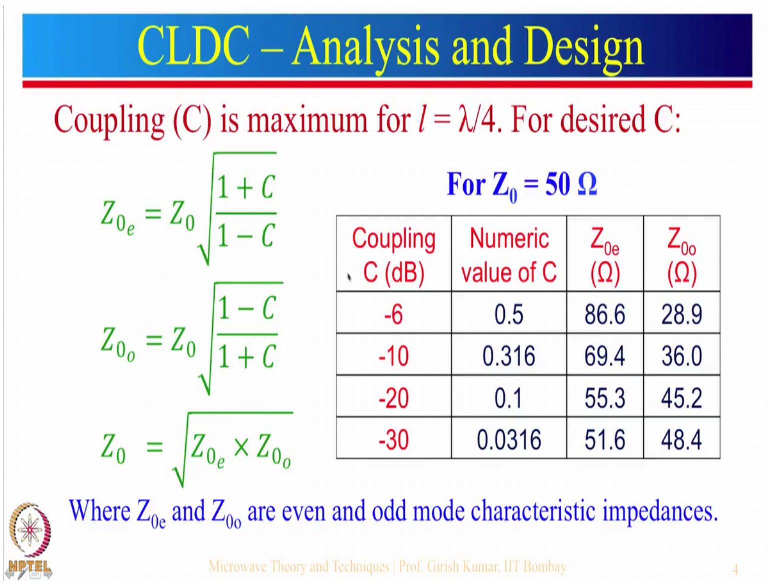
So, now you can apply its concept of the charge theory, so if there is a plus charge here plus charge here. So, that will be the field distribution and over here we can say current will be equal to 0, a 0 current at this particular periphery can be also termed as H wall or magnetic wall.

So, let us see from here we can say the equivalent capacitance. So, let us say C 1 1 is the equivalent capacitance for this particular micro strip line and C 2 2 is the equivalent micro strip for this, most of the time these two will identical, so we can say C 1 1 will be equal to C 2 2. Now this capacitance is shown over here, but that capacitance would not be there because there is an open circuit. However, when we look at the odd mode excitation, now let us say this is plus 1 this is minus 1, so there will be field going from here to here. So, just think about if this is a plus 1 voltage and this is a minus 1 voltage here we have a 0 volt. 0 volt is equivalent to short circuit and short circuit can be represented by electric wall.

So, now in this particular case we will have this capacitance C 1 1, we will have a capacitance C 2 2, but from here to here there will be equivalent capacitance which is actually let us denote as C 1 2, but here we have shown that as 2 C 1 2 in series with 2 C 1 2. So, in series we know that capacitances get divided. So, the equivalent capacitance will be C 1 2 and this is one since it is a shorted wall, so that is going to ground. So, one can see that in case of the even mode the equivalent capacitance of this line will be let us say C 1 1, but for odd mode equivalent capacitance will be C 1 1 in parallel with 2 C 1 2. So that means, the equivalent capacitance here will be C 1 1 plus 2 C 1 2.

So, now we will define even mode and odd mode impedances, but first let just look at conceptually. So, we know that impedances given by 1 over j omega C. So, compare to this, this capacitance is going to be large, so if the capacitance is large that means, Z equal to 1 by j omega C will be small. So, for this if we define even mode impedance and for this we define odd mode impedance. So, since odd mode impedance has larger capacitance odd mode impedance in general is smaller than the even mode impedance.

(Refer Slide Time: 07:47)



So, coupling is maximum when the length of the coupled line is equal to lambda by 4, we will see some simulated results and then I will show you what happens when the length is different. But just to tell you the derivations are there in many of the books you can have a quick look into that, but here we want to tell you the concept part. So, coupling is maximum for l equal to lambda by 4 and then for desired coupling this is the expression given ok.

So, odd mode impedance and even mode impedances are given by this, now this formula is valid for l equal to lambda by 4 not valid for any other value of l, because we had designing it for maximum coupling. So, let us see what we have here, so this is a even mode impedance which is equivalent to characteristic impedance of the line multiplied by you can see over here C is coming in the numerator here C is in the denominator plus and minus sign is there and these 2 are reversed. So, we can say that since the numerator has a plus sign this value will be greater than Z o o of course, if coupling is negligible. In that case we can say Z o e will be equal to Z o o and the characteristic impedance then is defined as a you can say square root of Z o e and Z o o. So, Z o e and Z o o are even and odd mode characteristic impedance.

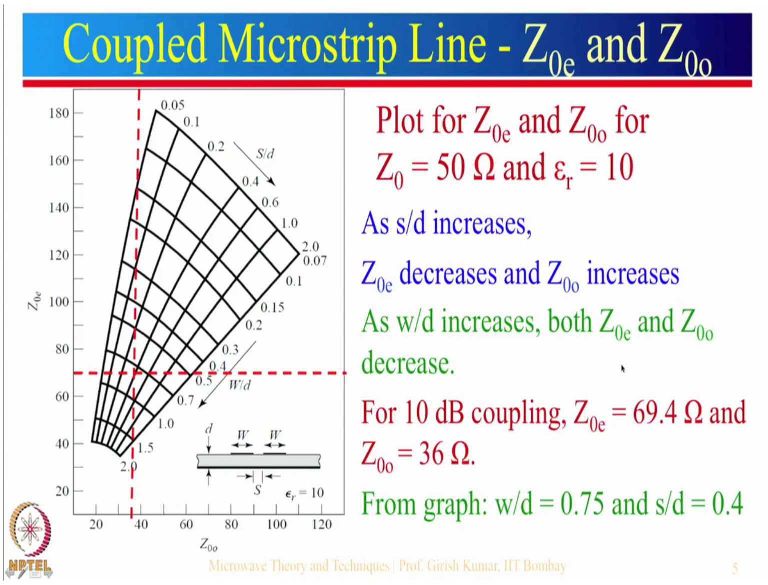
So, now let just look at the design, so for Z 0 is equal to 50 ohm we substitute here and then C. Now I have put here C minus 6 minus 10 minus 20 minus 30, but I just want to also mention that many a times they talk about 10 dB coupling or 20 dB coupling. So, when they said 10 dB coupling that does not mean that you will get more power or 20 dB coupling means more power no that is just a notation they generally use that coupling is 10 db.

But in reality coupling is minus 10 dB and this coupling is basically ratio of voltages. So, what you have to do to find the numeric value you apply to this 20 log of this value which is equal to minus 20 dB ok. So, please ensure that do not apply 10 log formula for this because 10 log of 0.1 this will be minus 10 db. So, which is not correct you have to use 20 log 0.1 which is minus 20 dB. So, for the desired value of coupling we first find the numeric value of C. Then we substitute these values over here and then calculate even mode and odd mode impedances which are given over here. So, just to bring to your attention as you can see that coupling is reduced from minus 6 to this you can say Z o e is also reducing where as if the coupling reduces Z o o is increasing.

And you can see that as the coupling becomes weak instead of minus 30 if we take minus 40 you will see that these two impedances will become approximately equal. And the reason for that is let us say I have a one coupled line and the another line is put quiet far away. So, if the other line is put far away then what will happen the coupling between the 2 will be very, very small. So, whatever is the characteristic impedance of this line will not be equal to Z 0 the characteristic impedance of this line will also be equal to Z 0.

However when we bring them closer then we will have even mode and odd mode impedances. So, now, for minus 10 dB just remember these two number, so Z o e is 69.4 Z o o is 36. Now you will take a design example for these values of even and odd mode impedances.

(Refer Slide Time: 11:50)



So, these are coupled micro strip line even mode and odd mode impedances. So, what we have the curve here even mode is shown on this side, and odd mode impedance is shown on this side. Now you see multiple these lines over here we will try to make thing simple for you.

So, here what it shows here s by d, so s is the gap between the coupled line and d is taken has depth of this particular substrate. I just want to mention some books use the symbol d some books use the symbol h. So, for d is the depth and h is h height of the substrate. So, one can see that here S by d is increasing, so as S by d increases what we can see at this point you can say Z. Even mode is higher and Z odd mode impedance is relatively lower, but as we go on increasing the value of S by d you can see that Z even mode decreases and Z odd mode increases. So, we can say now at as S by d increases Z o e decreases and Z o o increases.

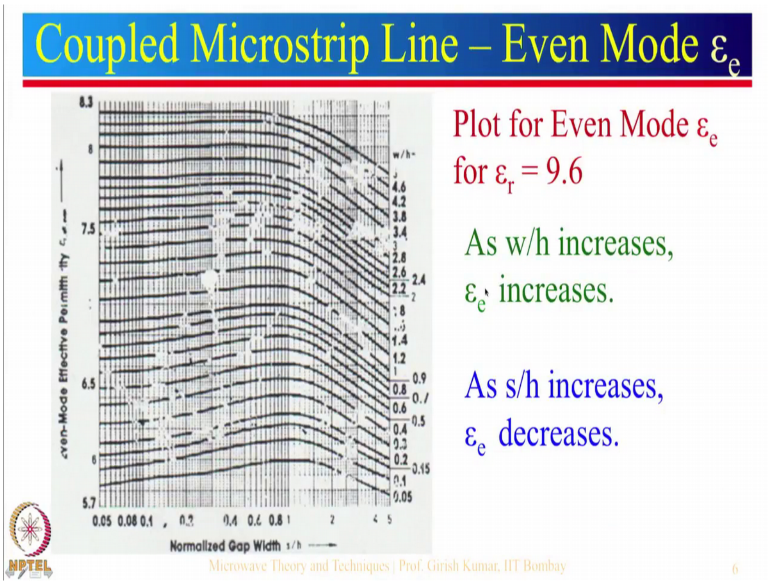
Now, let just look at what are the other plots here, so here was the plot of W by d W by d is increasing this way you can see that. If W by d is increase from let us say 0.1 2 let us say 1, one can see that from here if you look at corresponding value of even mode and odd mode impedances they are relatively higher compare to if you look at the Z even mode and odd mode impedances corresponding to W by d equal to 1.

So, we can say that as W by d increases both even mode and odd mode impedance decrease. So, now, recall from the previous example for 10 dB coupling. Now you can see that I have not written here minus 10 dB ok, but it should be obvious that coupling is going to be less this is just a general nomenclature 10 dB coupling or 20 dB coupling. So, that is why I wrote there, but please remember C is equal to minus 10 dB and for that we had seen Z even mode was 16 9.4 and odd mode was 36 ohm.

So, let us try to locate this on this particular curve here. So, this is 69.4 so, we draw a line from here close to 70 draw horizontal line and then 36 ohm. So, corresponding to 36 ohm we draw a vertical line see this value. So, from here we can read the value of s by d you can say it is 0.4. So, that is s by d equal to 0.4 and this particular point corresponds you can see here w by d is this particular curve for 0.7 and this is 1, so you can say that this is approximately 0.75.

I just to want to mention, so this particular curve is not for all values of epsilon r this is specifically given for epsilon r equal to 10 and Z 0 equal to 50 ohm. Now this is about even mode and odd mode impedances, similarly we have even mode and odd mode dielectric constant also.

(Refer Slide Time: 15:18)

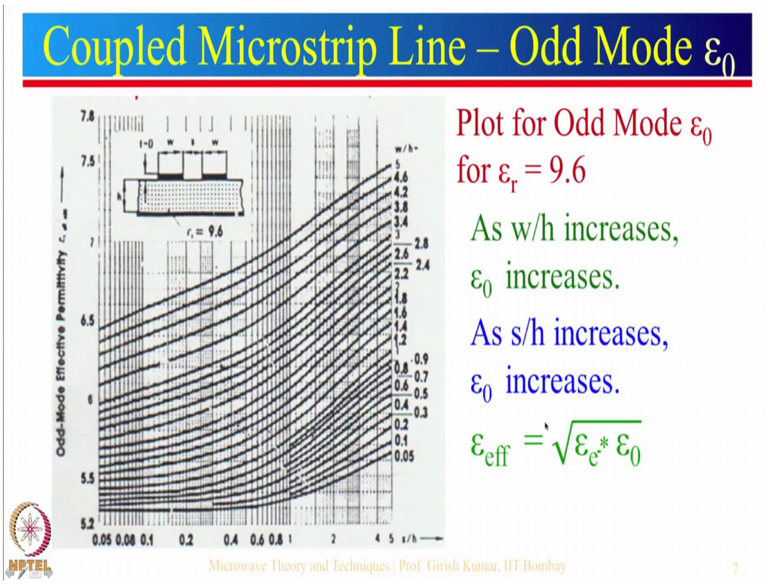


So, this is the curve for even mode epsilon e, so what we have here let us see these are the different values along this it is w by h is increasing along this axes. And s by h is increasing along this axes and this one here is a even mode effective dielectric constant.

So, this plot is for even mode for epsilon r equal to 9.6. So, let us see if we increase w by h along this thing you can see that the epsilon e is increasing ok. So, we can say safely as w by h increases epsilon e increases and that should be obvious in if you recall as the width of the micro strip line increases. So, what happens the mode wave is confined within the dielectric and we had also taken a general case if w by h becomes infinity then epsilon e becomes epsilon r. So, as w by h increases epsilon e increases.

Now, you can see that these are the cur values for s by h s by h is increasing. So, let us see here as s by h increases in the beginning the relation is almost close to flat, but for larger value of the gap s by h greater than 1. You can see that these values are decreasing of course, there is a little bit of a different variation for very small values of width. But in general we can say as s by h increases beyond say 10 value epsilon e decreases.

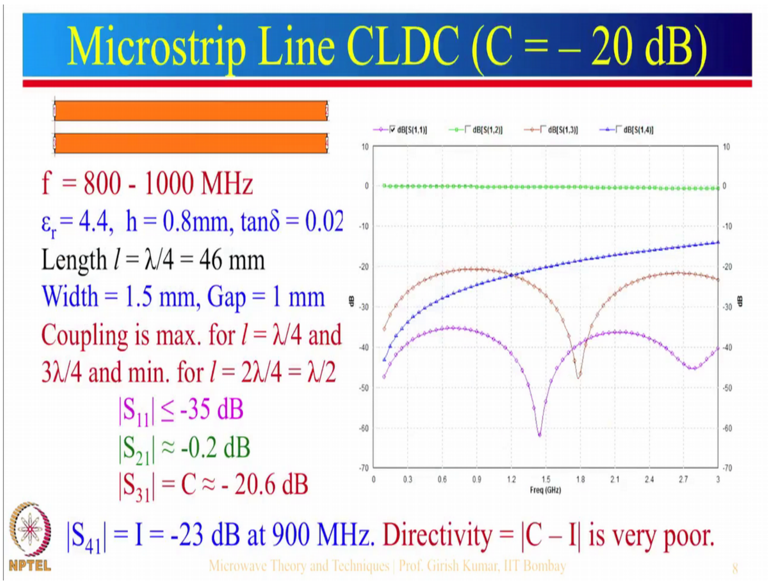
(Refer Slide Time: 17:03)



Now, let us look at the odd mode epsilon 0, so again the plot is for same value of epsilon r equal to 9.6. So, see here what we have odd mode epsilon 0 is shown over here this is s by h and this is w by h. So, we can see again as w by h increases we can see that the epsilon 0 keeps on increasing. So, we can safely write now as w by h increases epsilon 0 increases.

Now, this is here s by h increasing along this particular axes. So, we can say that as s by h increases we can see that epsilon 0 also increases. However, when we do the analysis we do not really speaking take all the time even mode or odd mode epsilon 0, what we take generally is effective value of the dielectric constant. And that is given by square root of epsilon e multiplied by epsilon 0. So, even mode and odd mode you multiply them take a square root and that will be epsilon effective. So, this is the value which is generally use for designing the coupled micro strip line, so let just take a example now.

(Refer Slide Time: 18:20)



So, here is an example where we have taken a micro strip line which is for coupling equal to minus 20 dB. So, please don't get confused sometimes I write minus 20 dB or sometimes write 20 dB. So, generally speaking remember they do write coupling equal to 20 dB, but it is always minus 20 dB.

So, here the design let us see what we have done, so we have design this coupler for 800 to 1000 megahertz frequency range this basically covers the you can say GSM 900 band as well as CDMA band also. So, we have taken and low cast substrate because this is required for commercial application which is very price sensitive. So, here normal glass epoxy substrate which is also known as fr 4 substrate. So, epsilon r is 4.4 thickness is 0.8 mm tan delta is 0.02. So, for this we have to calculate the length, so length should be equal to lambda by 4.

So, if you take a approximate the center frequency is 900 megahertz at 900 megahertz wave length is 33 centimeter. 33 divided by 4 will be let us say approximately 8 centimeter then divided by square root of epsilon e comes out to be a about 46 mm, so width of the line is 1.5 mm. In fact, if this particular width is almost same as a micro strip line width 450 ohm ok, because the gap is relatively large you can say here the gap is 1 mm because the coupling is for minus 20 dB.

So, now let us see the results you can see here this is the plot for the coupling. And one can note that coupling is maximum around this frequency which is about 0.9 gigahertz, and because we had design this whole thing for 900 megahertz. So, we can see that the coupling is maximum here around 900 which is lambda by 4 coupling is minimum around 1.8 gigahertz. Which corresponds to l equal to lambda by 2 and then again coupling becomes maximum at 3 lambda by 4 and that curve will keep on repeating. So, we need to focus at this particular point.

So, now let us see what are the other plots over here S 1 1, so S 1 1 is this plot in the purple color. So, one see that S 1 1 is very good it is less than minus 35 dB over this very large bandwidth. Now, let us see what is S 2 1 S 2 1 is this curve here you can see that S 2 1 is also relatively flat which is around 0.2 dB. Ideally it should happen 0 dB, but because we have taken a lossy substrate and also there will be small radiation from these lines hence it is about 0.2 db, but still it is very small.

You can see here this is the coupling value which is 20.6 dB. So, even though you may say we had designed for 20 dB this is 20.6 which is very, very close to that. However, just to tell you instead of taking 1 mm if you take 0.9 something mm then you can get minus 20 dB. We did not optimize this particular thing for whether I will tell you the reason and the reason is the last curve here which is the blue curve. Now this blue curve is nothing, but you can say S 4 1 which I had mention earlier it is supposed to be an isolated port. And isolated port should have ideally minus infinity dB or may be minus 50 dB or minus 100 dB, but you can see it is only minus 23 dB.

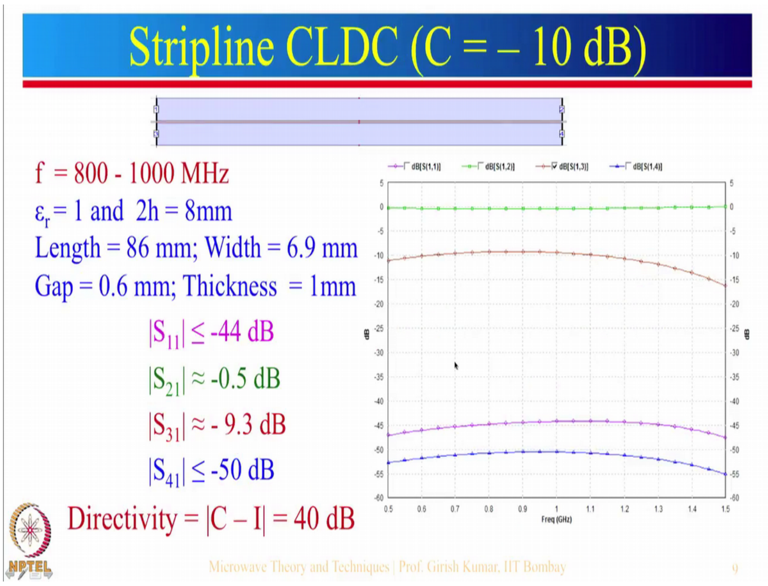
Now, will define a term directivity, now directivity defined here is the difference between the coupling and the isolation. Generally we take a magnitude of that and the difference over here if you see it is just about 2.4 dB which is very, very poor. Ideally we would like this directivity to be 30 dB or 40 dB or more, I just want to tell I mean if you have taken a antenna course in fact we are going to cover antennas later on.

There we are going to define directivity in a different way. There the directivity will be something similar to gain of the antenna here please do not mix up with that it is not the gain of the antenna or gain of the micro strip line or a coupler here directivity is as simple as the difference between C and I and this is very poor.

So, as I said generally we would like directivity to be high. In fact, if you read some of the books they do mention that if you design a coupled micro strip line this is the isolated port value may be of the order of 100 minus dB and so on. But as you can see it is not so good the reason for that is that the micro strip line configuration. Especially when you take a different epsilon r then 1 value then what happens because of this different epsilon r then 1. So, epsilon odd mode and epsilon even mode values will be different whereas, when we do the calculation we take epsilon effective.

So, for odd mode as well as for even mode the epsilon effectives are different so, that lengths behave differently for even mode and odd mode values hence its generally speaking micro strip lines are not very good when it comes to the directivity. So, one should think about the alternate thing the two possibilities are there, one is if you use a very small value of epsilon r. Suppose you use epsilon r close to 1 which will be like an air substrate. So, if you use air then what happens? Even mode and odd mode epsilon will be exactly same you can get a better directivity.

(Refer Slide Time: 24:51)



So just to illustrate that here is an example using strip line. So, what is a strip line as I had mentioned when I talked about transmission line a micro strip line requires only one substrate. So, we have a ground plane and we has a micro strip line whereas, a strip line has a another substrate put on top of that and there is top one will be now ground plane here the bottom is ground plane.

So, here what we have done the strip line has been used in a slightly different fashion, here we have used epsilon r equal to 1. So, this is air and 2 h which is the total thickness of the strip line is about 8 mm which is from ground to ground. And here since it is epsilon r equal to 1, which is air what we have actually taken we have actually taken a metallic plate of thickness 1 mm.

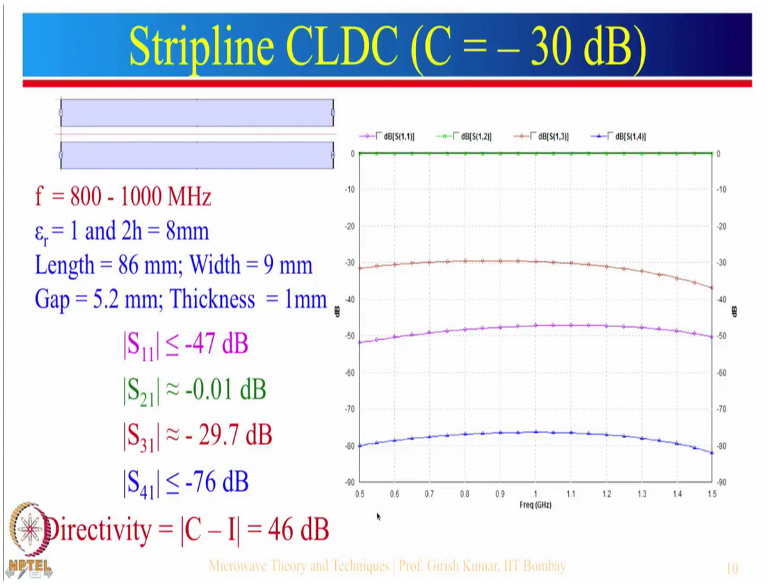
So, now metallic plate is taken here another metallic plate is taken thickness of 1 mm width is given over here which is about 6.9 mm. And the gap between the two which looks very small over here is about 0 point 6 mm. So, these two metallic plates are kept in parallel with each other and fed at that ends ok. So, now, there are these 4 ports are there let us see what results we get over here. So, let us see S 1 1 which is less than minus 44 dB over this entire frequency range which is from 0.5 to 1.5. You can see here this is a minus 40 dB line another minus 45 dB you can see that S 1 1 is less than minus 44 dB so that is absolutely fantastic.

Let us look at S 2 1, S 2 1 is 0.5 dB and you can see that it is relatively flat, now you may think that S 2 1 is large which is point 5 dB so insertion loss is more. Now that is not correct actually if you define coupling as 10 dB then approximately 0.5 dB will go to the direct port ok. So, there is actually speaking no additional loss and by using a strip line configuration we have also ensured that there are no radiation losses, because there is a ground at the bottom ground at the top and we also enclose the whole thing in a box. Now here S 3 1 is actually equal to minus 9.3 dB again you might wonder well we had a design objective of minus 10 db.

Here we are getting minus 9.3 db, I just to want to mention that this design is still better the reason for that is that. We are getting from here to here minus 9.3 db, but then we will be connecting connecters are the two end. So, connecters may have a loss of 0.2 dB or even 0.3 dB depending upon the quality of the connecter or may be even that connected coaxial lines also will have some additional losses. So, this S 3 1 effectively may lead to approximately minus 10 db.

Now, let us see what is S 4 1 here S 4 1 here is less than minus 50 dB over this entire range you can see that this is the minus 50 dB line. So, over this which is less than that, so let us see what is directivity you can see that the difference between this and this is about 40 db. So, that is a very good value of the directivity, let us take one more example.

(Refer Slide Time: 28:35)



Now, here the example is for coupling of 30 db. So, for 30 dB we have kept all the other things same frequency range is same epsilon r is same. So, only thing what it changes now is that the gap is now much larger earlier the gap was small, now the gap is larger let us see what results we get here.

So, let us start with S 1 1 S 1 1 is less than minus 47 db. So, here is a line for minus 40 dB, this is minus 50 you can see that this is less than minus 47 dB over the entire range. Let us see what is S 2 1 you can see that S 2 1 is 0.1 dB ok. So, you may again thing over losses are very small insertion loss is very small. Now, the reason is since we have designed for minus 30 dB very little power is going to the coupled port. So, most of the power then goes to the port 2, now let us see what is S 3 1 it is about minus 29.7 dB the desired was minus 30 dB, as I mentioned that connecter losses may be there. So, that will compensate connecter losses say 0.12 0.2 or 0.3. So, that will result in to approximately minus 30 db. Now, let us see what is S 4 1, S 4 1 here is less than minus 70 6 dB if this is the curve here you can see this is minus 70 this is minus 80. So, if you now take the difference of these two that 40 6 dB. So, you can see that the directivity here is very, very high and that is what is the desired characteristic.

A few things I want to mention, so we have manufactured these things we tested these things also. There was a one small problem which we actually experience and that was aligning these two lines exactly you know at a separation of 5.2 mm. So, what happens the two lines have to be really put exact parallel and there is all the possibility when you are trying to align this there may be an error of even 0.21 or 0.2 mm.

So, what we notice that because of the miss alignment this number S 4 1 does not come out be minus 70 6 dB, but it actually becomes poorer. So, I can tell you a better way to do the fabrication is that instead of fabricating then one strip separately and the another strip separately. What you do, you actually get it fabricated let us say we had use CNC machine to do the fabrication.

So, what you do instead of fabricating these two separately what you do? You join two thin lines very thin lines let us say over here and over here very very thin may be of the order of 0.1 or 0.2 mm and then get it fabricated and then put it on the connectors at the end connectors these thing will get supported. Once you have done the soldering and other thing mounted then you just remove that very thin connecting strip.

So, this way what will happen you just you know take it knife and cut it on. So, now, what will happen during the fabrication itself the separation has been maintained very good. So, if you just remove that now the fabrication will not lead to much of a alignment error at all and you can get a much better result.

So, today just to summarize we talked about coupled micro strip line these coupled micro strip lines are actually speaking good for realizing coupling of minus 10 dB or minus 20 dB or minus 30 dB. They are not very good for realizing tighter coupling which is let us say of the order of minus 3 dB or minus 6 dB. The reason for that is if you want to design very tight coupling then the gap between the two lines become very, very small.

So, in the next lecture we will talk about another type of a coupler where we can get a tighter coupling may be even a 0 dB to minus 1 dB to minus 2 dB up to about minus 10 dB. So, till then have a good time we will see you next time bye.