Millimeter Wave Technology
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Module 8
Lecture No 37
Millimeter Wave Systems (Contd)

So, now we are considering some external noise which is incident from left-hand side and altogether we want to express the system by some equivalent noise temperature, then how to calculate it?

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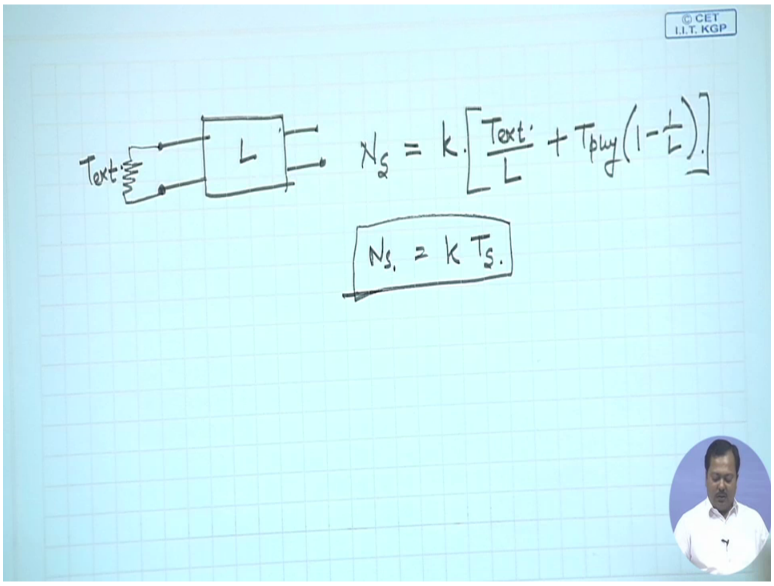

So we have a 2 port network which is providing some internal noise and it is also connected to some external source of noise, which can be given by T external. So in that case then the total noise power at the output N s, this is equal to k T external by L, this is for the contribution from left-hand side + T physical into 1 by 1 - L, whatever we have seen we can represent it by some effective noise temperature T s, k Ts, so N s this is equal to k T s.

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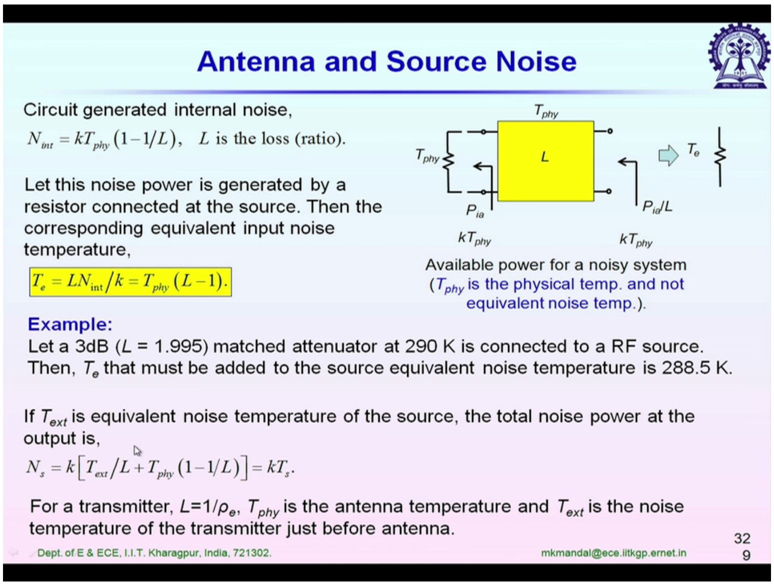

Now consider one antenna, so here you can see here so N s it is equal to k into T s. Now consider 1 antenna which is connected to a transmitter, now antenna it will have some efficiency. Let us say antenna efficiency is given as 90%, then and if any power we feed to antenna it will be attenuated by antenna and this value it can be given by that 90%, if we convert it to fraction 0.9. Or we can say L loss due to antenna; this is 1 by Rho or 1 by 0.9. Then T physical is the antenna temperature let us say, so this is the physical temperature of the antenna and T external is the noise temperature of the transmitter just before antenna. So in that case we can calculate, then what is noise power available from this antenna and source, which can be given by k T s.

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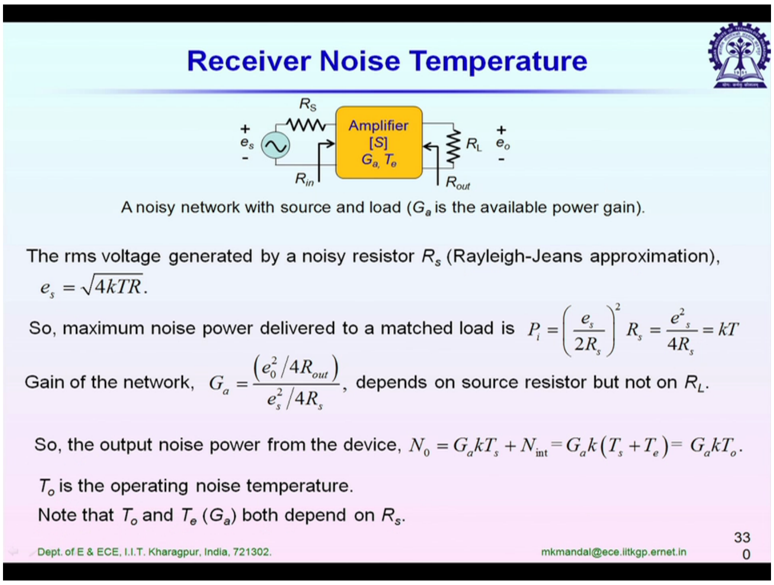

Let us consider a receiver now and we are going to calculate the overall receiver noise temperature. So what we will be doing, let us first consider one amplifier, a 2 port network again.

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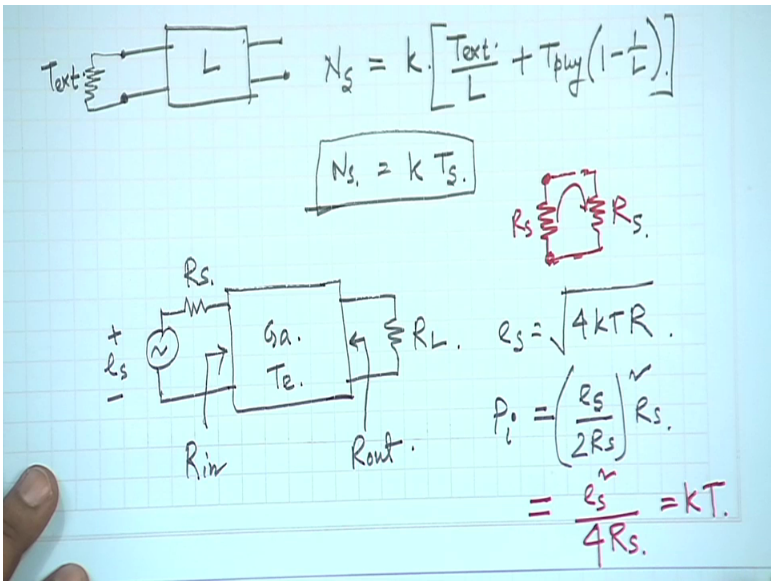

So the amplifier amplification factor is given by G a, it is sometimes called the available gain and T e is its effective noise temperature. Now it is connected to some external resistance, which is given by R L at right-hand side and left-hand side it is connected to a source of internal resistance R s. And if the source power is 0, in that case the power which is incident from left-hand side, it is only the noise power. Also, the input and output resistances they are also given for the amplifier. Now the noise voltage available because of the noise power generated by R s that can be given by e s = square root of 4 k T R, so maximum noise power delivered to a mesh load, we are considering one mesh scenario that is P i this is equal to e s by twice R s whole square into R s.

So you see here what we are considering, so R s this is the noise source, I want to extract noise power from the source or we can see in other way. We are connecting a resistor here, so some noise power will be delivered to the resistor, then we are considering what is the maximum noise power that is being delivered to this resistor and that happens according to maximum power transfer theorem when this R this is equal to R s or we can write down this is equal to R s. So in that case if I want to calculate P i, this is simply I square into R, then the current component went through it, this is e s by twice R s whole square multiplied by R s or we can write down this is equal to e s square divided by, 1 R s is cancelled out so 4 R s and this is equal to k T, which already we have seen.

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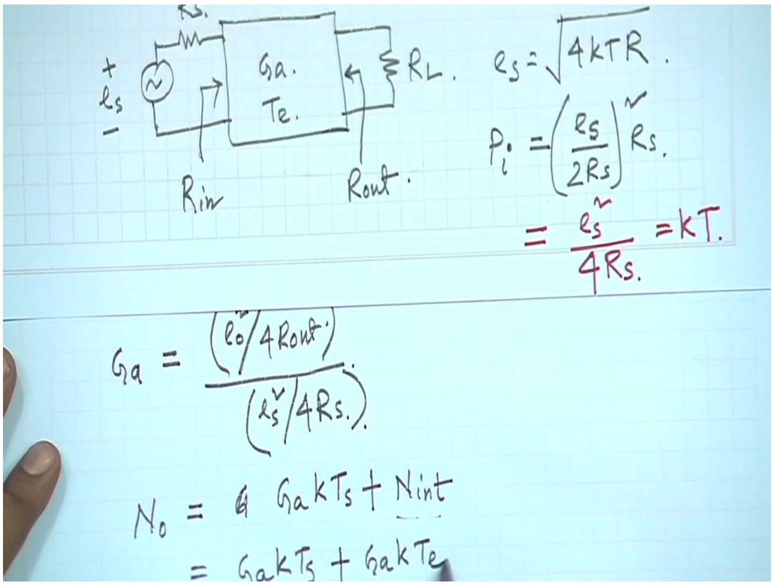

Now, gain of the amplifier G a we can express in terms of the input noise power and output noise power. So output noise power is e 0 square divided by 4 into R out and the input noise power this is e s square divided by 4 into R s. So one interesting thing then Gain you see for C amplifier also if we want what to calculate the overall gain of any C amplifier it depends on R l, but simply if I say what is the gain of a C amplifier, we do not consider R l, we take just the open circuit at output voltage and then calculate what is the gain of the amplifier. Now if you change R l, obviously the available power to R l it will change, but when we call the G a or gain of the amplifier then we do not consider R l, but this gain it depends on the source register R s.

So here also then this G a it depends on R s, but not on R l. So output noise power if I want to calculate at output terminal let us say, we are denoting it by N 0 so that is equal to G a k T s, so k T s this is the incident power from left-hand side, which is being multiplied by gain of the amplifier G a. In addition to this, the amplifier itself it will produce some noise, which is given by N internal. N internal this factor we can also express in terms of T effective noise temperature, which is given T e, so we can also write down that this is equal to G a k T s + N internal this is equal to G a k into T e or this is equal to G a k T s + T e.

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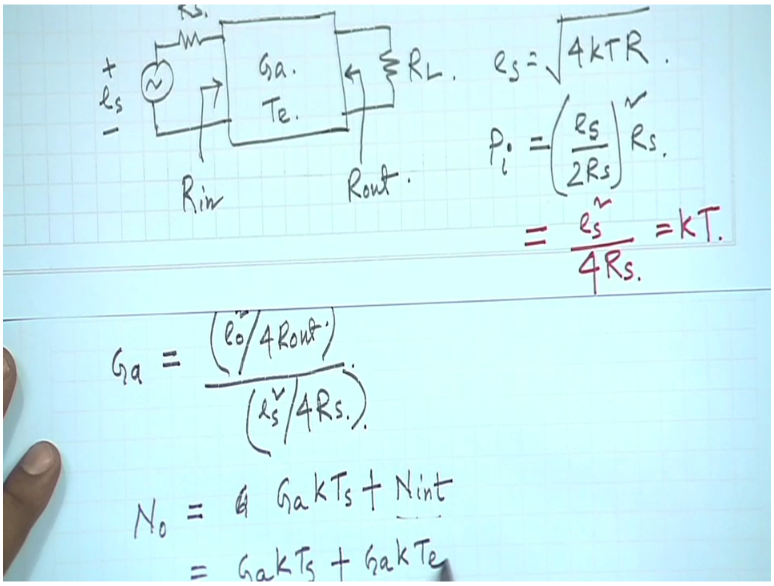

Let us represent it by effective temperature G a k T 0, so T 0 this is called the operating temperature operating noise temperature. So you see here, so this is the amplifier and left-hand side we have a noise source connected to this amplifier and right-hand side we have a load resistor connected here, then we calculate it we expressed already a G a in terms of the input and output noise power and from that we calculate that we calculated the output noise power from the device, so output noise power what we see that it contains the contribution due to the external noise source, which is G a k T s. In addition to that, this amplifier itself produce some noise, which is given G a k T e, so all together this effect we can represent by some operating noise temperature T 0, so N 0 then that is equal to G a k T 0, So T 0, T e, G a all functions of R s , but they do not depend on R l.

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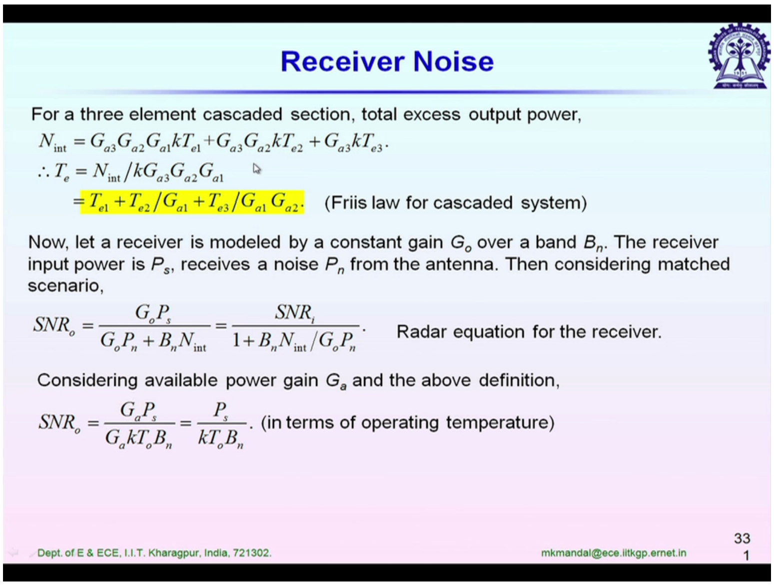

And in this case also we assume that the output R l is mesh to this and so it is the worst-case scenario, this N 0 this is the highest available noise power from the amplifier on the noisy source. Now let us consider several 2 port components they are connected in Cascade, so that means what we are considering let us say we have 3 amplifiers; the first one gain is given by G a 1 and the effective noise temperature is given by T e1.

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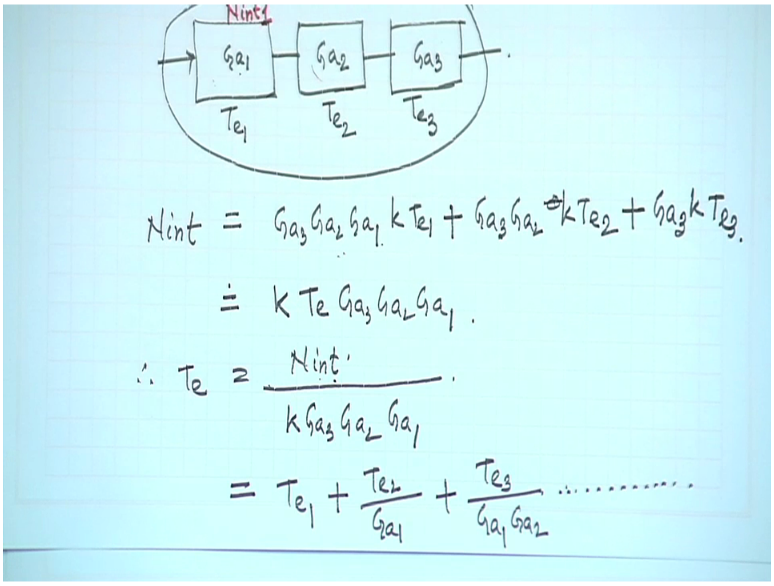

It is followed by another amplifier for which gain is G a 2, effective temperature is T e 2. Again we have one more G e 3, effective noise temperature T e 3 and we want to calculate what is the overall noise contribution of this system, so if we know for 3 we can do it for N components in Cascade. Then N internal we can write down this is equal to, so you see this first amplifier whatever noise it will produce let us say that is given by N internal 1, so this N internal 1 it will be amplified by G a 2, further it will be amplified by G a 3, but whatever noise produced by the third component this component is not being amplified by left-hand that is G a 1 or G a 2. Then the total noise contribution N internal; for the first one this is G a 3, G a 2 into G a 1, k T e 1.

So k T e 1 this is the noise produced by the first one and it is being amplified by all these 3 amplifiers. Then for the second one G a 3 G a 2 into k T e 2 and for the third one this is G a 3 k T e 3. So if we represent it this overall contribution, if we represent it by some effective temperature let us say T e, in that case we can write down this is equal to k. T e is the overall equivalent noise temperature, then k T e into G a 3, G a 2, G a 1, so therefore T e this is equal to N internal divided by k G a 3 G a 2 G a 1. So what we are assuming, as if one resistor of equivalent noise temperature T e is connected to left of this system and system itself is noise less so that is why we are multiplying by 3 gain factors G a 3, G a 2 and G a 1.

So in terms of the individual noise temperature we can also express it, so you just put that value of N internal whatever we obtained in this first equation. So if we put this value here, so it becomes T e 1 + T e 2 by so remaining term is G a 1 + T e 3 remaining terms G a 1 G a 2. For N components if we have N number of components simply we can extend it, so it will become for Nth term T e n and below we have G a 1 G a 2 to till G a (N-1), so this is called the Friis law for cascaded system.

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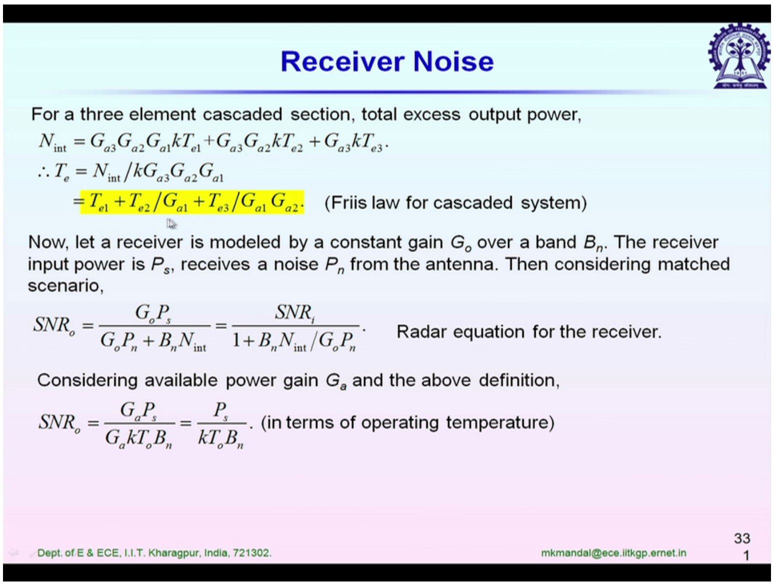

So what we see that if we have many Cascade connections, the contribution of noise from the first component it is dominant over all others. That is why when we design any receiver, the first component is chosen which will have minimum contribution of noise, so that is why we use low noise amplifier typically, which will provide very low noise and after that whatever components we are having their contribution is smaller compared to the first component. So now let us consider a receiver, it is modelled by a constant gain G 0 over a band B n, we are introducing now some bandwidth given by B n. Then the receiver input power is given by P s and it receives a noise power P n from the antenna, then considering matched scenario so always by default we will be considering matched scenario, so whatever power is coming from left-hand side so it is being observed right-hand side half of that observed in the load.

So then SNR at the output of the receiver that is equal to you see this is G 0 SNR is signal-to-noise ratio, so signal at left-hand side is P s it is being multiplied by G 0, so at output available signal power is G 0 into P s. And what is the output noise power, so left-hand side we have receive P n noise, it is being amplified by G 0 times by the receiver chain + we have some internal noise contribution because of the receiver cover bandwidth B n, B n multiplied by n internal and it can be given by equal to SNR at the input divided by 1 + B n N internal divided by G 0 P n. How we come here, simply you divide both numerator and denominator by G 0 P n, so then the top one it becomes P s by P n, which is SNR at the input.

So this equation is called Radar equation for receiver, it is one important parameter. Now considering available power gain G a and this above definition, we can also express SNR at the output, so in terms of operating temperature this is equal to G a into P s divided by G a k T 0 B n, so this is the operating temperature and simply then this is equal to P s by k T 0 B n, so you remember recall this T 0 is the operating temperature. Now noise bandwidth, so what if we are many times calling noise bandwidth B n and we are using it to calculate overall noise power, then what value should we take for B n for any given channel. Let us say we are using a channel bandwidth 1 gigahertz so should we take simply B n = 1 gigahertz.

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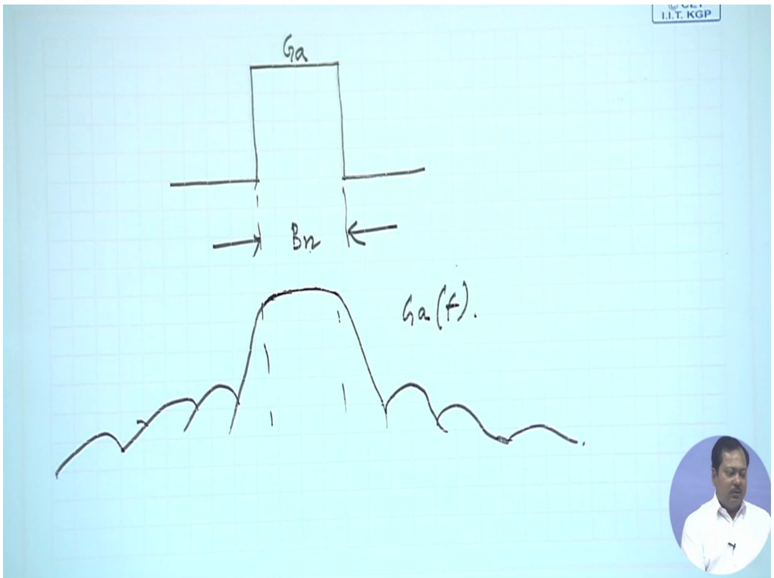

So whatever definition the significance of B n till now we have used, it is like one simple window function which has some value over the given bandwidth and out of this band it has 0 value; but it is not the practical scenario. So let us consider any practical case so in this expression when we use some value of B n, so that means let us say we are considering the ideal scenario, this is the 1 gigahertz channel bandwidth it is given B n and then model it by a constant gain G a, when we talk about the gain of the amplifier or gain of the receiver G 0 whatever and out of this band this G a is exactly 0. But for any practical system consider any band pass filter or anything, so for that it is not constant but it becomes a function of frequency and we have contribution due to you see other frequency components, so it will vary.

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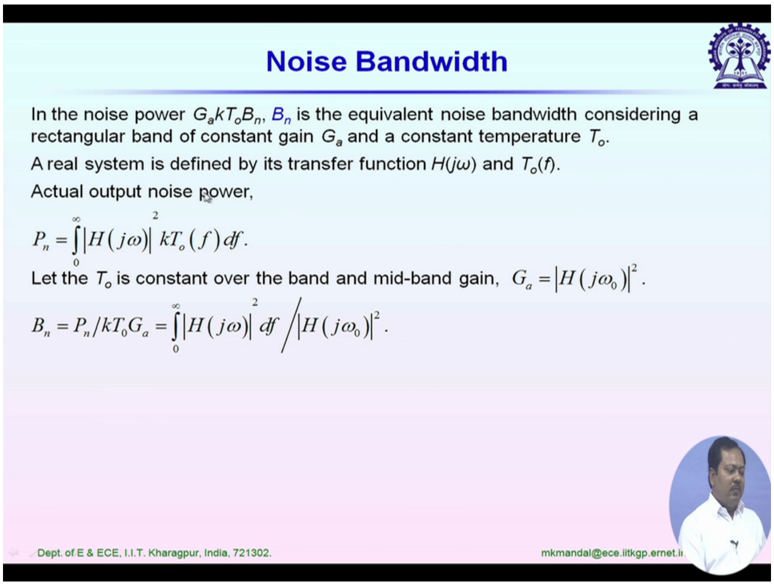

So gain G a it is a function of frequency and bandwidth B n, then what value we should take for this type of practical scenario, so what we do here there is a way of calculation. For a real system obviously it will be defined by its transfer function H, which is a function of j omega and the corresponding temperature, which previously we consider constant over the frequency, but practically it should be a function of frequency. Then actual output noise power we should consider all the frequency bands starting from 0 to infinity and we integrate it over 0 to infinity H j Omega square k T 0 d f. Now if T 0 is constant over the band and let us say mid-band gain is given by G a = H j Omega 0 square in that case so we are assuming T 0 is constant otherwise, it is becoming complicated, for simplification this assumption.

So B n this is equal to then total noise power P n divided by k t 00 G a or 0 to infinity this integration value divided by H j Omega 0 whole square. So from this expression we can calculate B n value, but even then you see here we consider T 0 is constant over this given bandwidth. Next noise factor, so total noise contribution it can be calculated in terms of noise temperature, also sometimes another parameter is used to quantify the noise contribution that is called noise figure, we can calculate it for any given 2 port devices, so usually if it is a lossy device with some insertion loss let us say L in dB, and then noise figure in dB it simply becomes L. If you buy any active component like an amplifier or some active mixer, usually the noise figure value will be written or given by the manufacturer, it can be also measured in in lab experiment by using spectrum analyser and standard noise source values or VNA Vector Network Analyser.

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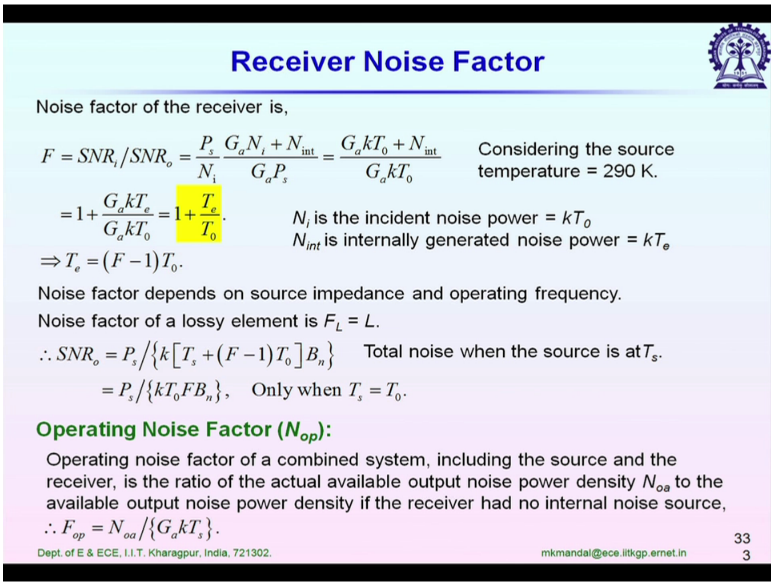

So in general then what is first let us define noise factor of a 2 port network. Noise factor F, this is the ratio of signal to noise ratio at the input terminal divided by signal to noise ratio at the output terminal, so SNR at the input divided by SNR at the output. Now signal to noise ratio obviously is better at left-hand side compared to right-hand side at the output, why? Because at output side we have additional noise generated by the component itself, so that is why F this is always greater than 1. If we express it in dB, we call it noise figure and that is always a positive quantity, so for a given system then already we did it, let me express mathematically.

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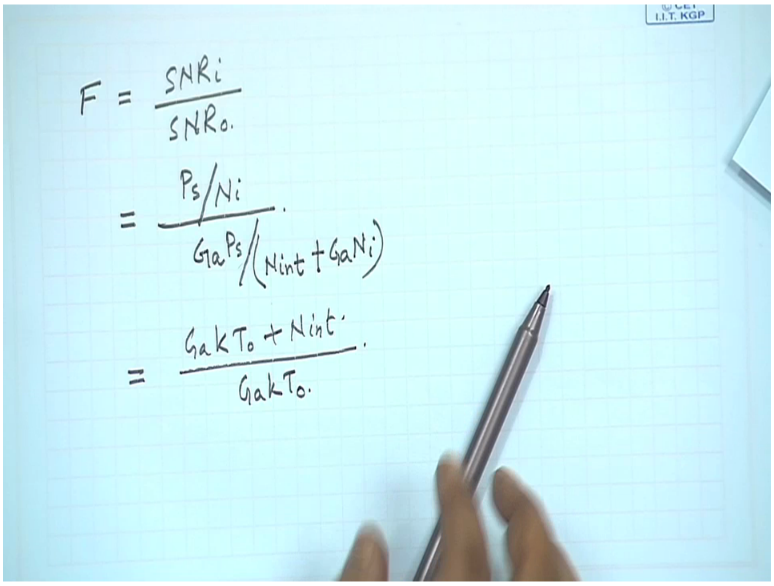

So then the noise factor F this is equal to SNR at the input terminal divided by SNR at the output terminal, so at the input terminal let us say the power already whatever we assumed in previous example P s is the incident power and let us say N i is the incident noise from left-hand side, we are considering per unit hertz. So this is the SNR at the input side, now we can calculate SNR at the output side so then the available power is the application factor G a multiplied by P s divided by total noise, total noise is some noise internally generated inside the 2 port device + the contribution from left-hand side, which is G a into N i. So this is equal to G a k T 0 + N internal divided by G a k T 0. Now it is a function of temperature, you see what value we should take for T 0, so if the noise from my left-hand side it changes, obviously this value will change.

So then if we buy let us say one amplifier from market, some noise figure or noise factor is given with that then what it denotes, because it becomes a function of input noise. So usually a standard temperature is considered to calculate noise factor and hence figure that is 290 Kelvin. So if I do not consider simply actual scenario practical scenario, by noise factor we mean the noise contributed by the component it has been calculated at a given T 0 = 290 Kelvin. So from this then you see if I put N internal that is given by G a k T e, T e is the equivalent noise temperature so then it becomes simply 1 + T e by T 0. So T e, this is the effective noise temperature of the 2 port device itself, T 0 this is for standard calculation we will consider 290 Kelvin.

Then we can express T e also in terms of F, so T e = F - 1 into T 0 this is another important expression. So if F is given, we can calculate what is the effective noise temperature T e, if T e is given we can calculate what is the noise factor F, so they are related by this important relationship. This noise factor depends on source impedance and operating frequency obviously, if we have a lossy network as I discussed it will provide you some insertion loss or power will attenuated by that 2 port network. If the loss is given by L then simply its noise factor is equal to L. And now we are considering a different scenario, let us say this source temperature is not T 0, it is given by T s whatever we considered in the previous case. Okay, so let us take a break then we will consider a practical scenario with a given temperature T s thank you.