Photonic Integrated Circuit

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Lecture 35

Light Modular Introduction

Hello, everyone. Let us look at another section on Photonic Integrated circuits. In this series we are going to look at active devices. So, what do we mean by active devices? So, when a device or photonic device can change the property of light when it has an external influence. So, in passive device we did not give this external influence. So, the structure itself took care of whatever changes we would like to do, it could be power division, combining, polarization, splitting. So, all these functionalities were taken care by the structure itself.

So, now in active devices, we are going to look at a waveguide where you have light propagating through this and we are going to apply some external energy to this, it could be electric field for example. So, when you apply an electric field, then based on the material property; this is strongly material and field interaction. So, based on the material property the electric field could induce some changes in the material, and this change would subsequently affect the light propagation.

So, there is a series of events that will happen, the moment you apply an electric field the material is going to react to that field and because the material property changes, the light propagating through the material will also experience a change. So, this is an example of an active material or active medium in this case. So, the active devices are used in for many different applications.

One of the primary application that we use this active devices is for light modulation. So, what is light modulation? Where do we use light modulation? And what are all the figure of merit of this optical modulation process, is something that we are going to know in this particular lecture today. So, let us look at that.

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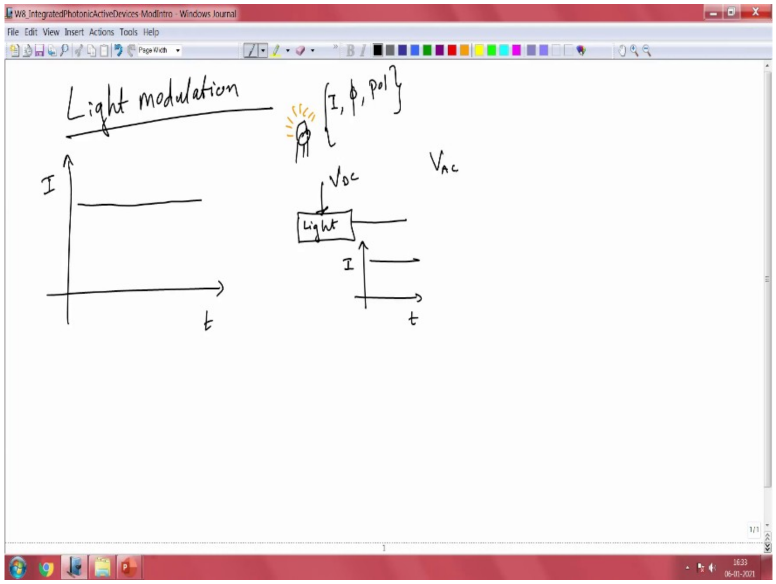

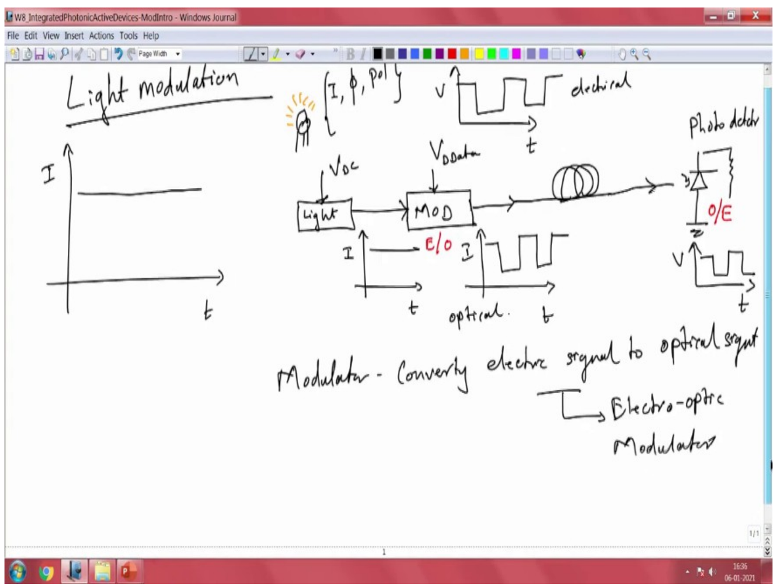

So, the active process that we are going to look at is modulation. It is called light modulation. So, first of all, why do we need this modulation? And what is this modulation all about? So, when you take light as a function of time, the emitter is going to emit a certain intensity, flat intensity. It could be a very simple, a diode that is emitting light and as a function of time this diode will emit an intensity 'I' let us say. It us a continuous wave and there is no change in the intensity as a function of time.

But then, there are multiple properties to this emitted light. So, you have intensity and you have phase and you also have polarization. So, these are all the properties that we have from a light source. So, you could change any of this, you could change the intensity, you could change the phase, you could change the polarization. And this dynamic change or changing this basic property as a function of time is what we call modulation.

Where do we use this modulation? Primarily when you want to communicate or imprint data onto this optical signals. So, a simple way to to look at this is by taking a simple architecture where we have a light source. This is a light source and we need to give some current to this. So, there is a an external electrical energy is something that we do and then it emits light. And this light is going to be constant with respect to time. There is no change we have.

But then I have some information. So, I have, I have information that is a function of time or I can say digital data in this case. So, digital data is there. So, this data will have its own voltages, this is an electrical signal. And now I want to put this electrical signal into this optical carrier. And I am going to put this in and this particular device is called the modulator device. And this modulator is going to convert my continuous wave signal that I have intensity into an intensity modulated signal now. So, this is the optical that we have and this is the electrical signal that we have.

So, in other words the the modulator converts electrical signal to optical. And and this particular transfer of energy that is electrical to optical we could call this as electro-optic modulator. So, now, the signal is modulated now. So, I can send this signal through fibre here or any medium for that matter. And then the output I can put it through a photodiode. So, this is a photo detector. And this photo detector will again convert my optical change in the signal to a current change that we have. So, you can also connect it through a resistor and that would give you a voltage change.

So, now, you can see the whole purpose of using a modulator is to convert electrical to optical and then your photodiode will convert optical to electrical. So, this is a very simple network that you can think of, very simple transmission schematic. So, now the question to ask here is why do we need a modulator that is sitting outside? Why cannot we directly change the current source to your light source here.

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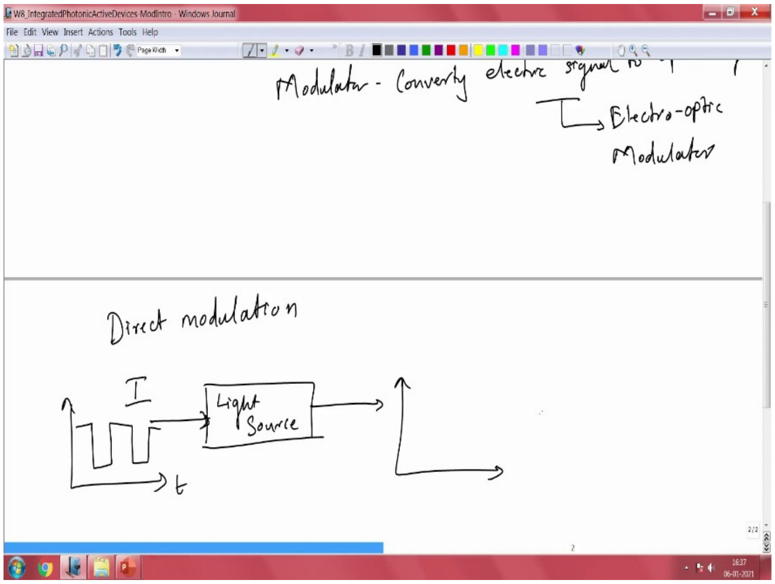

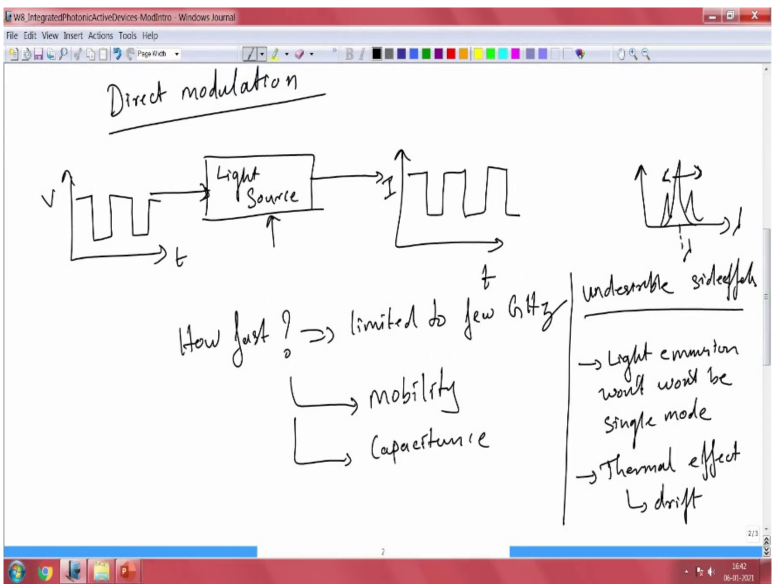

So, one can also do that. It is not forbidden to change the current that is flowing through. So, that is called direct modulation. In direct modulation you can take the light source and then I can change the current going through this light source. I can change this as a function of time, as a function of time I can change the current going through. And this will result in a light source. So, let us say instead of making it current, I will just make it as voltage so that we do not have confusion between 'I' the intensity and the current there. So, the intensity of light would also increase and decrease now.

So, now, it is indeed possible to change the output intensity by directly changing the energy that you give into this light source by changing the voltage or current into this light source. But now, the question is how fast can you do this? So, how fast can you do this, depends on the source. So, this is how fast is the question, but then it is limited to few gigahertz, let us say few gigahertz.

So, it is not, it will not be very fast. you can indeed do that, but then there is a limitation to this and this limitation comes from how quickly you can pump in the charges and extract the charges. And at the same time the mobility of the the charges there: mobility, capacitance, that you have in the in the circuit, will dictate how quickly you can change this current going into the circuit. So, this is, this is all possible, but there is a limitation and this is the reason why it is preferred to put the modulation outside which is called external modulator. So, external light modulators.

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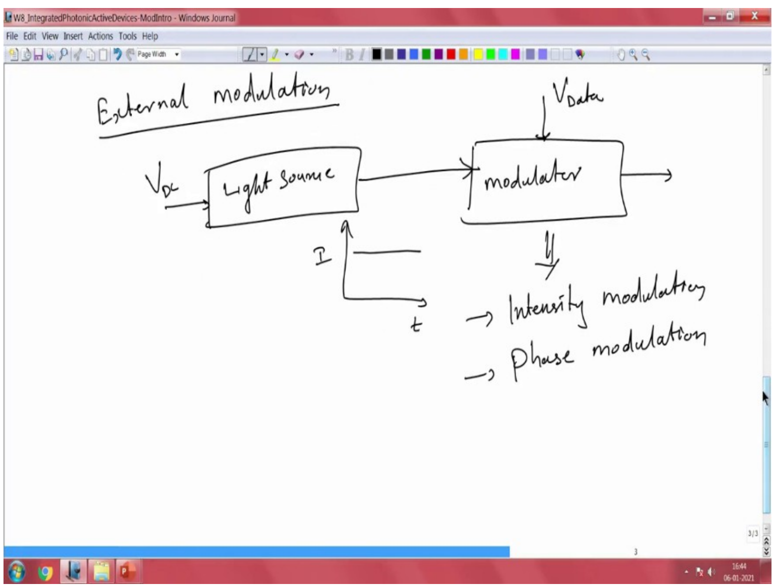

So, external modulation is another way of doing it. So, one more thing that there is an issue, when you have this current modulation is limited by mobility, capacitance, as I mentioned. But then there are undesirable side effects, undesirable side effects of doing so. So, what is that? You will have, you will not have single mode, emission will not be single mode.

So, what do we mean by this? So, the spectrum will start changing, you ideally want a laser source like this let us say. But then it starts to create sidebands and it will start moving left and right as well. So, there will be a hopping that happens and this is one of the undesirable characteristics when you do a direct modulation.

So, the other thing is there is there is nothing that you can do about the threshold current that you have because it will always have a threshold current. And because you are going to swing this one there is also going to be a thermal effect and this thermal effect will also start to drift the performance of this light source that we have. So, again it will start making the the peak here drift from the decide wavelength λ.

So, directly changing the light source or directly modulating the light source is not desired for these reasons. One is the limitation, the other one is the inherent inability to maintain the quality of output that you have. And that is the reason we go for external modulation. The external modulation the configuration is rather straightforward. So, you have light source and then we put a modulator here outside.

So now all the data that we are going to feed is to this particular modulator and light source remains just same. So, we just provide a DC and the light is going to, the light source is going to give me a constant power out as a function of time. And now the light source is very stable. So, we are not going to change any of the properties of this light source. So, it remains identical, same throughout the usage period.

But now, the modulator is now dynamic. So, the external modulator changes the intensity now, by using its property we will see that shortly what property are we going to exploit. And by using this modulator, one could do different things. So, you could have intensity modulation, you could have intensity modulation or you could have pure phase modulation. So, this is possibility when you use an external modulator.

And now, since the modulator is outside the light source you can change the modulator and improve the performance by just switching to a different kind of material or different kind of architecture without having any effect on the light source and also the general architecture itself. So, this this gives us a lot of flexibility in the architecture that we would like to implement for transmitting data primarily. So, what are all the properties of this light modulator?

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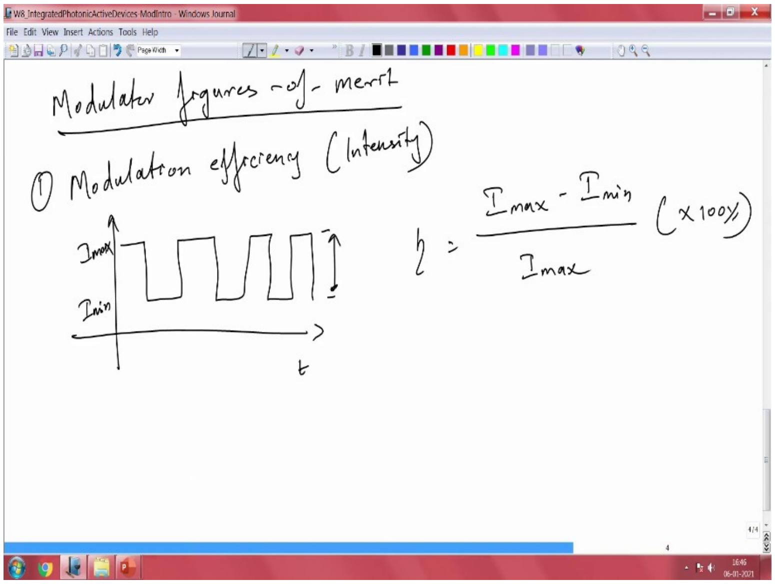

So, let us look at some of the figures of merit of this modulator, modulator figures of merit. So, what are these figures of merit? So, let us start with the efficiency itself. The first thing is modulation efficiency. So, let us say this is for the intensity, intensity modulator. So, we set the modulator is going to change the intensity of light. So, that means as a function of time you will have the intensity of light is getting changed and you have 'I_{max}' and then 'I_{min}'.

So, now that the intensity change that modulation efficiency is nothing but $\frac{I_{max} - I_{min}}{I_{max}}$. So this is in percentage. So, this is called the modulation efficiency. So, how efficiently you could change the intensity of light. So, the next thing is the modulation is also characterised by what do you call the depth of modulation. So, what is the depth between or a ratio between the maximum and minimum.

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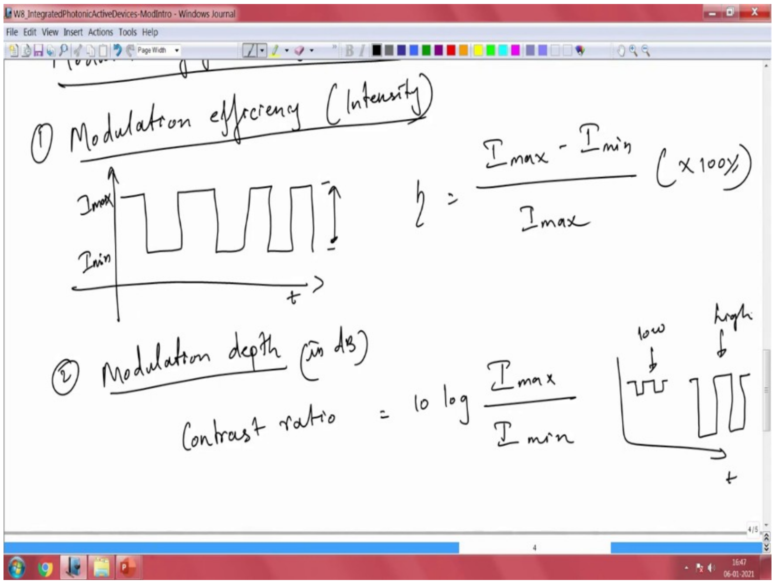

So, that is the next property which is called modulation depth. And this is usually represented in dB's. So, normally we represent this in dB's and that is nothing but the contrast ratio, contrast ratio, which is nothing but $10\log\frac{I_{max}}{I_{min}}$. So, the difference between the maximum and minimum is what we mean by modulation depth. So, the higher modulation depth is always preferred.

So, instead of having very small difference we would like to have a large, larger difference here. So, as a function of time, so, this has low modulation depth and this has high modulation depth. And this will also mean that when you have higher contrast ratio or higher modulation depth, your modulation efficiency is also higher. So, that is something that we should know as another figure of merit.

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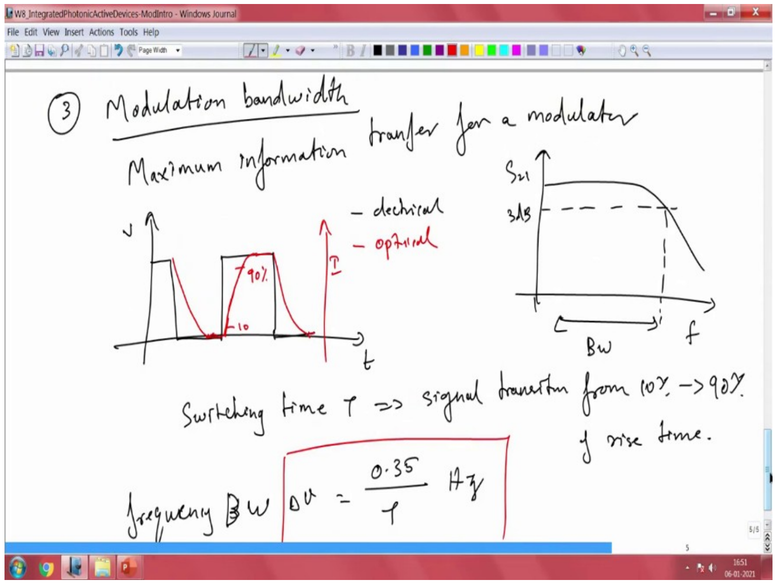

And the next one is modulation bandwidth. So, what is the bandwidth of this modulator? So, when we say bandwidth this is nothing but maximum information transfer. So, what is the maximum information transfer for a modulator? So, usually you have this as a function of frequency you have 'S21' and you will have this frequency spectrum a 3dB this is called your bandwidth. So, this is modulation bandwidth. It is nothing but 3dB of your frequency response.

The other way to look at the modulation bandwidth is by looking at the time response. So, you have a signal, let us say this is my electrical, that is in red here, black here. So, this is the voltage and now this is optical. So, how the optical signal is going to follow. So, the optical signal will have its own time constant. So, when it is coming down so, it might have its own time constant like this and then when it goes up it is going to have something like this. So, it might reach here and then it might turn back here. So, like this your signal is going to change as a function of optical intensity.

So, this, the time require for it to go from 10 percentage to 90 percentage and this is called the switching time. The switching time 'τ' is nothing but signal transition from 10 percentage to 90 percentage of it, so, of 90 percentage of rise time. So, that is called ' τ ' here. So, now, we can measure this there is a transient response here and based on that we could say our bandwidth here the equivalent bandwidth.

So, frequency bandwidth '$\Delta\vartheta$' is nothing but, 0.35 is a constant here, ' τ ' hertz. So, this is our thumb rule for calculating the bandwidth of of your modulators. So, we just look at the transient time response and then we can calculate from this, what is your bandwidth. So, the other way to calculate the bandwidth is by looking at the frequency response.

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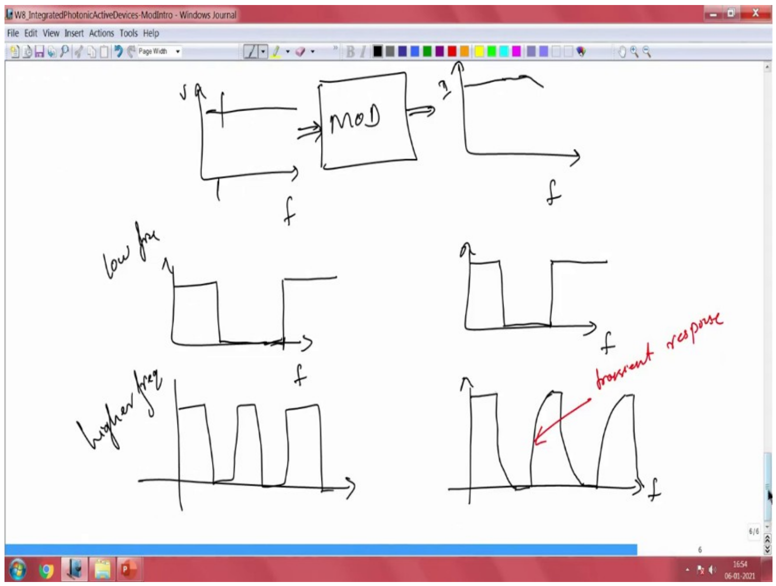

So, what we do there, is take the modulator and feed the modulator with a constant frequency. So, you have input frequency to the modulator. So, this is our input and then we are going to look at how the output is going to look like. Let us say for really low frequencies, so, this is low frequency. So, that means your signals are sparsely spaced. So, there is the time period is very long. And then when we look at the optical out. So, low frequency and this is your optical out. So, the optical out would also follow the signal. So, that means there is a complete reproduction of whatever we have given as input.

So, now let us say this is our intensity, this is a certain voltage that you have. So, now when I am going to change high frequency, so, or I say higher frequency. So, now, the signal is not anymore really relaxed. So, what you could, you could see here is the signal starts to show some transient. So, here you see the transient response. So, there is a time constant associated with this. So, you are, you are getting closer when you are increasing it, but now the signal is not as good as you see it here. So, there the intensity starts to come down, the response starts to come down.

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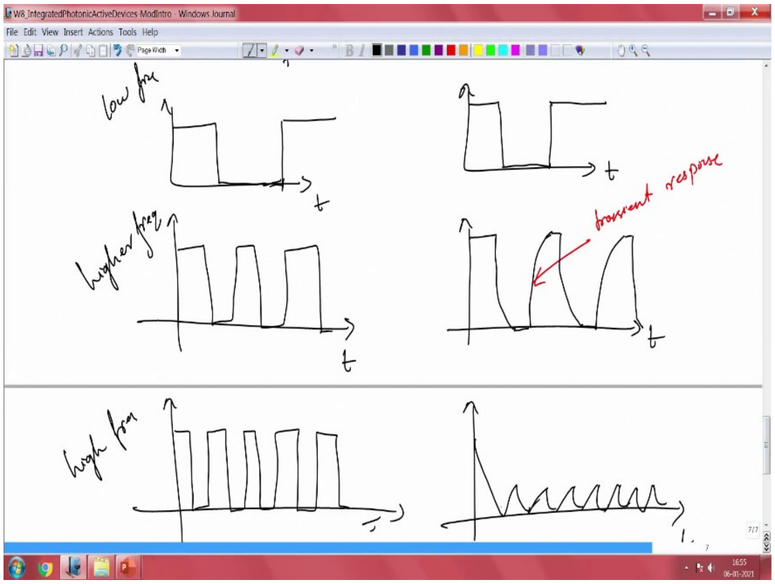

But then if I keep increasing the frequency now, if I keep increasing the frequency now, so this is high frequency now. So, this is has a function of time. So, now I have high frequency and now, the signal cannot respond to this. So, you are, you are going to go down, but then it cannot raise up. So, now all you see is very small signal here that is not able to respond to the signal that you have. So, because of this so you are 'τ' is pretty large. So, you will not be able to respond to the signal at all.

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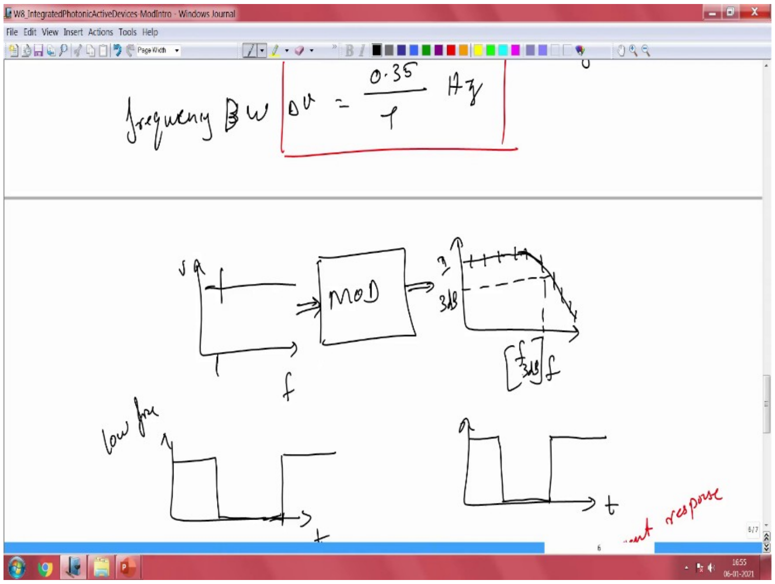

So, because of this limitation your output in response is going to go down. So, you take each and every frequency here and then measure the quality of your output and by looking at the 3dB level, you know, what is your bandwidth here. So, this is your frequency 3dB. So, this is what you are looking at. So, this is how you could do a simple frequency sweep and then check the bandwidth here. So, this is, this is how you measure the bandwidth.

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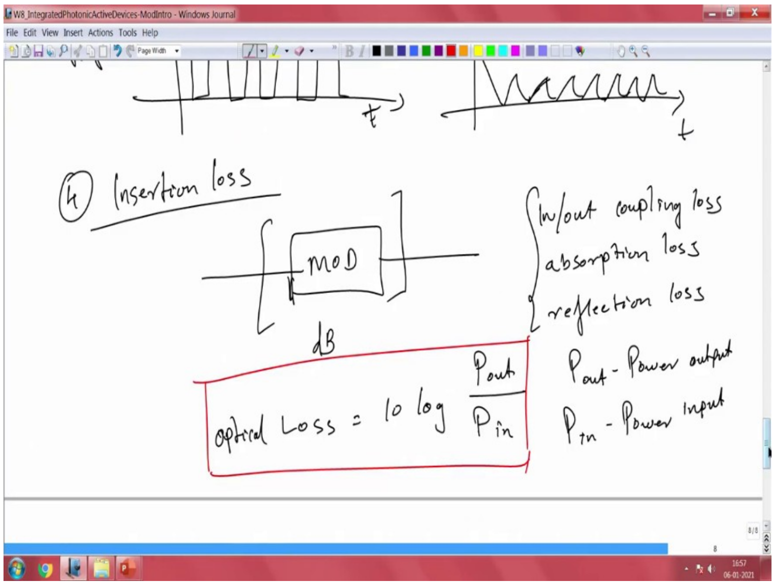

The next parameter that we could measure is the insertion loss. So the parameters that we talk about the figure of merit, fourth parameter is insertion loss. So, this is something we have seen earlier, which is nothing but the power loss that we have when the modulator is placed. So, you have a modulator and then you come in and then you go out. So, what is the total loss, so what is the total loss from this particular modulator? So, there could be an input coupling loss.

So, let me write it down here so, that you can keep it in mind. So, input coupling loss in and out coupling loss and we could have absorption loss in the modulator you could have reflection loss in the modulator. So, all these things contribute to the insertion loss. So, that loss is given by $10\log\frac{P_{out}}{P_{in}}$. So, '$P_{out}$' is power output and '$P_{in}$' is power input. This is our optical. So, this is optical loss. So this is how one could characterise the insertion loss.

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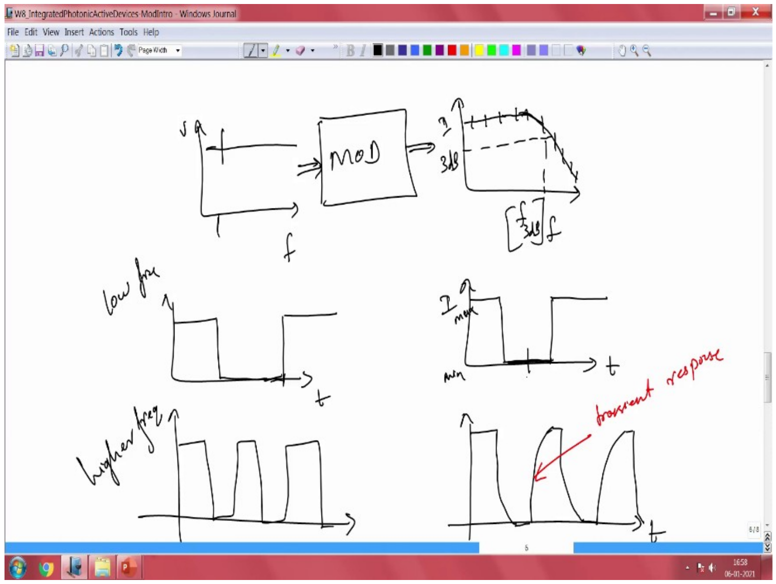

So, this should not be confused with the contrast that we have. So, here the intensity is high. So, you have high intensity this is max and this is min. So, when when you have to operate it at as a switch, as a modulator, so, you have to make sure that there is no power coming out, this is not actually loss. So, this is coming from the operation. So, the loss is when it is max.

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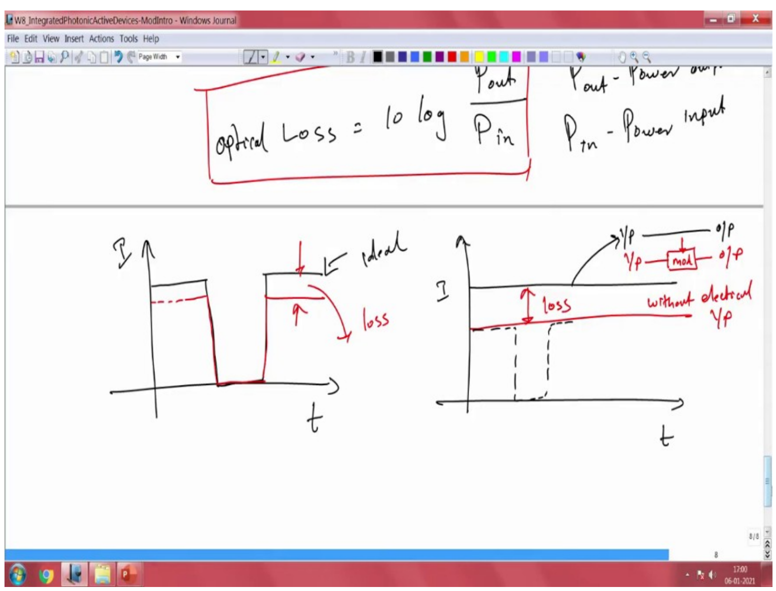

So, when you are transmitting when you are at the transmission mode. So, let us say this is the ideal transmission as a function of 't'. So, this is ideal, but then because of the loss you will have like this, so this is our intensity. So, this difference is what we call loss from the cavity. So, this is the loss that you have, but then how do we characterise this between ideal, you do not have ideal but you only have something that is loss. The way to do that is by measuring the transmission without any, without the modulator. So, without the modulator, so, you have input and then you have output so, there is no change at all. So, there is the intensity as a function of 'I'.

So, now, when you put there is input and there is modulator and there is output. In this case, you are, you are not even giving any input to this. So, then the intensity will look something like this. So, here your 'V_{data}' is 0 let us say there is no data that is giving or it is always high. So, without, without electrical input. So, this difference is what we call the loss. So, whatever you do, the modulation it is going to be within this range only, but then in the absence of the modulator, so, this is the absence of the modulator, you will have higher power going through this, and this is what we call insertion loss.

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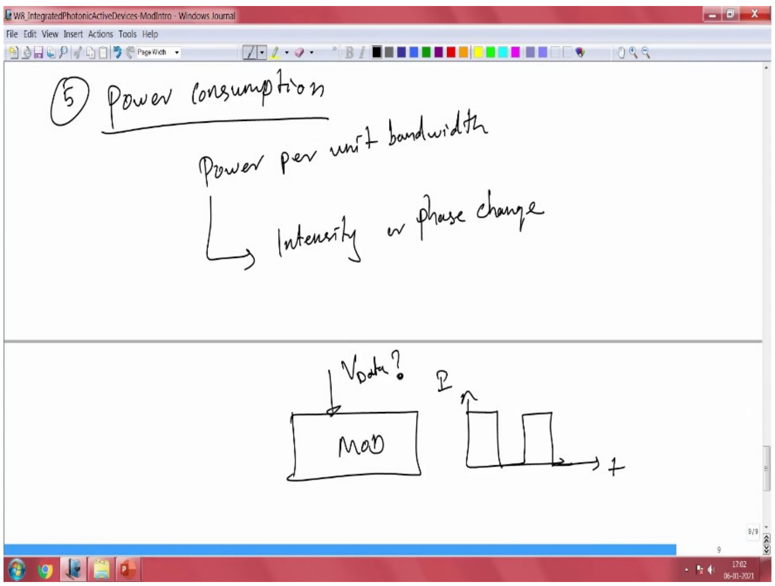

So, the next parameter is power consumption. What is the power consumption? So, power consumption primarily refers to the electrical energy that you give into this modulator to get the required intensity or phase change. So, that is nothing but power per unit bandwidth, how much power is required to achieve the required transmission for that required speed. So, this is the power required either for intensity change or it could be phase change it, could be any. So, you are going to give some electrical power.

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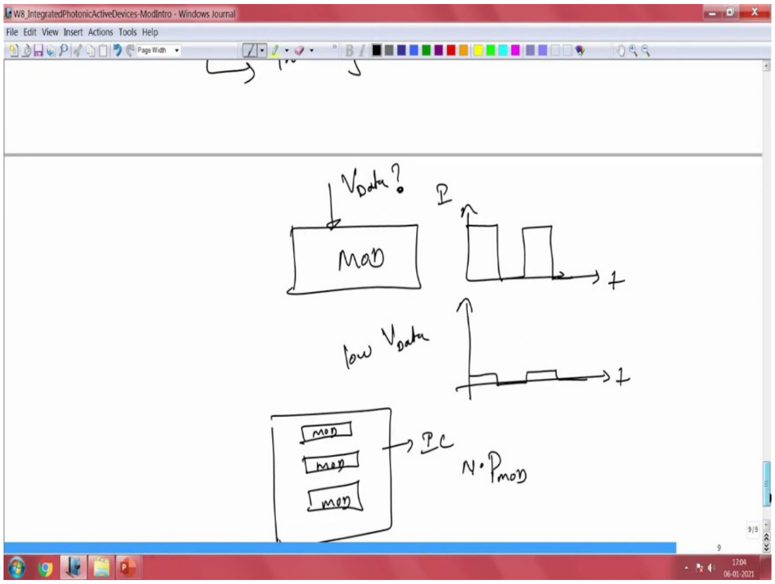

So, 'V_{data}' to this modulator. And what is this power required in-order to get the intensity swing that you are looking for? When 'V_{data}' is very low, so let us say your 'V_{data}' is low, so that is very low. That means, what you will get is something like this. So you won't be able to distinguish between 1's and 0's.

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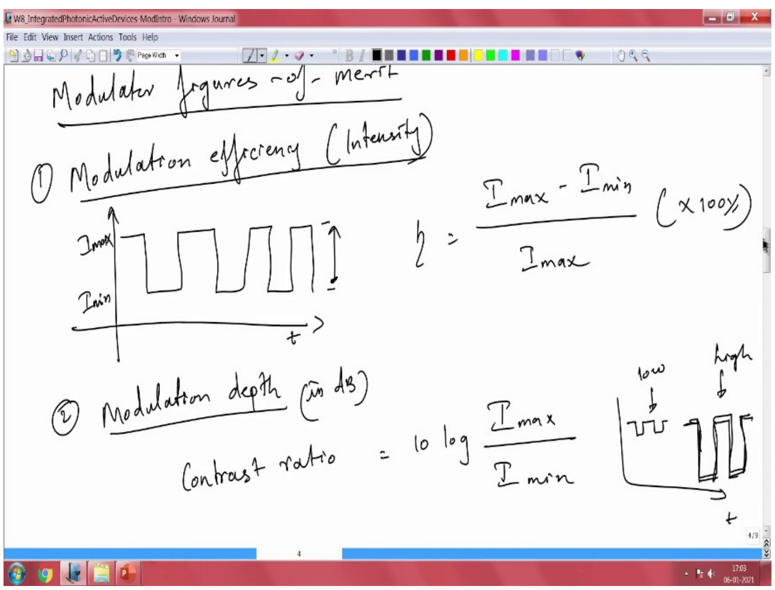

So, in order to make the necessary contrast, in order to get the best efficiency we have to go back here and then look at how we define efficiency. In order to get the efficiency your modulation depth should be higher. So, the modulation depth is achieved by having a larger swing here. So, there is a larger swing that you are looking for and this large swing is a function of electric power that you put in. So, your modulator should be able to get the required swing even with very low voltages. So, that is how a good modulator is designed and chosen. So, it is 'V_{input}' is one kind of energy source that we have inside. And we could also have other type of modulators for example, you could have Acousto optic modulators.

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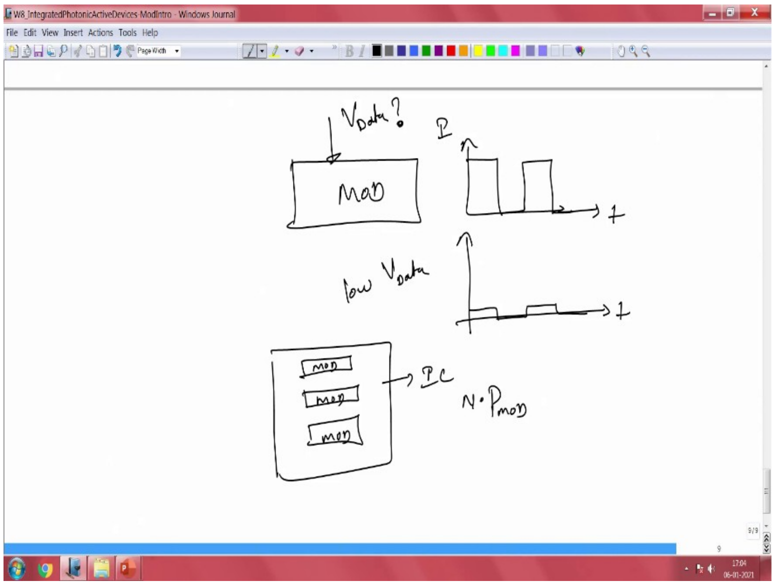

So, in that case, again the voltage that you give and the power you dissipate in the device. And this particular power consumption also depends on the number of modulators you have on a single chip, let us say. So, you could have one single chip with 'N' number of modulators. So, you could have an array of modulators on a single IC. So, this is a single IC that would have multiple modulators.

So, in this case, your power consumption will be N times your modulators. So, you have power consumption will be N times the power consumption on each modulators. So, it scales up. So, the power consumption is a function of the number of devices that you have in this. So, it can be a very simple calculation like 'VI' that gives you the power consumption, but if depending on the configuration, you could have slightly complex power calculation here, but nonetheless, power consumption is an important metric that we should keep in mind.

So, so far we have looked at 5 metrics here, which are important metrics when it comes to light modulation characteristics, starting from modulation efficiency, modulation depth, modulation bandwidth, followed by insertion loss and finally power consumption. So, these are all the characteristics with which we will characterise a modulator.

So, with that we have a brief understanding now of the requirement. So, when I want to change the intensity of light or phase of light, for example, I need to make sure that these parameters are taken care, the efficiency, the contrast ratio and the power consumption and how fast I can make this work. So, that is again very important when you talk about data communication. So, based on these parameters, one should look, design their device to meet the required specification. So, how do we design it, so, what property are we going to exploit to realise this. So, that is what we are going to look in the next lecture. Thank you very much for listening.