Fiber-Optic Communication Systems and Techniques
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Lecture – 47
Optical Modulators-I (Current modulation)

Hello and welcome to NPTEL MOOC on Fiber-Optic Communication Systems and Techniques. In this module, we will begin with part 3 of the course. So, far what we have looked at in part 1 and part 2 are the kind of building blocks that are necessary to discuss the issues in part 3. In part 1, we had a reasonably detailed look at optical fiber itself. We saw how a pulse can propagate through the fiber and what does the optical fiber do to such a pulse that is propagating.

Of course, we have considered only simple impairments that the optical fiber would induce on the pulse for example, we have looked at the fact that pulses when they propagate through the fiber will be attenuated, because of the fiber attenuation and they will be either broadened or compressed, but most of the times they will be simply broadened because the pulses propagate and they are affected by the dispersion that is present in the fibers.

We also solved the wave equations to understand, what kind of modes are present in a fiber and different types of fiber for are also considered. So, we considered single mode fibers, we considered multimode fibers, we considered step index Refractive Index profiles and then we considered greater index profiles and then we saw that the fundamental mode of the fibers regardless of what shape that you have, for the Refractive Index is that it will be an LP01 mode and most long haul optical communication systems will always use a single mode optical fiber because, those are the fibers that eliminate intermodal dispersion have low loss and also they are less susceptible to effects of dispersion.

So, this is what we have seen in part 1. And in part 2, we saw the other part of the Optical Fiber Communication System that is you have a source, in the form of a semiconductor laser diode and with some modifications or in fact, which much simpler structure you can also have light emitting diode we did not discuss much about that.

But, light emitting diodes work on the basis of spontaneous emission while the semiconductor laser diodes work on the basis of stimulated emission. We saw the structures how these double heterostructure lasers and quantum well lasers are actually used to make very good lasers and basically laser is an oscillator ok. So, just as you have an RF oscillator or a Crystal oscillator, the purpose of a laser diode is to actually generate as much as possible a pure tone signal of certain frequency ok.

We will of course see that, not every laser and in fact, we cannot find any idea lasers because all practical lasers will have a certain amount of line width and this non 0 line width will contribute to the phase noise that is induced by the laser ok. Of course, the amplitude one would expect it to be constant, but this amplitude would also not be constant or we talk about the power; power will not be constant, there will be random fluctuations of the power and this power fluctuations is also something that, one needs to address if you want to make use of these semiconductor laser diodes as sources for optical fiber communication system.

We also saw that it is not only necessary to convert you know, information which is usually in the form of an electrical format into an optical format; we haven't seen the devices yet, that they can do, but we are going to discuss those devices in this module. But we do know that such devices have to exist, those that convert the information or data that is in the electrical format into the optical format laser must be involved a device called modulator must be involved. And after modulation of the laser light or the light from the laser diode, you will have information propagating in the optical domain where it can be coupled to the fiber via, some other WDM Couplers with we saw that not only one particular laser diode or one particular channel can be propagated in a fiber.

Simultaneously, many channels can propagate and this necessitates the use of multiplexers, de-multiplexers, optical filters so on and so forth. And to over or to compensate the losses that the pulses will experience as they propagate through the fiber you will have to place (Refer time: 04:36) amplifiers and we saw that there are two kinds of optical amplifiers, RBM doped fiber amplifier and semiconductor optical amplifier. Although for all, long haul optical communication systems it is the erbium doped fiber amplifier that is used and these amplifiers have to be kept at every so and so distance and these distance between two amplifiers is called as the span of the optical link and the span is usually about 100 kilometers, 80 to 100 kilometers.

So, we have seen this in part 2; of course, when the pulses reach the end of the fiber they have to be converted back into the electrical domain that is, information which is in the form of modulated light will have to be converted back to the electrical domain and we know that there are devices called photo detectors which, have this job of converting which which perform this job of converting information in the light or in the optical domain onto the electrical domain.

Of course, we have seen that, all this infrastructure is necessary except for the modulator which we are going to talk about. And in part 3 of this course beginning today, we will actually put these devices into use in the sense that we are going to consider, how exactly can one start implementing enough optical fiber communication system and when one implements an optical fiber communication system, what are the impairments that are going to affect the signals that are propagating and how can one remove or mitigate these impairments.

Because, if you do not mitigate the impairments that happen to the optical signals propagating through this optical fiber communication system then, what you will have, is a mismatch between what you receive and what you have transmitted. In the case of an analog signal this mismatch will be in the form of a distortion and noise added to the waveform and you normally quantify this mismatch by the signal to noise ratio.

You would say that, while at the transmitter the signal to noise ratio was so and so db whereas, at the receiver if you do not correct for the impairments if you do not mitigate the impairments the signal to noise ratio would have decreased considerably and perhaps render the entire communication system unusable ok.

On the other hand, in the digital modulation schemes you will be transmitting usually in the form of binary signals that is you will be transmitting bits of 1 and 0 or some sequence which represents the information that is given to be transmitted and the mismatch will be occasional errors that the receiver would make in deciding between a 0 and a 1.

So, if you compare to the total bits that are transmitted and look at how many bits are at the receiver are in error, you will come up with what is called as a bit error rate. That is, you assume that these errors are going to be there on an average, but I mean you normalize it with respect to the transmission rate and then you say that, this is the bit error rate of the system and one of the important things that you will have to take care when you design communication systems is to keep this bit error rate as small as possible.

About 30 years ago or maybe 25 years ago, many people used analog communication. We know, what are the analog communication types? We have learned analog I mean amplitude modulation, phase modulation and frequency modulation. But, in today's communication technology analog communication especially in the long haul optical fiber communication simply does not exist. Everything has become digital modulation because of the various you know, advantages that are offered by the digital communication system something that we do not want to go into the details here.

But, suffice to say that, most of our communication systems today especially, the long haul optical communications is in the form of digital communication. And therefore, this part 3 will focus mainly on digital communication, occasionally we will talk about analog modulation or analog modulation techniques as well. But, most of our focus will be on the digital communication. Well, we will also not consider the optical networks in the sense that, our consideration in part 3 will simply be from point to point optical communication link.

So, you have a transmitter you have a fiber and then you have a receiver ok, we do not consider the cases where you have multiple transmitters, multiple receivers and multiple optical links interconnected to form a network that is something that can be done in a different course. If they understand how to make good links, then we will be taking one step to make good optical networks as well.

So, that is what our focus will be point to point links, point to point optical communication systems ok. We talked about lot of devices in the previous modules those WDM components which kind of help us, in realizing the full optical fiber communication system. But we left out one very important component called the modulator; of course, that is what we are going to cover in this model.

So, let us look at what this modulator is and how do we implement this modulator? We know that if the data needs to be transmitted on the fiber, the data which is usually in the form of a current or a voltage or we say that the data is in the form of an electrical signal ok, has to be converted into the optical format ok.

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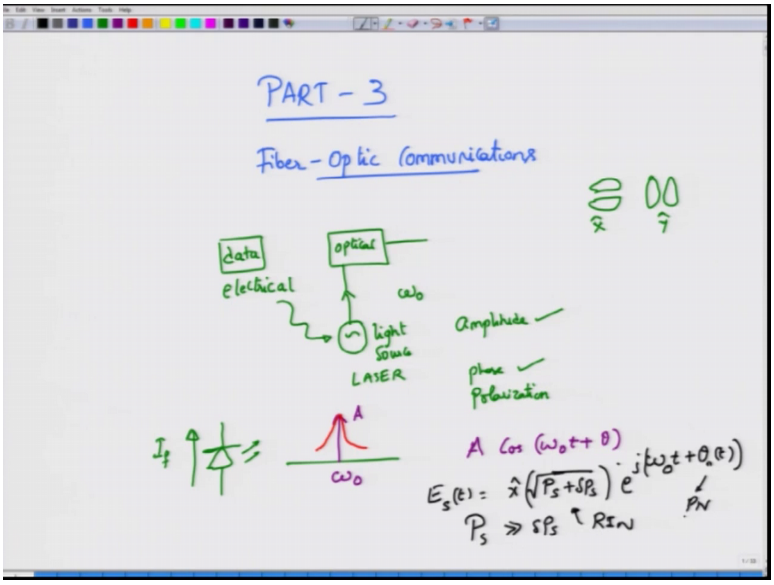

So, has to be converted into the optical format and this conversion can be done or conversion has to be done by utilizing a light source because, light source is the one that would actually generate light ok.

So, you have a light source of course, in the case of fiber optic communication system, we know that this light source is going to be a laser right. So, this laser would generate light at a given frequency or at a given wavelength. We will assume for simplicity that we are dealing with the wave I mean frequency over here ok. And once the light comes out of the laser diode semiconductor laser diode one of it is properties will be used to modulate the data onto the optical carrier.

So, I cannot just take the data in the electrical format and put it on to the optical fiber, I have to modulate this information or you have to change the optical signal in accordance with this electrical signal. So, what you actually have, to do is to perform the process of modulation wherein the carrier properties and what are the carrier properties? The carrier properties will be amplitude frequency phase and in the case of optical fiber communication you also have an extended degree of freedom contest polarization we have seen that LP01 mode can actually come in two different varieties right.

So, this is also LP01 more this is also LP01 mode, one is an x polarized wave and the other one is a y polarized mode. And information on each of these modes can be independently modulated by changing the amplitude frequency or phase ok. If this change is usually in the form of a continuous change then, we call this as a continuous wave modulation or analog modulation, but in the case of digital modulation things can actually be discrete ok.

We will not look at any modulation technique that would involve frequencies no, we are not going to modulate frequencies in this course we are only going to modulate amplitude and phase. Of course, frequency modulation is a very important technique, but not quite popular in the optical fiber communication systems at least not something that we are going to discuss it in this course ok.

So, to sum up you need to have data in the electrical format and then convert the data in the electrical format into the optical format or into optical domain. Now, how do we go about doing that? We know that, laser source is essentially a forward biased semiconductor junction right. So, it is a p-n junction which will be producing light send in some amount of current which would be the forward current of a forward biased p-n junction which is acting like a laser.

We know that, when we forward bias the junction, you are going to move lot of electrons from the valence band into the conduction band and because, you have used this hetero structure lasers you would confine these carriers in their appropriate bands whether they are in the conduction band or in the valence band. And just a small amount of forward bias current would then induce that these carriers would recombine and then give off radiation which when you enclose in the form of a mirror, would form a self sustaining emission of light called as a laser and the light that comes out of a laser usually in the spectral domain ideally one would expect it to be just a pure tone you know of the frequency omega naught having some amplitude whatever the amplitude and a phase which is kind of fixed with this one.

So, if you want to write down an equation you would probably write an equation like this, A Cos omega 0 t plus theta where, A is the amplitude which is well defined no noise on that and frequency of omega 0 which is again well defined and theta is a phase constant arbitrary phase constant, but it is also time independent phase ok. This is what, one would expect.

Unfortunately, what you get is this kind of a laser output ok. So, if I want to express that one, I should actually write down the electric field that comes out of the laser in this manner. So, let us say this is E s of t it could be coming out with up certain polarization. So, I am going to write down the polarization as x here. But please remember it can be any polarization, I have just indicated that with x.

And then there is a steady state power that the laser would put out, but then this power would also be or this power would actually, be subjected to some kind of a fluctuation which are denoted by delta A and this delta A would correspond to the amplitude fluctuations, but in reality it is the fluctuations of the power.

So, maybe instead of writing this in this manner by separating out the amplitude, I can include that in the power itself by writing this as P s plus delta P s where, delta P s is called as the relative intensity noise; it is random and then it has certain characteristics or certain distributions that we do not really need to go into at this point. Usually, these lasers are operated with P s much larger than delta P s and where is the source of this delta P s? Well, you guessed it the source for delta P s is always the amplified spontaneous emission noise or rather the spontaneous emission in the laser.

So, spontaneous emission induces both change in the, or induces both fluctuations in the amplitude as well as in the phase. So, how does it induce the change in the phase? Well, this is what you're going to get you will get in the complex form you have e power j omega 0 t plus theta n of t where, theta n of t corresponds to the phase noise which again has it is origins in the spontaneous emission ok.

In spontaneous emission causes random or incoherent phases to be applied on to the well defined signal and this is what your actual output would look like. So, you have relative intensity noise which affects the intensity or the amplitude and causes fluctuations. And then you have a phase noise which affects the phase of the or pretend as you have guessed by now if you have not already guessed; phase noise will be very very important when you consider systems in which information is modulated in the form of a phase, right. So, when phase is modulated unwanted phase noise would actually cause errors. So, this is what your laser would produce.

Now, there is one straight forward way of modulating the laser output and that would be to modulate the current source itself ok.

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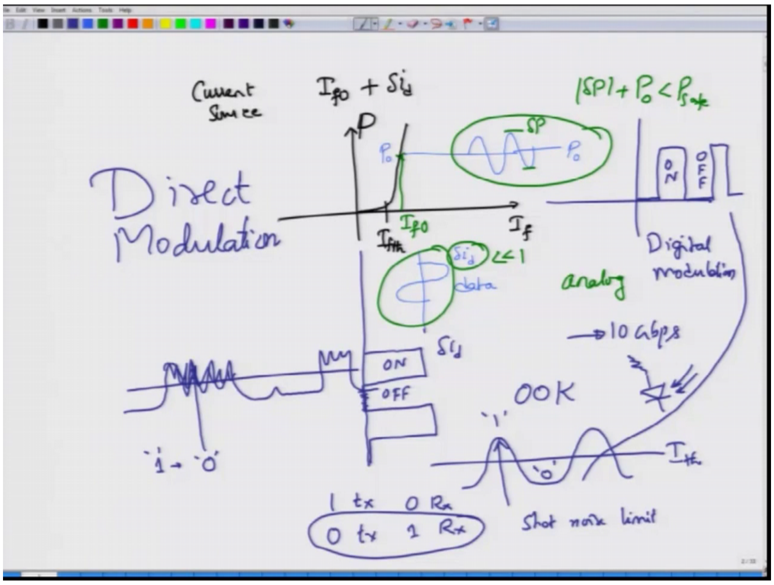

So, I can put the current source to generate some constant value which I will call as say I f 0 and I f 0 would be the bias current that is necessary to sustain the lasing action of the semiconductor laser diode and any data that I want to transmit I can actually put that data as or superimpose that current onto the forward bias current.

So, if you look at how the current forward current versus the light output which is usually, denoted by L and L stands for luminosity, but in our case we can equally think of this as the power that is coming out from the laser diode. You would see that this actually follows more or less this characteristic as the forward bias increases the power increases. There is a certain threshold value that is necessary for the laser to begin acting like a laser itself below that the laser would not leave. And just about at I f ph which is a threshold current then the laser will you know generate most of it is light in the form of spontaneous emission.

And that is precisely the area where leads can be designed, but if you bias the laser with a current which is greater than I fd h that is a threshold current then it starts emitting light and if you increase the forward bias current then the power increases rapidly usually you have a sort of current limiting mechanism in your circuit in the form of a laser driver ok, but nevertheless your laser driver will usually operate at a certain operating current. So, I f 0 would be the operating current ok.

Now, if you want to modulate data which I will assume that the data would look like this in the form of a simple sinusoidal signal that when you have, light which is in this modulated or this is a modulating signal or the data signal out here. Then what it means is that, when the data is passing through 0 the current through the device is if 0 and when the current starts to increase the output power also starts to increase and then decrease around this current or the operating current P 0.

So, with a mean value of P 0 you can actually around that value of P 0 or around the value of I f 0 if you happen to put your data current delta I d then it is possible for you to actually modulate the laser output. And then almost faithfully reproduce whatever the information that you have by modulating the intensity or the power of the laser right. So, this is very important what you are doing is to modulate the intensity what is happening to the phase? Lot of things can be happening to the phase, but I do not want to look at phase because my information is not you know in the form of a phase, but it is only in the form of intensity.

Admittedly, this type of a modulation is not very spectrally efficient will be usually limited by the speed at which I can modulate the laser current. Because when I modulate the laser current carriers have to recombine and then they have to you know again be you know pushed into the bands appropriate bands and confine and then recombined these processor all not instantaneous, there is some delay in moving the electrons from the valence band to the conduction band and then when the laser or the when the carriers decide to recombine to generate light.

So, all those delays have to be considered and those delays also are part of a, the you know the factors that limit the rate at which I can modulate the intensity of the light. I can also modulate the phase, but usually we do not really do that phase modulation onto the laser current. What I just described is analog modulation because the output is changing almost in the same manner as the input ok. But please remember that the peak change or the peak change in the power must be.

So, that the total power delta P maximum value plus the operating power P 0 must be less than whatever the safe limit of operation of a laser ok. So, that really means that delta I d magnitude is usually very small compared to 1. So, this was analog modulation, I can explain the same idea to digital modulation as well you know instead of modulating this type of a waveform. I can now, operate the laser in a different condition or different operating region.

So, I will operate the laser at this point and then move a digital signal like this right. So, I will apply a current which is in the form of a step or a pulse and the effect of this current pulse delta I d is that I am now moving the laser from below the laser threshold; that is when, delta I d is 0 you can see that in this region the output corresponding output will be 0, because you do not have light lazing out and then, there will be very very small amount of light power that may come out.

Because in most of the cases, there will be slight amount of power that would be coming out, but that is very small. But when delta id is made larger, but when the pulse occurs, then it would provide sufficient forward biasing. So, that the light output or the laser then generate light output in accordance or into the duration over which this is turned on.

So, this is the digital modulation and as I told you this digital modulation format is widely used. In fact, it is widely used up to 10 Gbps standards in about 15 years ago, this was the only format that was widely prevalent. Because for that time the bandwidth requirement was alright it was not very high and these data rates were sufficient for those data rates as such, but the most important point is what you have done is to turn the laser on and off accordance with the pulse which is on and off.

So, when the pulse current pulses on the late output is also on. So, effectively what you have done is to keep a shutter. So, you this shutter will open when the current pulse comes in and this shutter will close when the current pulse will be turned off ok. And therefore, this type of a modulation is called as on off keying and how do I receive this on off keying output after propagation the optical pulses would mostly look like this of course, they will also be noise, but I am not indicating the noise here and what you have to do, is to put a threshold and then compare the current or the current that you would obtain; so, this is the optical signal of course, you have to put this one through a photodiode.

So, light is incident on this photodiode and then the photodiode will generate appropriate current and this is the current pulse waveform. And then you put a certain threshold value of the current which will then if the sample output that you get will be above the threshold you will have obtained bit 1, if it is below the threshold you would have received bit 0.

Occasionally, when there is noise you would actually make an error and it can be shown that there will be significant noise. So, this would not be exactly like a square wave it will be very noisy like this, but when you keep a threshold and then you are sampling got an unfortunate time, then you may declare a bit as 1 or a bit as 0 instead of a bit as a 1 ok, and thereby making a error of one kind ok. This is an error where you have transmitted 1, but you decoded the received symbol as 0 ok.

You will also make an error when you make or when you send transmission a 0, but you will receive this as receiver as 1, but this usually does not happen for a photo detector that is operating in the so, called short noise limit which, we have already discussed a little bit short noise and thermal noise right. Because short noise depends on the optical power it will be usually quite noisy for bit 1 and usually that not much noisy except for the thermal noise in bit 0 transmission.

So, this is the older digital modulation technique and this type of a modulation is called as direct modulation. Because no other device was externally used to model it, but in practice you will have to use an external modulator.

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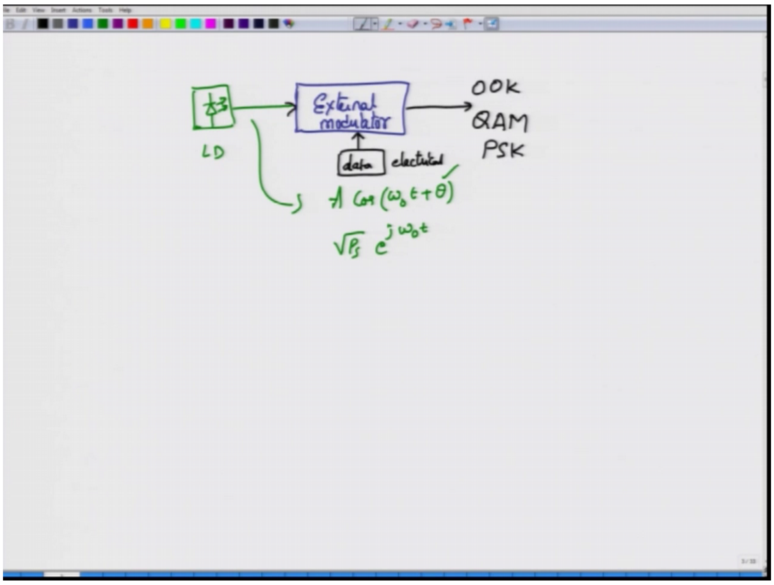

Because as the data rate increases the direct modulation of the laser cannot happen because, the laser has all those time delays that I just spoke about you know in the form of carriers being recombined, carriers being moved from one band to another brand and collection of those carriers light and all those things.

So, the rate at which you modulate will not be possible by more than 10 Gigabits per second. And moreover you normally when you modulate this you know even in the on off keying, you will introduce sufficient chirp and remember what is chirp? Chirp is the unwanted phase fluctuation not that you care about that phase, but what this unwanted phase fluctuations will do is to kind of broaden the spectrum of your data.

So, because phase fluctuations in time turn out to be frequency fluctuations in time as well because d phi by dt where phi is the phase is directly proportional to the instantaneous frequency. So, as the data rate increases beyond 10 Gbps and you use only laser current to modulate that is a direct modulation. Then in addition to the spectrum that you get the spectrum will become chirped and chirping will cause the spectrum to broaden. And this broadened chirp will be so, much that it may actually start spilling over to the other channels as well.

So, this is not clearly an efficient usage of the spectrum and therefore, you do not see any type of a modulation beyond, simple on off keying for data rates that is less than 10 gigabits per second in the direct modulation scheme. So, then what do we do, we actually have an option of what is called as external modulator. So, in an external modulator I have a laser diode ok, I have a laser diode and then this laser diode will be used as a simple oscillator ok.

The laser diode will produce light and then I take that light which can be to a good degree approximated as A Cos omega 0 t plus theta or I can write down in the more common format of root P s e to the power j omega 0 t I have neglected this theta I am assuming ideal light coming out from the laser diode, but then I can put an external device and then drive the data. So, whatever data that I want to transmit will still be in the form of an electrical current or a voltage.

But this electrical current or a voltage will go to an external modulator which will then depending on the type of the external modulator will generate on off keying it will generate the most general format of modulation called as quadrature amplitude modulation and it can also do what is called as P S K which is phase shift keying, please note that we are dealing almost exclusively with digital modulation formats only.

So, how exactly do we do this and when you look at direct modulation the simplest variable to control was the intensity of the light or intensity of the laser. Is it the same with the external modulator which is the simplest variable to contour which is a simplest modulator structure then use an external modulator is what we are going to talk about in the next module.

Thank you very much.