Fiber-Optic Communication Systems and Techniques

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Lecture – 48
Optical Modulators – II (Electro-optic modulators)

Hello and welcome to NPTEL-MOOC on Fiber Optic Communication Systems and Techniques. In this module, we will continue the discussion of modulator and as we saw at the end of the last module that we need external modulators if you want to modulate optical signals at a rate which is greater than 10 gbps. So, this external modulator can also be used for modulation at lesser rates as well there is no restriction on that rate and in general they offer much more superior performance compared to the direct modulators.

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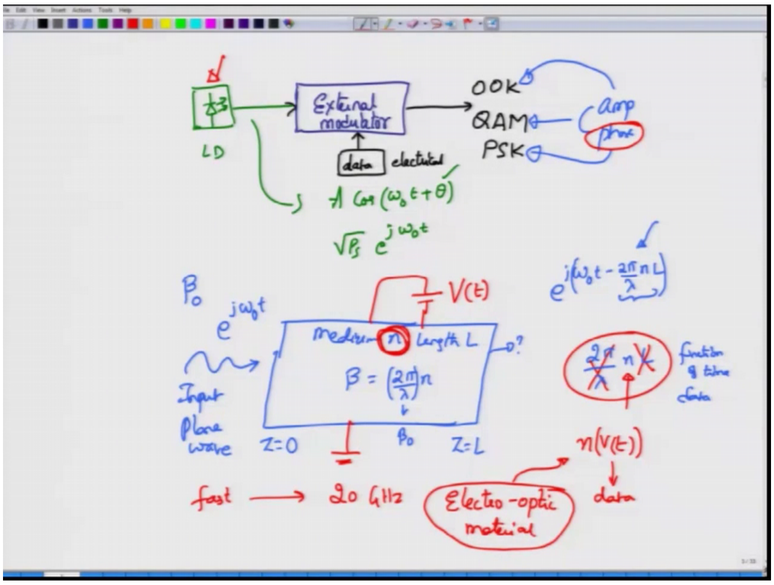

So, in the case of this external modulator that we had light source is the laser diode and the output from the laser diode one of the characteristics as I told you amplitude or its phase will have to be modulated and combined modulation is also possible and this combined modulation is the so called quadrature amplitude modulation. But, if you modulate only phase you will get phase shifted keying and if you mole it only amplitude we will get on-off keying, ok.

And, I teached you in the last module saying that in the indirect modulation case it is the power that is the simplest variable to control and therefore, on-off keying is the most simple modulation technique that is possible. But, what is the simplest variable to control when it comes to external modulator it turns out not the amplitude, but the phase, how? Suppose, I consider an input plane wave you know imagine that you have a nice input plane wave propagating and I have a medium of some length L and the refractive index of this medium is n.

Now, I know that at the position say Z equal to 0 the input wave will be represented by e power j omega 0 t. Do not worry too much about the getting the exact thing right here, this is only an idea of what the external moderator is going to do, a proper analysis this is something that unfortunately I cannot do it in this course. But, you can refer to our earlier NPTEL courses on electromagnetics where we have discussed what kind of moderators are used and how to analyze those moderators as well. Well, we did not call moderators there we said that those are birefringence media and then how to analyze light propagation in birefringence media we have discussed in those NPTEL modules or NPTEL courses.

I have a plane wave that you know imagine a plane e power j omega 0 t happily propagating in air and now reaches this medium of refractive index n and then begins to propagate. What would happen at the output of this medium? Well, just at the output of the medium we know that if the wave had a propagation constant of beta then there will be a phase change which is given by 2 pi by lambda n into L, that correct? Yes, because 2 pi by lambda is the free space value of beta, but this was free space where you can think of this as beta naught, but the value of beta inside the medium is given by 2 pi by lambda times n, where 2 pi by lambda is basically beta naught as I told you.

So, in the medium the propagation constant is beta and because the medium has a length of say Z equal to 0 to a length of L going from 0 equal to 0 to 0 equal to L this is what you are going to obtain, right. Now, you might say where is the phase modulation happening here? Well, not you know something I want to make this term which is the phase term right 2 pi by lambda n into L let me write down this separately this 2 pi by lambda into n into L, I want to make this term be a function of time. Because, if I make this function of time or function of the external data signal which itself will be a function of time then I will be done. Is it possible for me to change the length of the medium? Yes, it is possible for you to change the length of the medium.

However, changing the length would be very very slow process and therefore, not suitable for a high speed optical communication system, right. So, changing the length is not a good option. Can I change lambda? Can I make the wavelength depend on the data which itself depends on time? Yes, it is possible, but that would require again to make changes in the physical device which is producing that wavelength which is our laser diode. So, you have to move the mirrors to adjust the laser to go to a different lambda, all those things are still possible, but those are again very slow process and usually not even the correct process because you want your carrier to be of a fixed frequency or to be of a fixed lambda as such, right you do not want to change that one.

So, the only option that is now seems to be final to change anything as a function of time is somehow make n depend on time via a data which itself can be in the form of a voltage. Let us assume that this is a form of a voltage and I somehow can make the refractive index of the material depend on the voltage that is applied onto the medium then it is possible for me to change the phase term as a function of the data. So, this voltage represents data which is time varying usually and if I can somehow make the refractive index depend on this voltage, then I am done.

There are materials which are really fast, I mean something like 20 gigahertz bandwidth materials which means you can easily modulate around 40 gigabits per second and more depending on the modulation format these materials are called as electro optic materials and what is an electro optic material? Electro optic material or electro optic crystal has precisely this property. Its property is that it is susceptibility or equivalently the refractive index can be altered by applying a certain voltage externally.

So, if I apply a voltage V which will be a function of time. So, this will be a voltage that is a function of time, then the refractive index of the medium actually changes and this change is usually very fast having typical bandwidths of up to 20 gigahertz. And therefore, these external modulators which make use of this electro optic materials are the preferred choice to modulate the optical signal and what was the term that we modulated? It was the phase that will that be modulated and remember if you were to go back to RF communications or in other type of no data rate communications the phase modulation structure, the phase modulated structure was actually very very difficult, right.

It was not so straightforward as a amplitude modulation whereas, in optical modulator (Refer Time: 07:00) optical modulators it is the phase which can be modulated rather easily compared to the amplitude. It does not mean that you cannot model it amplitude, but the first or the basic requirement of or the basic building block of an external modulator is that of a phase modulator.

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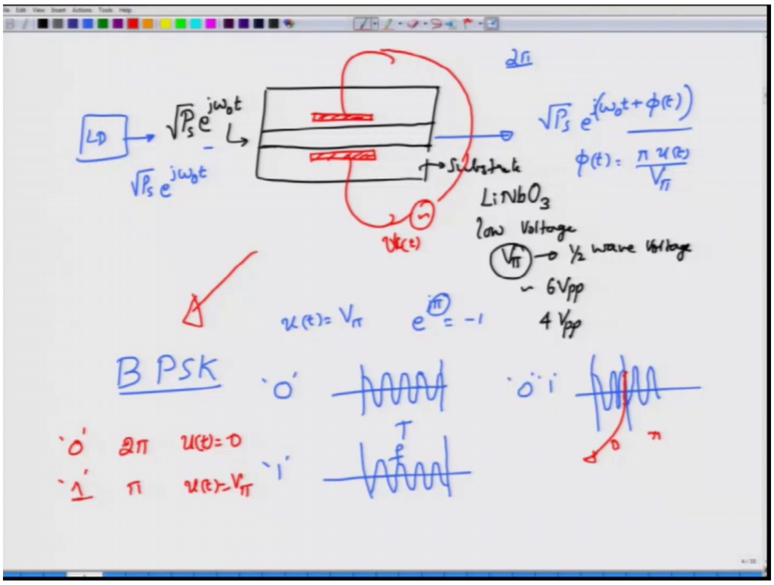

So, if we look at the integrated moderator structure you would see something like this. This is the substrate which is an electro optic substrate and the most popular electro optic substrate which has this large bandwidth, high electro optic coefficient and an appropriate voltage value of studies you know you can modulate. But, if your voltage requirements are like say 100 volt, 200 volt then it makes no sense, right. But, these lithium niobate crystals which are used as electro optic substrate are characterized by the low voltage requirement.

In fact, it turns out that there is something called as V pi; V pi stands for half wave voltage. If you apply a voltage of V pi volts then the input and output phase will be out of phase by 180 degrees and that is the voltage that is required to make that situation happen is called as the V pi of the device and this V pi is about 6 volt peak to peak. In fact, in some cases it is just 4 volt peak to peak for lithium niobate crystals of appropriate length, ok. So, this is the substrate that you would actually use and make a waveguide.

So, luckily this is also can be used as a waveguide and you first draw an optical channel this is essentially an optical waveguide. Let us redraw the optical channel. So, this is my optical channel, I send light in from this side again the equation for the light will be more or less the plane wave condition that we are writing. So, it would be square root P s e power j omega 0 t and I put two electrodes, we put two electrodes and connect these electrodes to external connections or external wires in such a way that we can apply a voltage across this.

So, when you apply a voltage V of t to this one or u of t to this one. So, we will use u of t as the voltage, that just for notation. Then the output that you get, light output that you get will be written as P s e to the power j omega 0 t times or plus phi of t where phi of t is equal to pi u of t by V pi. The reason why we have written this phase term as pi u of t by V phi is because when u of t is equal to V pi then the phase term will be e to the power j pi or minus 1 or 180 degree out of phase.

So, if you compare this wave at the output to the input electric field you will see that there is a phase difference of phi of t and when u of t is equal to V pi which is a constant, then the output will be out of phase by 180 degrees with respect to the input phase, but this is important, right. So, you have now shown that it is possible for you to modulate the phase by applying an external signal u of t. So, this is the external signal and this is what a phase modulator can do.

Now, what can we do with this phase modulator? Let us consider the simple modulation format called as binary phase shift keying. What is this binary phase shift keying? It means that if there is a bit 0 then you transmit a cosine wave of some phase. So, let us say this is the time interval called as the signaling interval, this is the interval over which you are sending a bit 0 and then you want a cosine wave to go something like this have all of those this is actually supposed to be equal periods, but please do not worry about the way I have drawn. So, this has a certain frequency f 0 and it has a certain phase which is 0.

So, if you compared to a standard cosine wave you can see that this is a phase 0 that is possible, right. So, we will also have to consider you know correct cosine wave here. So, which means that I have to now come up with this one, right yeah. So, this is my one period over which or one time interval over which I am sending 0 by actually transmitting a cosine wave. In the context of our BPSK you have a laser diode and the laser diode would be producing light which is approximately square root P s e power j omega 0 t and if I were to configure this external phase modulator such that the input and output are of the same phase or 2 pi phase difference which does not matter, then I have actually implemented this bit 0 or I have sent out bit 0.

For bit 1 what it would require is to send out the same cosine wave, but this time you want the cosine wave to be 180 degrees opposite in phase. So, you will have 180 degree like this and then it would also be over the same time interval. So, when you transmit a sequence 0 and 1 together you will see that it would go something like this and then it would start abruptly at this point. So, you can see that there is a phase jump here and this phase jump will be jumping only between two phases which is 0 and pi, ok.

So, this is how a BPSK system would work and for me to implement this BPSK format using this phase modulator is very simple. I have to configure the phase modulator in such a way that I get 0 or equivalently 2 pi phase shift when bit 0 is transmitted and I get pi or any of it is odd multiples if I am transmitting bit 1. I can obtain a pi phase shift between the output and the input by setting my u of t to be equal to V pi and if I set u of t is equal to 0, then I will obtain 0 phase or if I can set u of t is equal to 2 V pi I will obtain phase which is again 0. So, I have now using a phase modulator I have implemented this simple constellation called BPSK.

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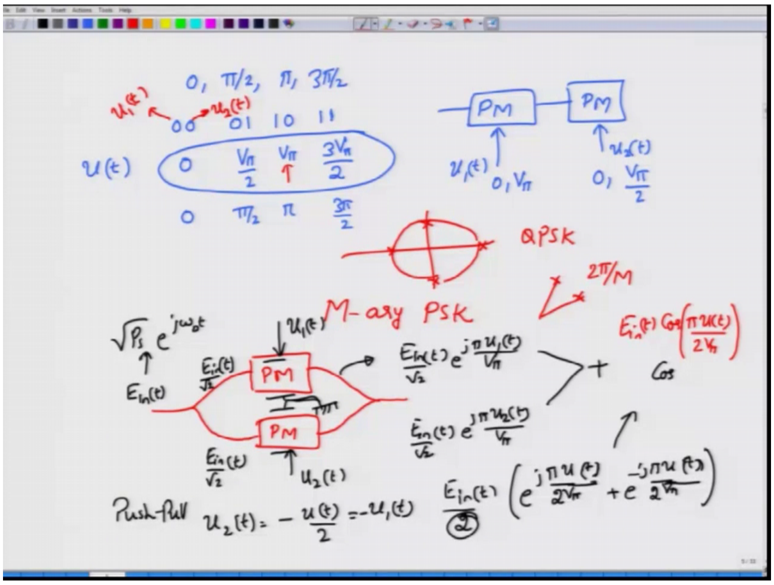

Now, if you maybe you are not satisfied with a BPSK modulation format you want to send out phases which are 0 pi by 2 let us say pi and 3 pi by 2. You will select 0 when the bit sequence is 0 0, you may select pi by 2 when the bit sequence is 0 1 and for reasons which we will discuss later on pi will be 1 0 and then let us say this is 1 1.

So, how do I now implement phase modulator how do I use my phase more later to generate these different phases? One way would be to set my input electrical signal u of t to 0 volts and to set this to V pi by 2 volt, set here as V pi and then set 3 V pi by 2, correct? So, when I do that the total output phase will be 0 pi by 2 pi and then 3 pi by 2 which is what I want, but this requires my u of t signal to be multivalued. I have to send in depending on the bit sequence I have to send for different voltage levels which sometimes is not very ideal.

So, in that case what you do is you use two phase modulators. So, you have one phase modulator and you have another phase modulator this phase modulator sending the data which we will call as say u 1 of t which can be either 0 or V pi, which means that when u 1 of t is 0 this phase monitor will add 0 phase or it will add V pi phase or pi phase. And, onto this modulator you send in u 2 of t and different signal, but it will have it is amplitude half of what the previous one is. So, this will switch between 0 and V pi by 2, right.

So, the first symbol can be sent or set by u 1 of t the second symbol can be set by a different signal u 2 of t, u 1 of t goes to the first modulator u 2 of t goes to the second modulator. So, now, you can see when u 1 of t is 0, u 2 of t is 0 the output phase will be 0 when u 1 of t is 1 while u 2 of t is 0 you will get this V pi and therefore, the phase shift will be pi and so on. And, this four different phase points can actually be represented as four points on a circle because the amplitude is not changing only the phase is changing and this type of a modulator is called as QPSK modulator and the modulation format is called as QPSK modulation format which stands for Quadri Phase Shift Keying format, right.

By cascading multiple such moderators you can actually generate even more phase shifts or by utilizing multi level electrical signals you can also generate more phase states. And, in general, you can actually implement M-ary phase shift keying signals in which the two constellation points will be separated by an angle of 2 pi by M, where M is usually an even number multiple of 2. This was about phase modulator. I can actually take two phase modulators and then create an intensity modulator. How do I do that? I use a device which we have discussed in the previous modules called as a coupler, ok.

What does the coupler do? It takes in light which we will call as E in of t, which I will write E in of t as the electric fields square root P s e power j omega 0 t ok. So, this is E in of t and I split it into two parts. One part will be I am assuming that we are using a 3 db coupler or 50 50 coupler. So, I have E in of by root 2 of t going in here and maybe you have a j E in by root 2 of t, but I can remove this j by simply making some changes into the modulator structure by actually having an extra phase shift by making the length of the second arm to be different from the length of the first arm and actually remove this j term over here ok. So, I will simply have E in of t by root 2 E in of t by root 2 coming into these two phase modulators.

Now, when I apply u 1 of t to this one and u 2 of t as two different signals, then combine the two outputs what will I get here? I will get E in by root 2 of t e to the power j pi u 1 of t by V pi, and then you have E in by root 2 of t e to the power j pi u 2 of t by V pi, and then when you combine them the combination will be the addition over here, you can actually put in these matrices for the couplers and then show that this is the case. So, what you will get at the output will be the input signal E in of t by root 2 because you are combining them again there will be 1 by root 2 1 by root 2, so, which essentially becomes half. So, you have E in of t by 2 e to the power j pi u 1 of t by V pi plus e to the power j pi u 2 of 3 by 3 pi. I am assuming that both phase modulators have the same value of the pi.

Now, what I will do is very interesting. I will take u 2 of t and then make this equal to minus u of t by 2, where u of t is the actual data that I am transmitting or the information that I am going to give and then this will be equal to u 1 of t as well. So, what we mean here is that u 1 of t will be u of t by 2. So, this will actually be minus u 1 of t then. So, u 2 of t will be minus u of t by 2. So, I can go and substitute those into this expression. So, I will get u of t, right I will get u of t by 2 and then I will have a minus 2 V pi and instead of u 2 of t I will simply have u of t because I have set my signals in this fashion.

How can I set this in this fashion? This is called as the push-pull mode and you can actually do that by going back to the electrodes that are present here and then you tie these electrodes up to a constant or to the same signal and then you apply an external u of t which will be pushing them into this fashion, ok. So, one phase modulator experiences an increased u, while the second phase model experiences the decreased u at the same time this is just like making a plus VCC and minus VCC connection from 2 I know from my given power supply.

So, this is exactly the same thing that we are going to do here. So, one of thing will be u of t by 2, the other one will be the complimentary minus u of t by 2 and totally together what you get here will be this e to the power j V pi by 2. So, yeah here you will get u of t minus j pi u of t by 2 V pi. You have e power j x plus e power minus j x together this becomes cosine right. So, there will be a two factor up there. So, that 2 and these 2 will cancel each other. So, the output which I will write here will be E in of t which is not changed, but it is amplitude is cos pi u of t by 2 V pi. So, you can see that I have now managed to change the amplitude as well.

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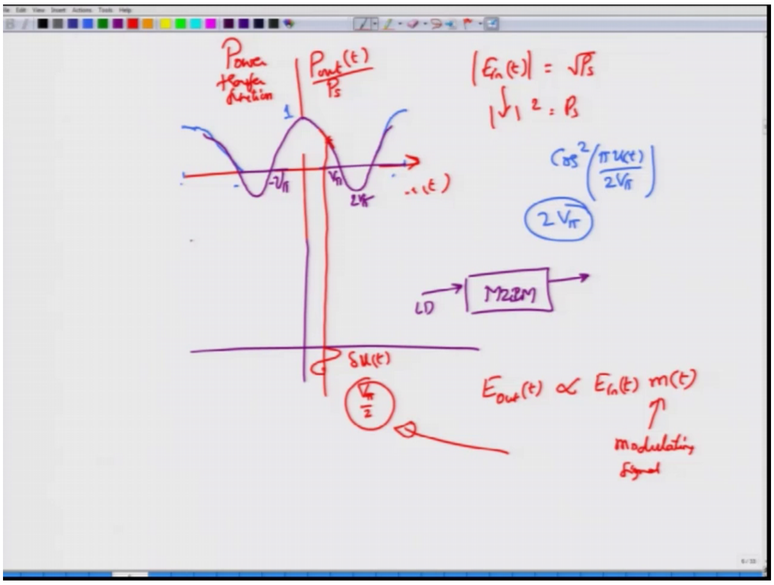

And, when you plot as a function of u of t when you plot the output power assuming a constant input power, remember E in of t magnitude will simply be square root of P s and it is magnitude square will be P s itself which is the input power which is constant, but the output power can change because u of t can change and if you divide the output power to the input power then you get what is called as power transfer function,.

It is not really a transfer function, but because you are relating the input to the output it is kind of looks like a transfer function and this transfer function will be very interesting. So, it as u of t increases, so, for u of t equal to 0 what you are looking at is cos square pi u of t by 2 V pi, remember this right and it is a cosine square because I am looking at the power and not the amplitude. So, at u of t equal to 0 I have cos square of 0 which is 1. So, you start off at this point and when u of t is equal to V pi we will get cosine square of pi by 2.

Because V pi and V pi will cancel you will get cosine squared of pi by 2 which will be 0. So, do you see that V pi it will be 0 at minus V pi as well. It will reach some other value at half, but this is what the equation would look like or this is what the plot would look like. What would happen at 2 V pi you will have cosine square of pi, but cosine square of pi is nothing, but 1 again. So, this will be 2 V pi and then when you go back to the maximum value we will again have minus 2 V pi.

So, what you see is that this is actually periodic with a period of 2 V pi because the same picture keeps repeating every 2 V pi shifts away. So, this is a power transfer function, but if you were to look at the field transfer function, ok, the field transfer function will look slightly different, it would look like this. So, it would actually be it will be slightly above here and then it will go in this manner it will actually do a cosine signal and you will see that if you switch your data between these two regions then in addition to switching the amplitudes you can also switch the phase.

So, a single modulator which is this combination of two phase modulators rate as we have called is called Mach-Zehnder Interferometeric Modulator or MZIM. It will take in whatever the light that comes out from the laser diode and actually produces an output whose amplitude and phase both can be modulated. So, this is actually a very general modulator structure by choosing appropriate u 1 of t and u 2 of t, you can modulate the amplitude alone, you can modulate the phase alone or you can modulate both amplitude and phase and this structure MZIM is available to us in the form of an integrated optical circuit.

The two arms are very nicely matched the signals u 1 of t and u 2 of t can be nicely made into complimentary format. Usually you do get full control over u 1 of t and u 2 of t, externally you can control both of them, but you can also get modulators where this connection, external connections has already been done for you and you simply have to apply a single signal u of t and then you know you will be able to obtain this modulation.

Now, with this device you can actually perform a linear analog modulation. How do we do that linear analog modulation? Well, what you have to do is to remember that this is a power transfer function right and this was the field transfer function I am not currently interested in the transfer function of the field, but let us off the power, but I am actually interested in the power transfer function let us say. So, this is what the power transfer function would look like. So, this will be V pi and this will be 2 V pi actually. So, we have to shrink this one because I drew it in that manner.

So, notice here that if my u of t would be operated in this region. So, I actually put this here which would be about V pi by 2, and then have a small signal variation around this V pi by 2. So, not too large variation, but a very small variation around this value of V pi by 2, ok. So, at V pi by 2 you can see that there is a cosine curve which is now decreasing in this manner. Of course, it is a non-linear way it is decreasing, but when your applied voltage delta u of t let us say is very small around this region V pi by 2 then you are pretty much operating in this region. And in this region by actually substituting these values into the transfer function you can show that e out of t that is the output electric field will be linearly proportional to E in of t times m of t, where m of t is the modulating signal ok.

So, you can show that this condition is possible by operating V pi of t and delta u of t is what I have called as m of t. So, that is the modulating function and you can actually implement a linear modulation or analog modulation or amplitude modulation using this device.

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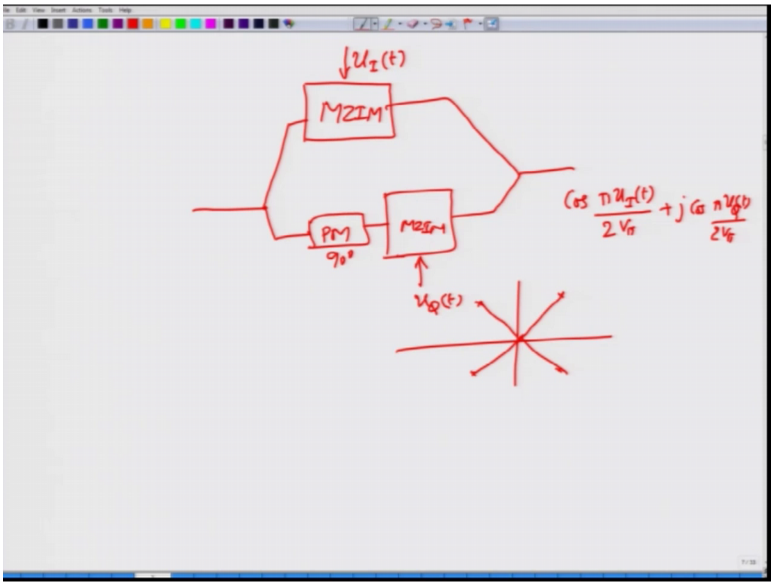

Then there is another device called as IQ modulator. In this IQ modulator what you do is that you actually have MZIM in one arm, ok. You send out the input light is split into two parts. So, you have a phase modulator which is configured to provide 90 degree phase shift and then you have one more MZIM and the signal to this MZIM will be together called as u I of t and the signal to this one will be called as u Q of t and then you combine these two outputs onto a output coupler.

And, you can show that this one in the form that we have written the complex form the transfer function the field transfer function will look something like this. It will be cos pi u I of t by 2 V pi plus j cos pi u Q of t by 2 V pi and you can control this u I of t and u Q of t by external controls. So, that you can actually instead of having a one dimensional modulation you can have modulation of any constellation possible. So, this IQ modulator can be used to modulate or implement higher order modulation formats and that is also widely used.

Now, that they are also widely used. IQ moderators are again available in the form of an optical integrated circuit and they are very popular because they can be used to modulate any of the constellations that you want. And you can combine this IQ modulators Mach Zehnder Interferometric modulators and phase modulators to implement almost virtually any type of modulation scheme that you can think of. In fact, IQ modulators and phase modulators are combined to implement what is called as 16 QAM or 64 QAM square transfer constellations and I know Mach-Zehnder interferometric modulator and phase modulators are used to implement what is called as the 16 or 64 QAM star constellations, ok.

Anyway we will see some of these constellations later on when we talk about digital modulation schemes which is what we are going to do after a brief review of some important topics from communication systems in the next module.

Thank you very much.