Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – III
Module – IV
Optical receivers-I
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So far in the modules earlier modules we have talked about optical transmitters in this module and in the next module we will discuss optical receivers and then we will come back to transmitter physics behind transmitters and physics behind receivers so at this point we are not really interested in how to implement a receiver how what physical device actually is used to convert the optical signal into electrical signal except but I can mention that this is a photo diode okay.

We are not looking at the physics behind photo diode or the circuits that would be implementing the optical receiver this is the configuration idea again going back the approach that we have taken in this course we will first describe by mathematical expressions what is the basic idea behind this block optical receivers block and then come back and discuss the physics behind it you know at a later stage so having said that optical receivers are used to convert optical signals.

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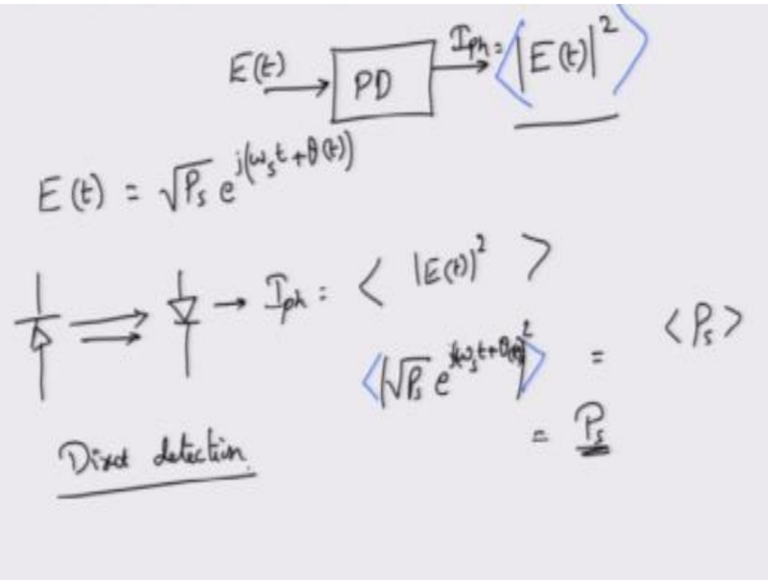

Into electrical signals okay optical signals are the once which are generated by the optical transmitter so you take the continues wave laser diode you can pulse shape it or you can shape that signal and then modulate that optical pulses in order to generate an optical wave form so you will getting modulated optical wave form after transmission through the fiber and may be other components WDM compounds and eventually arrives at the receiver input okay so at the receiver input the signal will usually be very small.

So you will have to amplify the signal first and after amplifying you will have to pass it through a filter in order to remove the extraneous noise that is not required for us to process this way now your optical wave form is ready for conversion to electrical signal you might ask why should I convert this into electrical signal the answer is very clear the information originally was in the electrical domain and I need to extract that electrical information from the optical signals.

So I need to convert optical to electrical signal what form of electrical signal if use a photo diode then this convection is usually in the form of a photo current so it will produce a current an optical a photo diode will produce a current okay so this is the photo diode for us this is just a block diagram at this point you send in a optical signal say E(t) okay where E stands for the electric field and what you get here would be a signal electrical signal which is proportional to $E(t)^2$ mod $E(t)^2$ E(t) could be a complex wave form you know the passer wave form and you will generating the signal or the photo current which is time varying but it would be magnitude of E(t)2.

For example let us consider a continuous wave so if my electric field incoming electric felid is a simple continuous wave signal from the laser diode this could be equivalent of having a laser diode and the connecting a photo diode okay so this would be the simple situation in which I am talking laser diode giving it a certain current not ,modulating anything just giving it a current and then putting a photo detector to detect the signal what do I see this E(t).

What I get can be represented as $\sqrt{}$ Ps $e^{j\omega}s^{t}$ you can also have some phase information sitting inside okay this phase information if you have not actually modulated the signal will simply correspond to some phase of set or some random phase which is associated with the laser, okay. So when you look at that into the photo detector what you see is the photo current which is actually the average of $|E(t)|^2$ I sorry I forget to put in the average what you get here is the average value of $|E(t)|^2$ but what is the average value in this particular example?

In this case I know that E(t) is given by $\sqrt{}$Ps $e^{jwst\ +\theta(t)}$ so if I take the magnitude square here I get Ps and then average this one out the fast varying time component drops out and I simply get Ps, okay which would be the power with which the laser is supplying the signal, okay. Forget about this half or other factors they would be a half corresponding to the cosine signals do not worry about those factors.

What is important to notice that a photo detector or a photo diode which is acting as a photo detector will generate an electrical signal which gives you the photo current which is given by average value of $|E(t)|^2$ now this is very crucial for you to note that, we have seen some modulation techniques which only alter the amplitude of the optical signal this is the amplitude shift keying that we discussed in earlier models.

We have also seen in earlier modules those modulation techniques which will alter not only the amplitude but both amplitude as well as phase they also seen those which will alter only phase so if the information is residing in the phase θ(t) and I have used a photo detector to detect my signal optical signal and convert that into electrical signal have clearly loosed all the information about the phase.

I have totally lost it, right. So there has to be a way in which I have to extract information which is located in the phase of the optical signal but still use the photo diode, okay. So we will see what kind of a receiver circuit is required in order to do that one, we also discussed one modulation technique we called as differential QPSK or differential BPSK this differential modulation was in the form of encoding phase as the or encoding the symbols as the phase difference between present and previous symbols, right.

So the next symbol that you are going to obtain will be a function of present and the previous symbols so the phase difference between those two was actually being transmitted so in a similar way if I want to extract the phase difference between two time slot I have to convert the phase difference between two time slot into intensity value so again we will see what kind of an optical receiver is required for that.

So although this is titled as optical receivers we are really looking the detection mechanisms a full receiver will consists of a biasing circuit it will also consist of some low noise amplifier and a main amplifier a low noise amplifier is also sometimes called as a pre-amplifier and then you will have a main amplifier some additional filtering circuit some detection and synchronization and timing circuits.

All these circuits essentially form a part of optical receiver we are of course only going to concentrate on one particular component known as the photo detector and what are the receiver topologies what are the photo detection topologies that, will enable us to extract information from phase of the optical carrier or extract information about the phase transition, okay. Whatever we have done by putting up a laser and a photo detector is known as direct detection.

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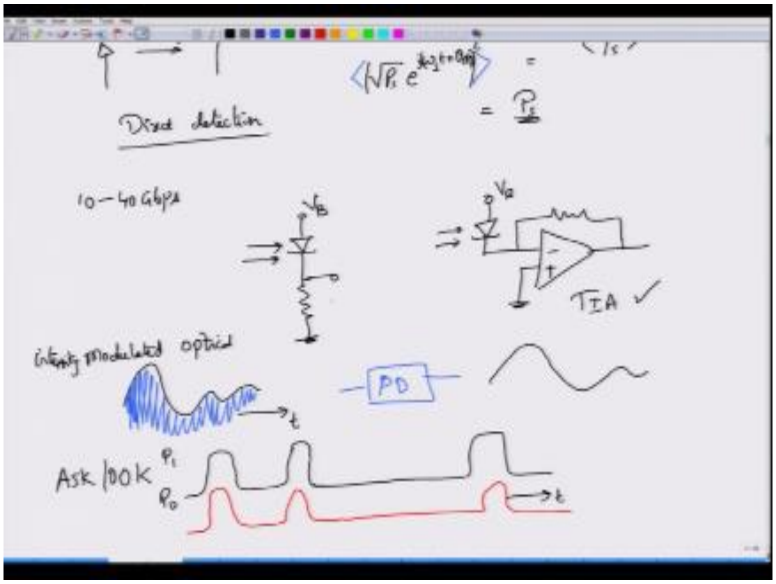

Even today for 10 GBPS – 40 GBPS data rate systems direct detection laser intensity modulation and direct detection is a simplest hardware efficient and most widely understood and you know implementable detection receiver topology all that you have to do in the direct detection is we have to simply put a photo detector the optical signal comes and falls on the photo detector and you simply generate the photo current okay this photo current can flow through a certain resistor generating the voltage or you can in a more common scenario you can actually convert this photo current into voltage by putting a current to voltage convertor in this fashion this one is simple receiver module.

Whereas you know this is a simple module where as this is called as Trans impedance amplifier okay this structure is quite widely used for photo detection purpose what does this detection mechanism consist of simply consist of a appropriately biased photo detector followed by a way to convert current into voltage you can do that by simply putting up a big resistor or can put up that came resistor but couple it through this open in order to form the Trans impedance amplifiers circuit okay if my intensity is changing.

This way optical intensity and it is changing very slowly this is not the carrier optical that is changing please remember this, this is not the optical carrier this is the modulated laser light okay this is the modulated optical or intensity modulated okay this is the intensity modulated optical signal as a function of time then if this modulation is quite slow right so if you remember it there is actually a very high speed carrier sitting here right so there is a carrier here so what you are actually looking at is the intensity that is getting modulated right.

So this is the modulated way from a slowly varying envelope if you put this one through the direct detection photo receiver or a photo detector what you will see is a photo current which will essentially vary in the same manner has the input if I am using amplitude shift keying or equivalently and on of keying by optical way from could look like this, this right so I have wherever I have pulse there would some signal and when there is no pulse the optical power could be sitting at P0 so this would be the power levels through which.

This is switching as a function of time then if you detect it by photo detector what you will see is essentially the same way from okay it some changes minor changes but that is okay, okay so this is the photo detector and this.

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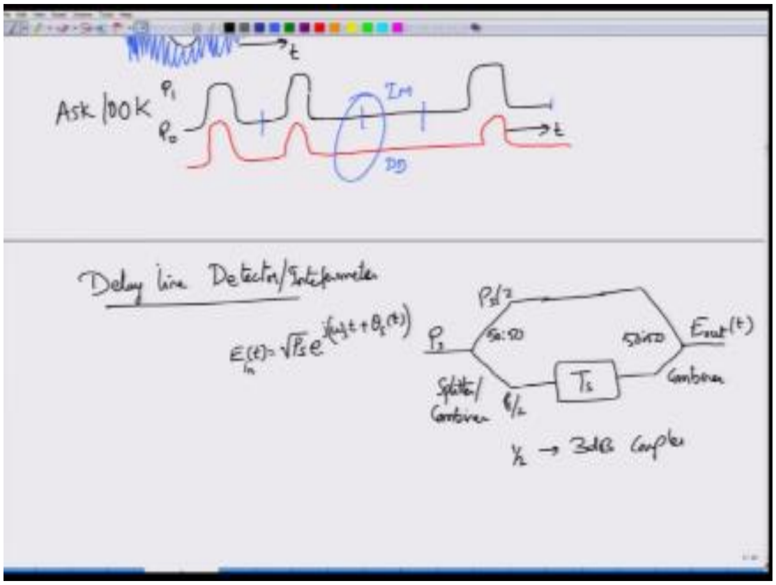

Mechanism of which your modulating intensity and then detecting directly is called as I'm DD transmission system and IMDD transmission system as I said if quite popular and it is widely used for 10 to 40GB PS optical communications system you have to notice something else there was absolutely no mention of the phase so as long as I am able to determine the bit boundaries which is known as the syncanization problem I do not have to know what is the optical phase here in fact my detection method is insensitive to optical phase so this is the direct detection which is completely insensitive.

To optical phase now let us look a different mechanism or a different receiver topology which is called as delay line detection or delay line detector what is this delay line detector do now I take the signal which I want to detect optical signal okay this would be the optical signal that I want to detect E of t which can be written as ЛPS $e^{j\omega st} + \theta_s$ of t where θ_s would correspond to the modulation that I have done okay this is the phase which have modulated so this signal is input to this device called as delay line interfere meter or rather delay line detector or delay line interferometric detector okay what is this do you first spilt your signal into two parts okay and then delay one part by a symbol time Ts this of course assumes that I know where the symbol time begins and ends that is I know where the clock information is but that is something that can be easily extracted okay, or it can be generated rather easily.

So if I have we been able to do that then I what I do is I take the signals split into two portions then delay one portion and then combined them at the output stage okay this particular device which is splitting a signal is called as a splitter or a combiner because this is a two way device so you take the signal from the left hand then it will split the signal into two equal parts, here we are assuming equal parts you can actually split them in any ratio you want, you want to split the top part to contain 90% energy, bottom to contain 10% energy or welcome to do so, okay. So in this case because we are splitting equally and this splitting is actually power splitting so we say this as 50, 50 coupler, okay.

Power being split into half so if you start with a power Ps the power in this wave form, in this r is Ps/2 power in this RmPs /2 this 1/2 corresponds to 3dB, right. So if you look at the power to power ratio here, this is ratio is 1/2 half, upper arm to input that 1/2 corresponds to loss in terms of 3dB so this is called as a 3dB coupler, a splitter combiner 50, 50 coupler or equivalently 3dB coupler.

Similarly on the other side what do I have, I have a combiner, right so I have again a combiner which will combine in the same ratio, so I have a combiner which is combining in the same ratio in order to generate the output signal which let us call it is as $E_{out}(t)$, so this E(t) or $E_{in}(t)$ is given by this expression and this is what we want to find out what is $E_{out}(t)$.

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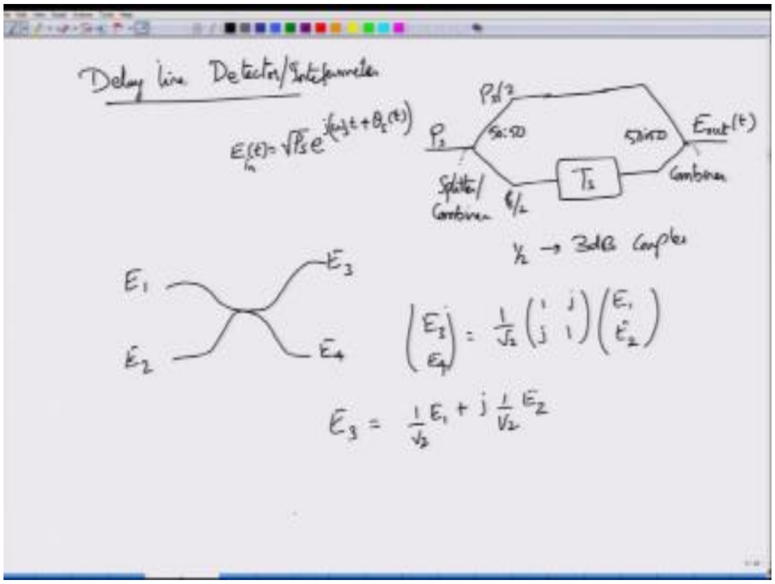

Delay line Detector/Interferometer

$E_{in}(t) = \sqrt{P_s} e^{j(\omega_s t + \theta_s(t))}$

1/2 → 3dB Coupler

$$\begin{pmatrix} E_3 \\ E_4 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}$$

$$E_3 = \frac{1}{\sqrt{2}} E_1 + j \frac{1}{\sqrt{2}} E_2$$

To do that I need to know in terms of electric field what happens to the signal as they get split here, okay as they get split there will be a phase, you can actually construct a splitter in such a way that there is a relative phase between these two or there is no relative phase, okay. A general splitter will consists of two ports, okay and output also consists of two ports so in this particular example you can think of the other port being contributing nothing it is a 0. Similarly, this other port has been neglected, okay.

So what is this, so if you call this as E1, call this as E2 then E3 and E4, this E3 and E4 which are the signals at this output can be written as $1/\sqrt{2}$ 1jj and 1, this j stands for 90^{o} phase difference, okay times E1 E2, simply saying that optical signal E3 at this port is given by $1/\sqrt{2}$ times the input signal E1+j $1/\sqrt{2}$ times E2 this j indicated that there is a phase difference, so the component of E2 that goes to E3 will suffer a 90^{o} phase difference whereas the component of E1 which goes to E3 will suffer no phase difference between compare to this, okay.

So that is the meaning of having a j, you can construct in a very different manner in which the phase difference can maintained as 180^{o}, okay.

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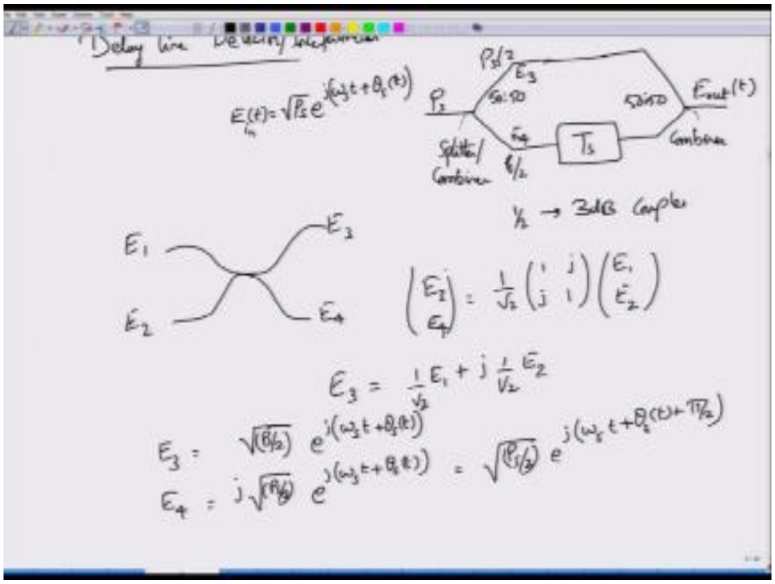

$$E_{in}(t) = \sqrt{P_s}\, e^{j(\omega_s t + \theta_s(t))}$$

$$\begin{pmatrix} E_3 \\ E_4 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}$$

$$E_3 = \frac{1}{\sqrt{2}} E_1 + j \frac{1}{\sqrt{2}} E_2$$

$$E_3 = \sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t))}$$

$$E_4 = j\sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t))} = \sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t) + \pi/2)}$$

So let us take this 1jj1 as our example and then continue to proceed further, so here if you look at this delay line interfere meter clearly there is similarly only one arm so let us say that is E1 arm, there is no signal in the E2 arm, so E2 will be equal to 0, so what would be the split values here, so if I call this as E3 and E4 what would be E3 and E4, E3 will be $\sqrt{Ps/2}$ it would actually be $1/\sqrt{2}$ but I have taken that 2 inside the root, so it would be $\sqrt{Ps/2}$ $e^{j\omega st+\theta s(t)}$ whereas E4 which is coming because of E1 will be given by $\sqrt{Ps/2}$ there is a j here , $e^{j\omega st+\theta s(t)}$ which can be written as

$\sqrt{Ps/2}\ e^{j\omega st+\theta s(t)}+\pi/2$ so transposing or transferring this j multiple into exponential allows me to rewrite them in this fashion.

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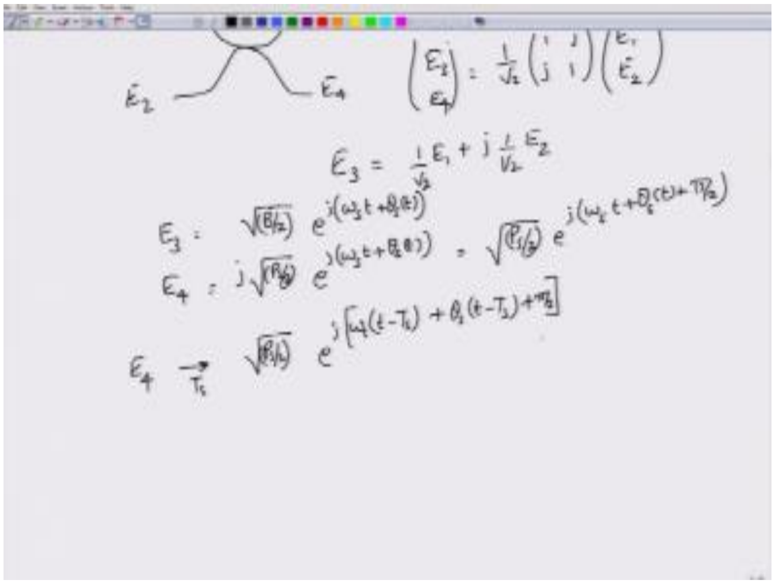

$$\begin{pmatrix} E_3 \\ E_4 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}$$

$$E_3 = \frac{1}{\sqrt{2}} E_1 + j \frac{1}{\sqrt{2}} E_2$$

$$E_3 = \sqrt{(P_s/2)}\ e^{j(\omega_s t + \theta_s(t))}$$

$$E_4 = j\sqrt{(P_s/2)}\ e^{j(\omega_s t + \theta_s(t))} = \sqrt{(P_s/2)}\ e^{j(\omega_s t + \theta_s(t) + \pi/2)}$$

$$E_4 \xrightarrow[T_s]{} \sqrt{(P_s/2)}\ e^{j[\omega_s(t-T_s) + \theta_s(t-T_s) + \pi/2]}$$

So you can see that these two signals are 90° out of phase, okay. Now you delay E4/1 time period so if you delay this one by one time period, what you get is $\sqrt{Ps/2}$ there is no change in the amplitude or we are going to assume that the amplitude is not changing so much, there is a change here in place of t you write (t-Ts)+θs(t-Ts)+ there is a π/2 factor, right. So this ωs(t-Ts) and if you expand it out you are going to get ωst and ωsTs, right that particular term ωs.Ts as long as you know what is ωs and you know what is Ts it is simply a constant.

Eventually that will go away, but at this point let us not make it 0 so this is e4 that you are getting at this point.

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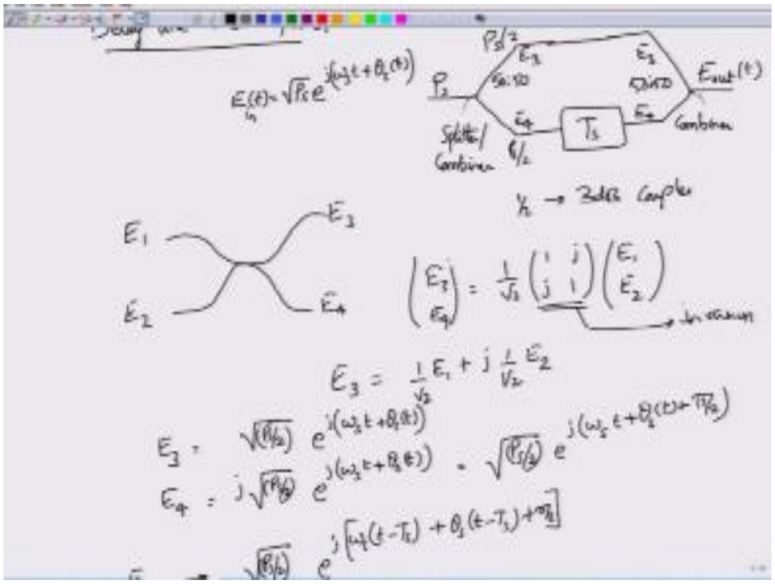

$$\begin{pmatrix} E_3 \\ E_4 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}$$

$$E_3 = \frac{1}{\sqrt{2}} E_1 + j \frac{1}{\sqrt{2}} E_2$$

$$E_3 = \sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t))}$$

$$E_4 = j\sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t))} = \sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t) + \pi/2)}$$

$$\sqrt{(P_s/2)}\, e^{j[\omega_s(t - T_1) + \theta_s(t - T_1) + \pi/2]}$$

So this is e4 after delaying buy 1 unit e3 has not suffered any delay so e3 comes in directly was it is now you have to combine to combine them you simply have to invert this particular matrix right so this matrix represents the splitter matrix with e1 and e2 as inputs e3 and e4 as outputs now with e3 and e4 as inputs what would be e1 so you have to invert this matrix I leave this inversion as an exercise to you.

What I will assume here is that e3 will join e out as it is whereas e4 will undergo another 90^0 phase difference okay. You can verify that. I am not going to do that one I leave that as an exercise.

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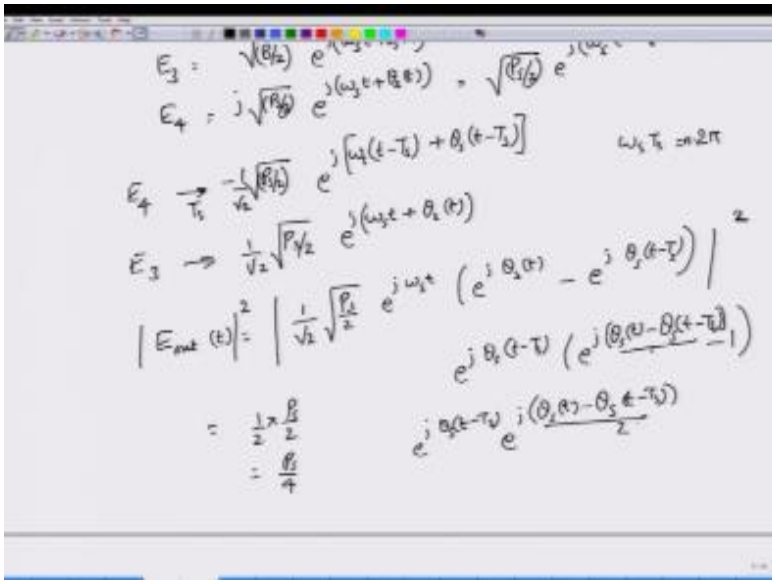

$E_3 = \sqrt{(P_s/2)}\; e$

$E_4 = j\sqrt{(P_s/2)}\; e^{j(\omega_s t + \theta_s(t))} = \sqrt{(P_s/2)}\; e$

$e^{j[\omega_s(t-T_s) + \theta_s(t-T_s)]}$ $\quad \omega_s T_s = n2\pi$

$E_4 \xrightarrow[T_s]{} -\frac{1}{\sqrt{2}}\sqrt{(P_s/2)}\; e$

$E_3 \rightarrow \frac{1}{\sqrt{2}}\sqrt{P_s/2}\; e^{j(\omega_s t + \theta_s(t))}$

$|E_{out}(t)|^2 = \left| \frac{1}{\sqrt{2}}\sqrt{\frac{P_s}{2}}\; e^{j\omega_s t}\left(e^{j\theta_s(t)} - e^{j\theta_s(t-T_s)}\right)\right|^2$

$e^{j\theta_s(t-T_s)}\left(e^{j\underline{(\theta_s(t)-\theta_s(t-T_s))}} - 1\right)$

$= \frac{1}{2} \times \frac{P_s}{2}$ $\quad e^{j\theta_s(t-T_s)}\, e^{j\frac{(\theta_s(t)-\theta_s(t-T_s))}{2}}$

$= \frac{P_s}{4}$

So if you multiply e4 by another factor of j and then divided by √2 so multiplying by j is equivalent of increasing the phase by π/2 so in place of π/2 I can remove this π/2 and write is has π okay so please note that this would be actually been different so I can write this as π but $e^{j\pi}$ is nothing but – right -1 so I can remove that also, and then write down this as – and then because there is 1/√2 down there right.

I am adding them by 1/√2 the √1/√2 as well what would be for e3, e3 would be 1/√2 ps/2 under √ e^{j} **Ω** st + θs(t) correct now when you take these two signals and sum this, this would be the output signal that you are going to get so e out of t is given by 1/√2ps /2 under √ ej **Ω** st is constant so I can pull that one out and what I get is $e^{j\theta}$s(t) - $e^{j\theta}$ s(t) – t which is the phase difference 1 unit earlier t-t as I symbol period earlier this constant value **Ω**s x ts I can chose this.

Right I can c hose this to be some multiple of 2π some integer multiple of 2π so I can remove that from the concentration so this would be the electric field that I am going to get now what I do is I take this output electric field and then put a photo detector here, so that what I get is magnitude square and a average of this okay leaving the average part for you guys to work out what I get here is ½ x ps /2 which is basically ps /4 and then this e^{j} **Ω** st magnitude square will go away.

So what you have to do is first write down $e^{j\theta}$s(t) and then take this θ s(t) – ts as a common factor and pull it out okay so if I pull that one out so what I get is $e^{j\theta}$s(t) – ts this is the phase one previous instant so I am taking that out so if iu take that out I get $e^{j\theta}$s(t)- θ s(t) – ts – 1 correct, now what I do is I take this fellow half of this out so I get $e^{j\theta}$s(t) – ts and $e^{j\theta}$s(t) - θs(t) – ts /2 out so if I take this half out.

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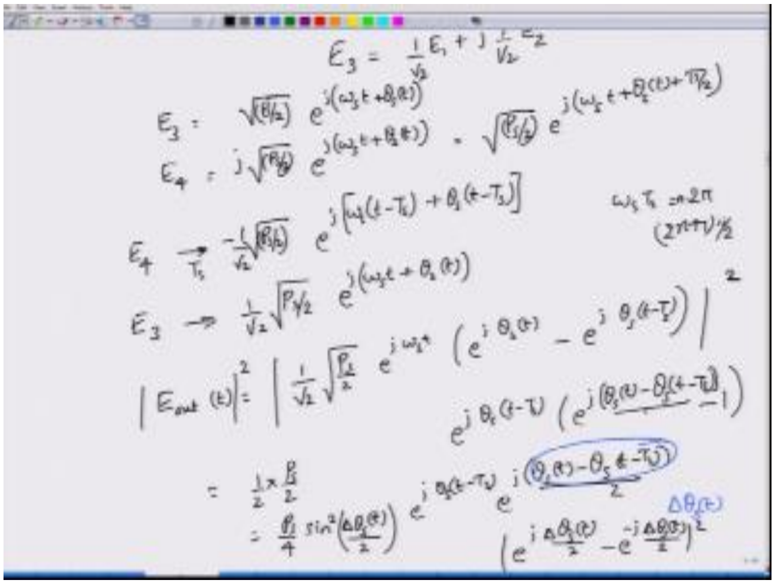

$E_3 = \frac{1}{\sqrt{2}}E_1 + j\frac{1}{\sqrt{2}}E_2$

$E_3 = \sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t))}$

$E_4 = j\sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t))} = \sqrt{(P_s/2)}\, e^{j(\omega_s t + \theta_s(t) + \pi/2)}$

$E_4 \xrightarrow[T_s]{} -\frac{1}{\sqrt{2}}\sqrt{(P_s/2)}\, e^{j[\omega_s(t-T_s) + \theta_s(t-T_s)]}$

$\omega_s T_s = n2\pi$

$(2n+1)\pi/2$

$E_3 \to \frac{1}{\sqrt{2}}\sqrt{P_s/2}\, e^{j(\omega_s t + \theta_s(t))}$

$|E_{out}(t)|^2 = \left|\frac{1}{\sqrt{2}}\sqrt{\frac{P_s}{2}}\, e^{j\omega_s t}\left(e^{j\theta_s(t)} - e^{j\theta_s(t-T_s)}\right)\right|^2$

$e^{j\theta_s(t-T_s)}\left(e^{j(\theta_s(t)-\theta_s(t-T_s))} - 1\right)$

$= \frac{1}{2}\times\frac{P_s}{2}\, e^{j\theta_s(t-T_s)}\, e^{j\frac{(\theta_s(t)-\theta_s(t-T_s))}{2}}$

$\Delta\theta_s(t)$

$\left(e^{j\frac{\Delta\theta_s(t)}{2}} - e^{-j\frac{\Delta\theta_s(t)}{2}}\right)^2$

$= \frac{P_s}{4}\sin^2\left(\frac{\Delta\theta_s(t)}{2}\right)$

This first term will have a half with the phase different the second term will have e-j phase difference by 2 so if I call this θ s(t) – θ s(t) – ts as δθ s(t) which is the phase difference evaluated now okay so if I look at this phase difference what I get here is ej δθ s(t) /2 –e^{-j} δθ s(t)/2 right and then take the magnitude square so I know that this is e^{jx}-e-j x type of a situation right taking this nothing but two sin x so then squaring up will be give me $\sin^2$ x.

So I get ps / 4 $\sin^2$ of δθ s(t) /2 when the phase difference is equal to 0 I get 0 when the phase difference is equal to π I get π/2 $\sin^2$of π/2 which is maximum and I get a power of ps / 4 if you are not happy with sin2 do not worry instead of taking this Ωs x ts as n x 2π you can simply take this as some 2n + 1 x π/2.

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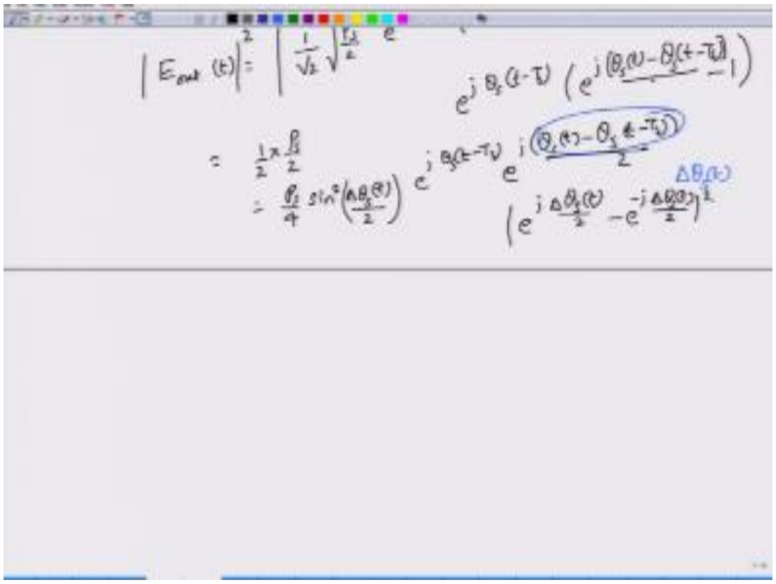

$$|E_{out}(t)|^2 = \left|\frac{1}{\sqrt{2}}\sqrt{\frac{P_s}{2}}\; e \quad e^{j\theta_s(t-\tau)}\left(e^{j(\theta_s(t)-\theta_s(t-\tau))}-1\right)\right|$$

$$= \frac{1}{2}\times\frac{P_s}{2}\; e^{j\theta_s(t-\tau)}\; e^{j\frac{\boxed{(\theta_s(t)-\theta_s(t-\tau))}}{2}}$$

$\Delta\theta_s(t)$

$$\left(e^{j\frac{\Delta\theta_s(t)}{2}} - e^{-j\frac{\Delta\theta_s(t)}{2}}\right)^2$$

$$= \frac{P_s}{4}\sin^2\left(\frac{\Delta\theta_s(t)}{2}\right)$$

So that will add in place of sin it will convert that sin x cos okay, so you get ps/4 cos 2 of δθ s(t) /2 so you can simply adjust the operating point of this interferometer in order to reflect whether the phase difference of 0 should give you.

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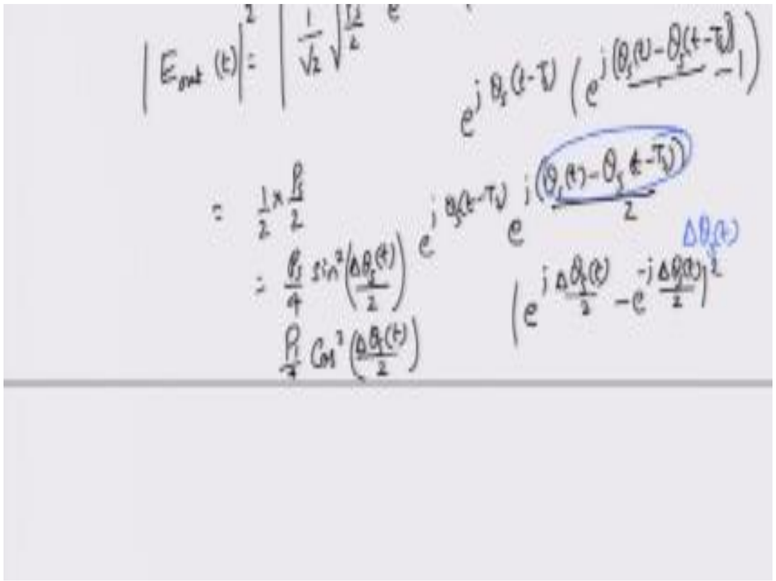

Maximum, or whether the phase difference of 0m should give you minimum. So this is the preferred one and so I can go to the preferred this one and this could b the photo current I am going to obtain, what you have to observe is the this photo currants is the function of $\cos^2$, $\cos^2$ or $\sin^2$, doesn't really matter in fact, one half will give the $\cos^2$ and the other half will give the $\sin^2$ t the output.

Bt what is important is, this function of the phase difference between present and the previous slot, so if the present start is 0, the previous slot is л, you get the phase difference of – л and then $\cos^{2(-}$л/2) but $\cos^{2(-}$л/2) is nothing but 0. So this way you can actually extract, if the output is 0 you know that the present and previous symbols are not having the same phase, they are having different phase. So you can use this to decode DBPSK.

If the phase differences can go to л/2 then there will be change in the amplitude level, so if the phase differences can be 0, л/2 or л or 3 л/2, then the amplitude corresponding amplitude would be maximum, so you get a maximum, you get a maximum for л and 0 and you get for л/2 you get $\cos^{2\,(}$л/4) which is half. So your signal level goes to minima half and the max. So looking at these inputs you will be able to tell us whether the phase difference between this slot and the previous slot was equal to л or it was equal to л/2 or 3л/2, both are the same and it was equal to 0.

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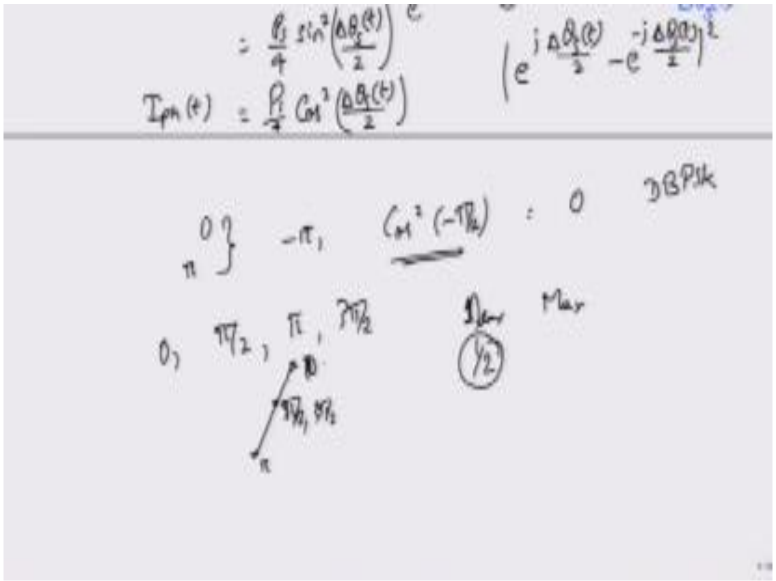

So by looking at the output, whether it is minima half way mark or the maxima, you will be able to tell us what is the phase difference, and then the Δϕs (t) and you can use this to demodulate, differentially encoded QPSK signal or the DQPSK signal. We will stop at this point, where is one final detector we need to talk about, which is called as coherent detection. The importance of coherent detection has grown so much over the recent years that the present generation and the next generation optical networks are using coherent detection.

The primary difference between the coherent detection and the other detection, the first one was direct detection which did not use any information about the phase, thee second on was differential detection was based on the idea that you have a phase difference but this phase difference is not coming in from the actual carrier, but it is coming from the present symbol or rather the previous symbol. So you’re looking at the difference in the phases band then converting the difference in phase to intensity.

So the phase difference was previous symbol that is θs (t)-ts, this coherent detection is completely different. This detection mechanism actually extracts, actually starts with the local oscillator, whose frequency is related to the signal frequency and whose face is locked to the carrier frequency. Remember carrier can be about 1000 kilometers away and then you somehow have to have a local oscillator, whose phase is in some definite phase relationship, which have to track the carrier phase be in a certain phase relationship.

The problem is not as trivial as I am telling you, it is very, very complex problem and previously the coherent detection mechanism did not have a good interest because this face lock loops, which are used to track the carrier phase, very difficult to implement with optical means. Today you do the implementation in the digital signal processing domain, therefore this coherent detection combined with DSP has taken over the transmission technique in the optical communication system.

So all present and the next generation optical communication systems are using or will use coherent detection and corresponding digital signal processing. So we will start with coherent detection in the next module and then we will come back and jump back to transmitter physics. Thank you.

<u>Acknowledgement</u>
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Sharwan
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Lalty Dutta
Ajay Kanaujia
Shivendra Kumar Tiwari

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