Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

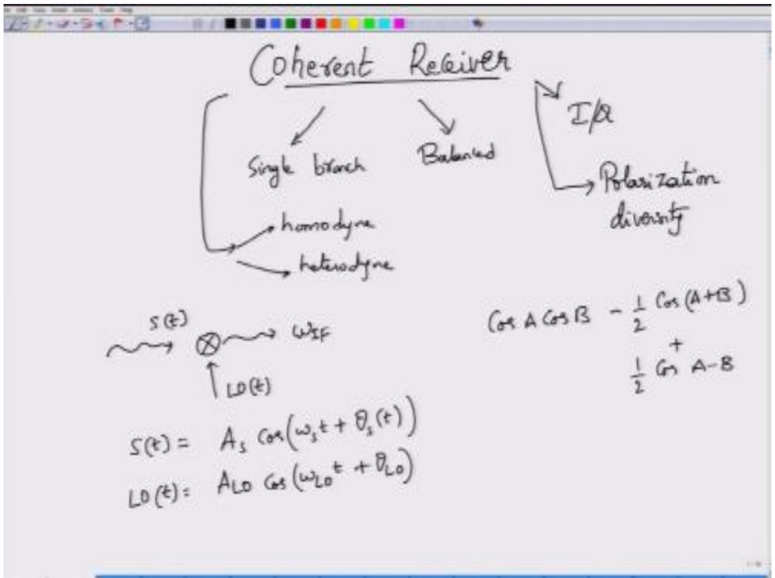
Week – III
Module – V
Optical receivers-II

by
Prof. Pradeep Kumar K
Dept. of Electrical Engineering
IIT Kanpur

In this module we will discuss various types of coherent receivers that are used in optical communications in the previous module we have discussed direction reduction receiver as well as the homo self delayed delaine interferometer detectors those detectors did not actually utilize a local phase reference this local phase reference is given for coherent receivers by a form of a local oscillator so just as you have a transmit or a signal laser diode you will have to have a laser diode at the receiver as well.

In order to generate the optical signal which will be used as the reference signal to compare against the incoming signal if you recall what is the basic coherent receiver system you know you must have studied a super heterodyne receiver or a heterodyne receiver the incoming signal call this as some.

(Refer Slide Time: 01:08)

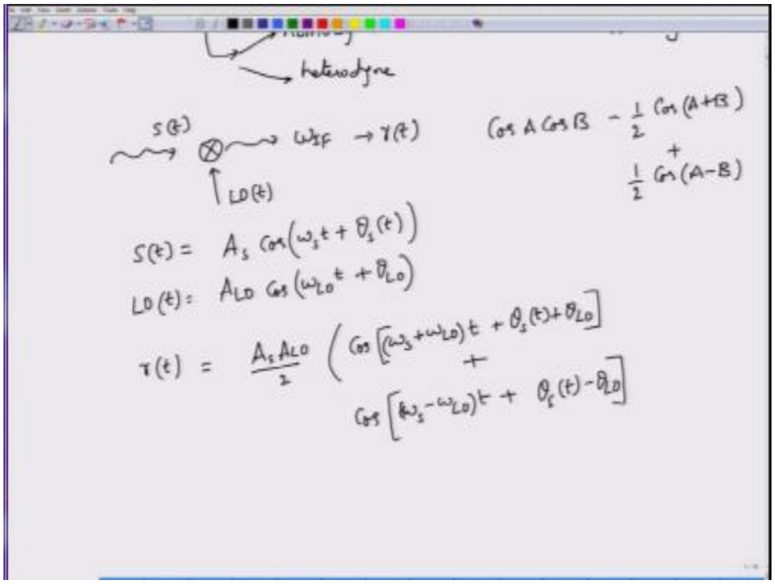


S(t) will be multiplied by a local oscillator call this as some Lo(t) okay and then the resulting signal is proceeded further if the incoming signals frequency is different from the local oscillator frequency then you end up with what is called as a intermediate frequency your spectrum will be centered at the intermediate frequency otherwise the spectrum will be centered at 0 intermediate frequency o intermediate frequency is nothing dc right.

So the principle of operation of this one would that if I assume for example s(t) to be sinusoidal signal so let us say which is phase modulated so I have As cos $\omega_s t$ which is where ω_s is the incoming signal frequency the sinusoidal signal frequency it is phase has been modulated so it is phase is $\theta s(t)$ and if I assume that the local oscillator signal has an amplitude of ALo okay and it also has a certain local oscillator frequency ωLo+ some usually constant phase of set which is θ Lo.

So if we assume that these are the two then you can multiply them and then utilize the formula for cos A cos B no which will be something ½(cos A+ B) + ½ (cos A- B) so if we use these formula because these two are cosine signals I can multiply them I won’t show the details but this is a very simple fact that you can.

(Refer Slide Time: 02:52)



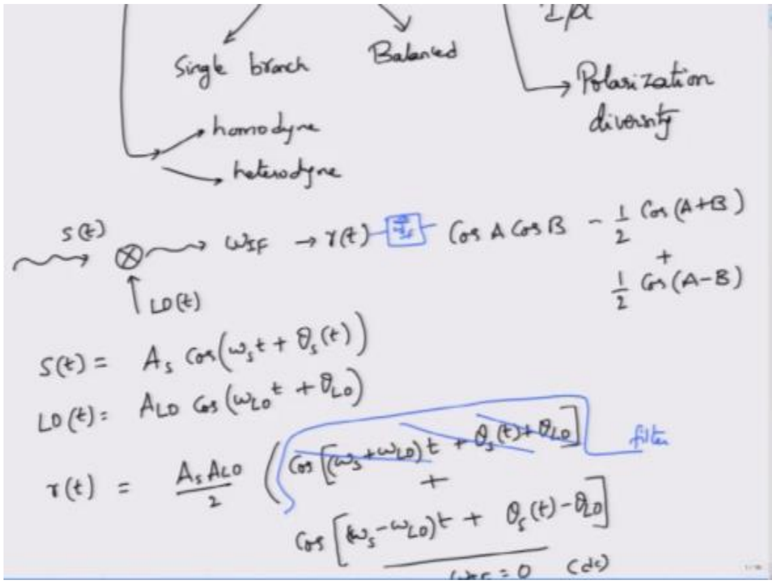
Find from applying the trigonometric formula what you end up so if call this signal as say r(t) what you end up after the mixer this is mixer or a multiplier is this signals so you have As ALo/2 which is the conman factor that I can take it out and then you have 2 components ω_s +$\omega_{Lo\,t}$ +θ_s(t) + θ Lo okay so this particular cosine signal that you have here a phase modulated cosine signal is centered at a frequency $\omega_s + \omega_{Lo}$ which both of them are typically close to each other and they are very large so ω_s could be for example 2.4 gigahertz and ω_{Lo} will be very close to that.

It would be anywhere between say 19900 megahertz to 2800 megahertz okay this is just an example frequency that I am considering in optical signals these frequency are much different but if you take ω_s and ω_{Lo} both to be large as well as ω_{Lo} is approximately ω_s this signal no the one that we have written here cos of $\omega_s + \omega_{Lot}$ will be oscillating with a very large frequency it is actually centered at a very high frequency.

Much higher compared to the intermediate frequency where as the intermediate frequency coming in well this is the cos A+ B term so what we have is the plus term here you will also have cos A- B term correct so for the cos A-B term what do you get cos($\omega_s - \omega_{Lo}$)t+ θ_s(t)- θ_{Lo} as

I said θ_{Lo} is just a constant or more or less a constant for many application so you can safely ignore that.

(Refer Slide Time: 04:49)



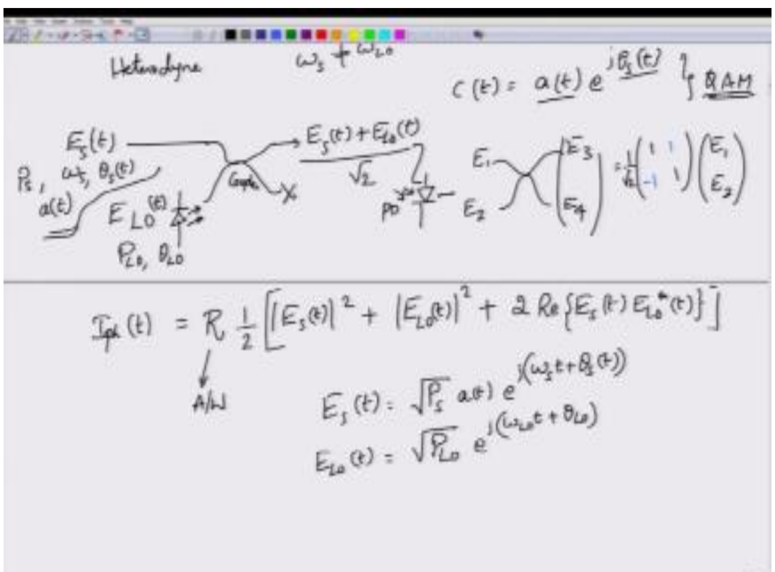
But what is interesting is that you get one spectrum which is centered at a difference frequency which is $\omega_s - \omega_{Lo}$ we say that this is homodyne or 0IF in when $\omega s = \omega_{LO}$ so if you where to tune the local oscillator frequency to be equal to the incoming signal frequency this $\omega\ s = \omega_{LO(t)} = 0$ right so that the spectrum will be centered at $\omega_{IF} = 0$ in other words this would be centered at DC for homodyne or 0_{IF} a transceivers, on the other hand if $\omega_{\ LO}$ is not equal to ω_S then we call this as heterodyne receiver.

So in this particular case ω_s is not equal to ω_{Lo} and the intermediate frequency is centered not at 0 but at some other frequency, okay. Now, one can eliminate this $\omega s + \omega_{Lo}$ terminate I can eliminate this term by filtering it out so if I putting a filter which will only pass the signal which is centered at ω_{IF} and rejects this other signal $\omega s + \omega_{LO}$ signal then this term can be eliminated, okay.

So I have a filer essentially a filter centered at ω_{IF} so that only the signal around that will be transmitted and this high frequency signal which is oscillating at $\omega s + \omega_{LO}$ can be eliminated so a coherent receiver or sometimes called as a synchronous receiver is basically consists of a multiplier in order to generate a signal at ω_{IF} followed by a filter, okay. This filter will be centered at ω_{IF} it is essentially a band pass filter.

If ω_F is not 0 or it could be a low pass filter if $\omega_F = 0$ now this is a general receiver that you have you are probably familiar with, now how do we implement this optically? Do I have an optical multiplier, tells what that I do not have an optical multiplier, so what do I do? Well look at this scheme, okay.

(Refer Slide Time: 07:08)



You have an incoming signal because this is optical we will switch to the electric field notation for this, so I have $E_s(t)$ which is the incoming signal which is modulated at the transmitter if I put in a coupler a device which we discussed in the previous module if I put in a coupler and to this coupler I send in one more signal which is the local oscillator, okay. So I can write down the local oscillator as $E_{LO}(T)$ it is also a local oscillator this signal will be characterized by its frequency ω_S and its phase θ s(t), okay.

It will also be characterized by its power which is Ps finally it will be characterized also by its amplitude changes a(t) obviously this c(t) the complex envelope of the modulation is given by a(t) x $e^{j}\theta s(t)$ correct, so this a(t) is the amplitude modulation part and θ s(t) is the phase modulation part for a BPSK signal a(t) is constant = 1 for example whereas θ s(t) is 0 and Π for a QPSK signal a(t) is different.

Or you can think of a(t) as constant but θ s(t) being Π/4, 3 Π/4, 7 Π/4 and 5 Π/4 for a general Quam signal both a(t) as well as θ s(t) will change, okay. So giving rise to a general Quam signal and the objective of the receiver the optical receiver would be to extract both a(t) as well as θ s(t), so this incoming signal is characterized by all these parameters the local oscillator is characterized by its local oscillator power.

Its frequency oscillator θ_{LO} this θ_{LO} is also varying but since this is an oscillator which is under our control we can keep this oscillations to minimum in other words we can spend a lot of money to purchase good quality, local oscillator this cost is not an issue for us and for a long call communication systems it is especially important to have pure local oscillators whose phase noise is very small.

Now this device is the coupler we have already seen how to relate this outputs of the coupler we had written down a general coupler configuration with E1, E2, E3 and E4 and we set that E3 and E4 are characterized by certain matrix for a 50, 50 coupler this is 1/ √2, 1j j1 times the incoming signal right or the input signals E1 and E2 right so this could give me the output relation to the input relation.

It is also possible to actually fabricate a, coupler whose relationship is slightly different this becomes 1 and this becomes -1 that is to say I can fabricate a coupler by adjusting the phase or the length of the coupling elements something that we will study later which will then give me a character which will then give me a coupling matrix which is 1 1 – 1 and 1 this 1/√2 to indicates the amplitudes are getting split into 1/√2 so that the powers are getting split into half okay so applying this coupler matrix to the equation and then for the moment neglecting this part.

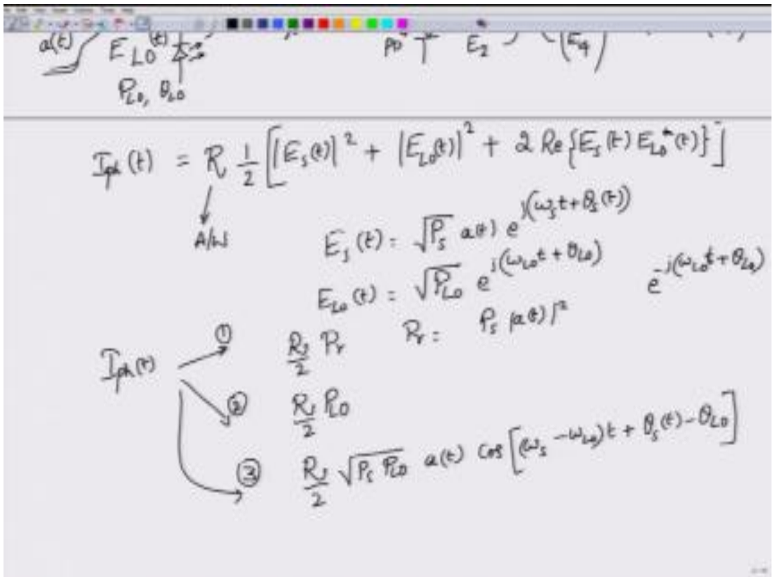
What do I get at this output port6 what do I get at this output port I get Es of t + E_{LO} of t divided by √2 this is the electric field are the light be that I am going to get at the output of the coupler please remember this Es of t is the incoming light which is modulated coming from the fiber and then it has been amplified filtered and all that now that is being mixed or coupled with the local oscillator like B this is also light this device basically mixes to optical fields are optical signals to generate Es of t + E_{LO}/ of t/√2 okay next what we do is we put in a photo detector we put in a photo detector.

And then look what happens at the output of the photo detector if I call the output of the photo detector as the photo current I_{ph} of t_{ph} stand for the photo current in our notation so Iph of t is given by 1 ½ because the photo current is proportional to the intensity of the incoming signal right so intensity is electric field square mod electric field square and there is also a proportional constant which is called as responsively if the photo diode this responsively is usually given by or given in terms of ampere per watt.

Okay so if I putting one watt of optical power I get 1 ampere of photo current okay so this value is given typically in ampere per watt so if I now do Es of t + E_{lo} of t mod square what I get is Es of t2 + this R x 1/ ½ is a constant I am going to remove that one outside I get E_{lo} of t magnitude square + two times real part of Es of t E_{lo} complex conjugate of t if you are surprise by this please remember that we have been following the facer notation for the optical fields right our incoming signal Es of t is actually given as a of t $e^{j\omega st}$ + θs of t there is also square of PS this is the incoming signal.

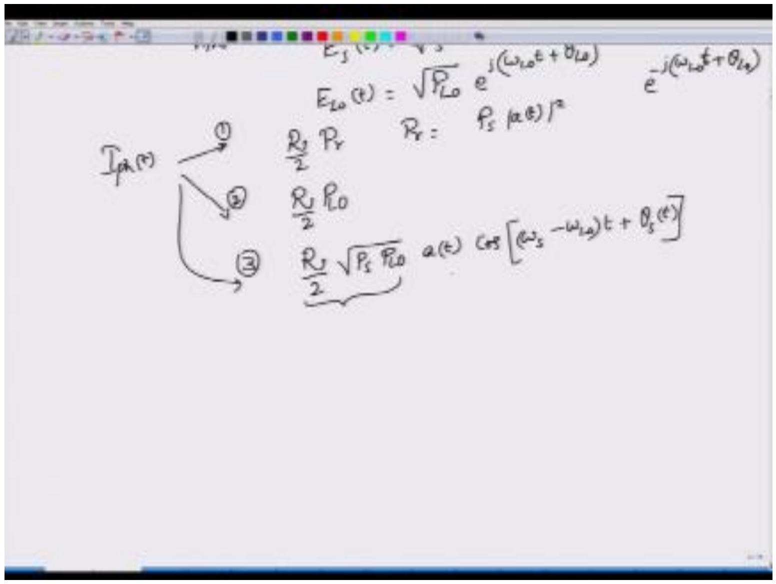
The local oscillator signal will also be given in the phase notation as square of PLO e it is not modulated so it is simply $e^{j\omega LO}$ of t + θ_{LO} okay so if you substitute these two expressions and then simplify the photo current.

(Refer Slide Time: 13:13)



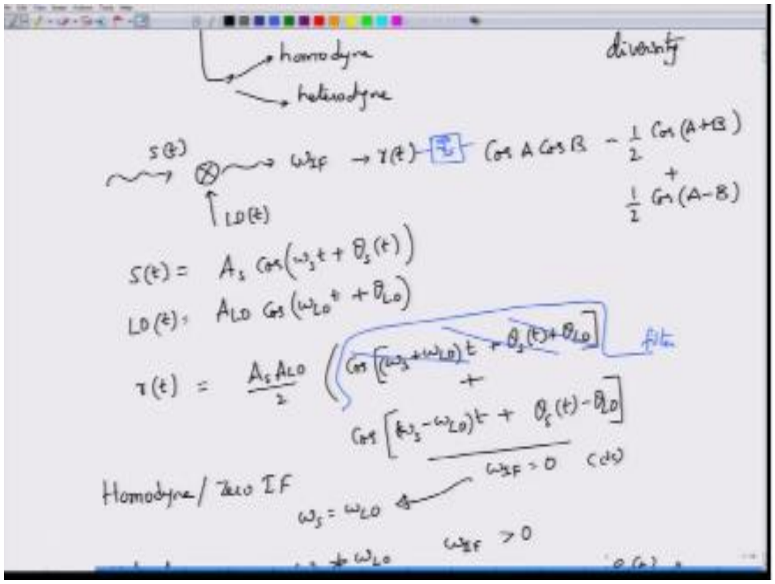
Will consist of three terms the first term is R/2 Pr okay where Pr = Ps s of t magnitude square okay Ps is incoming signal amplitude so Ps a of t magnitude square this $ej^{\omega st\ +}$ θ s of t will go away because of the modulus operation the second term is R/2 PLO, PLO is the local oscillator power okay and finally the third term which your interested will be R/2 square of Ps PLO there is a of t I was assumed a of t to be real therefore I have pulled out a of t outside and then I get real part of this so if you take the complex conjugate of the local oscillator field you will get e – $^{j\omega LO}$ of t LOT + θ_{LO} so if you putting that into this expression what is the Cos of ωs – ωLOT + θs of t – θLO as I said θ LO is just a constant for you.

(Refer Slide Time: 14:31)



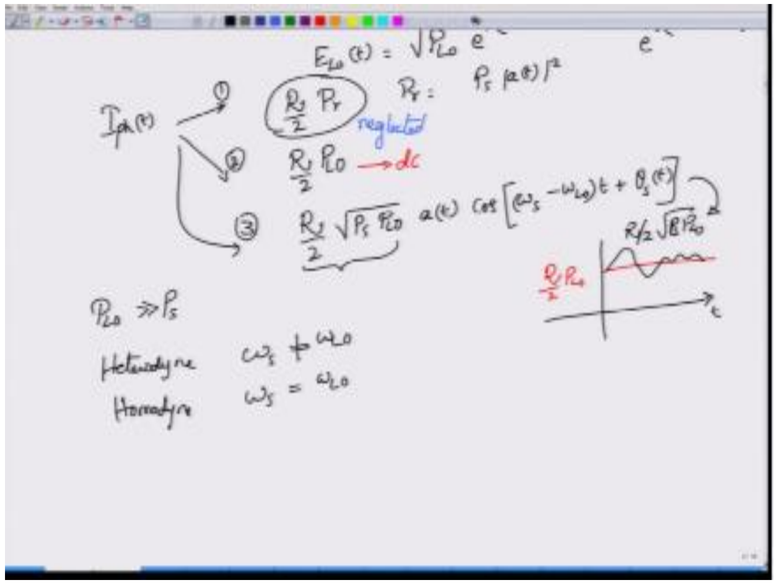
Okay for us in this particular scenario so you can safely eliminate this θ_{LO} well safely is probably a strong word but for now we can eliminate this θ_{LO} okay now do you observe that whatever the third term that you have obtained if you leave out the propornality constants is exactly the same thing as you have obtained from the typically heterodyne receiver that we have considered earlier correct so in the earlier case we.

(Refer Slide Time: 14: 59)



Where we consider the heterodyne receiver you had the output which was $\cos(\omega s\text{-}\omega lot+\theta s(t)\text{-}\theta lo$ where θlo was the phase of the local oscillator which if you remove it will then become exactly equal to the signal that you have obtained in this case, so what you have done is to take two optical signals.

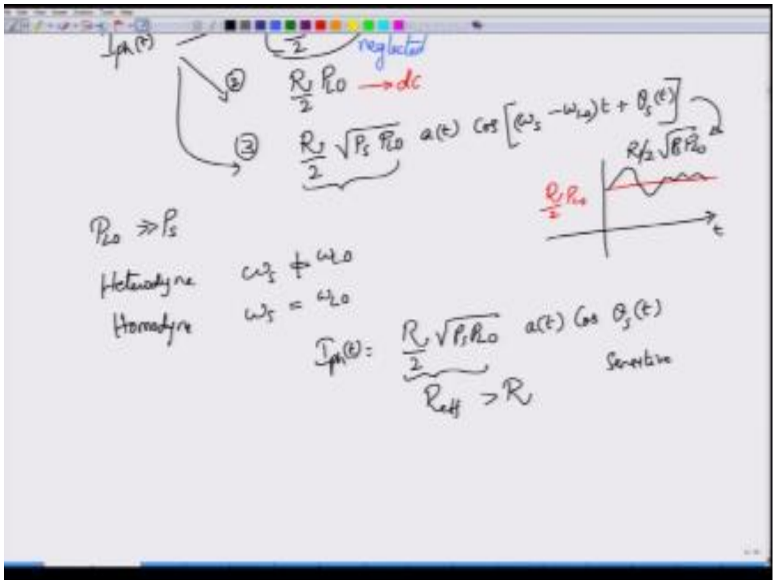
(Refer Slide Time: 15:23)



And then realize the multiplication operation without actually having a multiplier, it do not have a multiplier in the optical domain but you have realized a multiplier in the optical domain by this operation, okay couple of points P_{Lo} is typically much larger than Ps therefore the first term can be neglected in comparison to the second terms, so neglect that in comparison to the second term, the second term is essentially dc, okay because you are not modulating the local oscillator this is a dc signal for us so it is simply means that this time varying information is riding on this dc signal, right.

So you have, if you look at it as a function of time there is a dc signal which corresponds to $R/2P_{Lo}$ and then there is a time varying signal, okay which corresponds to $R/2\sqrt{PsP_{Lo}}$ and whatever that other factor a(t) cos $\omega s-\omega_{Lo}$ something. Again, this would be heterodyne when ωs is not equal to ωLo this is called as homodyne, when ωs=ωLo, okay.

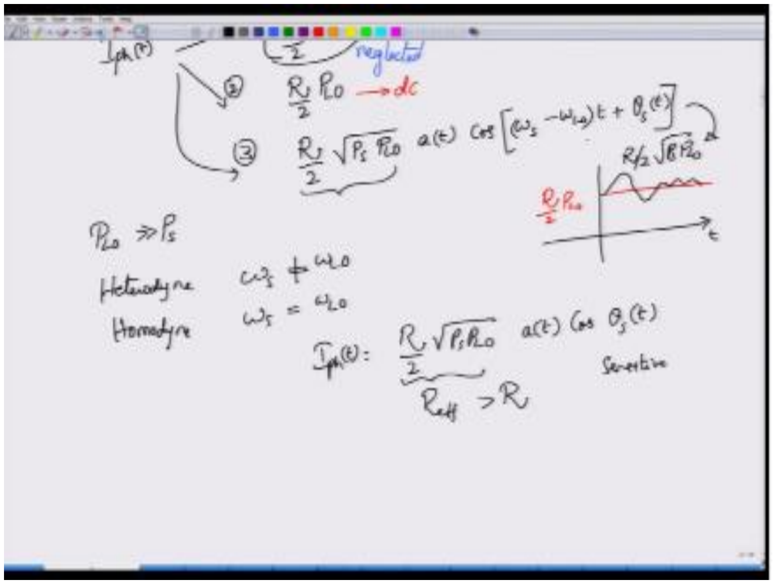
(Refer Slide Time: 16:44)



So when $\omega_s=\omega_{Lo}$ the third term simply becomes $R/2\sqrt{P_sP_{Lo}}\, a(t)\cos\theta_s(t)$ so you are manage the obtain the photo current and if I am neglecting the dc part of course I am neglected the dc pat here the time varying component is given by a new value of effective responsively you know the simple photo detector has a responsively of R, this one has the photo detector responsively an effective photo responsively of $R/2\sqrt{P_sP_{Lo}}$ and Ps, PLo will be very large, typically very large chosen, so that the effective R is much larger than the simple R that you obtain.

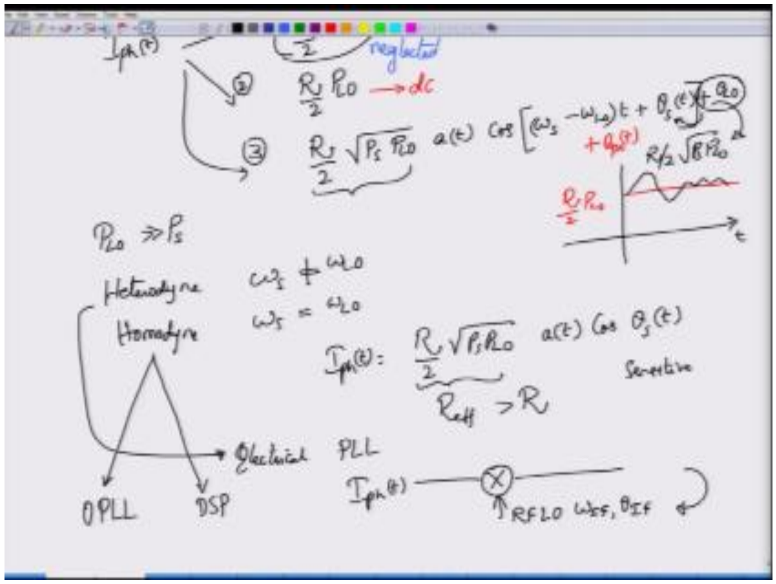
In other words, because R effective is larger than R this is much more sensitive, okay compare to direct detection receiver in fact the sensitivity was the main factor which people were trying to capture by going into the coherent receiver designs in the early 90s. But the problem is that you need to have a good phase relationship, right so we have to establish a definite phase relationship with the incoming signal while the local oscillator is.

(Refer Slide Time: 17:59)



While the incoming signal is cos θs(t), right the local oscillator signal should be tuned exactly to ωs, if I am implementing homodyne more over it must also have a definite phase relationship, while this is cos that incoming signal is also cos, if the incoming signal is cos I cannot have a local oscillator which is sin then they would not mix pretty well. So this was actually realized in two ways.

(Refer Slide Time: 18:23)



If you talk about heterodyne receivers you can then put a electrical PLL, a PLL being a phase lock loop. What do I do, this is the photo current after removing the DC part this is the AC part of the photo current, okay. So this AC part of the photo current if you look it will have this frequency offset ωs-ωLo the difference the frequency offset, which you can somehow estimate and correct and the in addition to $\theta s(t)$ there will also be this $-\theta Lo$, right.

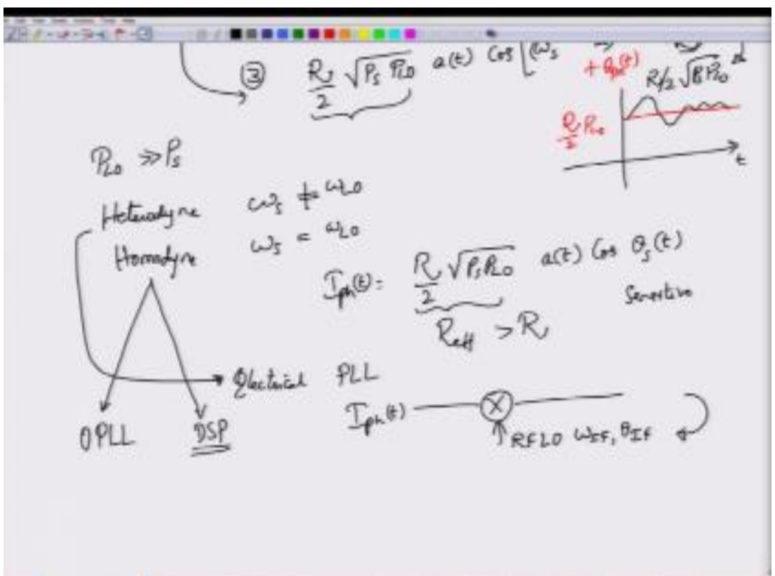
You can control this θLo such that it will track this signal $\theta s(t)$ while $\theta s(t)$ is the moderating signal, in reality there is also another phase component that it is in the incoming signal, this is called as the phase noise of the transmit lasers, okay. In addition to this there would be other types of phase noises not just the laser diode phase noise the fiber also introduce the certain amount of phase noise.

All these things will degrade the performance of the coherent receiver system, unless you are able to track it, to track that you take the signal now this is in the electrical domain what you do is, you simply take this Iph(t), right multiply this one by a microwave or an RF local oscillator whose frequency is ω If and which are the certain phase θIf, okat and then you get the signal you adjust based on the output this local oscillator frequency as well as the phase, okay. So this PLL that you are implementing is in the electrical domain which is much, much simpler than implementing a PLL in the optical domain.

Okay however the problem is heterodyne is not as sensitive as homodyne so you want to be able to use the homodyne coherent receiver but if you want to use homodyne coherent receiver you have to build a optical phase lock low right.

So you want to build an optical phase lock lop or you can explode very nice DSP algorithms in order to extract the phase okay or estimate the phase okay.

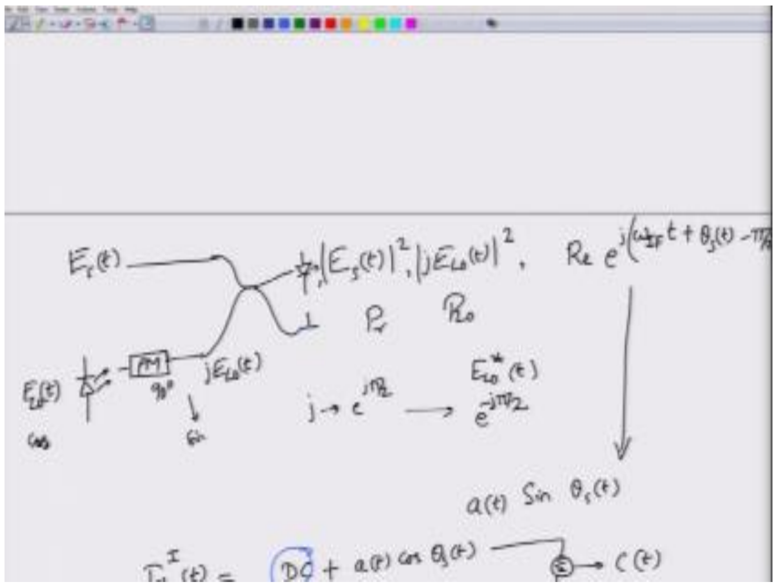
(Refer Slide Time: 20:32)



This is the technology that is currently being used so we use high speed DSP is in order to estimate the phase of the incoming signal in order to perform carrier recovery as well as for incarnating or local oscillator with the incoming signal. Okay something that we will talk about it in the later in the course okay we have talked about the coherent receiver homodyne one thing you might have notice is that this photo current that we have obtain.

So if we look at this photo current this photo current is only extracting a(t) cosign of θ s_t what happen to sin θ s_t well I need to extract that also right. So I can extract that sin θ s(t) by altering this coherent receivers in a slightly different way.

(Refer Slide Time: 21:18)



So I take the incoming signal as it is which is E_s (t) and then put it through the coupler but instead of sending this signal from the local oscillator directly coupling it to the directly to the coupler what I do is I send it through a phase modulator okay I send this through a phase modulator and set the phase modulator such that it provides 90^0 phase which means that instead of E_{lo} (t) going in to the coupler what you get is J_{elo}(t).

So if E_{lo} id cos signal here after phase modulation this becomes sin so now you compare your incoming signal with sin and then you will be able to extract it like if you look at the output again for moment negating this second harm if you look at the output you will finds the signal component so $[es(t)]^2$ after putting a photo detector of course. So if you put a photo detector you get three terms $[es(t)]^2$.

You get E_{lo} (t) rather you get J E_{lo} $(t)^2$ but because phase has no value for the power this is as good as just getting E_{lo} here and as good as getting pr here I am removing this r/2 factors you can fill in this later. And then finally what you get I_{us} real part of e^j Ω I_{ft} + θ s(t) – $\pi/2$ why do I have to put a - $\pi/2$ remember you want to find out E_{lo} complex congregate of t right, so I need to put in E_{lo} complex congregate this j can be written as $e^{j\,\pi/2.}$

So when I take the complex congregate this becomes $e^{-j\,\pi/2}$ so because of this -$\pi/2$goes in to this one and what is cos of something - $\pi/2$ it is sin of that quantity right so this real part becomes sin and assuming Ω if = 0 for the homodyne case I get sin θs(t) a of t is as it is appearing so I have now obtain by using two different couplers and four different or at least in this case I have use two different photo diodes.

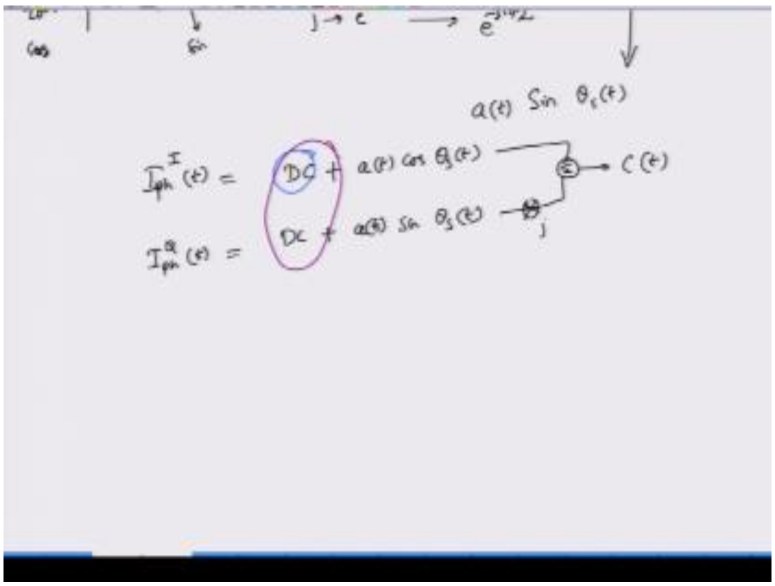
Okay what I have obtain is some DC quantity + a(t) cos θs(t) some Dc + a(t) sin θs(t)okay these are two electrical signals these are the photo currents one is the in phase component the other is the quadrature component okay so I have obtained in phase as well as quadrature component by using some electrical means I can add them after multiplying the quadrature component by j okay.

And then adding them in order to obtain both in phase as well as quadrature component so I will actually be able to extract this c (t) which is the complex envelop that we had used the modulation signal complex amplitude you will be able to extract this c(t) you might be asking one additional question well how note this DC term is there anything that I can do to eliminate DC term yes there is in fact if you look at this term which we have neglected here right.

This other port which we have neglected this one which we have neglected here rather than neglecting it let us put it to some use see what you get at the output oaky so you get at the output after photo detector will be J_{elo} $(t)^2$ and instead of having real part of something over here the plus sign, we get a minus sign, why do I get a minus sign, go back to the metrics of the coupler, this term is Es+Elo whereas this term is Es-Elo. So I get minus, I will just write down only that part, so I get minus real part of e^j something something very similar. Now what I do is I subtract them by putting up a electrical subtractor.

These are two photo currents, I can put may be op amp and subtractor, physically I subtract them; so that this Es (t) will go way, Pr goes away as well as this Plo goes away, but this is real part minus of minus real part, so this become double. There is already a half sitting there, that half will cancel, essentially the point here is we have eliminated DC signals. So I don't have to retain the DC signal for my in phase and quadrature components.

(Refer Slide Time: 26:05)

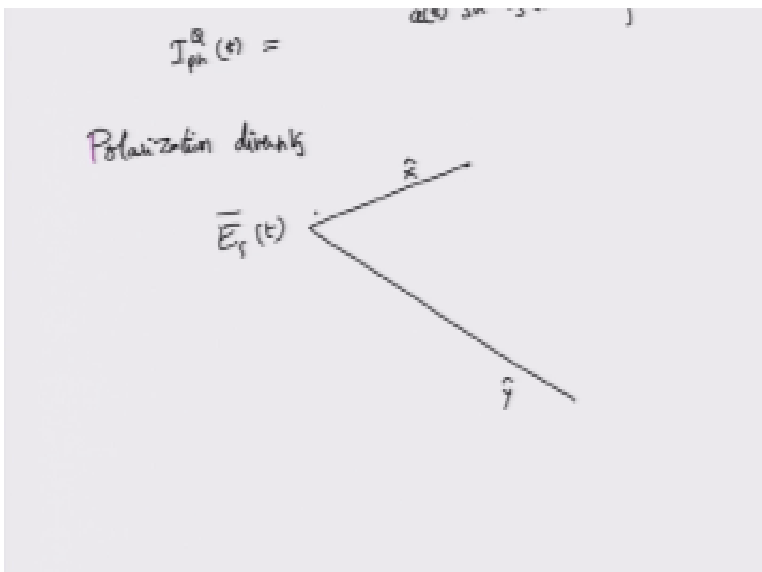


So I don't have to retain the Dc signals for my in phase and quadrature components, so I will directly able to obtain the in phase as well as quadrature components without having to deal with the DC problem. One final point we have obtained in phase as well as quadrature components, this is called as IQ demodulator or IQ receiver, because we're subtracting two photo currents in order to eliminate the DC, this is called the balance photo detection.

Balancing means you remove the DC component from the two signals by physically subtracting the photo currents, so once you do that the resulting signal will have no DC component at all. One final point is that the incoming signals we know that they are going to get polarized, although we behave not talked about polarization, optical signal can be polarized. So it is possible, in fact to have the two orthogonal polarizations, called them as x and y polarizations and the separately modulate the x polarization and modulate the y polarization.

O if I have two polarizations coming in, I don't want to lose the information in both the polarization. I want to extract information about polarization as well, how do I do that? Well there is a simple relative sense, there is a nice receiver called as polarization diversity receiver, this polarization diversity receivers simply take the incoming signal Ef (t), splits into two parts. This would be the x part of the Es(t), and this would be the y part that I to say, we assume that the incoming signal is polarized and I am representing the polarized signal by drawing a bar over the signal.

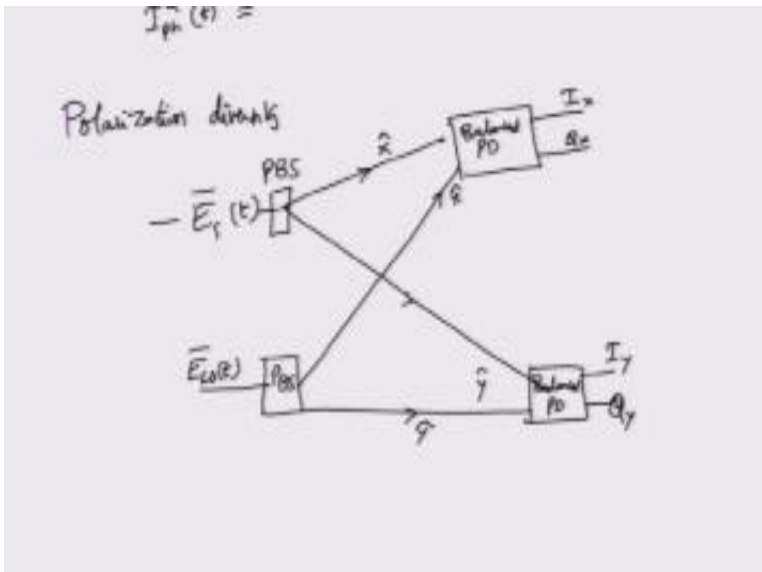
(Refer Slide Time: 27:59)



I can put what is called as a polarization, being splitter to split incoming signal into its orthogonal components, so I can split them into x and y, I can also do the same splitting by at the local, oscillator as well, so we will have El (t) which is also polarized. I can use the polarization in splitter, split the x and y polarizations, so this would be the x polarization, this would be the y polarization. Then I can use now the balance photo detector, in order to extract in phase as well as quadrature components.

Here let us call this as Ix and Qx, similarly I will have balanced photo detector here, to extract Iy, to extract the y components of the photo currents. So I have Iy and Qy, each of this remember needs a local oscillator which will be supplied by this particular components. So take the local oscillators split into two parts and then do a balance photo detector to recover Ix, Qx, Iy and Qy. So let us stop and continue in the next module. Thank you.

(Refer Slide Time: 29:13)



Acknowledgement

Ministry of Human Resource & Development

Prof. Satyaki Roy

Co-ordinator, NPTEL IIT Kanpur

NPTEL Team

Sanjay Pal

Ashish Singh

Badal Pradhan

Tapobrata Das

Ram Chandra

Dilip Tripathi

Manoj Shrivastava

Padam Shukla

Sanjay Mishra

Shubham Rawat

Shikha Gupta

K. K. Mishra

Aradhana Singh

Sweta

Ashutosh Gairola

Dilip Katiyar

Sharwan

Hari Ram

Bhadra Rao

Puneet Kumar Bajpai

Lalty Dutta

Ajay Kanaujia

Shivendra Kumar Tiwari

an IIT Kanpur Production