EF-306 – III test M:M:15

Attempt any three questions. All question carry equal marks.

Q1. Explain with diagram regenerative repeater

Q2. Explain Raman and Brillouin fiber amplifier

Q3. Explain the concept of cost-performance trade off.

Q4. Explain coherent detection method.

Q5. Explain principle of WDM.

1. <u>Regenerative Repeaters</u> — The function of the regenerator circuit is to reconstitute the originally transmitted pulse train, ideally without error. It is basically a receiver transmitter pair, that detects a weak signal, cleans it and sends the regenerated signal through another length of fiber.

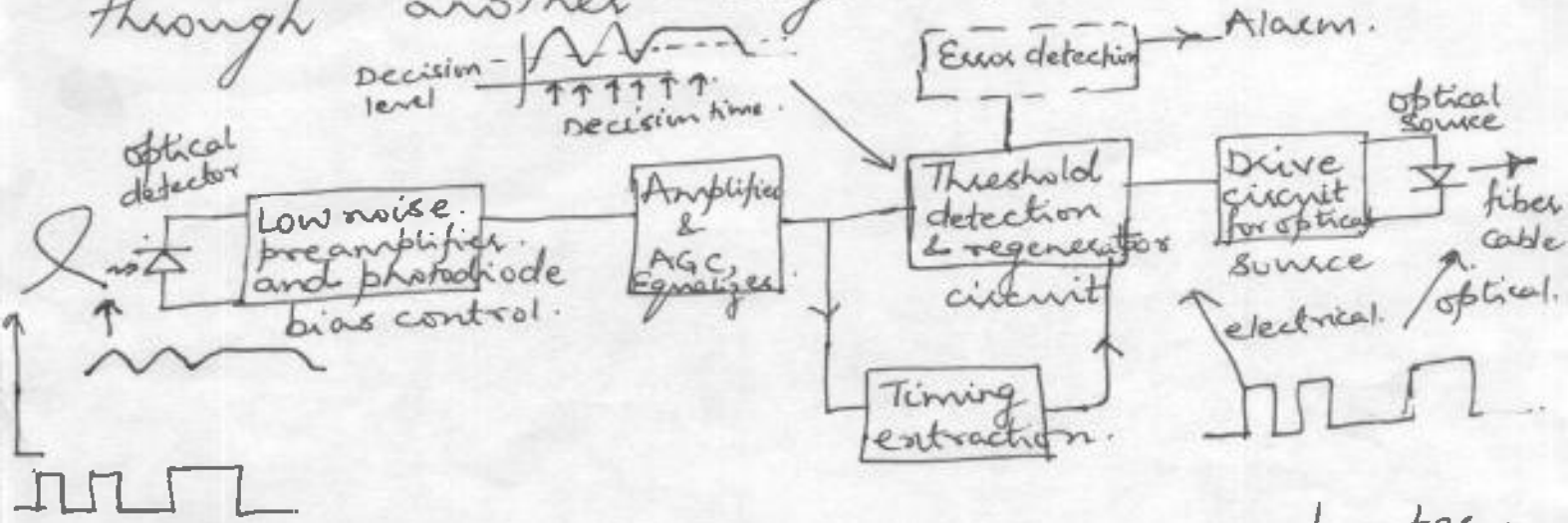


fig (1) Block diagram of regenerative repeater.

<u>optical detector</u> — detects the dispersed and attenuated optical pulse converting them in electrical form.

Low noise preamplifier — an provides initial amplification while keeping noise level low.

Amplifier, AGC & equalizer → The electrical signal is further amplified. AGC & equalizer are incorporated to maintain constant gain and to compensate for the transfer characteristic of fiber respectively.

Timing extraction — A ringing circuit or phase locked loop may be used to extract timing (clock) information. equal to bit interval rate.

Threshold detection & regeneration circuit → The

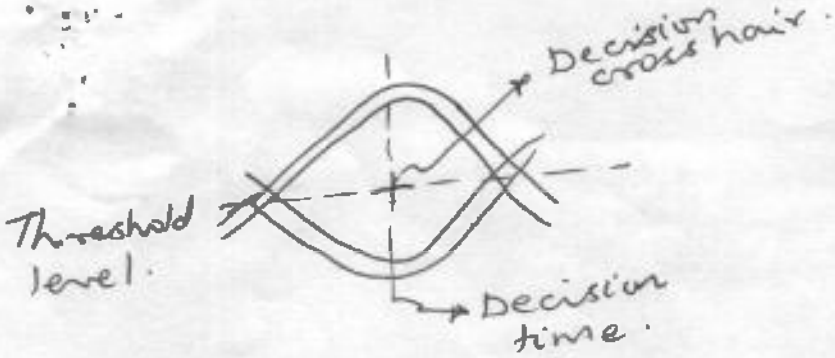
circuit samples the pulse train at a regular frequency equal to the bit rate. At each sample instant a decision is made of the most probable symbol being transmitted. This is achieved by setting a threshold above which a binary one is registered & below which a binary zero is recorded as shown in fig ①.

The regenerator circuit makes these decisions at times corresponding to the centre of bit intervals based on clock information provided by timing circuit. The symbols are thus regenerated in their original form before retransmission as an optical signal using source operated by electronic drive circuit.

In analog system, repeaters, filter, equalizer & amplify the received waveform but are unable to reconstitute the originally transmitted waveform entirely free from noise & distortion. Signal degradation in long-haul analog system is therefore cummulative. In contrast the signal degradation in PCM system is purely a function of quantization process & system bit error rate.

Reason for regeneration process - pg-619 Senior + Error in regeneration process.

A qualitative indication of performance of a regenerative repeater is can be obtained from observing eye pattern as shown in fig(2)



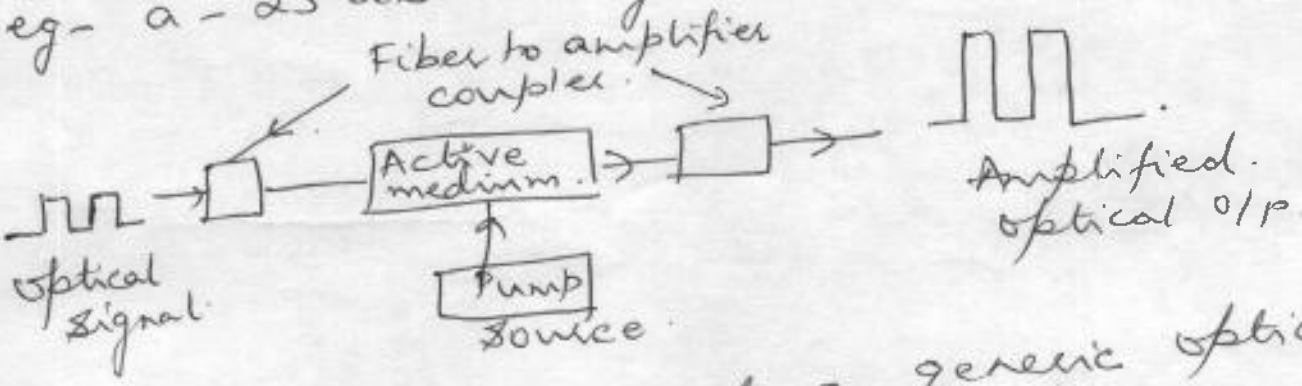
(b) Partially closed eye.

fig (a) open eye.

The open eye indicates reliable & regeneration on while partially closed eye indicates practical degradation due to intersymbol interference & noise.

2. Raman and Brillouin fiber amplifier-

A <u>Raman</u> optical amplifier is based on non-linear effect called stimulated Raman scattering (SRS) which occurs in fiber at high optical power. (eg 500 mW). The device absorbs energy from an external source called pump. The SRS effect due to an interaction between optical energy field and the lattice structure of material results in transfer of optical power from a high power pump wavelength (eg- 500 mW at 1480 nm) to information signal at longer wavelength (eg- a -25 dBm signal around 1550 nm).



Basic operation of a generic optical amplifier.

~~Basically what happens is that~~ If a photon with energy $h\nu_1$ is incident on a molecule having a vibrational frequency ν_m, the molecule ~~can~~ absorbs some energy from the photon. In this interaction, the photon is scattered, thereby attaining a lower frequency ν_2 and a corresponding lower energy $h\nu_2$. The modified photon

is called a Stokes photon. The signal from pump is the source of interacting photons & it supplies power to the ~~signal~~ generated wave. The light is scattered at longer wavelength, & if the signal is present at this longer wavelength, the SRS light will amplify it and the pump-wavelength signal will decrease in power as shown in fig (2).

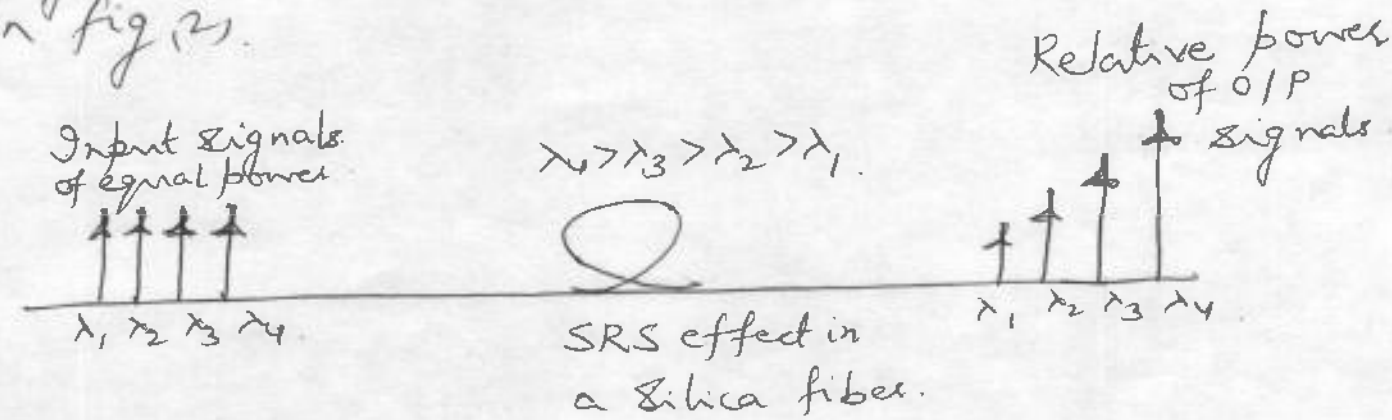


fig2 SRS transfers optical power from shorter wavelength (pump-signal) to longer wavelength (data signal). — The basic principle of Raman & Brillouin fiber amplifier.

The power transfer to higher wavelength occurs over a broad spectral range of 80 to 100 nm. The shift to a particular longer wavelength is referred to as the Stokes shift for that wavelength. Fig (3) shows the Raman gain spectrum for a pump laser operating at 1445 nm & illustrates the SRS induced power transfer to the signal at 1535 nm which is 90 nm away from the pump wavelength. The gain curve is given in terms of the Raman gain coefficient g_R units of 10^{-14} m/W

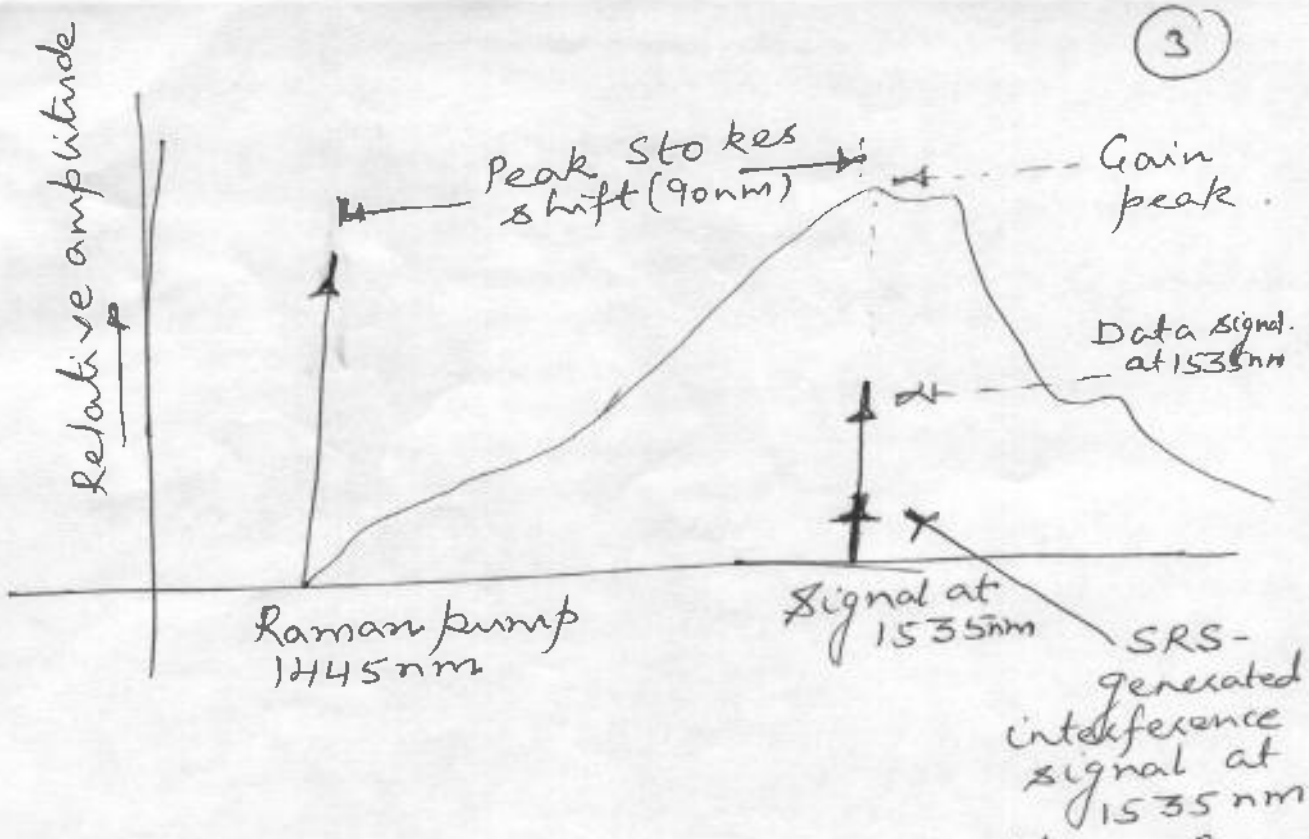


fig3 - Stokes shift & the resulting Raman gain spectrum from a pump laser operating at 1445 nm.

~~As~~ In comparision to EDFA amplifier which requires specially constructed optical fiber for its operation, a Raman amplifier make use of the standard transmission fiber itself as the amplification medium.

The Raman gain G_R is dependent on a number of factors including the fiber length, the fiber attenuation & the fiber core diameter.

$$G_R = \exp\left(\frac{g_R P_P L_{eff}}{A_{eff}\, k}\right)$$

where g_R = The power Raman gain coefficient
P_P = optical pump power
A_{eff} ~~Leff~~ = Effective fiber core area.
~~Aeff~~ L_{eff} = " " length.
k = Numerical factor that accounts for polarization scrambling between optical pump & signal.

By contrast, stimulated Brillouin scattering is a very efficient non-linear amplification mechanism that can provide high gains at modest optical pump power of around 1mW. However, it results from the scattering process in which the pump wavelength is often only around 20 Ghz distance from the frequency of the optical signal to be amplified. Moreover, it is a narrow band process and the gain-bandwidth may only be in the large 15 to 20 Mhz in silica fiber at wavelength of 1.5 μm. The limitation on the spectral bandwidth in a pure silica fiber is around 50 Mhz which fundamentally restricts the use of Brillouin amplifiers to relatively low speed communications

(22)

3. Cost / Performance trade off

Cost is primary consideration in real world system design. It is up to the user to make cost-performance trade off among received power, maximum bit transfer rate, acceptable system fidelity that is BER for digital system or SNR for analog system for specific applications. The designer should anticipate future events ranging from expansion to ways to repair a system in case of failure. The above parameters are directly related to the characteristic of source, fiber and detector.

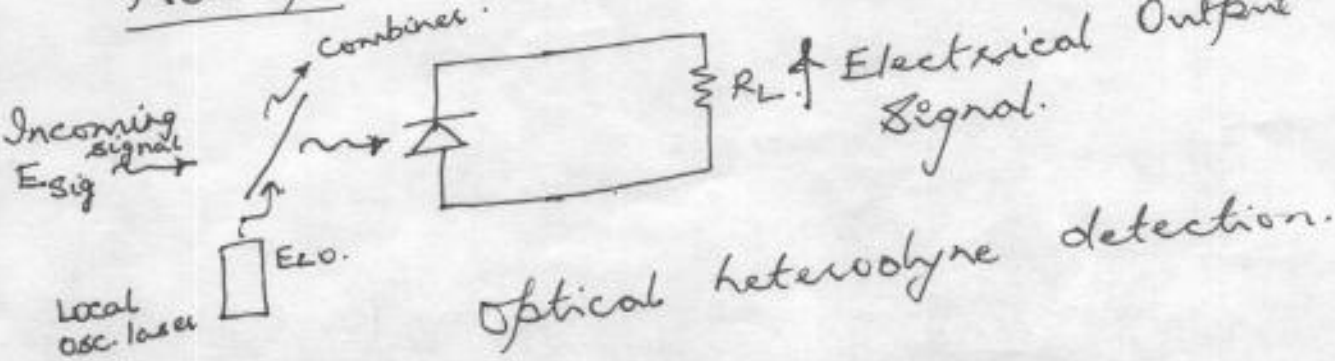
- LEDs are much cheaper and require less environmental protection than lasers, but they produce much less power and have high coupling losses. Their broad range of wavelengths and their limited modulation speed limits the system bandwidth.
- The performance of low-loss fiber, high sensitivity detectors and powerful transmitters must be balanced against price advantages of lower performance devices.
- Higher loss, low cost LEDS and low cost cables can be used for short distance communication.
- Light source and detectors for 1300 nm cost more than those for 800-900 nm window.

- Fiber, source and detector contribute a larger fraction of total cost and have more impact on long haul system. 1550 nm light source costs more than 1300 nm source. To provide low attenuation, reasonable bandwidth, they must have extremly narrow spectrum, small response time and should be used with dispersion shifted fiber. Avoiding repeaters or minimising number for repeaters required for long haul system can reduce lot of cost.
- Balance the advantage of eliminating extra components with higher costs of components needed to eliminate them.
- Cost can be reduced by taking future upgrade possibilities into account. For example, installing cables with more fibers than needed at the moment can avoid the high cost of burying and installing additional cable later.
- Leaving margin for repair and expansion reduces long term cost at increased performance
- The bit transfer rate depends upon overall system response time which depends upon response time of transmitter, fiber and receiver. Again the maximum transfer →

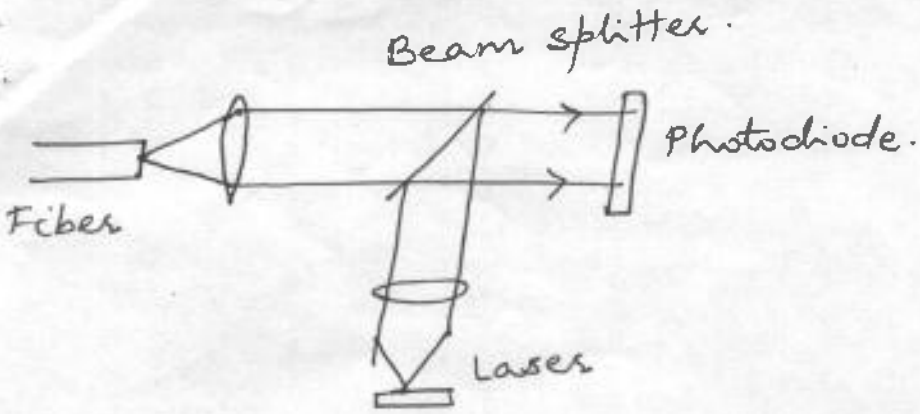
Coherent Detection.

The coherent optical receivers first add locally generated optical wave at nearby frequency $f_2(\lambda_2)$ to the incoming optical signal at frequency $f_1(\lambda_1)$ prior to detection. The resulting photocurrent is a replica of the original signal which is translated down in frequency from optical domain (around 10^5 GHz) to the radio domain (~~upto~~ ~~several~~ MHz at GHz) where conventional electronic technique can be used for further processing and demodulation. The heterodyne detector converts phase changes in the optic carrier to phase changes in the optic intensity. The latter variations are reproduced in the detected current waveform, making possible the reception and demodulation of frequency-modulated optic carrier. Coherent receivers are ~~also~~ effective for detecting intensity-modulated digital signals.

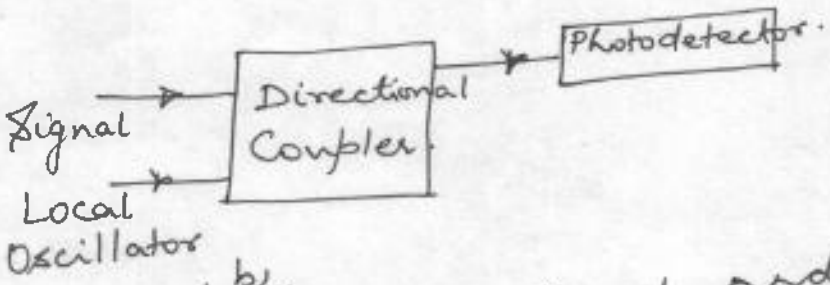
Principle of coherent detection.



Optical heterodyne detection.



(a)



(b).

Combining the signal and local oscillator beam with (a) Beamsplitter (b) Single mode biconical fused fiber directional coupler which gives excellent wavefront matching of the two optical signals.

Let electric field of transmitted signal E_{sig} & the local oscillator beam E_{LO}, respectively be

$$E_{sig} = E_s \cos[\omega_0 t + \theta(t)].$$

$$E_{LO} = E_L \cos[(\omega_0 + \omega_{IF})t].$$

where ω_0 = optic carrier frequency

$\theta(t)$ = frequency-modulated message

For modulation by single sine wave,

$\theta(t) = \beta \sin \omega_m t$ & β = modulation index.

For OOK signal θ is constant & E_s can take one of the two values during each bit interval, depending upon whether 0 or 1 is transmitted. For FSK modulation, $\theta(t)$ is either $\omega_1 t$ or $\omega_2 t$. - - - - - bwk - 264 -

Detected current $I_p \propto (E_{sig} + E_{LO})^2$.

$$\propto \left\{ E_s \cos[\omega_0 t + \theta(t)] + E_L \cos[(\omega_0 + \omega_{IF})t] \right\}^2$$

$$\propto \frac{1}{2} E_s^2 \left\{ 1 + \cos[2\omega_0 t + 2\theta(t)] \right\}$$

$$+ \frac{1}{2} E_L^2 \left\{ 1 + \cos[2(\omega_0 + \omega_{IF})t] \right\}$$

$$+ E_L E_s \left\{ \cos[\omega_{IF} t - \theta(t)] + \cos[2\omega_0 t + \theta(t) + \omega_{IF} t] \right\}$$

$\because 2\omega_0$ much greater than freq resp of detector $\therefore$ ~~con~~ are eliminated.

$\therefore$ ~~Average intensity~~

$$I_p \propto 0.5 (E_L^2 + E_s^2) + E_L E_s \cos[\omega_{IF} t - \theta(t)] \quad (2)$$

$\because$ optic power $\propto$ square of its electric field strength ($P \propto I$.)

The ~~corresponding~~ equation (2) can be written as.

$$I_p \propto P_L + P_s + 2\sqrt{P_L P_s} \cos[\omega_{IF} t - \theta(t)]$$

where P_L & P_s are the power in the local oscillator & signal beams respectively.

Further

$\because$ Output photo current $I_p = \eta \frac{e P_0}{hf}$

where η is the quantum efficiency

e = charge on electron.

h = Planck's constant.

f = optical frequency

P_0 = Incident optic power.

$$I_p = \frac{\eta e}{hf} \left[\underbrace{P_s + P_L}_{d.c} + \underbrace{2\sqrt{P_L P_s} \cos(\omega_{IF} t - \theta(t))}_{a.c} \right]$$

The third a.c term can be distinguished from first two d.c terms and I_p can be replaced by approximation.

I_s where

$$I_{s_{ac}} = \frac{\eta e}{hf} 2\sqrt{P_s P_L}\left[\cos\{\omega_{IF} t - \theta(t)\}\right] \quad (4)$$

indicating output from photodetector is centred on an intermediate frequency ω_{IF}. This IF is stabilized by incorporating the local oscillator laser in a frequency control loop.

For <u>Homodyne detection</u> $\omega_{IF} = 0$.

$$\Rightarrow I_s = \frac{2\eta e}{hf}\sqrt{P_s P_L}\cos\theta(t).$$

$$\text{or } I_s = 2R\sqrt{P_s P_L}\cos\theta(t).$$

$R =$ Responsivity of optical detector.

Advantages of coherent detection.

1. A potential improvement in receiver sensitivity upto 20dB can be obtained using coherent detection over direct detection. * - - - * → back page
2. Increased repeater spacing for both inland & undersea transmission system.
3. Increased power budgets to compensate for losses associated with couplers & optical multiplexer / Demultiplexer devices in distributed network.
4. The optic direct detectors do not reproduce variation in frequency or phase of the oscillating light wave. FM / PM is ineffective with direct detection method.

. However FM/PM, ASK, PSK FSK modulation system format (5) are possible with coherent detection.

5. Permits Dense WDM as channel spacing is reduced to a few hundred MHz as against ~ 100 GHz with system employing direct detection

6. Improved sensitivity to optical test equipment like OTDR.

Disadvantages.

1. Increased complexity
2. Increased cost.
3. The laser diode must be single mode device with extremely narrow linewidth spectrum. stablization required to maintain
4. Frequency correct IF. signal.
5. The signal and local oscillator beam alignment is critical. The two wavefront must be identical. and must concide. The spot size, polarizations & propagation direction of two beam must be same. Various counter measures are required.
6. The local oscillator signal must be close to the incoming signal power otherwise local oscillator quantum noise becomes the dominant noise source. However due to losses associated with coupling optic, higher local oscillator power is required Hence it becomes difficult to obtain shot noise limited receiver performance.

The use of polarization maintaining fiber to maintain SOP exhibit higher losses & are expensive to fabricate & bad

Comparision between Homodyne & Heterodyne detection.

The SNR for the ideal heterodyne detection receiver when local oscillator

power is large (ignoring the electronic pre-amplifier thermal noise and photodetector dark current noise terms).

$$\left(\frac{S}{N}\right)_{het\text{-}lim} = \frac{\left(\frac{\eta e}{hf}\right)^2 P_S P_L}{\frac{2e^2 \eta P_L B}{hf}} = \frac{\eta P_S}{hf\, 2B} = \frac{\eta P_S}{hf B_{IF}}$$

B_{IF} = IF amplifier bandwidth = 2B.

The SNR limit for optical homodyne detection can be deduced by reducing the receiver bandwidth requirement from B_{IF} to B as the output signal from photodetector appears in the baseband.

$$\left(\frac{S}{N}\right)_{hom\text{-}lim} = \frac{\eta P_S}{hf B}$$

Thus homodyne detection displays (1) potential 3dB improvement in SNR. ~~over heterodyne~~ detection. (2) Reduced receiver bandwidth requirement 3 Increased sensitivity (4). higher maximum transmission rate in comparison to heterodyne detection.

Disadv Phase locking of incoming signal (low ~~laser modulated signal~~ is extremely difficult with local osc

2. Puts stringent demand on laser line width & Frequency stabilization. Homsyn detection puts the least demand on injection laser phase stability.

Practical constraints

1. Requires Single mode laser with extremely narrow linewidth of around 10 KHz or less ~~are~~ ~~required~~ for improved SNR and for appropriate tunability with incoming signal. ~~is must~~

2. The state of polarization of incoming signal & local oscillator laser must be well matched. To maintain the state of polarization (SOP) following measures are taken

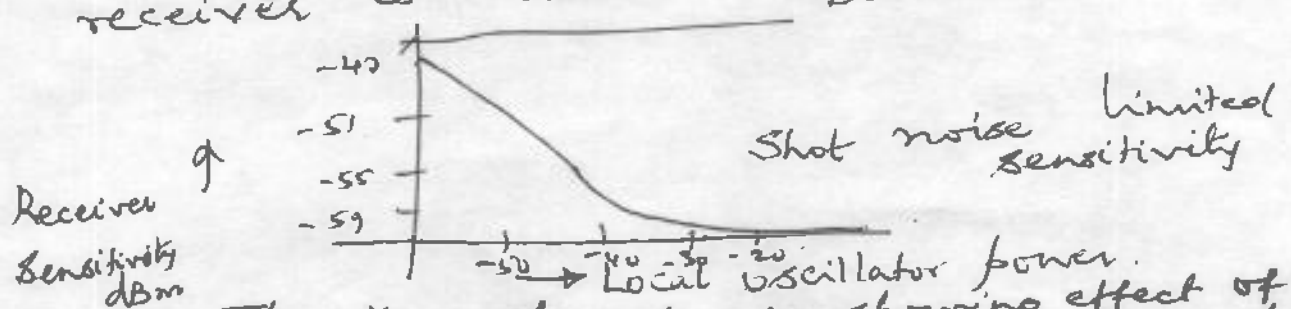
(a) The use of polarization maintaing (PM) single mode fiber

(b) The use of an SOP control device at the coherent optical receiver.

(c). The use of a polarization diversity receiver or polarization scrambling transmitter.

~~The~~ Active polarization state control can be accomplished using mechanical, electro-optic or magneto-optical technique.

3. The local oscillator power loss due to coupling optics & to suppress excess noise in local oscillator signal, balanced receiver is used. Direct detection sensitivity



Theoritical characteristic showing effect of LO power on homodyne RX sensitivity for PIN FET RX operating at 140 Mbit/s.

WDM

Principle of WDM – A distinctive operational feature of an optical fiber is that there is a wide spectral region in which optical signals can be transmitted efficiently. For full spectrum fiber this region includes the O-band through the L-band, which ranges from about 1260 to 1675 nm. With the advent of high quality light sources with extremly narrow spectral widths (less than 1nm), many different independent wavelength channels can be placed simultaneously in different segment of this wavelength range. The technology of combining a number of such independent information carrying wavelength onto the same fiber is known as WDM – Wavelength Division Multiplexing.

A characteristic of WDM is that the discrete wavelength form an orthogonal set of carriers which can be separated, routed and switched without interfering with each other. The isolation between channel holds as long as the total optical power intensity is kept sufficiently low to prevent nonlinear effects such as Stimulated Brillouin scattering & four wave mixing process from degrading the link performance.

The implementation of sophisticated WDM networks require a variety of passive and active devices to combine, distribute, isolate and amplify optical power at different wavelengths. Fig (1) & (2) shows a typical WDM link. At the transmitting end there are several independent modulated light sources, each emitting signal at unique wavelength. Here a multiplexer is needed to combine these optical outputs into a continous spectrum of signals and couple them onto a single fiber. At the receiving

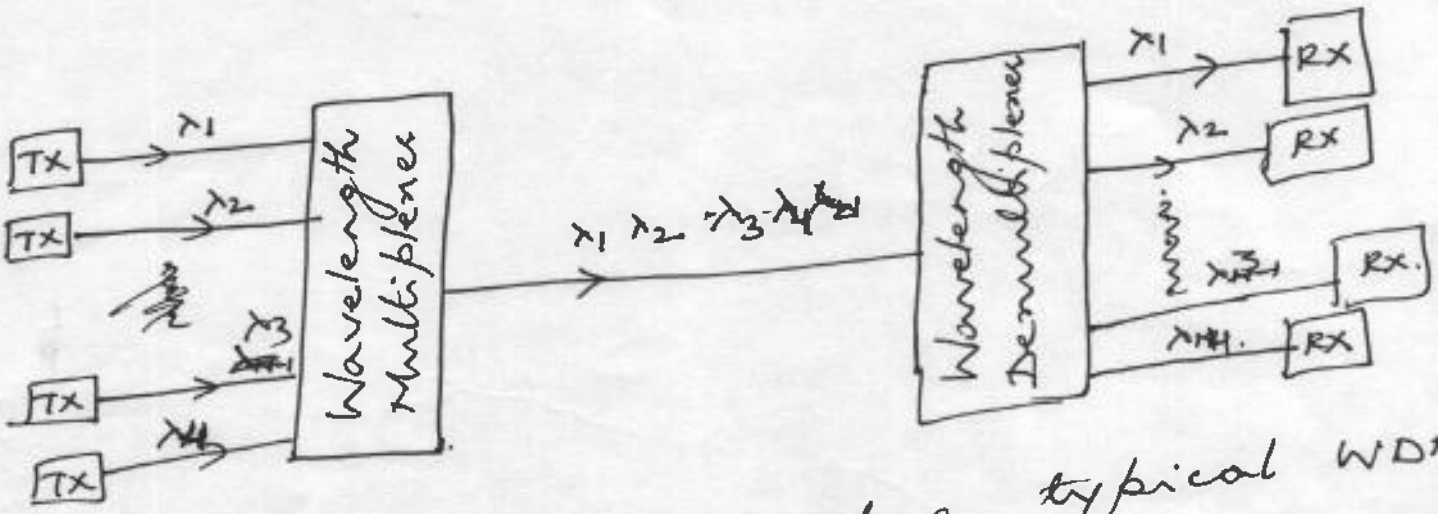


fig 1 - Implementation of a typical WDM link - simplex WDM link.

end a demultiplexer is required to separate the optical signals into appropriate channels for signal processing detection. In its simplest form this network is unidirectional - simplex network. It can however operate

in both direction if the wavelength separation/combination devices are bidirectional. A fully duplex network is shown in fig (2).

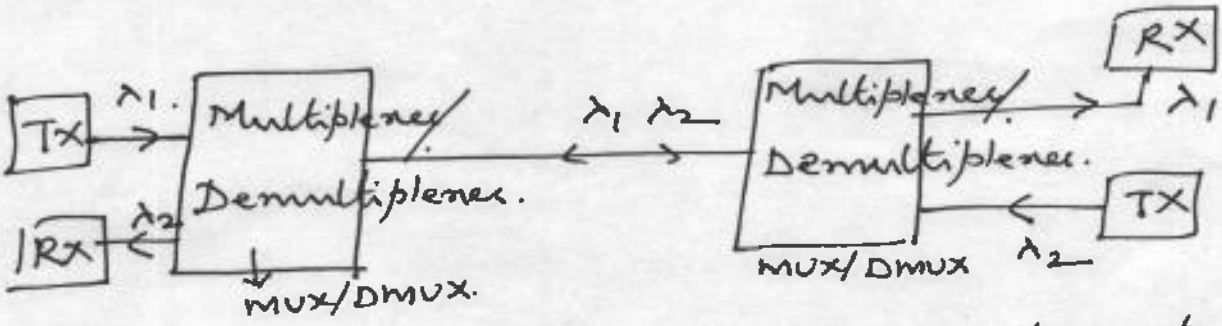


Fig 2 – A fully duplex network – Bidirectional ~~network~~ network.

MUX/DMUX → Bidirectional multiplexer.

The previously installed systems designed to operate with a single carrier, can be upgraded by WDM simply by changing the terminal equipment.

Multiplexers have been designed to accomodate numerous channels with bandwidths & spacing under (0.8 to 0.1 nm at 1550 nm. When there are more than just few (2 or 3) WDM channels, the system is referred to as dense wavelength-division multiplexing (DWDM).

Implementation of small wavelength separations require the use of stable, high quality, temperature controlled and wavelength controlled (frequency locked) laser diode light sources.