Q1.a.

$$\nabla \times E = -\delta B/\delta t \quad \text{—} \; (1)$$

$$\nabla \times H = \delta D/\delta t \quad \text{—} \; (2)$$

$$\nabla \cdot D = 0 \quad \text{—} \; (3)$$

$$\nabla \cdot B = 0 \quad \text{—} \; (4)$$

$$D = \varepsilon_0 E \quad \text{—} \; (5)$$

$$B = \mu_0 H \quad \text{—} \; (6)$$

Take curl of (1).

$$\nabla \times (\nabla \times E) = -\nabla \times (\delta B/\delta t) \quad \text{—} \; (7)$$

$$= -\frac{\delta}{\delta t}(\nabla \times B) \quad \text{—} \; (8)$$

Sub (5) & (6) into (2).

$$\nabla \times B = -\nabla \times (\delta B/\delta t) \quad \text{—} \; (9)$$

$$= \varepsilon_0 \mu_0 (\delta E/\delta t) \quad \text{—} \; (10)$$

[Bookwork]

(8) & (10) give.

$$\nabla \times (\nabla \times E) = -\varepsilon_0 \mu_0 \frac{\delta}{\delta t}\left(\frac{\delta E}{\delta t}\right) \quad \text{—} \; (11)$$

using operator identity $\nabla \times (\nabla \times \;) = \nabla(\nabla \cdot \;) - \nabla^2$ and remembering that in cartesian co-ordinates $\nabla \cdot E = 0$ (not given)

$$\nabla^2 E - \varepsilon_0 \mu_0 \frac{\delta^2 E}{\delta t^2} = 0 \quad \text{—} \; (12)$$

For only one spatial co-ordinate

$$\frac{\delta^2 E_y}{\delta x^2} - \varepsilon_0 \mu_0 \frac{\delta^2 E_y}{\delta t^2} = 0 \quad \text{—} \; (13)$$

5

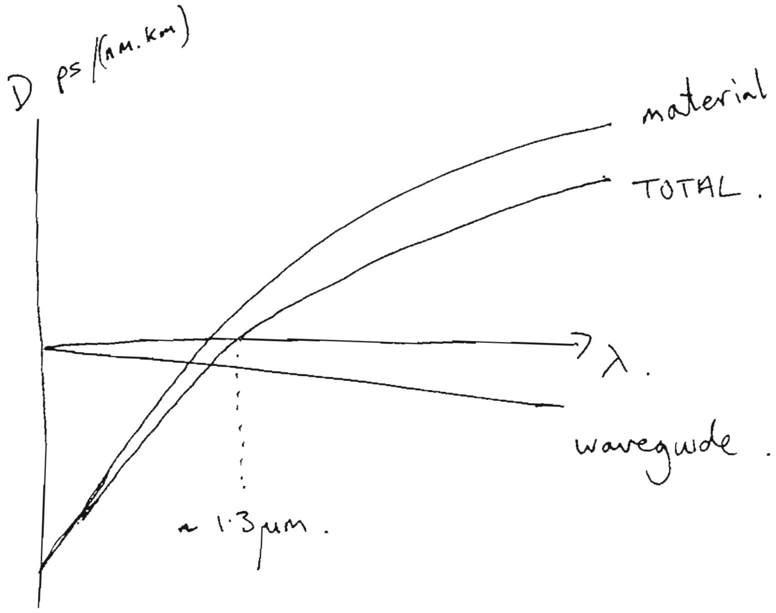
Q1. b.

Chromatic dispersion in silica glass is due to the group velocity varying with wavelength.

Group velocity is the velocity at which the envelope of a wave made up of multiple frequencies propagates through a medium.

3

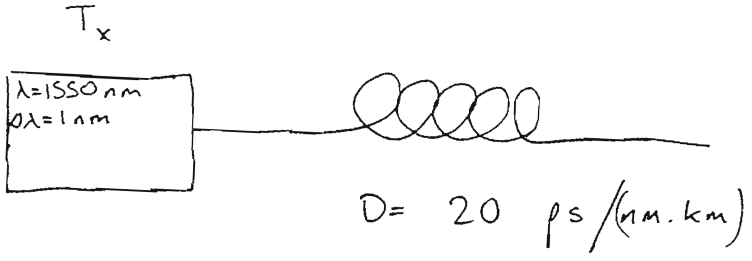
Q1. c

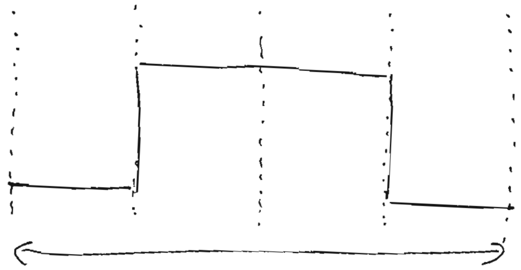


Total chromatic dispersion is made up of material chromatic dispersion ($v_{group}(\lambda)$), and correction due to geometry of waveguide which results in a slight variation in mode index with λ.

5

1. a.





$T_B = 1/1\times10^{9}$ Bits/sec.

$= 1\times10^{-9}$ seconds.

Allow broadening to be up to $T_B/4$ (can accept other assumptions).

= 250 ps.

∴ for 1 nm linewidth source, maximum length for this broadening $= \frac{250}{20} = \underline{12.5 \text{ km}}$.

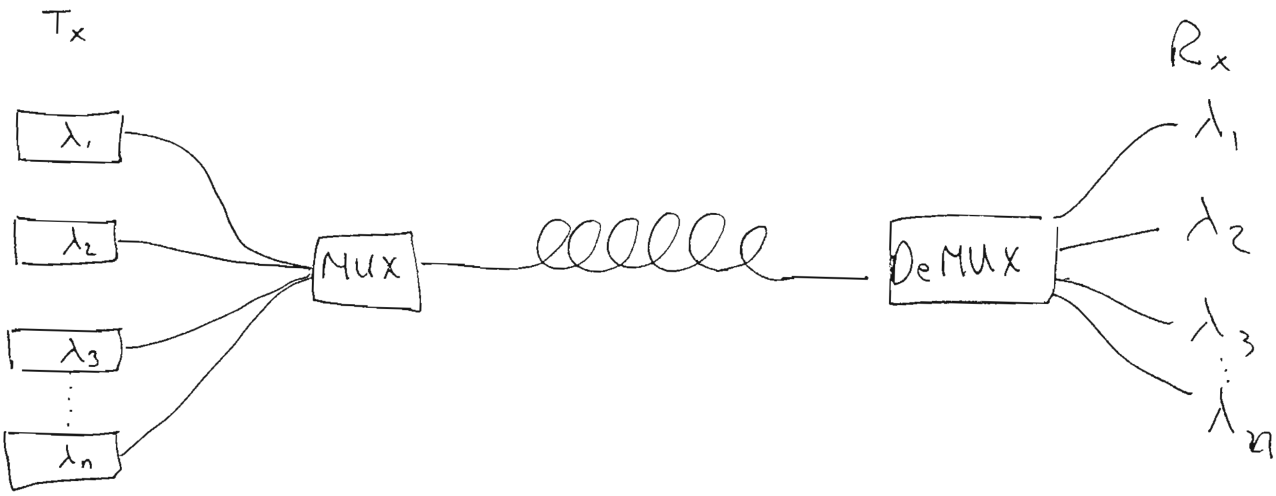
To transmit 10 G Bits/s over same distance :

1). Use narrower line width source.
2). Use Coarse WDM (10 x lasers at different λ).
3) Change wavelength to ~1.3 μm where D ~ 0.

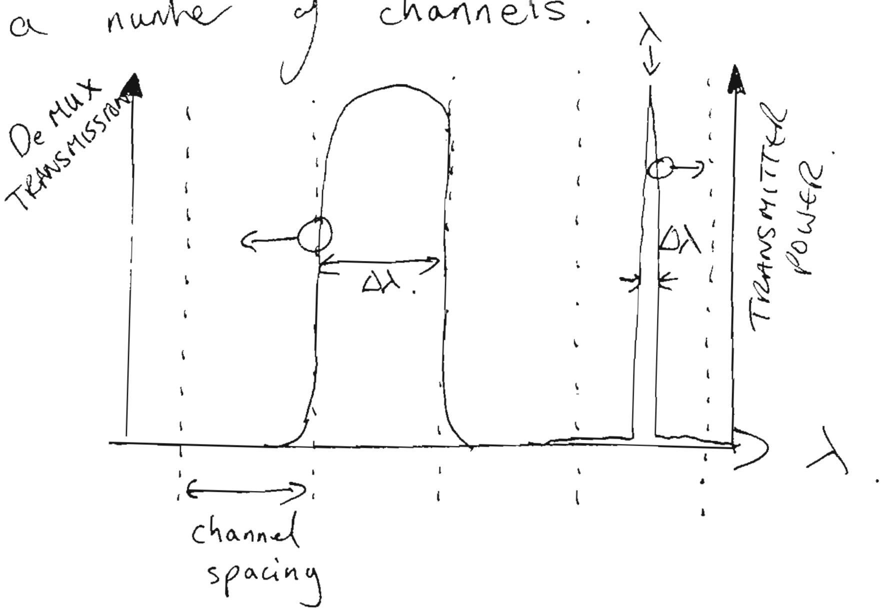
7

2.a.

WDM link – incorporate a number of optical channels in one physical channel.



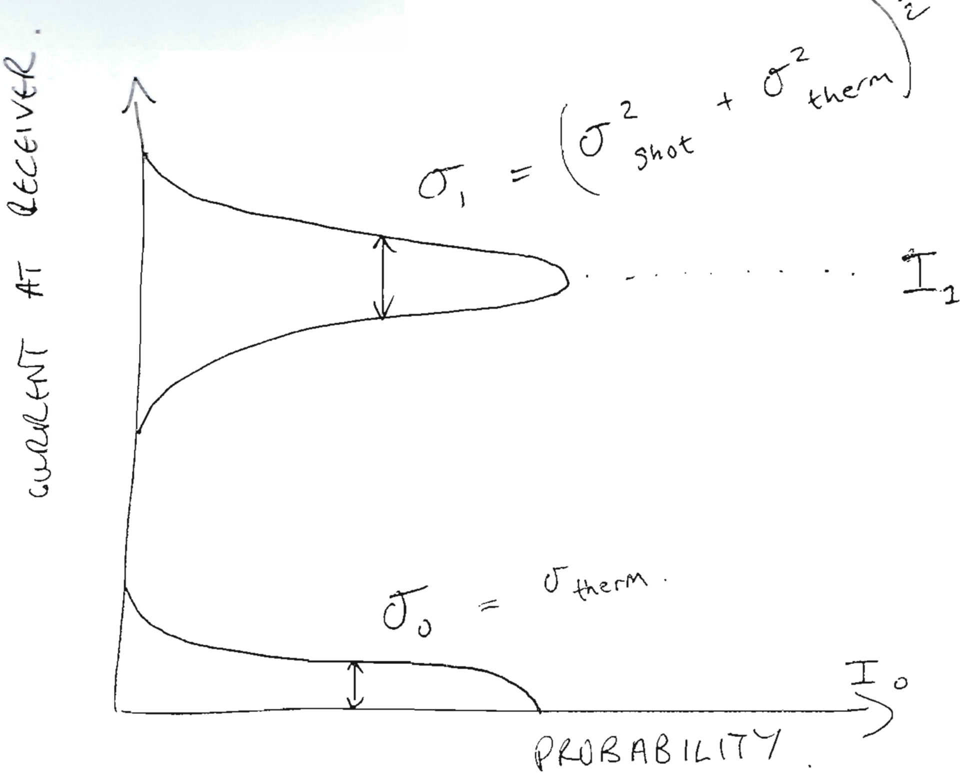
Relies upon very small interaction of light at small powers in simple glass. Wavelength spectrum is split into a number of channels.



Requirements on components

In order to achieve small channel spacing for maximum data rate need DeMUX components with high finesse & narrow spectral width. Need transmitter to have narrow linewidth and be centred in channel (i.e. tuneable to some degree).

2.b.



Bookwork

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$$

Current at receiver for no optical power $= I_0 = 0$. Additional thermal (Johnson) noise, giving linewidth σ_0.

Current at receiver for "1" $= I_1$ with noise σ_1 due to shot noise & thermal noise.

If "0" has optical power, and hence $I_0 \neq 0$ I_1 needs to increase to maintain BER. This is termed the extinction ratio penalty.

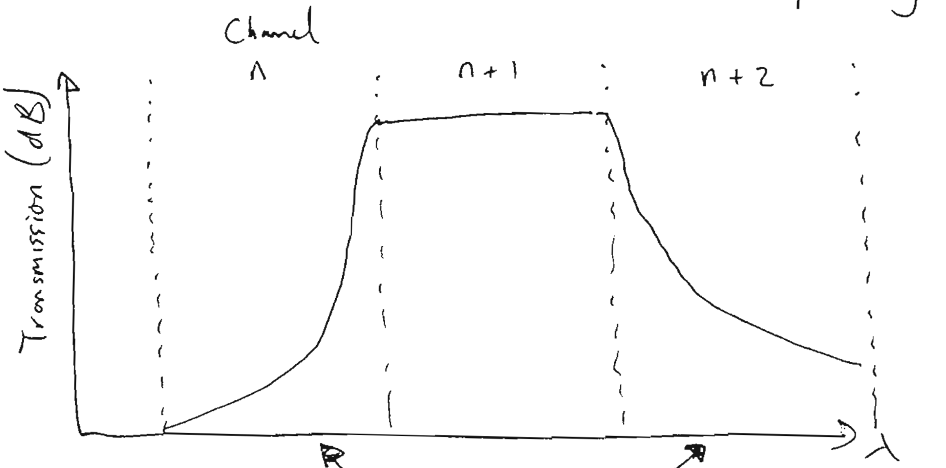
For high speed systems, lasers are used and are modulated above threshold resulting in a finite extinction ratio.

6

2 c.

Out of band crosstalk.

Filter / DeMUX Bandwidth is chosen to allow maximum transmission in-band, and high rejection out of band. However, small amount of power from neighbouring channels can 'leak' when cha spacing is small.



some signal from here is present

Bookwork

In-Band crosstalk

WDM components used for routing and switching in an optical network are not perfect. Other signals, at the same wavelength but destined for other physical channels may be present in addition to the desired signal.

Effect on System Performance.

Adds noise to the signal being detected, resulting in a power penalty to maintain a given BER.

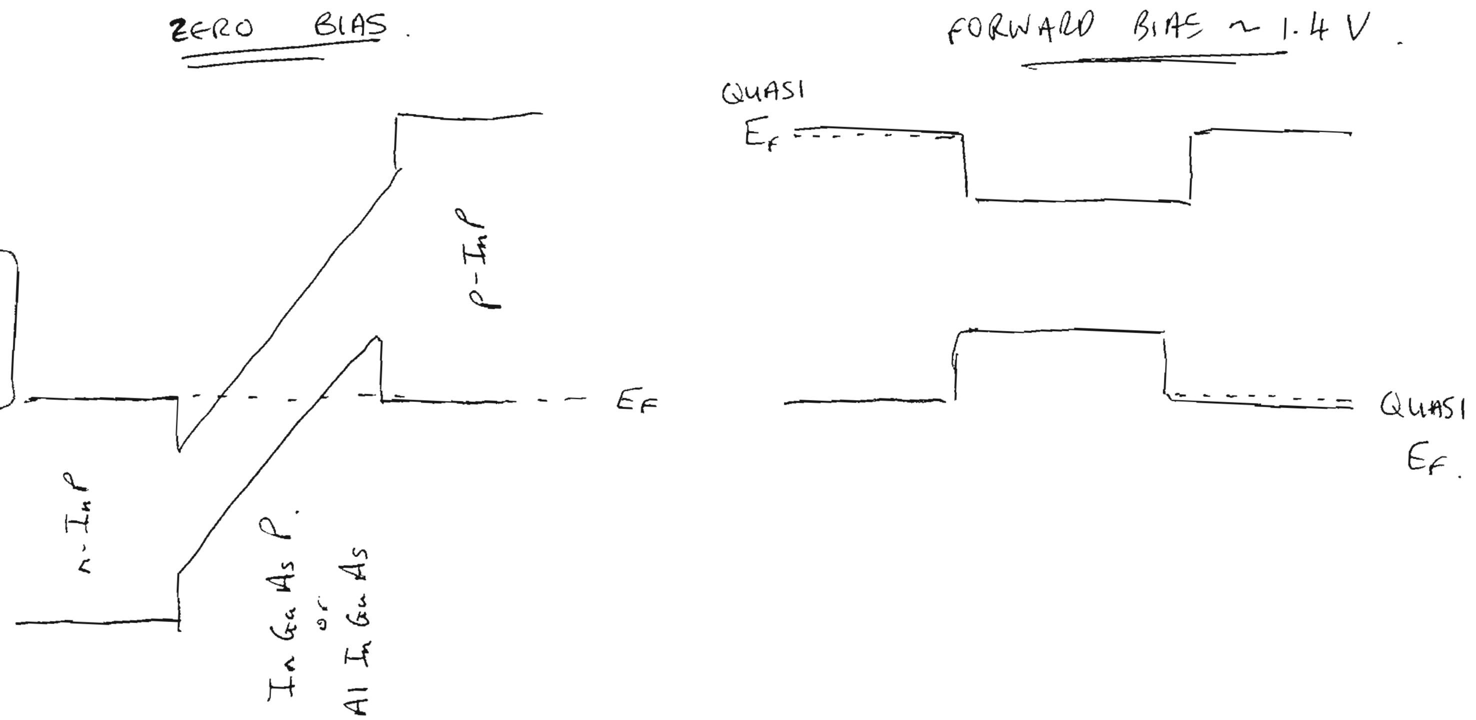
7

Q 3 a

As current is increased the relative probability of absorption and stimulated emission will change for a photon traversing the cavity.
At 0 current stimulated emission is not possible and Absorption of the photon is most likely. As current increases, Absorption is bleached and stimulated emission becomes more probable. At some current stimulated emission equals absorption process and photon loss from the cavity and the waveguide is transparent. Above this current there is gain. When gain equals all losses, lasing occurs (20 mA). Above this current the majority of additional current is converted to photons in the lasing mode and gain is clamped.

4

Q 3 b



Q3c

$$g_{threshold} = \alpha_i + \alpha_m$$

$$= 20 + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$$

$$= 20 + \frac{1}{2 \times 2.5 \times 10^{-2}} \ln\left(\frac{1}{0.32 \times 0.32}\right)$$

Problem

$$= 20 + \frac{1}{5 \times 10^{-2}} \cdot 2.27$$

$$= 65.6 \ \text{cm}^{-1}$$

Q3d

$$g^{modal}_{thresh} = \Gamma' g_{material}$$

$$= \Gamma' A N$$

$$I_{thresh} = q \cdot \frac{n_{thresh}}{\tau} \cdot \text{Volume}.$$

$$A = \frac{q \cdot g_{threshold} \cdot \text{Vol}}{\Gamma' \cdot I_{th} \cdot \tau}$$

n.b. care with units. dimensions in cm!

$$= \frac{1.6 \times 10^{-19} \times 66 \times 1.25 \times 10^{-10}}{0.4 \times 0.02 \times 1 \times 10^{-9}}$$

$$A = 1.65 \times 10^{-16} \ \text{cm}^2.$$

3 e.

From $g_{th} = \alpha_i + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$

- α_i reduced
- L - optimize - balance $g_{th} \downarrow$ and vol $\uparrow$.
- R_1, R_2 increased. Say one facet $R = 1$.
- thickness - optimise w.r.t. modal gain (Γ) and active volume.

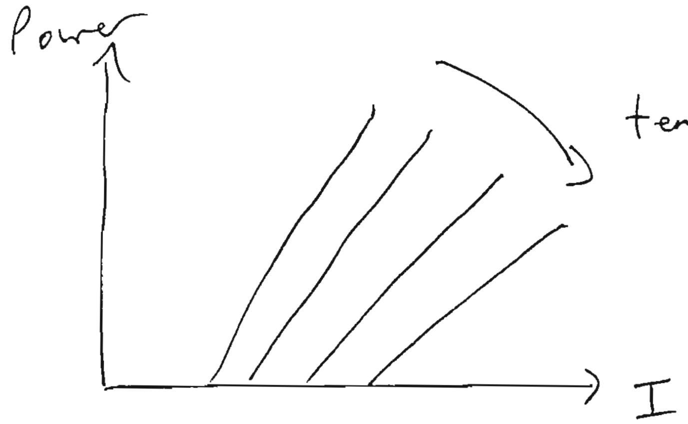
Alternatives →

- utilize QW, QD for reduced DOS.
- Seperate confinemet heterostructure for reduced active vol (but still "bulk."

1 mark each.

Q4 a.

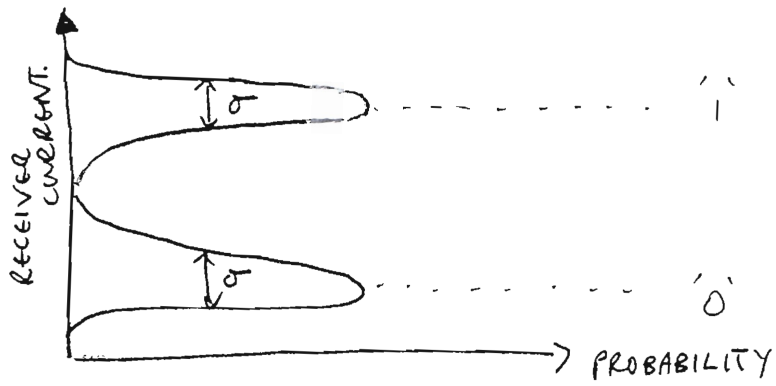
Effect of increasing temperature of a semiconductor laser is to change the electron and hole distribution function. The result is an increase in threshold current.



For the system BER, the effect of a variable laser temperature is that either power monitoring & feedback circuitry is required, or a variation in average launch power and extinction ratio must be accepted.
An increased extinction ratio results in increase BER while reduced launch powers reduce the power budget and limit max link length.

Q4 B

model



The noise on the receiver is dominated by thermal noise. Increased temperature therefore increase BER. A varying temperature has the effect of varying the BER.

Q4 c

Bookwork

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - g\, n_{ph}.$$

$$\frac{dn_{ph}}{dt} = g\, n_{ph} - \frac{n_{ph}}{\tau_{ph}} + \frac{\beta n}{\tau_{sp}}.$$

$$\tau_{ph} = \left\{ \frac{c}{n_g}\left(\alpha_i + \frac{1}{2L} \ln R_1 R_2\right)\right\}^{-1}$$

n = carrier density
J = current density
q = electron charge
d = thickness
= carrier lifetime
g = gain
n_{ph} = photon density in mode
τ_{ph} = photon lifetime
βn = fraction of spontaneous emission into lasing mode

steady state.

$$\frac{dn}{dt} = 0 \Rightarrow J_{th} = \frac{q\, d\, n_{th}}{\tau_{sp}}$$

$$\frac{dn_{ph}}{dt} = 0 \Rightarrow g(n_{th}) = \frac{1}{\tau_{ph}}$$

Q4 d.

Above threshold steady state $\frac{dn}{dt} = 0$, $\frac{dn_{ph}}{dt} = 0$

spontaneous emission into mode disrupts this equality.
As a result the electron and photon population oscillates as they continually attempt to relax to the steady state. The result is a noise peak at the natural frequency of the system.