2023 Past Paper –Question 1

(a) The power received is $200 \times 10^{-9} Js^{-1}$

Each photon carries hc/λ Joules of energy so the number is:

$$\frac{200 \times 10^{-9} \times 1550 \times 10^{-9}}{6.626 \times 10^{-34} \times 2.9979 \times 10^{8}} = 1.56 \times 10^{12}\ s^{-1}$$

At a shorter wavelength, the number would be smaller since it depends directly on the wavelength as seen in the expression above.

(b)

$$\mathrm{Loss} = 10\log_{10}(5 \times 10^{-3}/200 \times 10^{-9}) = 44\ \mathrm{dB}$$

So, the loss per km is:

$$\text{Loss per km} = \frac{44}{200} = 0.22\ \mathrm{dB\ km^{-1}}$$

(c) Assume ideal on-off keying, so the mean photocurrent is:

$$\bar{I} = \frac{\eta q \lambda}{hc} P_o = \frac{0.6 \times 1.602 \times 10^{-19} \times 1550 \times 10^{-9}}{6.626 \times 10^{-34} \times 2.9979 \times 10^{8}} \times 200\ \mathrm{nW} = 150\ \mathrm{nA}$$

Peak photocurrent, $I_1 = 300\ \mathrm{nW}$

(d) The noise factor, F, must be obtained from noise figure:

$$F = 10^{0.7} = 5$$

$$I_T^2 = \frac{4kTF\Delta f}{R_\mathrm{L}}\ \mathrm{A}^2 = \frac{4 \times 1.38 \times 10^{-23} \times 300 \times 5 \times 755 \times 10^{6}}{10^{5}} = 6.25 \times 10^{-16}\ \mathrm{A}^2$$

$$SNR = \frac{I_1^2}{I_T^2} = \frac{(300 \times 10^{-9})^2}{6.25 \times 10^{-16}} = 144$$

$$P_e = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{SNR}{8}} = \frac{1}{2}\ \mathrm{erfc}\sqrt{\frac{144}{8}} = \frac{1}{2}\ \mathrm{erfc}\sqrt{18} \approx \frac{1}{2} \times \frac{e^{-18}}{\sqrt{18\pi}} \approx 10^{-9}$$

(e)

$$\text{Errors per second} = 622 \times 10^6 \times 10^{-9} = 0.622$$

So, between each one there are:

$$\frac{1}{0.622} = 1.6 \text{ seconds}$$

This is too high for a modern system and so something must be done to ameliorate the effect of the errors.

(f) Three orders of magnitude means that the BER will become 10^{-12}

Using the expression given:

$$SNR \approx -18 \times (-12) - 17.4 = 198.6$$

Now,

$$I_1^2 = 198.6 I_T^2 = 198.6 \times 6.25 \times 10^{-16};\ I_1 = 352 \text{ nA}$$

Converting back to power based on previous calculation:

$$P_{\text{out}} = \frac{I_1}{2 \times 0.75} = \frac{176}{0.75} = 234.7 \text{ nW}$$

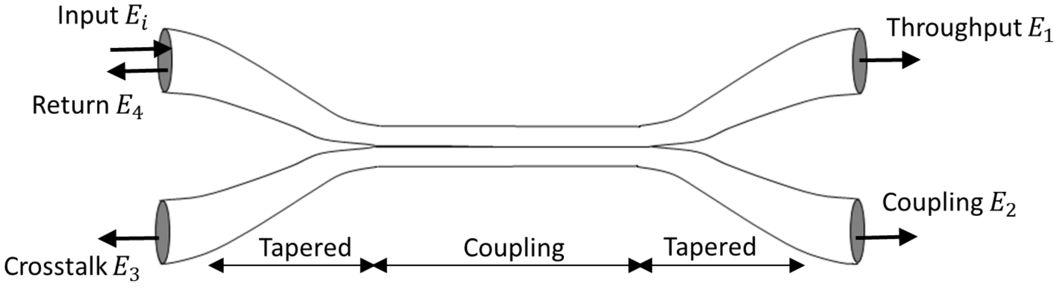
So, the loss per km is 0.15 so total is 30 dB:

$$10\log_{10}(P_{\text{in}}/234.7 \times 10^{-9}) = 30$$

$$P_{\text{in}} = 234.7 \times 10^{-9} \times 10^3 = 234.7\ \mu\text{W (or} - 6.3 \text{ dBm)}$$

2023 Past Paper –Question 2

(a) An optical fibre coupler is a device that distributes light from a main fibre into (occasionally) one or (more likely) two or more branch fibres (multiport fibre couplers).



A fused biconical tapered optical fibre coupler (shown above) consists of a thin portion in its centre, where the fundamental mode in the input fibre spreads into the lower fibre. The tapering is to reduce the fibre from its usual size to the reduced diameter central portion and must not be too severe or else the light can escape. This causes power transfer dependent on the wavelength and the dimensions. The mechanism for power transfer is thus by converting guided core modes to cladding and radiating modes that then transfer power from one fibre to another.

(b) In the coupler, there is a π/2 phase shift ($e^{j\pi/2} = j$) and the fraction of the power transferred to the bottom arm is ρ. The transfer matrix (TM) is:

$$\boldsymbol{T} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} E_i \\ 0 \end{pmatrix}$$

The device is symmetric so $c = b; d = a$; using this and what we know about the outputs:

$$\begin{pmatrix} \sqrt{1-\rho} \\ j\sqrt{\rho} \end{pmatrix} E_i = \begin{pmatrix} a & b \\ b & a \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} E_i$$

Multiplying out:

$$\sqrt{1-\rho} = a$$
$$j\sqrt{\rho} = b$$
$$\text{i.e. } \boldsymbol{T} = \begin{pmatrix} \sqrt{1-\rho} & j\sqrt{\rho} \\ j\sqrt{\rho} & \sqrt{1-\rho} \end{pmatrix}$$

The device is ideally lossless, so the $\boldsymbol{T}$ has determinant of 1, i.e.:

$$a^2 - b^2 = 1$$

The total power also does not change so:

$$|a|^2 + |b|^2 = 1$$

(c) For a waveguide modulator of length L with applied bias V,

$$\text{Transmission} = \exp\{-\alpha(V)L\}$$

Reading the absorption characteristic graph, $\alpha(V) \approx 415\ \text{cm}^{-1}$, so we need to convert this to m^{-1} and then multiply by the length thus:

$$\text{Transmission}_0 = \exp\{-41500 \times 50 \times 10^{-6}\} = 0.126$$

In dB

$$\text{Transmission}_0 = 10\log_{10} 0.126 = -9\ \text{dB}$$

So, the insertion loss is 9 dB.

(d) Power in 1 mW = 0 dBm

We need the transmission with the bias applied, from the graph this is ≈1000 cm^{-1}, so again convert to m^{-1} and multiply by the length:

$$\text{Transmission}_{\text{bias}} = \exp\{-100000 \times 50 \times 10^{-6}\} = 0.00674$$

In dB

$$\text{Transmission}_{\text{bias}} = 10\log_{10} 0.00674 = -21.7\ \text{dB}$$

For the couplers, each one loses 3 dB

Total loss is 9 dB

Output power when off is:

$$0 - 9 - 21.7 = -30.7\ \text{dBm}$$

Output power when on is:

$$0 - 9 - 9 = -18\ \text{dBm}$$

(e)

$$\text{Extinction Ratio} = -18 - (-30.7) = 12.7\ \text{dB}$$

2023 Past Paper –Question 3

(a)
(i) The normalised frequency (or the V parameter) of the optical fibre can be calculated using the following equation

$$V = \frac{2\pi a}{\lambda} NA = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$$

$$= \frac{2\pi \cdot 2 \cdot 10^{-6}}{1550 \cdot 10^{-9}} \cdot \sqrt{1.5^2 - 1.48^2}$$

$$= 1.9793$$

We have $V < 2.405$, therefore the fibre can only support a single-mode operation.

(ii) The pulse spread due to the chromatic dispersion can be written as $\Delta\tau_{CD} = D \cdot L \cdot \Delta\lambda$. Therefore, the pulse spread per unit distance due to the chromatic dispersion is:

$$\frac{\Delta\tau_{CD}}{L} = D \cdot \Delta\lambda = 16\ \mathrm{ps}\ (\mathrm{nm} \cdot \mathrm{km})^{-1} \times 0.01\ \mathrm{nm} = 0.16\ \mathrm{ps\ km}^{-1}$$

(iii) The frequency spread of the laser in terms of Hz $f = c/\lambda$

$$|\Delta f| = \left|-\frac{\mathrm{c}}{\lambda^2}\right| \Delta\lambda = \left|\frac{3 \cdot 10^8}{(1550 \cdot 10^{-9})^2}\right| \cdot 0.01 \cdot 10^{-9}$$

$$= 1.2487 \cdot 10^9\ \mathrm{Hz} = 1.2487\ \mathrm{GHz}$$

(iv) The first-order estimate of the $B \cdot L$ product offered by the single-mode fibre can be described by

$$B \cdot L \cdot |D| \cdot \Delta\lambda < 1$$

Therefore, we have the maximum fibre length that allows the stated bit rate is

$$L_{max} = \frac{1}{B \cdot |D| \cdot \Delta\lambda} = \frac{1}{15 \cdot 10^9 \cdot 16 \cdot (10^{-12}/10^{-9} \cdot 10^3) \cdot 0.01 \cdot 10^{-9}}$$

$$= 416670\ \mathrm{m} = 416.67\ \mathrm{km}$$

(b) The required 3-dB optical bandwidth can be described via

$$f_{3dB} = \frac{B}{\sqrt{2}} = \frac{15 \cdot 10^9}{\sqrt{2}}\ Hz = 10.607\ \text{GHz}$$

(c) For the NRZ signal, the maximum pulse spread at this transmission bit rate will be limited as

$$\Delta\tau = \frac{\sqrt{2}/2}{B} = \frac{\sqrt{2}/2}{2.0\ \text{Gbps}} = 353.5\ \text{ps}$$

The pulse spread due to the chromatic dispersion in the optical fibre is estimated as

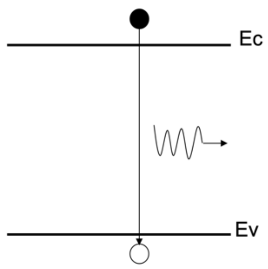
$$\Delta\tau_{CD} = D \times L \times \Delta\lambda = 25\ \text{ps}\ (\text{nm} \cdot \text{km})^{-1} \times 120\ \text{km} \times 0.2\ \text{nm} = 600\ \text{ps}$$

Therefore, the system will not work correctly.

2023 Past Paper –Question 4

(a)

The basis of LED light emission action is the spontaneous emission, namely a random photon-electron interaction that causes an electron to fall to a lower energy level, generating a random photon. The process can be described using the following diagram.



The basis of LASER diode is the stimulated emission, where a photon incident upon an electron in a high energy level causes the electron to fall to a lower level generating a second photon. The photon generated has the same frequency as the incident one and thus laser light is highly monochromatic and coherent (in phase).

(b)

Optical wireless uses devices to emit light (near infrared energy) through free space to a receiver at some point, which combines suitable optics and a photodetector plus receiver-amplifier configuration. Its strengths are that it can provide secure, high bandwidth communications over medium (500 metres) to short distances in air (and also underwater), both indoors and outdoors. It can operate at visible wavelengths (400 nm to 750 nm) and also near infrared (750 nm to 1500 nm).

Optical wireless also has the commercial advantage of being licence-free unlike the RF spectrum which is heavily regulated internationally. Optical wireless can operate in environments where there is a high degree of electromagnetic interference unlike an RF system. It does not also interfere with RF-sensitive equipment such as in hospitals or in military applications.

However, unlike RF it tends to be directional and relies in some ways on the optical properties of the environment. In particular, the ambient illumination (particularly outside) can be a challenge for optical wireless, as it is both high in level during daylight hours and it also creates considerable shot noise in the photodiode detector. (The answer can also include some discussion of configurations such as line-of-sight [LOS], Non-directed, etc. and application areas).

(c)

The total loss budget in this optical transmission link can be calculated as

$$Loss = L_{\mathrm{fibre}} + L_{\mathrm{splice}} + L_{\mathrm{connector}}$$

$$= 100\ \mathrm{km} \cdot 0.3\ \mathrm{dB\ km^{-1}} + 4 \cdot 0.25\ \mathrm{dB} + 2 \cdot 0.2\ \mathrm{dB}$$

$$= 30\ \mathrm{dB} + 1\ \mathrm{dB} + 0.4\ \mathrm{dB} = 31.4\ \mathrm{dB}$$

The receiver sensitivity can be expressed in dBm, where we have:

$$P_{\mathrm{Rx}}(\mathrm{dBm}) = 10 \cdot \log_{10}\left(\frac{5\ \mu\mathrm{W}}{1\ \mathrm{mW}}\right) = -23\ \mathrm{dBm}$$

Therefore, the minimum transmitted signal power should be

$$P_{\mathrm{Tx}}(\mathrm{dBm}) = P_{\mathrm{Rx}}(\mathrm{dBm}) + Loss$$
$$= -23\ \mathrm{dBm} + 31.4\ \mathrm{dB} = 8.4\ \mathrm{dBm}$$

If we convert the minimum transmitted signal power into mW

$$P_{Tx}(\mathrm{mW}) = 10^{\frac{P_{\mathrm{Tx}}(\mathrm{dBm})}{10}} = 6.92\ \mathrm{mW}$$