Answers to Coursebook questions – Chapter F3

1 $n = \frac{c}{c_m} \Rightarrow c_m = \frac{c}{n} = \frac{3\times10^8}{1.45} = 2.07\times10^8 \text{ m s}^{-1}$.

2 **a** Total internal reflection is the phenomenon in which a ray approaching the boundary of two media reflects without any refraction taking place.

b The critical angle is that angle of incidence for which the angle of refraction is 90°.

c The critical angle is found from $n_1 \sin\theta_c = n_2 \sin 90^\circ \Rightarrow \sin\theta_c = \frac{n_2}{n_1}$.

Since the sine of an angle cannot exceed 1, we must have $n_2 < n_1$ for the critical angle to exist. So total internal reflection is a one-way phenomenon.

3 $n_1 \sin\theta_c = n_2 \sin 90^\circ \Rightarrow \sin\theta_c = \frac{n_2}{n_1} = \frac{1.46}{1.50} \Rightarrow \theta_c = 76.7^\circ$.

4 As shown in the text (see page 564 in *Physics for the IB Diploma*), we must have $\sqrt{n_1^2 - 1.42^2} = 1 \Rightarrow n_1 = 1.7367 \approx 1.74$.

5 $A = \arcsin\sqrt{n_1^2 - n_2^2} = \arcsin\sqrt{1.52^2 - 1.44^2} = 29.1^\circ$.

6 It has to be exceptionally pure.

7 **a** Dispersion is the phenomenon in which the speed of a wave depends on wavelength. This means that the different wavelength components of a beam of light will take different times to travel the same distance.

b Material dispersion is the dispersion discussed in **a**. Modal dispersion has to do with rays of light following different paths in an optical fibre and hence taking different times to arrive at their destination.

8 For two main reasons:

i the laser (compared to the LED) is very monochromatic, i.e. its range of wavelengths is very narrow and so the problem of material dispersion is minimized and

ii the narrowness of the laser beam means that a lot of power can be injected into the optical fibre that will allow the beam to travel a long distance before amplification.

9 **a** $n = \frac{c}{c_m} \Rightarrow c_m = \frac{c}{n} = \frac{3\times10^8}{1.52} = 1.9737\times10^8 \approx 1.97\times10^8 \text{ m s}^{-1}$.

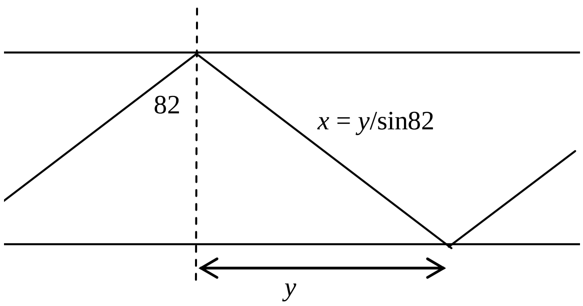
b The shortest time will be for a ray that travels down the length of the fibre on a straight line of length 8.0 km, i.e. the time of travel will be

$$\frac{8.0\times10^3}{1.9737\times10^8} = 4.05\times10^{-5}\text{ s}.$$

The longest time of travel will be for that ray that undergoes as many internal reflections as possible.

The length of the path travelled is then $\frac{8.0}{\sin 82^\circ} = 8.0786 \approx 8.08\text{ km}$ (see diagram)

and so the time is $\frac{8.0786\times10^3}{1.9737\times10^8} = 4.09\times10^{-5}\text{ s}$.



10 The height of the pulses will be less and the width of the pulses greater.

11 **a** A monomode optical fibre is a fibre with a very thin core, so that effectively all rays entering the fibre follow the same path.
In a multimode fibre (which is thicker than a monomode fibre), rays follow very many paths of different length in getting to their destination.

b The transition from multimode to monomode fibres offers a very large increase in bandwidth. As discussed also in **Q13**, dispersion limits the maximum frequency that can be transmitted and hence the bandwidth. A very small diameter monomode fibre will suffer the least from modal dispersion (and hence the distortion and widening of the pulse), and material dispersion is also minimized by using lasers rather than LEDs. Hence the bandwidth is increased as the monomode fibre diameter is decreased and laser light is used.

12 Advantages include:

i the low attenuation per unit length, which means that a signal can travel large distances before amplification,

ii increased security because the signal can be encrypted and the transmission line itself cannot easily be tampered with,

iii large bandwidth and so a large information carrying capacity,

iv not susceptible to noise,

v they are thin and light, and

vi do not radiate, so there is no crosstalk between lines that are close to each other.

13 Dispersion means that different wavelengths (frequencies) travel at different speeds (material dispersion). And waves travelling along different paths take different times to arrive (modal dispersion). Either way, this has the effect of distorting a pulse after travelling a certain distance in a medium.

a A square pulse, for example, will become wider. This is because the wavelengths travelling faster will 'move ahead' and the slow ones will be 'left behind'. Thus the pulse is wider and so its duration will increase. The bit rate is the inverse of the bit duration, and this implies that the bit rate will decrease as a result of dispersion.

b Another problem of dispersion is that the fast components in one pulse will catch up with the slow components in **another** pulse. This means that the pulses will start to overlap. Therefore dispersion places a limit on the maximum frequency that can be transmitted.

14 The main cause of attenuation in an optical fibre is impurities in the glass making up the core of the fibre.

15 It means that the power of the signal and the power of the noise are related by $30 = 10\log\frac{P_{\text{signal}}}{P_{\text{noise}}}$. This implies that $\frac{P_{\text{signal}}}{P_{\text{noise}}} = 10^3$.

16 It will be the same because the amplifier will amplify both the signal and the noise.

Explicitly, the new power after amplification will be $P'_{\text{signal}} = P_{\text{signal}} \times 10^{\frac{G}{10}}$ and $P'_{\text{noise}} = P_{\text{noise}} \times 10^{\frac{G}{10}}$, where G is the amplifier gain. Then the new signal to noise ratio is

$$10\log\frac{P'_{\text{signal}}}{P'_{\text{noise}}} = 10\log\frac{P_{\text{signal}} \times 10^{\frac{G}{10}}}{P_{\text{noise}} \times 10^{\frac{G}{10}}} = 10\log\frac{P_{\text{signal}}}{P_{\text{noise}}}$$, i.e. equal to the old ratio, 10 dB.

17 Let P_{in} be the power in to the first amplifier.

Then the power out of the first amplifier is $P' = P_{\text{in}} \times 10^{\frac{G_1}{10}}$.

This is input to the second amplifier, so its output is

$$P_{\text{out}} = \left(P_{\text{in}} \times 10^{\frac{G_1}{10}}\right) \times 10^{\frac{G_2}{10}} = P_{\text{in}} \times 10^{\frac{G_1}{10}+\frac{G_2}{10}} = P_{\text{in}} \times 10^{\frac{G_1+G_2}{10}},$$

showing that the gain overall is $G_1 + G_2$.

18 The power loss is $10\log\frac{P_{\text{out}}}{P_{\text{in}}} = 10\log\frac{3.20}{4.60} = -1.58\ \text{dB}$.

19 The power loss is $10\log\frac{P_{\text{out}}}{P_{\text{in}}} = 10\log\frac{5.10}{8.40} = -2.167\text{ dB}$.

So the loss per km is $\frac{2.167}{25} = 0.087\text{ dB km}^{-1}$.

20 The power loss when the power falls to 70% of the original input power is $10\log\frac{P_{\text{out}}}{P_{\text{in}}} = 10\log\frac{0.70P}{P} = -1.55\text{ dB}$. So, $12\times L = 1.55 \Rightarrow L = 0.13\text{ km}$.

21 There is no overall gain in power since $+15-12 = 3.0\text{ dB}$. Let the input power be *P*.

Then the output power is $P' = P\times 10^{\frac{G}{10}} = P\times 10^{0.3} \approx 2.0P$.

22 There is no overall gain or loss in power since $+7-10+3 = 0\text{ dB}$. So the output power is the same as the input power; the ratio is 1.

23 The overall gain is $10\log\frac{P_{\text{out}}}{P_{\text{in}}} = 10\log\frac{2P}{P} = 10\log 2 \approx 3.0\text{ dB}$.

Hence $-12+G-6.0 = 3.0\text{ dB}$ giving $G = 21\text{ dB}$.

24 $20 = 10\log\frac{P_{\text{signal}}}{P_{\text{noise}}} = 10\log\frac{P_{\text{signal}}}{45}$.

So, $\log\frac{P_{\text{signal}}}{45} = 2.0 \Rightarrow \frac{P_{\text{signal}}}{45} = 10^2 = 100$, giving $P_{\text{signal}} = 100\times 45 = 4.5\text{ W}$.

25 **a** See the graph on on page 569 in *Physics for the IB Diploma*.

b The attenuation per unit length is least for long wavelengths, in particular 1310 nm and 1550 nm, and these are infrared wavelengths.

26 **a** Noise is unwanted power from unwanted signals.

b **i** The main source of noise in a copper wire is the radiation it picks up from nearby wires and other sources of electromagnetic radiation as well as the radiation produced by the accelerated motion of the electrons as they move through the cable itself.

ii The main source of noise in an optical fibre is the dark current in the photodiode that is used to record the arrival of a signal at the end of the fibre.

c **i** Noise in a copper cable can be reduced by reducing its temperature and isolating it as far as possible from other sources of electromagnetic radiation.

ii Noise in an optical fibre can only be reduced by protecting the photodiode from other sources of light and using good quality electronics in the semiconductors of the photodiode junctions.