Answers to Coursebook questions – Chapter G1

1 **a** $t = \dfrac{8\times10^{3}}{3\times10^{8}} = 2.7\times10^{-5} \approx 3\times10^{-5}\,\text{s}$.

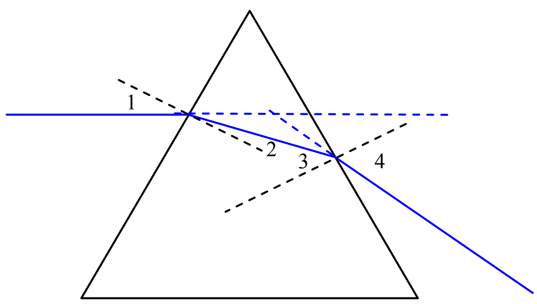
b It is much shorter than any human reaction time, which is why the experiment failed to give a finite speed of light.

2 The time to cover the distance D and back is $t = \dfrac{2D}{c}$.

The wheel needs to turn by an angle $\dfrac{2\pi}{720}$ radians in this time and so the angular speed of the wheel is $\dfrac{2\pi c}{720\times 2D}$.

With f revolutions per second, the angular speed is $2\pi f$ and so $\dfrac{2\pi c}{720\times 2D} = 2\pi f$, giving $c = 720\times 2Df = 720\times 2\times 8.65\times10^{3}\times 25.2 = 3.14\times10^{8}\,\text{m s}^{-1}$.

3 Look at the diagram that refers to the blue ray of light.



$1\times\sin 30^\circ = 1.328\times\sin\theta_2 \Rightarrow \theta_2 = 22.117^\circ$.

$\theta_3 = 180^\circ - \theta_2 - 120^\circ = 180^\circ - 22.117^\circ - 120^\circ = 37.883^\circ$

$1.328\times\sin 37.883^\circ = 1\times\sin\theta_4 \Rightarrow \theta_4 = 54.633^\circ \approx 55^\circ$

The deviation is

$$\begin{aligned}\delta &= (90^\circ - \theta_2 - 60^\circ) + (\theta_4 - \theta_3)\\ &= (90^\circ - 22.117^\circ - 60^\circ) + (54.633^\circ - 37.883^\circ)\\ &= 24.633^\circ \approx 25^\circ\end{aligned}$$

Similarly for the red ray,
$1 \times \sin 30^\circ = 1.321 \times \sin\theta_2 \Rightarrow \theta_2 = 22.241^\circ$

$\theta_3 = 180^\circ - \theta_2 - 120^\circ = 180^\circ - 22.241^\circ - 120^\circ = 37.759^\circ$

$1.321 \times \sin 37.759^\circ = 1 \times \sin\theta_4 \Rightarrow \theta_4 = 53.999^\circ \approx 54^\circ$

The deviation is

$$\begin{aligned}\delta &= (90^\circ - \theta_2 - 60^\circ) + (\theta_4 - \theta_3)\\ &= (90^\circ - 22.241^\circ - 60^\circ) + (53.999^\circ - 37.759^\circ)\\ &= 23.999^\circ \approx 24^\circ\end{aligned}$$

4 Differences include

i laser light is monochromatic (the light bulb's is not),

ii the laser light is coherent (the light bulb's is not),

iii the laser light is directional (the light bulb's is not).

5 **a** The information on a CD is stored as a series of bumps on a spiral. A laser illuminates one side of the CD and is reflected by it. When the laser beam is reflected from the **edge** of a bump, part of the beam travels an extra distance to get back to its source equal to twice the height of the bump. There will be destructive interference if this path difference is half a wavelength, and this is registered as a digital 1.

b The idea is to send a laser beam to a far away object and time the arrival time of its return. Knowing the speed of light allows the calculation of the distance. This idea has been used to measure the distance to the Moon accurately using reflectors left on the lunar surface.

c A bar code is a series of separated parallel black lines that are found on various products. The thickness of a black line is a code for the digits from 0 to 9 and so the pattern of lines is coded information (on, for example, the type of product, its price etc.). A laser beam is moved over the bar code and the reflected light is received by a photodetector. The intensity of the reflected light varies with the thickness of the black line (little reflection from thick lines, more for thin). Therefore the reflected intensity can be used to decode the information stored in the pattern of lines in the bar code.

6 Spontaneous emission is when an electron in an excited state makes a transition to a lower energy state emitting a photon in the process. In stimulated emission the same process takes place but the transition is induced by a photon that is incident on an atom with an electron in an excited state. The electron is stimulated to make a transition down to the ground state, emitting a photon in the process which is identical to the first, i.e. it will have the same **frequency, phase and direction**.

7 Reference to **stimulated emission**: a photon incident on an atom with an electron in an excited state can force or stimulate the electron to make a transition down to the ground state, emitting a photon that will have the same frequency, phase and direction as the original photon.

Reference to **optical pumping**: the idea is to force electrons to make transitions to excited states. The electrons will then very quickly (within 10^{-8} s) return to a metastable state (a state where electrons spend a relatively long time).

Reference to **population inversion**: is the situation when the number of electrons in the metastable state is far greater than that in the ground state.

Reference to **lasing action**: the electrons in the metastable state make transitions to the ground state emitting the laser light photons. These photons, going back and forth in between mirrors, are used to stimulate the emission of identical photons. For every photon causing stimulated emission we get a second identical photon, and so very quickly the intense, coherent laser beam is built up. Part of the laser beam emerges from the semitransparent mirror.

8 Population inversion means that an excited state has more electrons than the ground state.

9 **a** The power emitted may be thought to be spread out over the surface area of a sphere of radius d.

Then the power received per unit area, i.e. the intensity, is $I = \dfrac{P}{4\pi d^2}$.

b The same formula does not hold for a laser since the laser light is highly directional and the formula above assumes radiation equally in all directions.

10 **a** $I = \dfrac{P}{4\pi d^2} = \dfrac{60}{4\pi \times 4.0^2} = 0.30\ \text{W m}^{-2}$.

b $I = \dfrac{P}{A} = \dfrac{8.0\times 10^{-3}}{\pi(1.0\times 10^{-3})^2} = 2546 \approx 2.5\ \text{kW m}^{-2}$.

11 **a** **i** The first minimum in the diffraction pattern of the laser beam as it exits a circular aperture of diameter *d* is $\theta \approx 1.22\frac{\lambda}{d} \approx \frac{\lambda}{d}$.
Thus most of the power in the laser beam will be within this angle.

ii The momentum of the laser beam photons is $p = \frac{h}{\lambda}$. The photons will have an uncertainty in position of order $\frac{d}{2}$ as they exit the aperture. According to the uncertainty principle, they will then develop an uncertainty in momentum of order $\Delta p = \frac{2h}{4\pi d}$ in a direction parallel to the aperture, i.e. normal to the original direction of travel.
This means that the photons will deviate from the original direction by an angle of order $\frac{\Delta p}{p} = \frac{\frac{2h}{4\pi d}}{\frac{h}{\lambda}} \approx \frac{1}{2\pi}\frac{\lambda}{d}$.

The factor of $\frac{1}{2\pi}$ by which the two answers differ is not very different from 1, and so can be tolerated in an estimate such as this.

b Using $\theta \approx \frac{\lambda}{d}$ we get $\theta \approx \frac{632.8 \times 10^{-9}}{0.50 \times 10^{-3}} = 1.3 \times 10^{-3}$ radians.

c $D \approx \mathrm{d}\theta = 500 \times 10^{3} \times 1.3 \times 10^{-3} = 650\,\mathrm{m}$.

