Chapter 12: Optical Communications

1. Refraction

Learning Objectives:

At the end of this topic, you will be able to:

- describe how the refractive properties of glass allow signals to be transmitted over long distances in optical fibres.

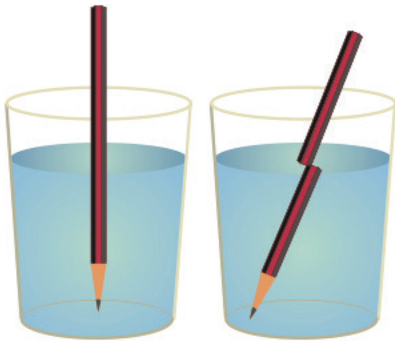
Reflection

When a light beam hits a mirror, it bounces off at the same angle - not surprising - as a ball does the same when it hits the ground, provided it isn't spinning.

Total internal reflection

Coming from the Latin verb "to break", this effect happens when a wave such as a light beam changes speed.

Refraction can result in strange visual effects like the one illustrated opposite.



The speed at which light travels depends on the material it is travelling through. In a vacuum, light travels at around 300 000 km s^{-1}; in diamond, around 124 000 km s^{-1}.

The wave speed determines the refractive index of the medium. The refractive index of the medium is defined as:

$$\frac{\text{speed of light in vacuum}}{\text{speed of light in the medium}}$$

If the refractive index of a medium is known, the wave speed in the medium can easily be calculated.

For example:

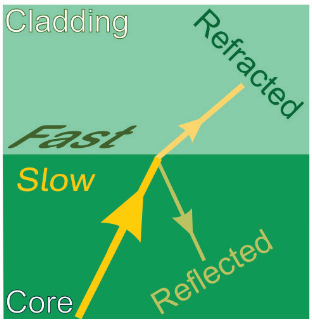
An optical fibre has a refractive index of about 1.5, so the wave speed in the fibre is:
$\lambda = 3 \times 10^8 \text{ m s}^{-1} \div 1.5 = 2 \times 10^8 \text{ m s}^{-1}$

The left-hand diagram below shows that when light beam enters a material where it travels faster, its direction swings towards the boundary.

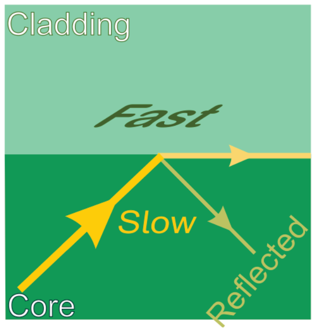
At one specific angle, called the **critical angle**, the refracted beam travels along the boundary, as shown in the centre diagram.

When the incoming beam moves further towards the boundary, there is no refracted beam. All the light is reflected at the boundary at the same angle as it arrives. This is known as **total internal reflection**, shown in the right-hand diagram.

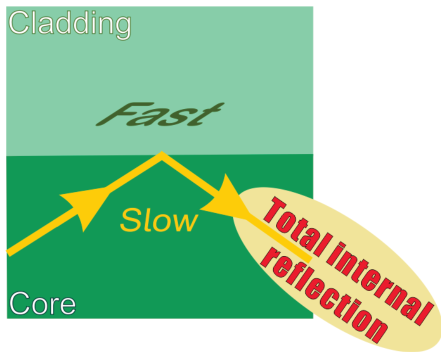
At less than the critical angle



At the critical angle



Beyond the critical angle

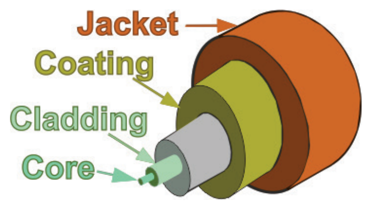


Total internal reflection can happen only when light arrives at a boundary between a 'slow' material and a 'fast' material, i.e. moving from an 'optically dense' material to an 'optically less dense' material.

Just to be clear, both materials are transparent. Light can travel through them, but in this situation, it all bounces off the boundary. The boundary acts as a perfect mirror.

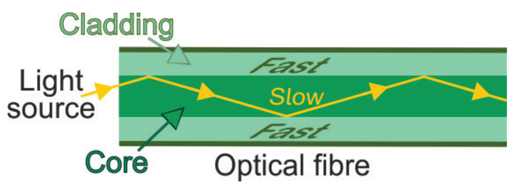
Total internal reflection is the key to optical fibre communication.

Optical fibres



The diagram opposite shows the simplified structure of an optical fibre.

The core and cladding act as a light 'pipe'. Provided that the angle is right, a beam of light bounces along the core, undergoing total internal reflection whenever it reaches the boundary between them.



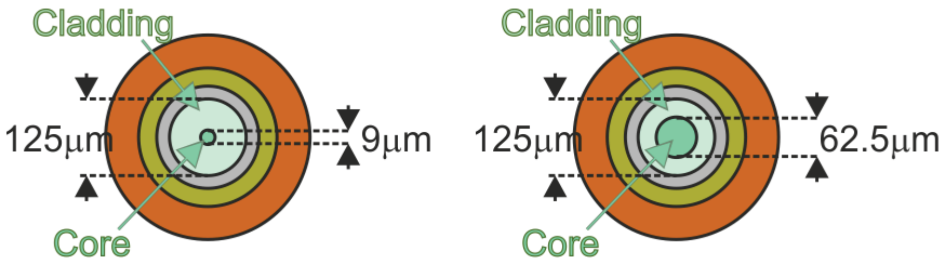
The jacket provides mechanical strength for the fibre.

Optical fibres come in two main types, single-mode and multi-mode.
The physical difference is that a single-mode fibre has a very fine core compared to that in a multi-mode fibre.

Optically, 'mode' refers to the way in which light travels down the fibre.
In a single-mode fibre, light follows one path only, parallel to the length of the fibre.

A multi-mode fibre, being fatter, can gather more light from the source, but it allows light to follow a number of different paths ('modes') in travelling down it.

The signal is not degraded as much as in multi-mode fibres, making single-mode more suitable for long-distance communication. They usually use laser light sources.
Multi-mode fibre transmission is more prone to dispersion issues and tends to be used for short-range communication, e.g. as the 'backbone' cable for broadband provision within a building.



Single-mode fibre Multi-mode fibre

Advantages of optical fibre communication

Bandwidth:
Fibre optic cables have a much greater bandwidth than copper cables, meaning that they can transport much more information in a given time. They can support data transmission speeds up to several gigabits per second.

Interference:
They are immune to electromagnetic interference, so that they can function in electrically noisy environments.

Security:
Optical fibres are difficult to 'tap' as they do not radiate electromagnetic energy which could be intercepted. It is the most secure medium available for carrying sensitive data.

Lower power loss:
Signals can be transmitted over longer distances before they need regeneration.

Physical properties:
Fibre optic cables are thinner and lighter than copper cables. They occupy much less space compared to copper cables of the same information capacity. They have greater tensile strength than copper cables of the same diameter.

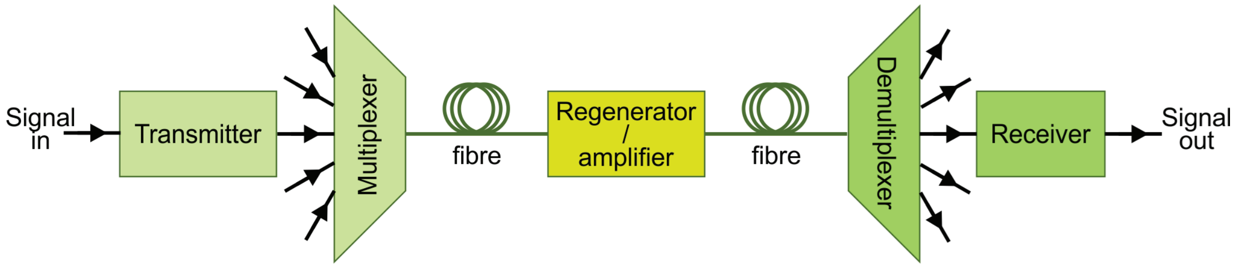
Disadvantages of optical fibre communication

Installation:
Optical fibres are difficult to splice together. Such connections result in loss of the light due to scattering. They are not as robust as copper wire - if bent too far, they break. They are highly susceptible to damage during installation.

Expensive to install:
Specialist technology is needed to install and test optical fibre systems.

Components of an optical fibre communication system

A basic fibre optic communication system consists of a transmitter that converts the electrical signal into a light signal. The light source is pulsed on and off. The pulses are carried by an optical fibre cable from source to destination. A light-sensitive receiver at the destination converts the pulses back into an electrical signal, the digital ones and zeros of the original signal.



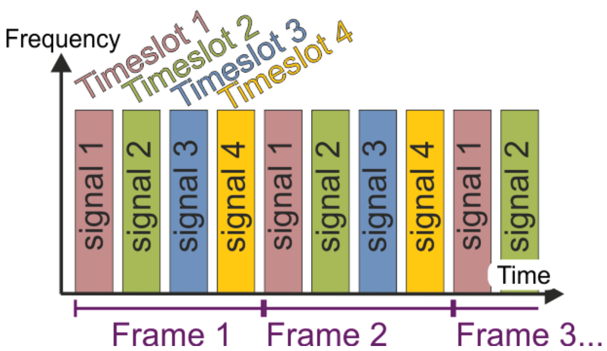
No communication system is loss-free. Where distances are big, a repeater may be used to boost and regenerate the original signal. There are a number of different approaches to the task, including ‘all-optical’ devices and ‘optical-electrical-optical’ systems that convert the optical signal back to an electrical signal for processing before converting it back to an optical signal.

Multiplexing

To make best use of the communication link, other optical signals are added, using a multiplexer. At the receiving end of the fibre, a demultiplexer separates the signals. Receivers then convert each back into electrical signals.

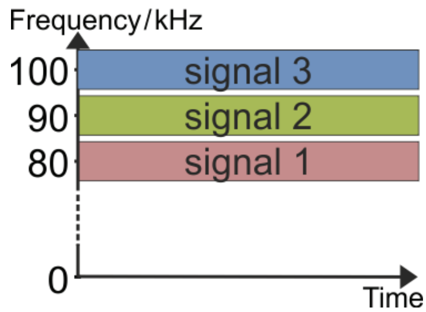
A number of techniques can be used to multiplex signals:

- Time-division multiplexing (TDM);
- Frequency-division multiplexing (FDM);
- Wavelength-division multiplexing (WDM).



The first of these, TDM, was covered in earlier chapters. It is commonly used in circuit-switched networks, such as the public switched telephone network (PSTN). In TDM, different signal sources take turns to use the communication link.

In FDM, all signal sources transmit continuously but modulate their information onto different carrier frequencies. The diagram shows three signals modulated onto carrier frequencies of 80 kHz, 90 kHz and 100 kHz.

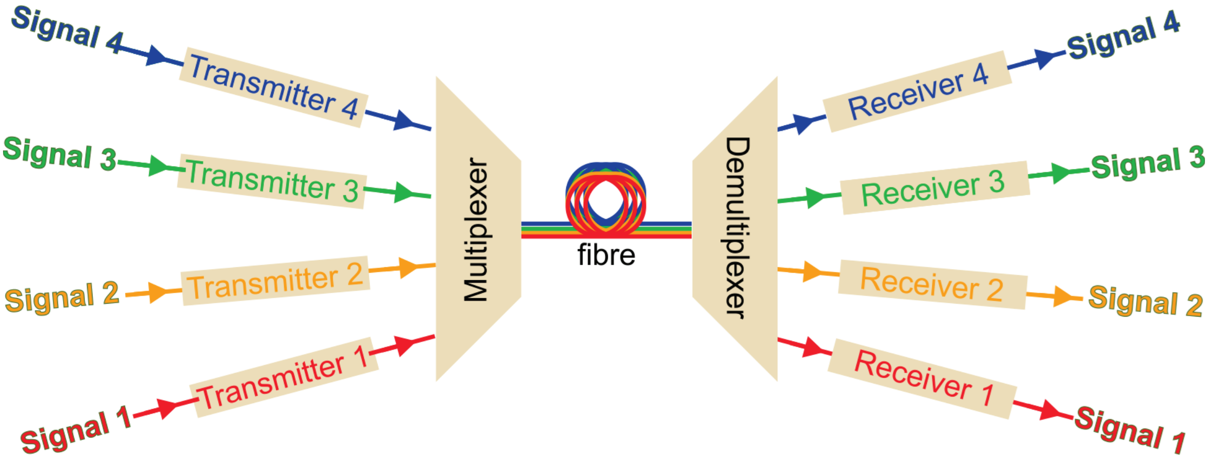


Radio and television broadcasting is an obvious example of FDM.

WDM is effectively frequency-division multiplexing. In optical communication systems, the signal is usually described by its wavelength, whereas in FDM, it is described by its frequency. This is purely a matter of convention since wavelength and frequency are both ways of describing the same information.

- FDM usually refers to multiplexing analogue electrical signals onto radio-frequency carriers, as in radio broadcasting. At the receiver, the signals are demultiplexed using electrical filters.

- WDM usually refers to multiplexing digital optical signals, typically up to sixty, onto different wavelength carriers (i.e. colours) generated by different laser light sources. The individual signals propagate down the fibre without interfering with one another. At the receiver, the signals are demultiplexed using optical filters.



The wave equation

As considered earlier, frequency and wavelength are related by the wave equation:

$$c = f\lambda$$

where	c	=	wave speed;
	f	=	frequency;
	λ	=	wavelength.

Remember that the wave speed is different for different medium.

Example 1:

A fibre optic cable carries a number of telephone signals using WDM.
One signal uses an infra-red carrier with a frequency of 120 THz.
The wave speed of infra-red light in the fibre is 1.8 x 108 m s^{-1}.

Calculate the wavelength of the infra-red carrier.

Using the wave equation

$$c = f\lambda$$
$$1.8 \times 10^8 = 120 \times 10^{12} \times \lambda$$
$$\lambda = \frac{1.8 \times 10^8}{120 \times 10^{12}}$$
$$= 1.5 \times 10^{-6} \text{ m}$$
$$= 1.5 \text{ µm}$$

Example 2:

(a) Determine the bandwidth available between the wavelengths 1300 and 1350 nm when the wave speed in an optical fibre is 2 x 108 m s^{-1}.

Using $$c = f\lambda$$

for a wavelength of 1300 nm:

$$2 \times 10^8 = f \times 1300 \times 10^{-9}$$
$$f = \frac{2 \times 10^8}{1300 \times 10^{-9}}$$
$$= 153.8 \times 10^{12} \text{ Hz}$$
$$= 154 \text{ THz}$$

for a wavelength of 1350 nm:

$$2 \times 10^8 = f \times 1350 \times 10^{-9}$$
$$f = \frac{2 \times 10^8}{1350 \times 10^{-9}}$$
$$= 148.1 \times 10^{12} \text{ Hz}$$
$$= 148.1 \text{ THz}$$

Bandwidth = 153.8 − 148.1 = 5.7 THz
= 5700 G Hz

(b) Determine the maximum number of channels available between these wavelengths when the channel bandwidth is 160 GHz.

Number of channels

$$N_{CH} = \frac{\text{available bandwidth}}{\text{channel bandwidth}}$$
$$N_{CH} = \frac{5700 \text{ GHz}}{160 \text{ GHz}} = 35.6$$
$$N_{CH} = 35 \text{ channels}$$

Exercise 12.1

1. A fibre optic cable carries signal with a frequency of 220 THz.
The wave speed of light in the fibre is 2×10^8 m s^{-1}.

Calculate the wavelength of the signal.

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2. A signal transmitted in a fibre optic cable has a wavelength of 840 nm.
The wave speed of light in the fibre is 2.1×10^8 m s^{-1}.

Calculate the frequency of the signal.

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3. (a) Determine the bandwidth available between the wavelengths 840 and 880 nm when the speed of light in an optical fibre is 2.1×10^8 m s^{-1}.

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(b) Determine the maximum number of channels when the channel bandwidth is 120 GHz.

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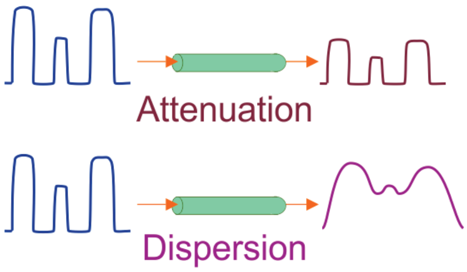
2. Losses in optical fibres

Learning Objectives:

At the end of this topic, you will be able to:

- describe the effects of dispersion, attenuation and radiation losses in optical fibre communication and the relative advantages of single and multi-mode optical fibres in a communication network.



Long-distance communication systems usually include repeaters to boost and regenerate the signal.
This is because a number of loss factors affect the signal.
These include attenuation, scattering, bending losses and dispersion.
They are usually expressed in decibels per kilometre (dB km^{-1}).

Attenuation

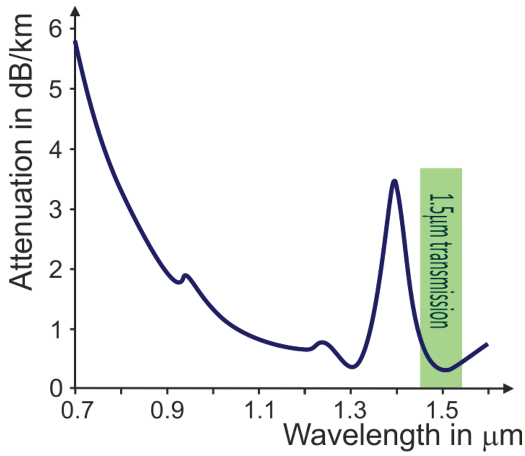
Attenuation is the loss of light energy between the input and the output signals. This loss depends on the wavelength of the light and on the nature of the propagating material and increases with the distance travelled through the material.
It is impossible to manufacture absolutely pure glass. Light is absorbed by glass in the optical fibre and is converted into other forms of energy, like heat.
The following table compares attenuation in dB with power loss expressed as a percentage:

Attenuation in dB	Percentage power loss
0.1	2%
3	50%
10	90%

There are three main causes of attenuation:

- absorption by the core and cladding (caused by the presence of impurities) and the leaking of light from of the cladding (when light reflects off the cladding / core interface, it actually travels for a short distance within the cladding before being reflected back);
- scattering losses caused by microscopic variations in the material and manufacturing imperfections;
- radiation losses occurring where at sharp bends in the fibre or where joints are misaligned.

Absorption is wavelength dependent as the graph shows, meaning that some wavelengths are more suitable than others for fibre optic communication, requiring fewer repeaters. Using a wavelength of 1.5 μm, for example, can reduce attenuation to 0.2 dB km^{-1}.



Attenuation is also caused by components such as cable splices and connectors, and by scattering and bending losses.

Scattering

This occurs when the light is diverted into other directions by impurities in the glass. Light is not absorbed, just sent in another direction.

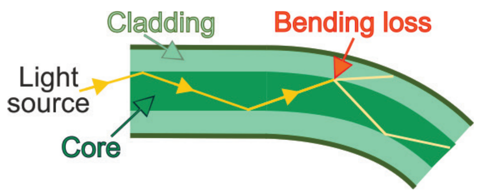
Bending losses

As pointed out earlier, total internal reflection occurs only when light arrives at the boundary between core and cladding at an angle ***beyond*** the critical angle.

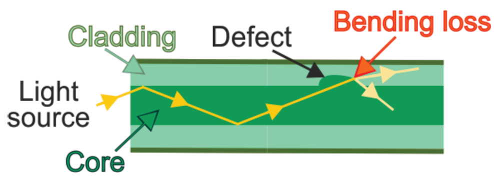
Where the fibre is bent, this condition may not be met and some of the light may be refracted into the cladding and lost. This is known as bending loss.

There are actually two situations in which this loss can occur:

- on a **macroscopic** level, where the fibre is curved for some reason, such as going round a corner in a building;

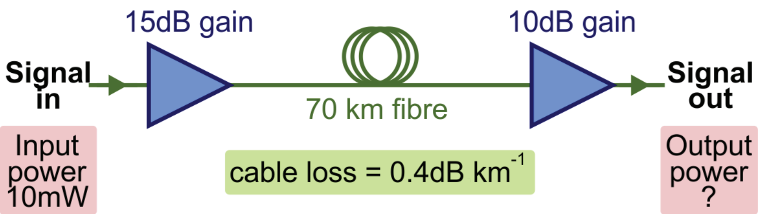


- on a **microscopic** level, where a defect in the surface between the core and the cladding modifies the angle at which the light strikes the boundary.



Output power/SNR of optical communication system

Example:



(a) Calculate the output power for the optical communication system shown in the diagram.

$$\text{Gain in dB} = 15 - (0.4 \times 70) + 10 = -3 \text{ dB}$$

$$\text{Gain in dB} = -3 = 10 \log_{10}\left(\frac{P_{OUT}}{10}\right)$$

$$-0.3 = \log_{10}\left(\frac{P_{OUT}}{10}\right)$$

$$10^{-0.3} = \frac{P_{OUT}}{10}$$

$$P_{OUT} = 10^{-0.3} \times 10 = 5.01 \text{ mW}$$

(b) The signal-to-noise ratio (SNR) at the receiver is 28 dB.

What is the maximum acceptable value of noise power at the receiver?

$$SNR = 28 = 10 \log_{10}\left(\frac{5.01}{P_N}\right)$$

$$2.8 = \log_{10}\left(\frac{5.01}{P_N}\right)$$

$$10^{2.8} = \frac{5.01}{P_N}$$

$$P_N = \frac{5.01}{10^{2.8}}$$

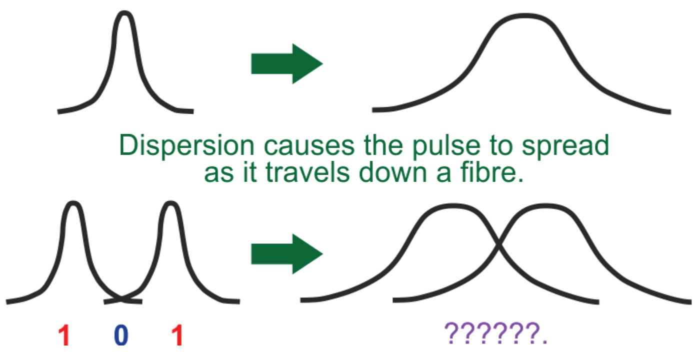
$$= 7.94 \times 10^{-3} \text{ mW} = 7.94\ \mu\text{W}$$

Dispersion

Dispersion is the spreading of the signal over time.

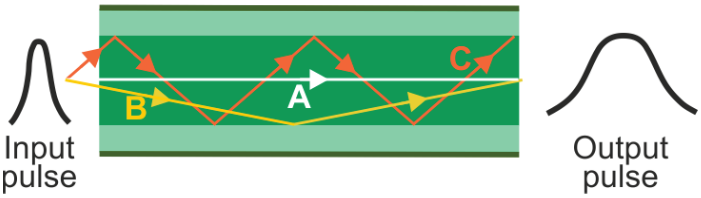
It limits the bit-rate (duration of each bit) and the distance that the signal can travel before becoming unrecognisable.

It has several possible causes, including modal and chromatic dispersion.



Modal dispersion

When a thick optical fibre is used, different light beams can travel by different routes (and so travel different distances). When they recombine, the original sharp pulse of light is spread into a less distinct signal.
In the diagram, light spreads out from the source and enters the fibre at various angles. Light following path **A** travels the shortest distance. Path **B** is slightly longer and path **C** longer still.
All three light beams set off together, as a sharp pulse. They reach the end of the fibre at different times, **A** first, then **B** and finally **C**. The original pulse has spread out.

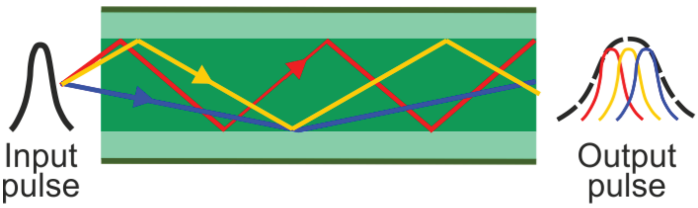


One way to minimise this problem is to use single-mode fibres.

Chromatic dispersion

The speed of light in an optical fibre depends on its wavelength (and colour). Each wavelength follows a different path through the fibre and so takes a different time to reach the end.

As a result, an initially sharp pulse of light containing a range of wavelengths becomes less distinct after passage through the fibre.



Laser light sources create less chromatic dispersion than LED sources because they emit a narrower range of frequencies.

Exercise 12.2

1. A digital optical fibre system has an input power of 10mW and a SNR of 60 dB.

   The ambient noise power is 1 x 10^{-14} W.

   (a) Calculate the minimum output power required before regeneration of the signal is necessary.

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   (b) Calculate the total attenuation in the optical fibre cable.

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   (c) Determine the maximum distance between regenerators to achieve an SNR of 60 dB when the attenuation in the cable is 1.2 dB km^{-1}.

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3. Optical technology

Learning Objectives:

At the end of this topic, you will be able to:

- describe the principles of operation of circuits for converting between electrical and optical signals
- describe the use of LED and laser light sources in an optical fibre transmitter.

Light sources for optical communication systems

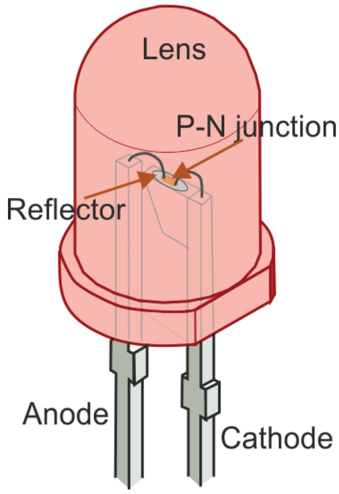
To be suitable, a source must:

- transmit light at a wavelength appropriate to the optical fibre;
- be able to be modulated fast enough to transmit data at the required speed.

The two common types of light source are LEDs and laser diodes.

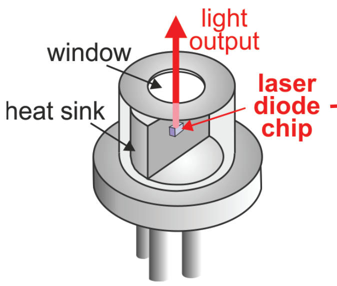
LED

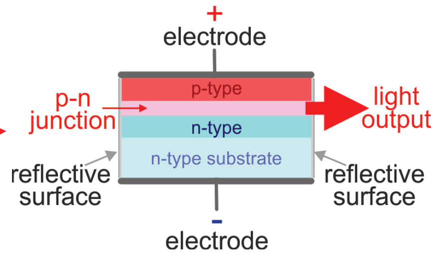
A light-emitting diode (LED) is a p–n junction diode that emits light when forward-biased. This is the result of holes from the p-type region annihilating electrons from the n-type region, creating a pulse of light. They are made from rather more exotic semiconducting materials than in standard silicon p-n junction diode, using compound semiconductors such as gallium arsenide and indium gallium nitride.
The colour of the light produced is determined by the energy band gap of the semiconductor. This light contains a narrow range of frequencies, though wider than that produced by a laser diode. As a result, chromatic dispersion is more of a problem with LEDs than with laser diodes.



Laser Diode

The laser diode is encapsulated in a similar way to the LED. As a high-power device, it requires a heat sink. At its heart is another type of p-n junction, as the right-hand diagram shows. Like LEDs, the laser diode p-n junction uses exotic compound semiconducting materials.
It generates light in a similar way to LEDs, from electron-hole pair recombination. However, the light generated bounces backwards and forwards in a resonant cavity formed by parallel reflective surfaces. In the process, it is amplified (the 'a' in 'laser'). A proportion escapes from one surface as an intense and coherent beam (i.e. a relatively continuous beam of light, travelling in a specific direction).





LED vs laser diode

The table compares some properties of LED and laser diode light sources for use with optical communications.

Property	LED	Laser diode
Cost	Low	High
Power output	Low	High
Speed	Low	High
Frequency range emitted	High	Low
Transmission distance	Short	Long

LEDs emit light over a much broader area than do laser diodes. As a result, the power they can deliver to an optical fibre is much less. This limits their use to multimode fibres and to short-to-medium transmission distances.
On the other hand, LEDs are more robust and have a greater life-expectancy. They also have a much higher power conversion efficiency, twenty to thirty times that of a laser diode.
Laser diodes can be switched more rapidly than LEDs, leading to greater data-transfer rates and can be used with both multimode and single mode fibres.

Energy and power considerations

Both LEDs and laser diodes convert electrical energy into light energy.
The energy, **E**, delivered by a light source in an interval of time, **t**, is given by the formula:

$$\mathbf{E = P \times t}$$

For this formula, **E** will be in joules when **P** is in watts and **t** is in seconds.

Example 1

A laser emits 16 mJ of energy in 2 ms.
Calculate the power delivered

Using

$$P = \frac{E}{t}$$

$$P = \frac{16 \times 10^{-3}}{2 \times 10^{-3}} = 8 \text{ mW}$$

Example 2

A laser diode with an average optical power output of 2W outputs 5000 pulses per second.
Each pulse has a duration of 200 ns.

What is the peak power delivered by each pulse?

Using **E** = **P** x **t** the energy delivered by each pulse, $E = \frac{2}{5000} = 0.0004$ J

This energy is delivered in time **t** = 200 ns,

so the peak power, $P = \frac{E}{t} = \frac{0.0004}{200 \times 10^{-9}} = 2000$ W

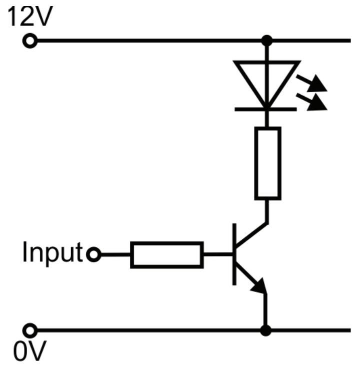
Encoders and decoders

At its simplest, an encoder converts electrical signals consisting of binary 0's and 1's, into pulses of light. A light pulse represents logic 1. Absence of light represents logic 0. These pulses travel down an optical fibre to a decoding device. This converts the pulses of light back into electrical binary signals.

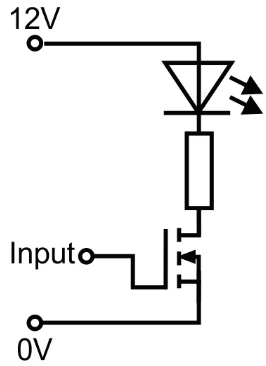
Transmitter driver circuits for LED light sources

The LED must switch on and off rapidly to generate the light pulses to represent the data being transmitted via the optical fibre.

The circuit diagram, shown opposite, uses a transistor to drive the LED. Typically, a current of 40-80 mA flows through the LED when lit.



Alternatively, a MOSFET can be used to drive the LED, as shown in the second diagram.

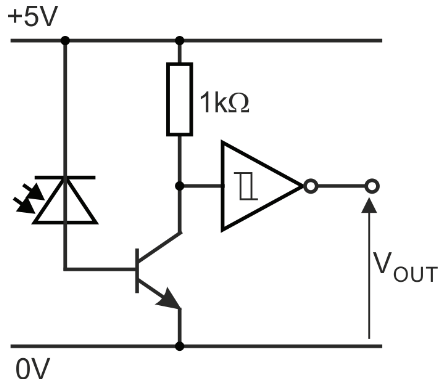


Receiver light detectors

At the other end of the optical fibre, a receiver converts the light pulses back into an electrical signal.

Photodiode detector

The photodiode is the most common light detector. When reverse-biased, a current can be created when light is absorbed.



The light creates electron-hole pairs, which separate to produce a tiny current.

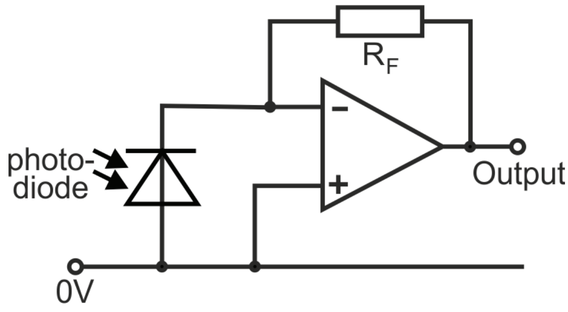
The Schmitt inverter cleans up the signal.

When light falls on the photodiode (i.e. a logic 1 signal), the base current increases, the transistor conducts and the voltage at the collector drops to approximately 0V.

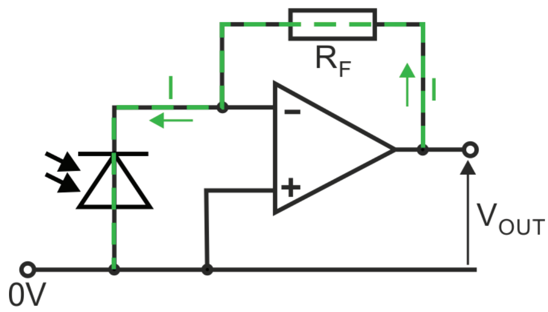
The output of the Schmitt inverter then goes high, outputting a logic 1 electrical signal.

Op-amp detector

This circuit is known as a current-to-voltage converter.



Assuming that no current flows into the inverting input of the op-amp (i.e. assuming that it has infinite input impedance), the photodiode current flows through the feedback loop from the output of the op-amp, as shown in the second diagram.



Provided that the output of the op-amp is not saturated, both inputs sit at the same voltage, 0V in this case, since the non-inverting input is connected to 0V.

The voltage drop across the feedback resistor, $\mathbf{R_F}$, is equal to **I** x $\mathbf{R_F}$. Therefore, the output voltage, $\mathbf{V_{OUT}}$, = **I** x $\mathbf{R_F}$.

In other words, the output voltage is proportional to the current, I, generated in the photodiode.

For a digital input signal, a typical value of diode current corresponding to logic 1 could be 0.3 mA giving $\mathbf{V_{OUT}}$ = 6V for a value of $\mathbf{R_F}$ of 20 kΩ.

Exercise 12.3

1. A laser emits 20 mJ of energy in 1.5 ms. Calculate the power delivered.

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2. A laser diode with an average optical power output of 3W outputs 4000 pulses per second. Each pulse has a duration of 250 ns.
What is the peak power delivered by each pulse?

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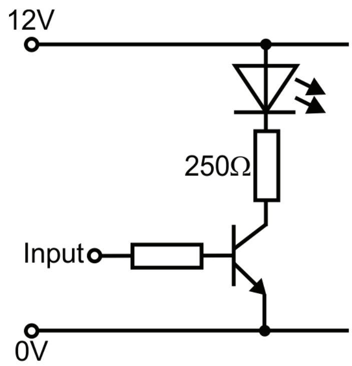
3. The diagram shows an LED transmitter.
A Logic 1 input saturates the transistor.
Determine the power in the LED if V_F = 2.2 V



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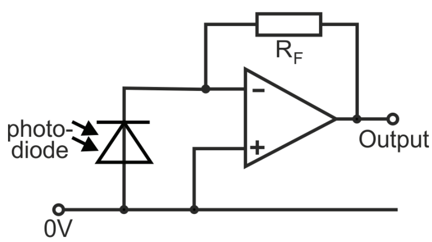
4. An optical fibre receiver is shown on the right.
A digital input signal corresponding to logic 1 produces a photodiode current of 0.4 mA.
Calculate V_{OUT} if R_F = 18 kΩ



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