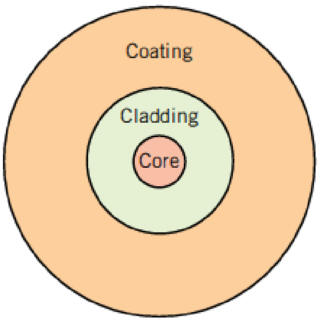
D) Optical Fibres

This makes use of the phenomenon of total internal reflection (see page 57 of notes) which occurs in considering refraction at an interface when light goes from an optically-dense (high refractive index n) medium to a less-optically dense medium (n') at greater than the critical angle θ_C where $\sin \theta_C = n'/n < 1$.

Basically, an optical fibre is a cylindrical composite material where there is a high refractive-index core surrounded by a lower refractive index cladding.

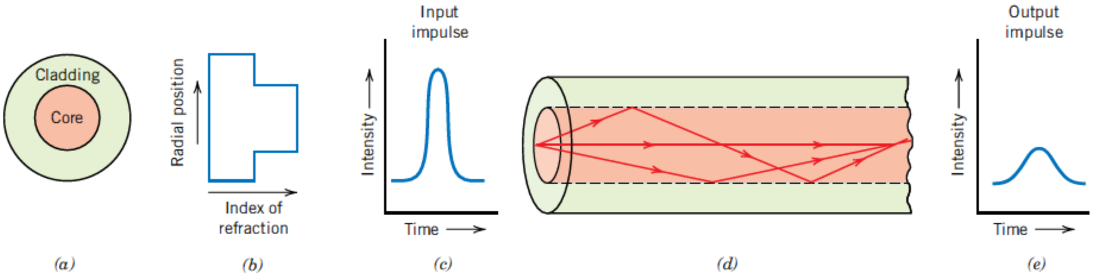


Cross section of a simple optical fibre, where the requirement is

$$n_{\text{core}} > n_{\text{cladding}}$$

The outer coating is present only to provide protection and physical strength / durability to the fibre.

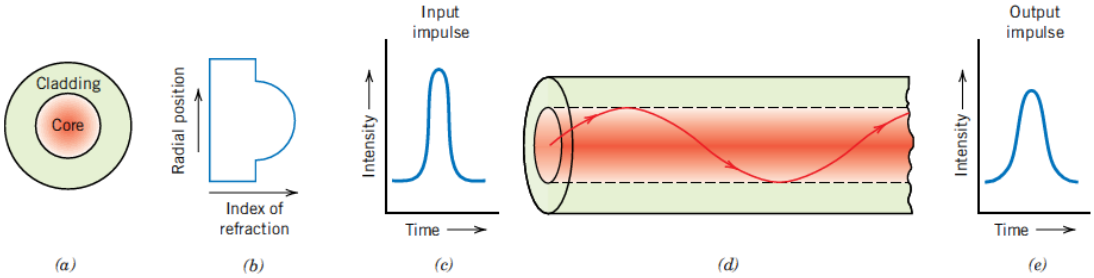
In the simplest case the core and cladding regions are each characterized by constant refractive indices:



Step-index optical fibre design: (a) Cross section; (b) Radial refractive index profile; (c) Input light pulse; (d) Internal reflection of light rays; (e) Output light pulse.

In the above design, the output pulse is generally significantly broader than the input pulse (an effect known as “pulse broadening”), which is an undesirable degradation of the signal being transmitted. It occurs because different light rays (injected at the same instant) can follow slightly different reflection schemes (at different angles) and arrive at the output at slightly different times.

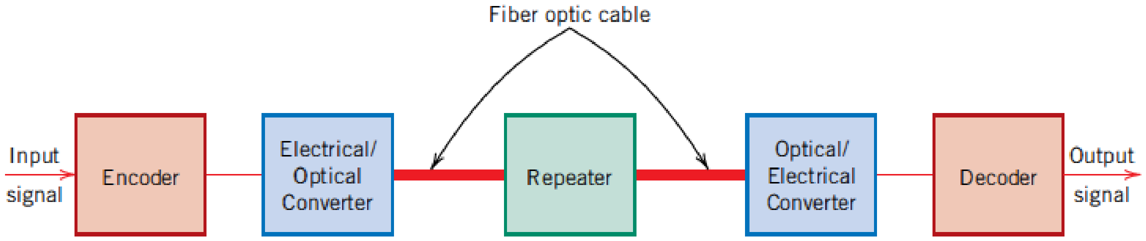
A better design is achieved by varying the refractive index of the core in the radial direction:



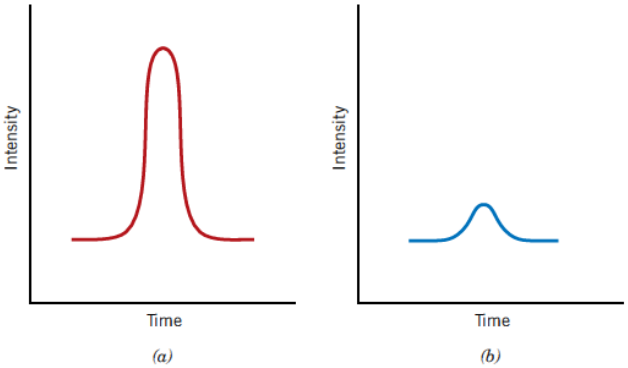
Graded-index optical fibre design: (a) Cross section; (b) Radial refractive index profile; (c) Input light pulse; (d) Internal reflection of light rays; (e) Output light pulse.

In this case, by making the refractive index of the core decrease with radial distance (usually in a parabolic fashion) until it reaches the cladding value, one particular optical path can be optimized and the pulse broadening can be considerably reduced. This grading of the refractive index is achieved by selectively adding impurities as a function of distance from the surface for the cylindrical core (e.g., B_2O_3 or GeO_2 impurities could be added to a SiO_2 silica glass core).

The elements of a practical optical fibre communications system are shown schematically below:



The input signal in electronic format must first be "encoded", i.e., converted to optical pulses that represent the 1's and 0's of the binary code. A simple scheme is as follows:



Digital encoding scheme for optical communication:
(a) A high-power pulse of photons corresponds to a "1";
(b) A lower-power pulse corresponds to a "0".

The converter is typically a semiconductor laser, which emits monochromatic and coherent light. The usual wavelengths are in the 0.78 µm to 1.6 µm range (in the infra red part of the em spectrum), because absorption losses are then much lower.

The optical pulses are then fed into the optical fibre (described earlier) and transmitted – distances up to about 40 km are possible without serious attenuation of the signal. For greater distances than that, a series of "repeaters" would be employed to amplify and regenerate the signal.

E) Inelastic scattering of light from materials

When light is incident on a solid material, a fraction might pass through without interaction (and so with unchanged frequency) while another fraction might be initially absorbed and re-emitted.

In the re-emitted case, there are several possibilities that include direct emission of a photon with the same energy (an "elastic" process) or emission of two photons (whose energies add up to the energy of the incident photon) or emission of one photon and one phonon (quantized lattice vibration).

For example, in a doped semiconductor we previously had (on page 59):

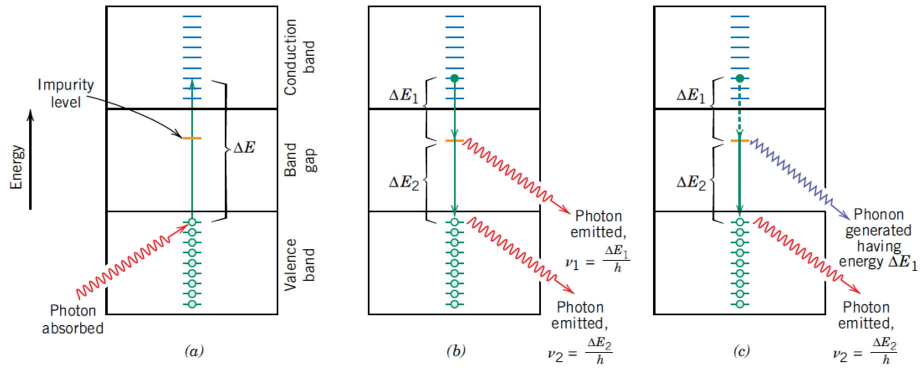
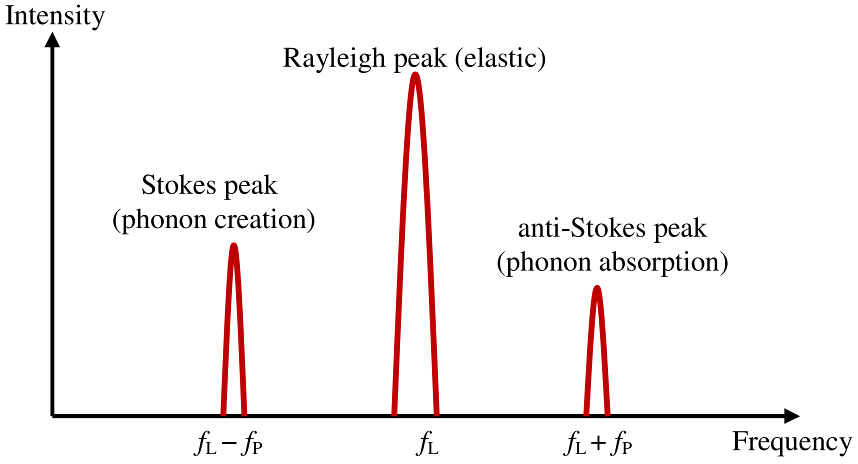


Diagram (c) on the right is an example of *inelastic scattering* of light. The outgoing, or scattered, photon has a different energy and frequency compared with the incident photon. The energy difference has been used to create the phonon, i.e., energy is given up to the crystal lattice of the material.

From energy conservation, incident photon energy > scattered photon energy
which implies incident photon frequency > scattered photon frequency

The inverse process in which the energy of an incoming photon and a phonon in the material combine to produce a scattered photon is also possible. In this case, energy conservation gives
incident photon energy < scattered photon energy
which implies incident photon frequency < scattered photon frequency

The experimental results for the scattering process would look schematically like



This is a plot of light scattering intensity (number of scattered photons) versus frequency. The main elastic peak (also called the Rayleigh peak) is very intense, and the other two inelastic peaks are very much weaker. The phonon creation and absorption peaks are referred to as the Stokes and anti-Stokes process, respectively.

There are two different experimental techniques in use, depending mainly on the magnitude of the frequency shifts. These are:

- Raman scattering – frequency shifts greater than about 0.15 THz (and typically up to ~12 THz); the scattered light is detected using a grating spectrometer.
- Brillouin scattering – frequency shifts less than about 0.15 THz (and typically greater than ~0.01 THz); the scattered light is detected using a Fabry-Perot spectrometer.

Note that 1 THz = 10^{12} Hz and the frequency for visible light is of order 5×10^{14} Hz, so the frequency shifts are relatively very small.

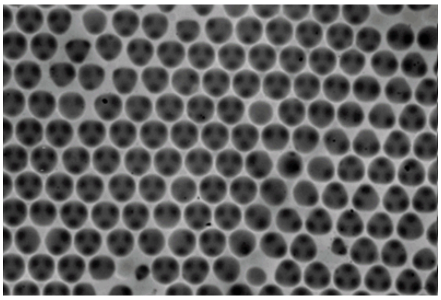
F) Photonic band-gap materials

"Photonics" is the analog of "electronics" where the idea is to use photons instead of electrons to transmit a signal (information). Potentially, a photonic (or any optical) device will work faster than a similar electronic device, because the speed of light is involved.

Most important electronic devices are based on semiconductor technology. The semiconductors have band gaps (typically ~ 1 or 2 eV), so there are valence bands and conduction bands and selective doping (addition of impurities) gives the possibilities of *n*-type and *p*-type materials. The search for photonic band-gap materials means finding (and controlling) the analogous behaviour using photons (light) instead of electrons.

This type of research was initiated around 1987 by two scientists, E. Yablonovich and S. John, working independently. The aim is to design an artificial crystal structure (with a well-defined periodicity) analogous to the atomic crystal structure of semiconductors like Si, Ge, or GaAs. The analog of doping with impurities in the semiconductor case, producing donors and acceptors, is to introduce structural defects in the periodic array in the photonic material. It is relatively straightforward to achieve the required "band-gap effects" in one dimension (1D) or even in 2D, but very challenging in 3D.

For example in 2D, honey-comb structures have been used with reasonable success:



A 2D photonic crystal having a honey-comb structure formed with holes through a solid structure. "Impurity bands" are introduced by forming lattice defects.

In 3D photonic crystals have been formed with some success using (e.g.) the so-called "wood-pile" structure illustrated opposite.