EC010 803 LIGHT WAVE COMMUNICATION

Objectives

• To understand the behavior of light wave

• To know principle of light wave communication and the characteristics of optical devices.

Module 1 (12hrs) : Recollection of basic principles of optics: ray theory- critical angle- total internal reflection - Optical wave guides - Propagation in fibre- expression for acceptance angle-numerical aperture- V number – modes, mode coupling - SI fibre and GI fibre - single mode fibers


References

1. John M Senior, “Optical fiber Communications Principles and Practice:”, Pearson Education
2. Djafar K Mynbaev, “Fibre optic communication technology:”, Pearson Education.
3. Franz and Jain , “Optical Communications Components and Systems”: Narosa
4. Harold Kolimbiris, “Fiber Optics Communications”, Pearson Education
7. Subir Kumar Sarkar, “Optical fibre and fibre optic communication”, S Chand & co. Ltd
**MODULE 1**

**Ray Optics:**

Ray Optics is based on three laws which describe the propagation of rays:

1. **Light rays in homogenous media are straight lines**

2. **Law of Reflection:** Reflection from a mirror or at the boundary between two media of different refractive indices: the reflected ray lies in the plane of incidence, the angle of reflection equals the angle of incidence.

3. **Snell’s law of refraction:** At the boundary between two media of different refractive index $n$, the refracted ray lies in the plane of incidence; the angle of incidence is related to angle of refraction as:

   $$n_i \sin \theta_i = n_t \sin \theta_t$$

**Critical Angle:** For $n_1 > n_2$, the angle of refraction $\theta_2$ is always greater than the angle of incidence $\theta_1$. When the angle of refraction $\theta_2$ is $90^\circ$, the refracted ray emerges parallel to the interface between the media. This is the limiting case of refraction and the angle of incidence is known as the critical angle $\theta_c$. 
Total internal reflection

At angles of incidence $\theta > \theta_c$, the light is totally reflected back into the incidence higher refractive index medium. This is known as total internal reflection.

Light ray guiding condition

Light ray that satisfies total internal reflection at the interface of the higher refractive index core and the lower refractive index cladding can be guided along an optical fiber.
Optical fiber structures

A typical bare fiber consists of a core, a cladding and a polymer jacket (buffer coating). The polymer coating is the first line of mechanical protection. The coating also reduces the internal reflection at the cladding, so light is only guided by the core.

![Diagram of fiber structure](image)

**V number**

The V number is a parameter which is often used in the context of step-index fibres. It is defined as

\[
V = \frac{2\pi}{\lambda} a.\text{NA} = \frac{2\pi}{\lambda} a\sqrt{n_1^2 - n_2^2}
\]

where \(\lambda\) is the vacuum wavelength, \(a\) is the radius of the fiber core, and NA is the numerical aperture.

The V number can be interpreted as a kind of normalized optical frequency. It is relevant for various essential properties of a fiber:

- For V values below \(\approx 2.405\), a fiber supports only one mode per polarization direction (→ single-mode fibers).
- Multimode fibers can have much higher V numbers. For large values, the number of supported modes of a step-index fiber can be calculated approximately as
\[ M \approx \frac{V^2}{2} \]

- The \( V \) number determines the fraction of the optical power in a certain mode which is confined to the fiber core. For single-mode fibers, that fraction is low for low \( V \) values (e.g. below 1), and reaches \( \approx 90\% \) near the single-mode cut-off at \( V \approx 2.405 \).

- There is also the so-called Marcuse equation for estimating the mode radius of a step-index fiber from the \( V \) number.

- A low \( V \) number makes a fiber sensitive to micro-bend losses and to absorption losses in the cladding. However, a high \( V \) number may increase scattering losses in the core or at the core–cladding interface.

- For certain types of photonic crystal fibers, an effective \( V \) number can be defined, where \( n_2 \) is replaced with an effective cladding index. The same equations as for step-index fibers can then be used for calculating quantities such as the single-mode cut-off, mode radius and splice losses.

**Acceptance Angle and Numerical Aperture**

The Numerical Aperture (NA) is a measure of how much light can be collected by an optical system such as an optical fibre or a microscope lens. The NA is related to the acceptance angle \( \theta_a \), which indicates the size of a cone of light that can be accepted by the fibre.

Only rays with a sufficiently shallow grazing angle (i.e. with an angle to the normal greater than \( \theta_c \)) at the core-cladding interface are transmitted by total internal reflection.
Any rays which are incident into the fiber core at an angle $> \theta_a$ have an incident angle less than $\theta_c$ at the core-cladding interface. These rays will not be totally internally reflected, thus eventually loss to radiation.

**Mode Theory**

The mode theory, along with the ray theory, is used to describe the propagation of light along an optical fiber. The mode theory uses electromagnetic wave behavior to describe the propagation of light along a fiber.
The optical wave is effectively confined within the guide and the electric field distribution in the x direction does not change as the wave propagates in z direction. The stable field distribution in the x direction with only a periodic z dependence is known as a mode. A specific mode is obtained only when the angle between the propagation vectors or the rays and the interface has a particular value. Hence, the light propagating within the guide is formed into discrete modes, each typified by a distinct value of $\theta$.

The component of plane wave in the x-direction is reflected at the interface between the higher and lower refractive index media. The component of wave in x-direction gives constructive interference to form standing wave patterns across the guide when the following condition is met.

$$\Delta \phi = m \ 2\pi , \ \text{where} \ m \ \text{is an integer}.$$  

**Mode Coupling**

The concept of mode coupling is very often used e.g. to describe the propagation of light in some waveguides or optical cavities under the influence of additional effects, such as external disturbances or nonlinear interactions. The basic idea of coupled-mode theory is to decompose all propagating light into the known modes of the undisturbed device, and then to calculate how these modes are coupled with each other by some additional influence. This approach is often technically and conceptually much more convenient than, e.g., recalculating the propagation modes for the actual situation in which light propagates in the device.

Some examples of mode coupling are discussed in the following:

An optical fiber may have several propagation modes, to be calculated for the fiber being kept straight. If the fiber is strongly bent, this can introduce coupling e.g. from the fundamental mode to higher-order propagation modes (even to cladding modes), or coupling between different polarization states. Bend losses can be understood as coupling to non-guided (and thus lossy) modes.

Nonlinear interactions in a waveguide can also couple the modes (as calculated for low light...
intensities) to each other. In high-power fiber amplifiers, a mechanism has been identified which can couple power from the fundamental fiber mode into higher-order modes. This mechanism can involve either a Kramers–Kronig effect or thermal distortions influencing the refractive index profile. This leads to a strong loss of beam quality above a certain pump power level.

Optical resonators (cavities) can exhibit various kinds of mode coupling phenomena. For example, aberrations of the thermal lens in the gain medium of a solid-state bulk laser couple the modes of the laser resonator, as calculated without these aberrations. In this situation, however, not all involved modes are necessarily resonant at the same time. This means then that the amplitude contribution which is fed e.g. from a fundamental (Gaussian) mode into a particular higher-order resonator mode in each resonator round trip will have a different phase each time. This nonresonant nature of the coupling means that the coupling will in general have a small effect – which is essential for laser operation with high beam quality, since otherwise aberrations would strongly excite higher-order modes, having a higher beam parameter product. Strong resonant coupling can occur in certain situations, involving frequency degeneracies of resonator modes.

Technically, the mode coupling approach is often used in the form of coupled differential equations for the complex excitation amplitudes of all the involved modes. These equations contain coupling coefficients, which are usually calculated from overlap integrals, involving the two mode functions and the disturbance causing the coupling. Typically, the applied procedure is first to calculate the mode amplitudes for the given light input, then to propagate these amplitudes based on the coupled differential equations (e.g. using some Runge–Kutta algorithm), and finally to recombine the mode fields to obtain the resulting field distribution.

An important physical aspect of such coherent mode coupling phenomena is that the optical power transferred between two modes depends on the amplitudes which are already in both modes. A consequence of that is that the power transfer from a mode A to another mode B can be kept very small simply by strongly attenuating mode B. In this way, mode B is prevented from acquiring sufficient power to extract power from mode A efficiently, so that
mode A experiences only little loss, despite the coupling.

**Optical Fibre**

An optical fiber is a cylindrical dielectric waveguide made of low-loss materials such as silica glass. It has a central core in which the light is guided, embedded in an outer cladding of slightly lower refractive index. Light rays incident on the core-cladding boundary at angles greater than the critical angle undergo total internal reflection and are guided through the core without refraction. Rays of greater inclination to the fiber axis lose part of their power into the cladding at each reflection and are not guided.

![Diagram of optical fiber with core and cladding](image)

\[ n_2 < n_1 \]

**STEP INDEX FIBERS**

Step-index fiber is a cylindrical dielectric waveguide specified by its core and cladding refractive indices, n1 and n2.

![Diagram of step-index fiber](image)
Graded index fibres

Index grading is an ingenious method for reducing the pulse spreading caused by the differences in the group velocities of the modes of a multimode fiber. The core of a graded-index fiber has a varying refractive index, highest in the center and decreasing gradually to its lowest value at the cladding. The phase velocity of light is therefore minimum at the center and increases gradually with the radial distance. Rays of the most axial mode travel the shortest distance at the smallest phase velocity. Rays of the most oblique mode zigzag at a greater angle and travel a longer distance, mostly in a medium where the phase velocity is high. Thus the disparities in distances are compensated by opposite disparities in phase velocities. As a consequence, the differences in the group velocities and the travel times are expected to be reduced. In this section we examine the propagation of light in graded-index fibers.

The core refractive index is a function \( n(r) \) of the radial position \( r \) and the cladding refractive index is a constant \( n_2 \). The refractive index profile is given by:

\[
n(r) = n_1 \sqrt{1 - 2\Delta \left( \frac{r}{a} \right)^\alpha}
\]
Single mode fibres

Single-mode fiber allows for a higher capacity to transmit information because it can retain the fidelity of each light pulse over longer distances, and it exhibits no dispersion caused by multiple modes. Single-mode fiber also enjoys lower fiber attenuation than multimode fiber. Thus, more information can be transmitted per unit of time. Like multimode fiber, early single-mode fiber was generally characterized as step-index fiber meaning the refractive index of the fiber core is a step above that of the cladding rather than graduated as it is in graded-index fiber. Modern single-mode fibers have evolved into more complex designs such as matched clad, depressed clad and other exotic structures.

Single-mode fibers (also called monomode fibers) are optical fibers which are designed such that they support only a single propagation mode per polarization direction for a given wavelength. They usually have a relatively small core (with a diameter of only a few
micrometers) and a small refractive index difference between core and cladding. The mode radius is typically a few microns.

A peculiar property of single-mode fibers is that the transverse intensity profile at the fiber output has a fixed shape, which is independent of the launch conditions and the spatial properties of the injected light, assuming that no cladding modes can carry substantial power to the fiber end. The launch conditions only influence the efficiency with which light can be coupled into the guided mode.

Intermodal dispersion can of course not occur in single-mode fibers. This is an important advantage for the application in optical fiber communications at high data rates (multiple Gbit/s), particularly for long distances. Essentially for that reason, and partly because of their tentatively lower propagation losses, single-mode fibers are exclusively used for long-haul data transmission, and nearly always for outdoor applications even over shorter distances. For short-distance indoor use, multimode fibers are more common, mostly because that allows the use of cheaper multimode data transmitters based on light-emitting diodes instead of laser diodes.

– Conditions for Efficiently Launching Light into a Single-mode Fiber

Efficiently launching light into a single-mode fiber requires that the transverse complex amplitude profile of that light at the fiber's input end matches that of the guided mode. This implies that the light source has a high beam quality (with $M^2 \approx 1$) that the light has a focus at the fiber's input end (for matching the plane wavefronts of the fiber mode) that the beam profile has the correct size and shape and is precisely aligned (concerning position and direction) to the core. More precisely, the error in position must be well below the beam radius, and the angular misalignment must be small compared with the beam divergence of the mode.

The launch efficiency under non-ideal conditions, namely with a wrong laser beam size or wrong angular alignment, can be calculated with equations as given in the article on fiber joints.

Generally, a long-term stable efficient launch of a free-space laser beam into a single-mode fiber requires well designed mechanical parts, which allow to precisely align and keep fixed the focusing lens and the fiber end while not exhibiting excessive thermal drifts. For single-
mode fibers with particularly large effective mode area (see below), it is easier to obtain the correct alignment concerning the focus position, but the angular alignment is more critical.

- Conditions for Single-mode Guidance

For step-index fibers, the condition for single-mode guidance can be formulated using the V number (normalized frequency), which can be calculated from the wavelength, the core radius, and the numerical aperture (NA): the V number must be below $\approx 2.405$. This requires that the core radius is small, particularly for fibers with high NA.

Typically, a fiber has single-mode characteristics only over a limited wavelength range with a width of a few hundred nanometers. The limit towards smaller wavelengths is given by the single-mode cut-off wavelength, beyond which the fiber supports multiple modes. This transition is very sharp and can easily be seen e.g. when tuning the launched wavelength around the cut-off wavelength: the shape of the transmitted beam varies rapidly in the multimode regime but remains constant in the single-mode regime. The long-wavelength limit of the useful single-mode region is usually given by excessive bend losses, by absorption of the material or (for certain fiber designs, e.g. with index-depressed cladding) by leakage into the cladding.

The International Telecommunications Union (ITU) has developed a number of standards for various types of fibers as used for optical fiber communications. Some of the most important of those standards concerning single-mode fibers are given in Table 1.

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<tr>
<th>Name</th>
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<tr>
<td>G.650.1 (06/04)</td>
<td>Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable</td>
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<td>G.652 (06/05)</td>
<td>Characteristics of a single-mode optical fibre and cable</td>
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<td>G.653 (12/06)</td>
<td>Characteristics of a dispersion-shifted single-mode optical fibre and cable</td>
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<td>G.654 (12/06)</td>
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<td>G.655 (03/06)</td>
<td>Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable</td>
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Multimode Fiber

Multimode fiber, the first to be manufactured and commercialized, simply refers to the fact that numerous modes or light rays are carried simultaneously through the waveguide. Modes result from the fact that light will only propagate in the fiber core at discrete angles within the cone of acceptance. This fiber type has a much larger core diameter, compared to single-mode fiber, allowing for the larger number of modes, and multimode fiber is easier to couple than single-mode optical fiber. Multimode fiber may be categorized as step-index or graded-index fiber.

The above figure shows how the principle of total internal reflection applies to multimode step-index fiber. Because the core's index of refraction is higher than the cladding's index of refraction, the light that enters at less than the critical angle is guided along the fiber.

Total Internal Reflection in Multimode Step-index fiber: Three different light waves travel down the fiber. One mode travels straight down the center of the core. A second mode travels at a steep angle and bounces back and forth by total internal reflection. The third mode exceeds the critical angle and refracts into the cladding. Intuitively, it can be seen that the second mode travels a longer distance than the first mode, causing the two modes to arrive at separate times. This disparity between arrival times of the different light rays is known as dispersion, and the result is a muddied signal at the receiving end. Graded-index refers to the fact that the refractive index of the core gradually decreases farther from the center of the core. The increased refraction in the center of the core slows the speed of some light rays, allowing all the light rays to reach the receiving end at approximately the same
time, reducing dispersion.

The above figure shows the principle of multimode graded-index fiber. The core's central refractive index, $n_A$, is greater than that of the outer core's refractive index, $n_B$. As discussed earlier, the core's refractive index is parabolic, being higher at the center. As the figure shows, the light rays no longer follow straight lines; they follow a serpentine path being gradually bent back toward the center by the continuously declining refractive index. This reduces the arrival time disparity because all modes arrive at about the same time. The modes traveling in a straight line are in a higher refractive index, so they travel slower than the serpentine modes. These travel farther but move faster in the lower refractive index of the outer core region.
Efficient transmission of light at the operational wavelength(s) is the primary function of fiber optics needed for a range of applications (e.g. long-haul telecommunications, fiber lasers, optical delivery for surgical or biomedical applications). Reduction in the intensity of light as it propagates within the fiber is called “attenuation”. The finite attenuation present in any optical fiber requires that fiber system design address degradation in signal strength through such approaches as signal amplification, interconnect optimization, fiber geometry design, and environmental isolation. An understanding of attenuation mechanisms and the potential for their minimization is, thus, of great importance in the efficient and economic use of fiber optics.

Any process that results in a reduction in the light intensity measured after propagation through a material contributes to the observed optical attenuation. In principle, all attenuation mechanisms can be traced back to the multilength scale structure of the glass itself (e.g. atomic structure, point defects, second-phase inclusions) or structures arising from the fiberization process and/or optical design of the fiber (e.g. interfacial structure at the core-clad interface, uniformity of core-clad structure along fiber length). Thus, the control of material structure (through composition, material processing, and fiber fabrication controls) is the primary means to reduce attenuation in the finished fiber. An understanding, however, of the underlying optical phenomena at work and their relationship to material composition and structure is needed. The overall optical throughput (transmission) of an optical fiber can be quantified in terms of the input optical power, \( P(0) \), and the output power, \( P(z) \) observed after light propagates a distance, \( z \), along the fiber length:

\[
P(z) = P(0)e^{-\alpha_{\text{total}} z}
\]

\[
\%T = \frac{P(z)}{P(0)}
\]

where: \( \alpha_{\text{total}} \) = the total attenuation coefficient (i.e. involving all contributions to attenuation); \( \%T \) is the percentage optical power transmission. The present module will provide an overview of the origins of optical signal attenuation in fiber optics. Optical phenomena contributing to attenuation that arise from materials-related mechanisms within the fiber will
serve as the primary focus.

**Optical Absorption**

Optical absorption involves the direct transfer of energy from the propagating light beam to the material structure, resulting in the excitation of the material to a higher energy state. This concept was previously examined in Module 1 in which the material was described in terms of a collection of oscillators, each available to absorb energy from an optical field oscillating at a frequency that is equal (or nearly equal) to the fundamental resonance frequency of given oscillator. The energy absorption promotes the oscillator to a higher energy level. This resonance condition is directly observed in the dispersion (frequency dependent) behavior of the complex dielectric function for the material which, in turn, gives rise to the complex refractive index at optical frequencies. In terms of the oscillator picture of a material, different structural elements will each contribute to the overall magnitude, and frequency dependence, of the optical absorption. Thus, the material composition and specific structural characteristics will directly impact the optical absorption observed at a particular wavelength of light. Some general contributions to optical absorption in fiber optic glasses are provided below:

**Intrinsic absorption: Base Glass**

The intrinsic optical absorption responses of core and clad glasses used were previously discussed as the primary factor dictating the transmission window (and ultimately the operational wavelengths) for an optical fiber. In the present context, the transmission window is defined by the spectral region bounded by the high optical absorption arising from electronic transitions across the band-gap of the material (higher energy absorption edge) and the excitation of vibrational motion of the extended glass network and more localized structural features (lower energy absorption edge). The high transmission spectral band that lies between these two absorption edges is often referred to as a “forbidden gap” referring to an absence of allowed energy states supporting energy absorption in this spectral range so that optical transparency is observed. A similar functional dependence of \( \alpha \) on frequency for the phonon-based absorption edge (i.e. defining the longer wavelength edge of the transmission window) results in a characteristic wedge shape in the spectral absorption loss characteristic of a particular material.
The figure below contains a representative spectrum of absorption losses defining the transmission window of a GeO2-doped silica glass often used as the core material in telecommunications fibers. Note that α is provided on a log-scale in terms of dB/km. The absorption edge due to electronic transitions across the band-gap for the glass is on the left (higher energies), while the phonon-based absorption edge is to the right (lower energies). Contribution from scattering losses is also included.

**Extrinsic absorption processes**

In addition to the energy structure of the base glass that defines the transmission window, the presence of defects in the glass structure (e.g. vacancies, over/under coordinated atoms) and/or dopants and impurities can produce localized energy states that exist within the forbidden gap. The presence of such states, thus, enables optical absorption at frequencies
within the transmission window. When such absorption processes are at frequencies resonant with the operational wavelength of the fiber, such structural elements present a significant problem in the development of low-loss fiber optic systems.

One of the primary absorbing species common in silica-based glass fibers is water (hydroxyls (OH-)) within the glass structure. The fundamental resonances for hydroxyl species, associated with bending and stretching modes of vibration, occur at 2.73 and 6.25 microns, well away from the near-infrared spectral range typically associated with telecommunications wavelengths. While the effect of such absorption processes on attenuation in the near-IR may initially seem minimal, overtones and combination vibrations result in significant absorption well into the near-IR.

**Optical Scattering**

In the context of factors contributing to the optical attenuation of light under low intensity conditions (linear optical phenomena), optical scattering is best described in terms of elastic phenomena. In this case, photons interact with spatial variations in material dielectric constant, such that the photons alter their propagation direction, phase, and polarization, without energy loss – i.e. the photon frequency after scattering remains the same, hence the process is called an elastic scattering process. These spatial variations in dielectric constant are usually localized and are called scattering centers. Scattering centers are associated with extrinsic, second phase impurities (including particulate inclusions and bubbles) or intrinsic fluctuations in material density and/or composition. Using current state-of-the-art silica glass fiber production methods, which largely exclude the formation of extrinsic sources of scattering, intrinsic scattering attenuation effects play the dominant role in telecommunications-grade fiber systems. Primary sources of elastic scattering arise from Rayleigh and Mie scattering in the fiber materials.

**Rayleigh Scattering** : Rayleigh scattering is dominant when light interacts with scattering centers whose size is much less than the wavelength of the light (typically $\lambda/10$). Even if care is taken to insure that the glass is formed to avoid phase decomposition, e.g. phase separation into two, immiscible glass compositions or crystallization (devitrification), there can still exist local fluctuations in glass density. These fluctuations are formed as the glass is cooled through the glass transition range in that different structural elements of the glass
network are frozen at different stages of the cooling process. The explanation for this is simple when it is realized that each structural element in the glass is characterized by a unique, individual structural relaxation time leading to a distribution of structural relaxation times for the bulk material. Such a variation in relaxation rate will result in localized density fluctuations, and Rayleigh scattering, even in very high purity glass.

For a medium with density fluctuations much smaller than the light wavelength, the attenuation coefficient can be given as:

\[
\alpha_{Rayleigh} = \frac{8\pi^3}{3\lambda^4} \left( \frac{n_1^2}{n_0^2} - 1 \right)^2 \beta k T_f
\]

where: \( n_1, n_0 = \) refractive index of the scattering center, medium; \( \beta = \) isothermal compressibility of the medium, \( k = \) Boltzmann’s constant, \( T_f = \) the fictive temperature of the glass (corresponding to the temperature at which density fluctuations are frozen into the glass as it is cooled through the transformation range).

Rayleigh scattering thus exhibits a characteristic \( 1/\lambda^4 \) behavior that favors scattering (and larger attenuation parameters) at shorter wavelengths. Related expressions, incorporating both density and compositional fluctuations for multicomponent glass systems also exhibit the same wavelength dependence.

**Mie Scattering**: As the size of the scattering center becomes larger, exceeding that valid for a Rayleigh scattering picture of the phenomena and approaching the wavelength of light, the scattering light intensity has a greater angular dependence and the process is governed by Mie scattering theory.

Typical fluctuations in density or composition at this size scale are associated with phase separation in the glass (i.e. associated with immiscible glass phases) and/or the development of crystallinity. Further increases in scattering center size results in a largely wavelength-independent scattering attenuation behavior, governed by the absorption and reflection behavior at the interfaces involved. It is important to note that, while conventional oxide (silicate-based) glass fiber systems are relatively free of such phase instabilities, the use of non-oxide glass systems for specialty fiber applications is often accompanied by decreased
phase stability, greater tendency for crystallization, and a greater propensity for environmental attack (water). Moreover, the reliance on melt-and-cast-type preform development with, for example, fluoride glass systems, often increases the probability of extrinsic sources of scattering from contaminant phases and bubbles both within the volume of the glass and at the core-clad interface.

**Bending Losses**

In addition to transmission losses associated with absorption and scattering within the glass components of the optical fiber, the fundamental characteristics of light propagation within the fiber design (i.e. core-clad geometry and index contrast) coupled with the uniformity and control of fiber parameters also present factors contributing to optical loss. Propagating modes within an optical fiber can be characterized by an electric field distribution with maxima inside the fiber core and evanescent fields that extend outside the fiber core into the cladding. Thus, some of the optical energy in the mode is actually propagating in the cladding.

![Diagram of curved fiber and its field distribution](image)

Two primary attenuation factors, dependent upon the external fiber geometry are of interest in this context:

**Macrobending losses**

If the fiber is curved around a corner, different portions of the same mode must travel at different speeds to maintain the integrity of the mode. However, for portions of the mode traveling through the “outside” of the curve, a small enough radius of curvature will require
that this portion of the mode travel essentially faster than light speed. Under these conditions, the mode integrity cannot be maintained and the energy radiates away from the fiber structure, thus contributing to a reduction in the optical power transmitted by the fiber. In general, the amount of attenuation increases exponentially with decreasing radius of curvature. For larger radii, the losses are typically very small, particularly compared with losses associated with the material phenomena described above. However, beyond a threshold radius, the losses become much larger. Given the increase in modal field intensity distribution near the cladding for higher order propagating modes, macrobending losses are more likely to affect these modes. Thus, a curved fiber typically does not support as many modes as a straight fiber of identical design.

**Microbending losses** : In this case, losses are associated with modal profiles sampling random, microscale fluctuations in fiber radius typically due to non-uniformity in fiber diameter arising during the fiber drawing process or in response to non-uniform radial pressures produced during cabling. The following figure depicts this phenomenon. Such microbends are essentially random variation in the fiber geometry (and propagating mode characteristics) along the propagation direction. The result is a coupling between guided wave modes and nonguiding (leaky) modes thus producing an effective loss or attenuation of light within the fiber. Careful packaging (cabling) of fibers and control of draw conditions during fabrication are critical to reducing these effects.
DISPERSION
Dispersion represents a broad class of phenomena related to the fact that the velocity of the electromagnetic wave depends on the wavelength. In telecommunication the term of dispersion is used to describe the processes which cause that the signal carried by the electromagnetic wave and propagating in an optical fiber is degraded as a result of the dispersion phenomena. This degradation occurs because the different components of radiation having different frequencies propagate with different velocities.
These phenomena are particularly important in optical telecommunication. In different periods of the historical development of the optical telecommunication the different kinds of dispersion played a different role. In the first period, when the multimode fibers with the step profile of the refraction index were used and the light was transmitted only on small distances at low transmission speed, the chromatic dispersion played a negligible role in contrast to the mode dispersion. The development of the multimode optical fibers with the gradient profile of the refraction index had reduced the mode dispersion considerably. Employing the single-mode optical fibers eliminated entirely the phenomenon of the mode dispersion and allowed to propagate the signal over large distances. However, with the higher transmission speeds gigabytes per second the chromatic dispersion became more and more essential on large distances. The technical problems related to the transmission in the second window, and particularly in the third transmission window became more and more dependent on the chromatic dispersion.
Simply speaking, chromatic dispersion means that the different wavelengths travel with different velocities even for the single-mode optical fibers. The chromatic dispersion is the characteristic feature of the material and it is impossible to avoid it, it can be only reduced. The radiation of shorter wavelengths has larger refraction indices than that for the longer wavelengths, so the light at different wavelengths is traveling with different speeds. The more monochromatic light from the transmitter the larger the velocity difference between the longest and the shortest component propagating through the fiber.

Mode dispersion
In a multimode optical fiber there is an additional dispersion - the mode dispersion which occurs even, when the light introduced into a fiber is an ideal monochromatic source.
Indeed, in a single-mode fiber we can assume with a good approximation that the optical path of the rays is directed along the optical axis of the fiber, because the radius of the core is very small (5-10 μm). In a multi-mode fiber the radius of the core is much larger (50-62.5 μm) and the rays can travel along different paths. In a multimode fiber with a step profile of the refraction index all rays travel with the same speed – the rays traveling along the fiber axis have the same speed as the rays traveling close to the core-cladding interface. As they cover the optical paths of different length at the same speed they reach the detector at different times. This leads to the temporal pulse broadening at the end of the fiber. This type of temporal broadening is called the mode dispersion.

**Chromatic Dispersion**

**Waveguide Dispersion** describes the dependence of the effective refraction index $n_{\text{eff}}=f(\nu)$ on the normalized frequency of radiation propagating through the optical fiber. The waveguide dispersion results in distribution changes of a mode power between the core and the cladding. The waveguide dispersion is an important parameter resulting in the frequency dependence of the group delay.

$$\tau_g = \frac{1}{\nu_g} = \frac{d\beta}{d\omega}$$

**Material dispersion**

Light ray is not monochromatic and the different wavelength components propagate through a fiber with different velocities. The temporal pulse broadening is due to the non-zero second derivative of the refraction index.
The total dispersion of a single mode fiber is the sum of contributions coming from the material dispersion and the waveguide dispersion. The increase of the negative slope of waveguide dispersion shifts the zero of dispersion towards longer wavelengths. Thus, the obvious way of dispersion minimum shifting to the III window of transmission is enlarging the influence of the waveguide dispersion. It can be done by enlargement of difference between the core and the cladding refraction indices. However, we should notice, that by enlarging this difference, we also increase the cut-off frequency.

**Optic Fibre Cables**

The heaviest use of fiber is in the telecommunications industry. Telephone companies initially used fiber to transport high volumes of voice traffic between central office locations. During the 1980s telephone companies began to deploy fiber throughout their networks. Fiber technology allows companies to "future proof" networks. We use the phrase "future proof" because fiber is theoretically unlimited in bandwidth. Bandwidth is a measurement of the data carrying capacity of the media (in this case, fiber). The greater the bandwidth, the more data or information that can be transmitted. Copper has a bandwidth and a distance limitation, making it less desirable.

Benefits of fiber include:

- High bandwidth for voice, video and data applications
- Optical fiber can carry thousands of times more information than copper wire.
• Fiber is more lightweight than copper. Copper cable equals approximately 80 lbs./1000 feet while fiber weighs about 9 lbs./1000 feet

• Low loss. The higher frequency, the greater the signal loss using copper cabling. With fiber, the signal loss is the same across frequencies, except at the very highest frequencies

• Reliability - Fiber is more reliable than copper and has a longer life span

• Secure - Fiber does not emit electromagnetic interference and is difficult to tap

Optical fiber is composed of several elements. The construction of a fiber optic cable consists of a core, cladding, coating buffer, strength member and outer jacket. The optic core is the light-carrying element at the center. The core is usually made up of a combination of silica and germania. The cladding surrounding the core is made of pure silica. The cladding has a slightly lower index of refraction than the core. The lower refractive index causes the light in the core to reflect off the cladding and stay within the core.

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**Fibre Connectors**

Several layers of buffer coatings protect the core and the cladding. The layers act as a shock absorber to protect the core and cladding from damage. A strength member, usually Aramid, is
around the buffer layers. To prevent pulling damage during installation the strength member is added to give critical tensile (pulling) strength to the cable. The outer jacket protects against environmental factors. The most widely used fiber connector is the SC connector. The SC connector's square cross section facilitates high packing density in connector panels. Network administrators need to take into consideration low loss, footprint size, and locking capabilities when selecting a fiber connector.

Fibers are assembled into either stranded or ribbon cables. Stranded cables are individual fibers that are bundled together. Ribbon cable is constructed by grouping up to 12 fibers and coating them with plastic to form a multi fiber ribbon. Stranded and ribbon fiber bundles can be packaged together into either loose or tight buffering cable.
There are two ways of linking two optical fibers:

1. Fusion Splice

This operation consists in directly linking two fibers by welding with an electric arc, by aligning best possible both fiber cores. The specific device to make this fusion is called a fusion splicer.

Advantages

- This linking method is fast and relatively simple to make.
- The light loss generated by the welding, due to an imperfect alignment of the cores,
remains very weak.

Drawbacks:

- This type of link is relatively fragile (in spite of a protection of fusion by a heat-shrinkable tube).
- It is a permanent link.
- It is necessary to invest in a fusion splicer.

2. Fibre Connectors

In this case, it is necessary to terminate a connector at each end of the fibers to be connected. The two fibers can then be connected by connecting the two connectors together.

Advantages:

- This type of connection is robust.
- The type of connector can be chosen according to the application field of the system.
- Connection is removable. It is possible to connect and disconnect two fibers hundreds to thousands times without damaging the connectors.

Drawbacks:

- The implementation is longer than fusion, and requires an experiment as well as specific tools.
- The light loss due to connection is higher than in the splicing solution.

Fibre Connector Types

Fiber termination in the ferrule
Whatever the needed connector, the first step consists in inserting the fiber in a ferrule, to allow to simplify the fiber handling with less risk to damage it. This ferrule is generally made of ceramics and is manufactured with high precision machining process. The different steps to terminate the fiber in the ferrule are the following:

- Fiber stripping to keep only the active layers (core and cladding).
- Fiber epoxy bonding in the ceramic ferrule. The fiber is introduced into the ceramic ferrule hole whose diameter is very precise, and adjusted to that of fiber.
- Fiber cleaving at the ceramic ferrule surface.
- Polishing of the end of the ceramic ferrule. Using lapping films of increasingly fine grains, the fiber surface is perfectly well polished, and all the awkward residual particles have been eliminated.

**Butt Joint Technology**

The principle of the butt joint connectors consists in putting in physical contact the two ceramic ferrules. To realign perfectly fibers face to face, we use an alignment sleeve generally in ceramics. The light passes thus directly from one fiber to the other.
Defects:
The alignment of fibers is never perfect, some light is lost when going from one side to the other. This loss can be high according to the residual defects of alignment or polishing.

Butt joint connectors characteristics:
- The loss of light generated by connection (called Insertion Loss) is low (approximately 3 dB typical).
- This type of connection is sensitive to pollution (dust, mud...). If a dirtiness stays between the two ceramic ferrules, a big part of the light can be lost.

Butt joint connectors examples:

**Lens technology (expanded beam technology)**

Principle:
The principle of the expanded beam connectors consists in placing a lens at the exit of each fiber, in order to widen the beam by collimating it - i.e. by creating light beams parallel to the optical axis. In this configuration, there is no more physical contact between the two optical fibers.
Defects:
In this case it is the alignment of the two shells one to the other which will guarantee that the collimated beam going out from the first lens will be well refocused through the second lens. The precision of the mechanical interface parts of the connector is highly important. As for the butt joint connectors, transverse and angular shifts, and also bad polishing will generate losses.

Lens connectors characteristics:
- The light loss generated by connection (called Insertion Loss) is more important than in the previous case, due to the presence of the lenses and sometimes also of windows (approximately 1 to 1,5 typical dB).
- This type of connection is much less sensitive to pollution because the beam is much larger than the one that goes out directly from a fiber. A dust at the interface of two butt joint connectors will create a much higher loss than located at the interface of two lens connectors.

Lens connectors examples:
**Fiber Couplers**

A fiber optic coupler is a device used in optical fiber systems with one or more input fibers and one or several output fibers. Light entering an input fiber can appear at one or more outputs and its power distribution potentially depending on the wavelength and polarization. Such couplers can be fabricated in different ways, for example by thermally fusing fibers so that their cores get into intimate contact. If all involved fibers are single-mode (supporting only a single mode per polarization direction for a given wavelength), there are certain physical restrictions on the performance of the coupler. In particular, it is not possible to combine two or more inputs of the same optical frequency into one single-polarization output without significant excess losses. However, such a restriction does not occur for different input wavelengths: there are couplers that can combine two inputs at different wavelengths into one output without exhibiting significant losses. Wavelength-sensitive couplers are used as multiplexers in wavelength-division multiplexing (WDM) telecom systems to combine several input channels with different wavelengths, or to separate channels.
MODULE III

Optical Source

- The heart of a fiber optical data system
- A Hybrid Device: Converts electrical signals into optical signals
- Launches these optical signals into an optical fiber for data transmission.
- Device consists of an interface circuit, drive circuit, and components for optical source. (LEDs, ELEDs, SLEDs, LDs, etc)

LIGHT EMITTING DIODE

A light-emitting diode (LED) is a two-lead semiconductor light source. It is a pn-junction diode, which emits light when activated. When a suitable voltage is applied to the leads, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence, and the color of the light (corresponding to the energy of the photon) is determined by the energy band gap of the semiconductor. An LED is often small in area (less than 1 mm²) and integrated optical components may be used to shape its radiation pattern.

Appearing as practical electronic components in 1962, the earliest LEDs emitted low-intensity infrared light. Infrared LEDs are still frequently used as transmitting elements in remote-control circuits, such as those in remote controls for a wide variety of consumer electronics. The first visible-light LEDs were also of low intensity, and limited to red. Modern LEDs are available across the visible, ultraviolet, and infrared wavelengths, with very high brightness.

Early LEDs were often used as indicator lamps for electronic devices, replacing small incandescent bulbs. They were soon packaged into numeric readouts in the form of seven-segment displays, and were commonly seen in digital clocks.

Recent developments in LEDs permit them to be used in environmental and task lighting. LEDs have many advantages over incandescent light sources including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching. Light-emitting diodes are now used in applications as diverse as aviation lighting, automotive headlamps, advertising, general lighting, traffic signals, and camera flashes. However, LEDs powerful enough for room lighting are still relatively expensive, and require more precise current and heat management.
management than compact fluorescent lamp sources of comparable output.
LEDs have allowed new text, video displays, and sensors to be developed, while their high switching rates are also useful in advanced communications technology.

Working: Electrons are free to move in the conduction band. Unbound holes are free to move in the valence band. Holes have positive charge while electrons have negative charge. When an electron combines with a hole energy is released. P type materials has free holes and an n type material has free electrons. When n type and p type materials are brought together without applied voltage a potential barrier exists at their junction. When a forward voltage is applied the potential energy of n type material is increased and that of p type is decreased. If the energy supplied is same as the gap energy electrons cross the barrier and combine with the holes. Energy lost during the re-combination is emitted in the form of a photon.

![LED Structure Diagram](image)

**LED Structure:**
The LED structure plays a crucial role in emitting light from the LED surface. The LEDs are structured to ensure most of the recombinations takes place on the surface by the following two ways.
- By increasing the doping concentration of the substrate, so that additional free minority charge carriers electrons move to the top, recombine and emit light at the surface.
- By increasing the diffusion length \( L = \sqrt{D \tau} \), where \( D \) is the diffusion coefficient and \( \tau \) is the carrier life time. But when increased beyond a critical length there is a chance of re-absorption of the photons into the device.
Surface Emitting LED
Surface-emitting LEDs (SLEDs) have a thin active layer parallel to the surface from which the light extracted. In a simple flat-diode configuration, the active layer is just below the emitting surface, and the current is applied with a ring electrode. The light emitted in the “wrong” direction is absorbed by the substrate. There are also devices where the substrate is made transparent, and the back electrode reflects back that light, so that at least some part of it can be used.

![Surface Emitting LED Diagram](image)

Edge Emitting LED
Edge-emitting LEDs have a structure similar to that of edge-emitting semiconductor lasers: they are emitting from the edge of a cleaved wafer, where the active region meets the cleaved surface. Such devices allow more efficient fiber coupling than surface-emitting LEDs. Applied in optical fiber communications, they allow higher data rates.

![Edge Emitting LED Diagram](image)
A variant of the edge-emitting LED is the superluminescent diode (SLD), where the spontaneous emission is substantially amplified within a waveguide. Here, the emission is much more directional, and as a consequence the brightness is much higher, even for SLDs with quite low output power.

**Emission properties**

Light emitted by LEDs has a low spatial coherence. It is originally emitted in all directions. Even though many LED devices emit light preferentially in one direction (often via built-in reflecting structures), the focusability (beam quality) is very low, compared with, e.g., that of laser diodes. The emission bandwidth is typically some tens of nanometers (e.g. 40 nm) or even > 100 nm, i.e., much broader than for laser diodes, and comparable to that of superluminescent diodes. This means that the temporal coherence is much lower than that of a laser, although it is much higher than for, e.g., an incandescent bulb.

**Efficiency**

The internal process of generating light in an LED, as described above, can have a very high quantum efficiency and power efficiency, at least in the blue–violet and in the red spectral region. Nevertheless, the device efficiency of early light-emitting diodes was relatively poor. The reason is that it was not possible to extract the internally generated light efficiently; most of the generated light was absorbed inside the device. A key challenge is total internal reflection at the surface of the semiconductor material: due to the high refractive index, light can escape only for relatively small angles of incidence, and even then there is substantial Fresnel reflection. In some LEDs, there is also a problem with reabsorption of light in the substrate.

In the 1990s, advanced LED designs were developed which allow fairly efficient light extraction and thus reach much higher device efficiencies. Examples for measures used are roughened surfaces and integrated photonic crystal structures. The luminous efficacy can now be well over 200 lm/W, i.e. substantially better than that of fluorescent lamps. Besides the efficacy of the light source itself, the directional emission makes it easier to achieve a high efficacy of the overall lighting system, comparing with omnidirectional emitters where a lot of light can be lost in a lamp housing.

A possible problem (called “efficiency droop”) of GaInN-based blue LEDs, as also used in white
LEDs, is that the efficacy tends to be decreased substantially when the LED is strongly pumped (for high-power operation). That problem appears to be caused by direct and indirect Auger effects.

**Device Lifetime**
Light-emitting diodes based on inorganic semiconductors can have very long lifetimes, which can exceed 100,000 hours. LEDs are therefore belonging to the most long-lived illumination devices. On the other hand, LEDs are relatively sensitive to excessive reverse voltages, and can be destroyed by electrostatic discharge when improperly handled. Also, the lifetime is severely reduced for operation with a too high current and/or at too high ambient temperatures.

**Electrical Characteristics**
As with any other semiconductor diode, a current can flow through an LED only from the p-doped part to the n-doped part (conventional current direction). A reverse voltage of a more than a few volts can destroy an LED.

In the forward direction, the current remains very small for low voltages and then rises very quickly (exponentially) with increasing voltage. Therefore, LEDs normally cannot be operated with a constant voltage; the current needs to be stabilized, e.g. by operation with a current source, or by using a simple series resistance for connecting to a constant voltage supply. The optical power is proportional to the operation current, except if the induced increase of temperature decreases the quantum efficiency. The operation voltage is largely determined by the bandgap energy of the material, and thus by the emission wavelength; red LEDs may be operated with less than 2 V, while blue ones require of the order of 4 V.

**Main Attractions**
The main attractions of light-emitting diodes are:

- The device efficiency (see above) can be very high, leading to a small electric power consumption and low heat generation. The effective efficiency of a lamp is often further improved by the more directed emission of LEDs, reducing the amount of light that is lost in the lamp housing.
- The device lifetime (see above) is very long. It normally ends with a gradual loss of brightness, rather than with abrupt failure.
- Larger LED lights contain multiple LEDs, and can remain largely functional when single
LEDs fail. This is particularly important where safety is critical (e.g. for traffic lights).

- Light with specific colors (e.g. for traffic lights) can be directly generated. This is more efficient than using e.g. an incandescent lamp with a color filter, which has to absorb much of the generated optical power.
- LEDs can be used in very compact and lightweight packages.
- They are mechanically very robust and can tolerate even severe mechanical shocks.
- When white light is generated by using separate red, green and blue LEDs, the color tone can be adjusted by adjusting the relative operation currents.
- Dimming is possible by reducing the current or by quickly switching it on and off with a variable duty cycle. In any case, the power efficiency is preserved when dimming an LED, and the color tone remains unchanged. Both would not be the case for a dimmed incandescent lamp.
- The output power of a light-emitting diode can be very quickly modulated. Modulation frequencies of hundreds of megahertz are possible, since the carrier lifetime is only a few nanoseconds. This is useful e.g. for optical data transmission.
- LEDs contain poisonous substances such as gallium arsenide, but only in small quantities.

Limitations

- The cost per watt of output power of an LED for illumination is fairly high. However, fast progress is being made to reduce that cost, mainly by increasing the output power of the LED chips. Also, the higher cost may be offset by reduced electricity consumption and the long lifetime.
- Although an LED produces less heat than an incandescent lamp with the same optical power, adequate heat sinking is necessary to prevent overheating, which would degrade the lifetime.
- The color rendering index of some white LEDs is low, making them unsuitable for certain applications.
- As the available electric supplies usually provide an (approximately) constant voltage, the operation current needs to be stabilized with some electronics. Fairly simple electronics may used, but often spoil the overall power efficiency.
Applications of Light-emitting Diodes

Small LEDs are very widely used as small signal lights. Operated with a current of e.g. 5–20 mA, such devices produce enough light to be seen in normal ambient light conditions, and different colors can be used, e.g. to signal different states of a device.

As LEDs can be quickly modulated, they are suitable for optical fiber communications over short distances. While the poor directionality of their emission requires the use of multimode fibers and thus restricts the transmission distances, the cost is significantly lower than for a system with single-mode fibers and laser diode transmitters. Moderately fast power modulation is also useful, e.g., for application in light barriers, as the modulated LED light is easily distinguished from the ambient light, and for remote controls.

The enormous progress in high-power LEDs has recently made it possible to use LEDs for larger signals and for lighting purposes. As the cost per watt is still relatively high, and the output power is limited, such applications started in areas such as traffic lights and stop lights for cars, where moderate optical powers are sufficient, the long lifetime is particularly important, and the efficiency advantage over a filtered incandescent lamp is very large. Another possible use is for the background illumination of liquid crystal displays, e.g. in screens of portable computers (laptops), media players and cell phones, where the reduced electricity consumption allows for a longer time with battery-powered operation. Another advantage for computer and TV screens is that brighter colors can be achieved, comparing with fluorescent lamp backlights.

Further improved devices will soon make it possible to use high-power white LEDs for the main lights of cars, for residential lighting and street lights. In some areas such as airplanes, the compact package size and the low electricity consumption are particularly important.

LASER

Semiconductor lasers are lasers based on semiconductor gain media, where optical gain is usually achieved by stimulated emission at an interband transition under conditions of a high carrier density in the conduction band.
The physical origin of gain in a semiconductor (for the usual case of an interband transition) is illustrated in figure above. Without pumping, most of the electrons are in the valence band. A pump beam with a photon energy slightly above the bandgap energy can excite electrons into a higher state in the conduction band, from where they quickly decay to states near the bottom of the conduction band. At the same time, the holes generated in the valence band move to the top of the valence band. Electrons in the conduction band can then recombine with these holes, emitting photons with an energy near the bandgap energy. This process can also be stimulated by incoming photons with suitable energy. A quantitative description can be based on the Fermi–Dirac distributions for electrons in both bands.

Most semiconductor lasers are laser diodes, which are pumped with an electrical current in a region where an n-doped and a p-doped semiconductor material meet. However, there are also optically pumped semiconductor lasers, where carriers are generated by absorbed pump light, and quantum cascade lasers, where intra-band transitions are utilized. There are three main processes in semiconductors that are associated with light:

**Light absorption:** Absorption occurs when light enters a semiconductor and its energy is transferred to the semiconductor to generate additional free electrons and holes. This effect is widely used and enables devices like to photo-detectors and solar cells to operate.

Spontaneous emission: The second effect known as spontaneous emission occurs in LEDs. The light produced in this manner is what is termed incoherent. In other words the frequency and phase are random, although the light is situated in a given part of the spectrum.

**Stimulated emission:** Stimulated emission is different. A light photon entering the semiconductor lattice will strike an electron and release energy in the form of another light photon. The way in which this occurs releases this new photon of identical wavelength and
phase. In this way the light that is generated is said to be coherent. The key to the laser diode operation occurs at the junction of the highly doped p and n type regions. In a normal p-n junction current flows across the p-n junction. This action can occur because the holes from the p-type region and the electrons from the n-type region combine. With an electromagnetic wave (in this instance light) in passing through the laser diode junction diode junction it is found that the photo-emission process occurs. Here the photon release further photons of light when they strike electrons and recombination of holes and electrons occur. Naturally there is some absorption of the light, resulting in the generation of holes and electrons but there is an overall gain in level. The structure of the laser diode creates an optical cavity in which the light photons have multiple reflections. When the photons are generated only a small number are able to leave the cavity. In this way when one photon strikes an electron and enables another photon to be generated the process repeats itself and the photon density or light level starts to build up. It is in the design of better optical cavities that much of the current work on lasers is being undertaken. Ensuring the light is properly reflected is the key to the operation of the device.

Common materials for semiconductor lasers (and for other optoelectronic devices) are:

- GaAs (gallium arsenide)
- AlGaAs (aluminum gallium arsenide)
- GaP (gallium phosphide)
- InGaP (indium gallium phosphide)
- GaN (gallium nitride)
- InGaAs (indium gallium arsenide)
- GaInNAs (indium gallium arsenide nitride)
- InP (indium phosphide)
- GaInP (gallium indium phosphide)

These are all direct bandgap semiconductors; indirect bandgap semiconductors such as silicon do not exhibit strong and efficient light emission. As the photon energy of a laser diode is close to the bandgap energy, compositions with different bandgap energies allow for different emission wavelengths. For the ternary and quaternary semiconductor compounds, the bandgap energy can be continuously varied in some substantial range. In AlGaAs = AlxGa1-xAs, for example, an increased aluminum content (increased x) causes an increase in the bandgap energy.
While the most common semiconductor lasers are operating in the near-infrared spectral region, some others generate red light (e.g. in GaInP-based laser pointers) or blue or violet light (with gallium nitrides). For mid-infrared emission, there are e.g. lead selenide (PbSe) lasers (lead salt lasers) and quantum cascade lasers.

Apart from the above-mentioned inorganic semiconductors, organic semiconductor compounds might also be used for semiconductor lasers. The corresponding technology is by far not mature, but its development is pursued because of the attractive prospect of finding a way for cheap mass production of such lasers. So far, only optically pumped organic semiconductor lasers have been demonstrated, whereas for various reasons it is difficult to achieve a high efficiency with electrical pumping.

**Types of Semiconductor Lasers**

There is a great variety of different semiconductor lasers, spanning wide parameter regions and many different application areas:

- **Small edge-emitting laser diodes** generate a few milliwatts (or up to 0.5 W) of output power in a beam with high beam quality. They are used e.g. in laser pointers, in CD players, and for optical fiber communications.

- **External cavity diode lasers** contain a laser diode as the gain medium of a longer laser cavity. They are often wavelength-tunable and exhibit a small emission linewidth. Both monolithic and external-cavity low-power levels can also be mode-locked for ultrashort pulse generation.

- **Broad area laser diodes** generate up to a few watts of output power, but with significantly poorer beam quality. High-power diode bars contain an array of broad-area emitters, generating tens of watts with poor beam quality. High-power stacked diode bars contain stacks of diode bars for the generation of extremely high powers of hundreds or thousands of watts.
**Surface-emitting lasers (VCSELs)** emit the laser radiation in a direction perpendicular to the wafer, delivering a few milliwatts with high beam quality.

Optically pumped surface-emitting external-cavity semiconductor lasers (VECSELs) are capable of generating multi-watt output powers with excellent beam quality, even in mode-locked operation.

**Quantum cascade lasers** operate on intra-band transitions (rather than inter-band transitions) and usually emit in the mid-infrared region, sometimes in the terahertz region. They are used e.g. for trace gas analysis.

**Typical Characteristics and Applications**

Some typical aspects of semiconductor lasers are:

- Electrical pumping with moderate voltages and high efficiency is possible particularly for high-power diode lasers, and allows their use e.g. as pump sources for highly efficient solid-state lasers (→ diode-pumped lasers).
- A wide range of wavelengths are accessible with different devices, covering much of the visible, near-infrared and mid-infrared spectral region. Some devices also allow for wavelength tuning.
- Small laser diodes allow fast switching and modulation of the optical power, allowing their use e.g. in transmitters of fiber-optic links.

Such characteristics have made semiconductor lasers the technologically most important type of lasers. Their applications are extremely widespread, including areas as diverse as optical data transmission, optical data storage, metrology, spectroscopy, material processing, pumping solid-state lasers (→ diode-pumped lasers), and various kinds of medical treatments.
Pulsed Output
Most semiconductor lasers generate a continuous output. Due to their very limited energy storage capability (low upper-state lifetime), they are not very suitable for pulse generation with Q switching, but quasi-continuous-wave operation often allows for significantly enhanced powers. Also, semiconductor lasers can be used for the generation of ultrashort pulses with mode locking or gain switching. The average output powers in short pulses are usually limited to at most a few milliwatts, except for optically pumped surface-emitting external-cavity semiconductor lasers (VECSELs), which can generate multi-watt average output powers in picosecond pulses with multi-gigahertz repetition rates.

Modulation and Stabilization
A particular advantage of the short upper-state lifetime is the capability of semiconductor lasers to be modulated with very high frequencies, which can be tens of gigahertz for VCSELs. This is exploited mainly in optical data transmission, but also in spectroscopy, for the stabilization of lasers to reference cavities, etc.

PIN DIODE
The PIN diode, p-i-n diode is essentially a refinement of the ordinary PN junction diode. Its development arose from the original PN diode development activities and applications for the new diode were soon found. The PIN diode differs from the basic PN junction diode in that the PIN diode includes a layer of intrinsic material between the P and N layers. As a result of the intrinsic layer, PIN diodes have a high breakdown voltage and they also exhibit a low level of junction capacitance. In addition to this the larger depletion region of the PIN diode is ideal for applications as a photodiode.

PIN diode development
After the PN junction was understood and further developed in the 1940s, other research into variants of the basic PN junction was undertaken. The first references to this was a low frequency high power rectifier that was developed in 1952 by Hall, and some later developments undertaken by Prince in 1956. Although the PIN diode saw some initial applications as power rectifiers it was later realised that the lower junction capacitance could be utilised in microwave applications. In 1958 some of the
first microwave devices were developed, and later during the 1960s they gained more widespread acceptance in this role.

With the introduction of semiconductors as photo devices the PIN diode saw its use increase as a photodetector. Its large depletion area was ideal for its use in this role.

**PIN diode basics and operation**

The PIN diode can be shown diagrammatically as being a PN junction, but with an intrinsic layer between the PN and layers. The intrinsic layer of the PIN diode is a layer without doping, and as a result this increases the size of the depletion region - the region between the P and N layers where there are no majority carriers. This change in the structure gives the PIN diode its unique properties.

**Basic PIN diode structure**

![PIN diode structure diagram]

The PIN diode operates in exactly the same way as a normal diode. The only real difference is that the depletion region, that normally exists between the P and N regions in an unbiased or reverse biased diode is larger.

In any PN junction, the P region contains holes as it has been doped to ensure that it has a predominance of holes. Similarly the N region has been doped to contain excess electrons. The region between the P and N regions contains no charge carriers as any holes or electrons combine. As the depletion region has no charge carriers it acts as an insulator.

Within a PIN diode the depletion region exists, but if the diode is forward biased, the carriers enter the depletion region (including the intrinsic region) and as the two carrier types meet, current starts to flow.

When the diode is forward biased, the carrier concentration, i.e. holes and electrons is very much higher than the intrinsic level carrier concentration. Due to this high level injection level, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from p to n region, which results in faster operation of the diode, making it a suitable device for high frequency operations.

**PIN diode uses and advantages**

The PIN diode is used in a number of areas as a result of its structure proving some properties which are of particular use.
• High voltage rectifier: The PIN diode can be used as a high voltage rectifier. The intrinsic region provides a greater separation between the PN and N regions, allowing higher reverse voltages to be tolerated.

• RF switch: The PIN diode makes an ideal RF switch. The intrinsic layer between the P and N regions increases the distance between them. This also decreases the capacitance between them, thereby increasing the level of isolation when the diode is reverse biased.

• Photodetector: As the conversion of light into current takes place within the depletion region of a photodiode, increasing the depletion region by adding the intrinsic layer improves the performance by increasing the volume in which light conversion occurs.

These are three of the main applications for PIN diodes, although they can also be used in some other areas as well.

The PIN diode is an ideal component to provide electronics switching in many areas of electronics. It is particularly useful for RF design applications and for providing the switching, or attenuating element in RF switches and RF attenuators. The PIN diode is able to provide much higher levels of reliability than RF relays that are often the only other alternative.

AVALANCHE PHOTODiode

Avalanche photodiodes have advantages in some applications although their use may be more specialized. The avalanche photodiode possesses a similar structure to that of the PIN or PN photodiode. A structure similar to that of a Schottky photodiode can also be used but this is less common. However the structure is optimized for avalanche operation.

The main difference of the avalanche photodiode operates under a slightly different scenario to that of the more standard photodiodes. It operates under a high reverse bias condition to enable avalanche multiplication of the holes and electrons created by the initial hole electron pairs created by the photon/light impact.

The avalanche action enables the gain of the diode to be increased many times, providing a much greater level of sensitivity.
Avalanche photodiode advantages and disadvantages

The main advantages of the avalanche photodiode include:

  Greater level of sensitivity

The disadvantages of the avalanche photodiode include:

  Much higher operating voltage may be required.
  Avalanche photodiode produces a much higher level of noise than a p-n photodiode
  Avalanche process means that the output is not linear

Circuit conditions

Avalanche photodiodes require a high reverse bias for their operation. For silicon, a diode will typically require between 100 and 200 volts, and with this voltage they will provide a current gain effect of around 100 resulting from the avalanche effect. Some diodes that utilise specialised manufacturing processes enable much higher bias voltages of up to 1500 volts to be applied. As it is found that the gain levels increase when higher voltages are applied, the gain of these avalanche diodes can rise to the order of 1000. This can provide a distinct advantage where sensitivity is of paramount importance.

The avalanche photodiodes are not as widely used as their p-i-n counterparts. They are used primarily where the level of gain is of paramount importance, because the high voltages required, combined with a lower reliability means that they are often less convenient to use.
MODULE – IV

Optical Amplifiers

As the optical signal travels in a fiber waveguide, it suffers attenuation (loss of power). For very long fiber spans, the optical signal may be so attenuated that it becomes too weak to excite reliably the (receiving) photodetector, whereupon the signal may be detected at an expected low bit error rate. To reach destinations that are hundreds of kilometers away, the optical power level of the signal must be periodically conditioned. Optical amplifiers are key devices that reconstitute the attenuated optical signal, thus expanding the effective fiber span between the data source and the destination. Some key characteristics of amplifiers are gain, gain efficiency, gain bandwidth, gain saturation, and noise. Optical amplifiers are also characterized by polarization sensitivity.

Optical amplifiers (GAs) are devices based on conventional laser principles. They receive one or more optical signals, each within a window of optical frequencies, and simultaneously amplify all wavelengths. That is, they coherently release more photons at each wavelength. This is a significant advantage of multiwavelength fiber systems over regenerators, because one device replaces many. OAs are 1R amplifiers (vs. 2R and 3R regenerators); that is, they only amplify directly an optical signal. There are two types of OA: the semiconductor optical laser type amplifier (SOA) and the fiber-type amplifier [erbium-doped (EDFA) or praseodymium-doped (PDFA)]. In addition, there are other amplifying devices that depend on the nonlinear properties of optical materials, such as Raman and Brillouin scattering. Optical amplifiers require electrical or optical energy to excite (pump up) the state of electron-hole pairs. Energy is typically provided by injecting electrical current (in SOA) or optical light in the UV range (in EDFA). To reduce optical signal losses at the couplings, antireflective (AR) coatings are used at the optical fiber-device interface.
Amplifiers are characterized by gain, bandwidth, gain over the bandwidth, maximum output power, dynamic range, cross-talk, noise figure, output saturation power, physical size, and so on. The output saturation power is defined as the output power level at which the gain has dropped by 3 dB. OAs, based on their structure, are distinguished as follows:

• Traveling wave laser amplifiers
• Fabry-Perot laser amplifiers
• Injection current distributed-feedback (DFB) laser amplifiers
• Stimulated Raman
• Stimulated Brillouin
• EDFA
• PDFA

Each structure has advantages and disadvantages depending on the application.

**SEMICONDUCTOR OPTICAL AMPLIFIERS**

The most important advantage of SOAs is that they are made with InGaAsP and are thus small, compact, and able to be integrated with other semiconductor and optical components. The SOA salient characteristics are as follows.

• They are polarization dependent, and thus require a polarization-maintaining fiber (polarization sensitivity in the range 0.5-2 dB).
• They have relatively high gain (20 dB).
• Their output saturation power is in the range of 5-10 dBm.
• They have a large bandwidth.
• They operate at the wavelength regions of 0.8, 1.3, and 1.5 μm.
• They are compact semiconductors easily integrable with other devices, which can also be used as wavelength converter.
• Several SOAs may be integrated into an array.

Because of nonlinear phenomena (four-wave mixing), however, SOAs have a high noise figure and high cross-talk level.
ERBIUM-DOPED FIBER AMPLIFIERS

One attractive fiber-optic amplifier (FDA) in optical communications systems, and particularly in DWDM systems, is the EDFA. The EDFA is a fiber segment a few meters long heavily doped with the rare earth element erbium (and also co-doped with Al and Ge). The erbium ions may be excited by a number of optical frequencies—514, 532, 667, 800, 980, and 1480 nm. The shortest wavelength, 514 nm, excites erbium ions to the highest possible energy level. From this level, it may drop to one of four intermediate metastable levels, radiating phonons (the acoustical quantum equivalent of photons). From the lowest metastable level, it finally drops to the initial (ground) level, emitting photons around 1550 nm in wavelength. Similar activity takes place with the remaining wavelengths, although the number of metastable levels decreases as the wavelength becomes longer. Finally, the longest wavelength, 1480 nm, excites ions to the lowest metastable level, from which it drops directly to the ground level. The two most convenient excitation wavelengths are 980 and 1480 nm. When a 980-nm or 1480-nm source propagates through an EDFA fiber, erbium ions are excited and stimulated emission takes place, releasing photonic energy in the wavelength range of 1520-1620 nm. EDFAs that perform best within the C-band are known as C-band EDFAs and those in the L-band as L-band EDFAs. When EDFA ions are excited by a 980-nm source, after approximately 1 μs the excited ions fall into the metastable energy level from which, if triggered, they drop to the ground energy level and emit light at the wavelength of the triggering photon.

If they are not triggered, after approximately 10 ms (known as the spontaneous lifetime), they spontaneously drop from the metastable level emitting light in the range around 1550 nm. In
communications, the bit rate is very high (Gb/s) and the bit period is very short (ps), compared with the long lifetime (ms); thus there is no intersymbol interference. However, at the absence of fast bits, the spontaneous emission adds to noise.

The EDFA amplifier consists of a coupling device, an erbium-doped fiber, and two isolators (one per EDFA end). The fiber carrying the signal is connected via the isolator that suppresses light reflections into the incoming fiber. The isolator at the output of the EDFA suppresses the reflections by the outgoing fiber. The EDFA is stimulated by a higher optical frequency (in the UV range) laser source, known as the pump. Laser light from the pump (980 or 1480 nm or both) is also coupled in the EDFA. The pump excites the fiber additives that directly amplify the optical signal passing through at a wavelength in the 1550-nm region. The pump laser is specifically designed for EDFA applications. Pump lasers are enclosed in a small package (approximately 20 X 15 X 8 mm”) with a connectorized single-mode fiber pigtail that can be coupled with the EDFA (fiber). Typical pumps have a wavelength of 980 or 1480 nm and an output power from under 100 mW to about 250 mW. In multimode fiber (EDFA), pumping can be done through the cladding (known as cladding pumping) using inexpensive 1-W diode (LED) pumps.

**Advantages of EFDA**

- A high power transfer efficiency from pump to signal (> 50%).
- Directly and simultaneously amplify a wide wavelength region (in the region of 1550 nm) at an output power as high as +37 dBm, with a relatively flat gain (> 20 dB), which is suitable to WDM systems.
- Saturation output is greater than 1 mW (10-25 dBm).
- Gain time constant is long (> 100 ms) to overcome patterning effects and intermodulation distortions (low noise).
- Large dynamic range (> 80 nm).
- Low noise figure.
- They are transparent to optical modulation format.
- Polarization independent (thus reducing coupling loss to transmission fiber).
- Suitable for long-haul applications.
- Modified EDFAs can also operate in the L-band.

**Disadvantages of EDFAs**
- EDFAs are not small devices (fibers are kilometers long) and cannot be integrated with other semiconductor devices.
- EDFAs exhibit amplified spontaneous light emission (ASE). That is, even if no incoming signal is present, there is always some output signal as a result of some excited ions in the fiber; this output is termed spontaneous noise.
- There is cross-talk.
- There is gain saturation.

EDFAs have found applications in long-haul as well as in wavelength division multiplexing (WDM) transport systems. Gain in excess of 50 dB, a wide bandwidth of 80 I-Lm, and very low noise characteristics have been demonstrated. A fiber span (hundreds of kilometers long) consists of fiber segments (tens of kilometers each). Optical amplifiers are placed at the interconnecting points to restore the attenuated optical signal. Thus, there may be several EDFAs along the fiber span (typically up to 8). However, three issues become important: gain flatness (all wavelengths at the EDFA output should have the same optical power), dynamic gain, and low noise. All wavelengths are not amplified through EDFAs in the same way; that is, the gain is not exactly flat. This issue is addressed with gain-flattening optical filters, passive in-line filters with low insertion loss, low dispersion, and stable performance over a wide range of temperatures.

The power pumped into an EDFA is shared by all wavelengths. The more wavelengths, the less power per wavelength, and vice versa. This has an undesirable effect in optical add-drop multiplexing (OADM) WDM with EDFAs. As wavelengths are dropped by an OADM and not added, EDFAs(in series with OADM) amplify fewer additional wavelengths, and as wavelengths
are added by another OADM, they are amplified less. That is, the gain does not remain at the same level from one OADM to the next. This imbalance is addressed by engineering the WDM system and dynamic gain control. Noise is addressed differently. It should be remembered that optical noise sources are cumulative and that the spontaneous emission of EDFAs introduces noise that degrades the SIN ratio. Thus when engineering a fiber-optic path, one may be tempted to try to overcome this by launching a strong optical signal into the fiber. However, near the zero-dispersion wavelength region, four-wave mixing could become dominant and could degrade the SIN ratio. The selection of power (per channel) launched into the fiber becomes a puzzle: amplifier noise restricts the minimum power of the signal, and four-wave mixing limits the maximum power per channel launched into the fiber. This implies the need to select a power level that lies between a lower and an upper limit. To determine the power level, many other parameters must be taken into account so that the required quality of signal is maintained. Some of these parameters are:

- Fiber length between amplifiers (km)
- Fiber attenuation (loss) per kilometer
- Number of amplifiers in the optical path
- Amplifier parameters (gain, noise, chromatic dispersion, bandwidth)
- Number of channels (wavelengths) per fiber
- Channel width and spacing
- Receiver (detector) specifications
- Transmitter specifications
- Polarization issues
- Optical component losses and noise (connectors, other devices)
- Quality of signal (bit error rate, SIN)
- Signal modulation method and bit rate
- Other design parameters

**WAVELENGTH CONVERTERS**

Wavelength conversion enables optical channels to be relocated, adding to the flexibility and efficiency of multiwavelength systems. Wavelength conversion may be achieved by employing
the nonlinear properties of certain heterojunction semiconductors. SOAs are also used as wavelength-converting devices. Their basic structure consists of an active layer (erbium-doped waveguide) sandwiched between a p-layer InP and an n-layer InP.

Various methods have been explored that are based on cross-gain modulation, four-wave mixing, dispersion-shifted fiber, and other interferometric techniques.

**Cross-Gain Modulation**
Gain saturation in an optical amplifier occurs when high optical power is injected in the active region and the carrier concentration is depleted through stimulated emission. Then, the optical gain is reduced. Based on this, consider two wavelengths injected in the active region of an optical amplifier. Wavelength \( \lambda_1 \) is modulated with binary data and wavelength \( \lambda_2 \) the target, is continuous (not modulated)

When the input bit in \( \lambda_1 \) is a logic one (i.e., high power) depletion occurs, it blocks \( \lambda_2 \). When the bit in \( \lambda_1 \) is a logic zero (no power) depletion does not occur, and \( \lambda_2 \) is at high power (logic one). Thus, a transfer of inverted data from \( \lambda_1 \) to \( \lambda_2 \) takes place. This method is known as cross-gain modulation.

**Four-Wave Mixing**
We have described four-wave mixing (FWM) as an undesirable nonlinearity. However, FWM can also be taken advantage of to produce at will an additional wavelength. Consider that a modulated wavelength \( \lambda_1 \) is to be converted to another, \( \lambda_2 \). Then \( \lambda_1 \) and two more wavelengths are selected, such that when all three are injected in the fiber device, FWM will cause a fourth wavelength to be produced, \( \lambda_2 \), which is modulated as the \( \lambda_1 \). A pass-band filter that passes
through only the new wavelength, $\lambda_2$, is placed in series to the FWM device.

**Optical Frequency Shifter**

Optical frequency shifters rely on the nonlinearity property of dispersion-shifted doped fibers, which produce a new wavelength when two wavelengths at high power and in close wavelength proximity interact (in the range of 1550 nm) as in FWM. Thus when a modulated wavelength $\lambda_1$, known as the probe signal, and also a continuous power wavelength $\lambda_2$, known as the pump, are launched into a 10-km dispersion-shifted fiber, a third modulated wavelength is generated. The new wavelength, $\lambda_3$, is at $\lambda_2$ shifted by an amount equal to the difference between the original wavelength of the signal and the pump. At the output of the dispersion shifted fiber an interference filter (IF) eliminates the probe and the pump wavelengths and allows only the frequency-shifted wavelength, $\lambda_3$, to pass through (thus acting as a band-pass filter).
MODULE 5
OPTICAL NETWORKS

Wavelength Routing Networks
Wavelength routing is a process in which arriving optical signals are directed to different output ports depending on the wavelength of the input. A network which uses this procedure is called a wavelength routed network. A wavelength router may be looked upon as a fixed wavelength demultiplexer which directs different wavelengths to different ports. A wavelength which is used for one destination is not available for another destination. Thus the device must also have wavelength converters in addition to optical cross connects. By changing the wavelength of an arriving input signal, one can change the destination port of the signal. A wavelength routing network has edge nodes which provide interface between the optical layer and other systems such as IP routers, ATM switches etc. All switching inside the optical layer is done by OXCs which may work in conjunction with wavelength converters. Wavelength routing requires that a route must be defined in the network which connects a source (input) with the destination. Such an optical path is called a light path (also called a clear path as the signal does not undergo any conversion from optical to electrical domain in its passage from the source to destination.)

In the figure shown, the edge nodes are marked E-1 to E-5 which are connected by fibers to all optical portion of the network. Two optical paths, one from E-1 to E-3 and another from E-2 to E-4 are shown in the figure. A wavelength which is being used for one of the light paths is not available for another path. In the optical domain there is no conversion from photon signal to electrical signal.
The implementation of wavelength routing is done as follows:
An OFC takes at each of its N input ports W signals of different wavelengths. If the signals can be directed to M output ports, the OFC acts essentially as W independent NxM switches. The figure shows equivalent switches for a 4x4 optical cross connect with 2 waves per fiber.

For a network not using wavelength converter, wavelength continuity condition requires that along any light path, the same wavelength must be used throughout. This is sometimes a restrictive condition because it does not allow establishment of a path between nodes even when a wavelength channel is available. Consider a case shown in the figure where two wavelengths $\lambda_1$ and $\lambda_2$ are available. There is one light path between N-1 and N-2 and a second light path between N-2 and N-3, the former using the wavelength $\lambda_1$ and the latter $\lambda_2$.
As only two wavelength are available, it is not possible to establish a light path between N-1 and N-3 (without violating continuity condition) though there is a free wavelength between each of the segments. However, if a wavelength converter is located at the node N-2, we may relax the continuity condition, as shown in the right hand figure. The degree of wavelength conversion used in a given network depends on the traffic pattern in the network. The figure below illustrates different situations for a single input port and a single output port.

- **No Conversion**: A network may allow no conversion at all in which case all the wavelengths are routed as such to the output port.
- **Fixed Wavelength Conversion**: A signal entering a particular node with a wavelength $\lambda_i$ always leaves the node with a pre-determined wavelength $\lambda_j$.
- **Limited Wavelength Conversion**: In this case, an input wavelength $\lambda_i$ can be converted to any of a limited number of wavelengths. For instance, in the figure, $\lambda_1$ can be converted to either $\lambda_1$ or $\lambda_2$ but not to $\lambda_3$. Similarly, $\lambda_2$ can be converted to $\lambda_1$ and $\lambda_3$ but cannot leave the node without conversion while $\lambda_3$ can be converted to any of the three wavelengths.
- **Full Conversion**: This is the case where any of the input wavelengths can be converted to any of the permitted wavelengths.

**Wavelength Switching Networks**

Wavelength Switched Optical Networks (WSON) are Wavelength Division Multiplexing (WDM) based networks that include switching elements that can switch based on the wavelength or the frequency of signals transported over optical fiber. Although originally included in the
overall set of Generalized Multi-Protocol Label Switching (GMPLS) based control plane protocols, optical technology developments have gone beyond the optical systems originally envisioned within GMPLS. Hence this current work aims to extend GMPLS and related technologies, in particular, the path computation element (PCE) to provide robust control of these emerging optical networks.

The basic WSON control plane standards thrust was divided into the following areas:

- Overall control plane approach to WSONs including key scope limitations of this initial effort.
- An information model and encoding for use in path computation for WSONs. In the optical literature this path computation process is denoted by routing and wavelength assignment (RWA)
- Extensions to the PCE communications protocol (PCEP) to allow path computation clients to request from a PCE server paths meeting WSON constraints and optimization criteria.
- Extensions to GMPLS routing protocols (OSPF, IS-IS) to convey additional information relevant to WSONs.
- Extensions to the GMPLS signaling protocol (RSVP-TE) to facilitate the setup and tear down of WSON connections.
- Considerations of optical impairments and the control plane (in close collaboration with ITU-T)

A WSON consist of two planes: the data and the control planes. The data plane comprises wavelength-division multiplexing (WDM) fiber links connecting optical cross-connect (OXC)s through a comb of several tens of wavelength channels, with typical data rates of 10 or 40 Gb/s. Optical end-to-end connections (i.e., light paths) are established in the optical domain and switched by OXCs at the wavelength granularity.

In WSONs the optical signal is switched at the wavelength granularity, therefore the wavelength assignment process, selecting the carrier of each established light path, plays a crucial role in dynamic network operation.

The dynamic provisioning and maintenance of light paths is managed by the control plane. The control plane is implemented on a separate network and typically employs one network
controller for each node in the data plane, as shown in the figure. The Generalized Multi-Protocol Label Switching (GMPLS) protocol suite, the de facto standard control plane for WSONs proposed by the IETF, is composed of three protocols.

**Network Protection and Survivability**

Network survivability may be defined as network’s ability to continue functioning correctly in the presence of failures of any network components. It is an important requirement for any optical networks due to their ultra-high capacity. A single failure can disrupt millions of applications and results in tremendous data and revenue loss to both end users and network operators. The common requirement of the downtime of a leased connection in the industry is less than 5 minutes per year. Although many network components can cause the failure of a connection, such as fibers, switches, transceivers and so on. But the most common network failure is the link failure. In general, there are two ways to provide recovery from failures, namely, protection and restoration. In the protection paradigm, each connection is provisioned and allocated certain amounts of spare resources for protection, which can be used to reroute the transmission upon a failure on the connection. The restoration paradigm does not assign any spare resource for the protection in advance. Upon a failure, network has to search spare resources to reroute each disrupted connection around the failure.

Link protection is designed to safeguard networks from failure. Failures in high-speed networks have always been a concern of utmost importance. A single fiber cut can lead to heavy losses of traffic and protection-switching techniques have been used as the key source to ensure survivability in such networks. Survivability can be addressed in many layers in a network and protection can be performed at the physical layer (SONET/SDH, Optical Transport Network), Layer 2 (Ethernet, MPLS) and Layer 3 (IP).

Protection architectures like Path protection and Link protection safeguard the above-mentioned networks from different kinds of failures. In path protection, a backup path is used from the source to its destination to bypass the failure. In Link protection, the end nodes of the failed link initiate the protection. These nodes detect the fault and are responsible to initiate the protection mechanisms in order to detour the affected traffic from the failed link onto predetermined reserved paths.
Link Protection in the Optical Transport Layer

In older high-speed transport networks, the SONET layer (also SDH) was the main client of the wavelength-division multiplexing (WDM) layer. For this reason, before WDM protection schemes were defined, SONET protection mechanisms were mainly adopted to guarantee optical network survivability. When the WDM layer was created, the optical networks survivability techniques in consideration were mainly based on many elements of SONET protection in order to ensure maximum compatibility with the legacy systems (SONET systems). Hence some of the WDM-layer protection techniques are very similar to SONET/SDH protection techniques in the case of ring networks.

Ring-Based protection

In the case of a link or network failure, the simplest mechanism for network survivability is automatic protection switching (APS). APS techniques involve reserving a protection channel (dedicated or shared) with the same capacity of the channel or element being protected. When a shared protection technique is used, an APS protocol is needed to coordinate access to the shared protection bandwidth. An example of a link-based protection architecture at the Optical Transport Network layer is a Bidirectional Line Switched Ring (BLSR). In a BLSR, every link can carry both the working and backup traffic at the same time and hence does not require backup links. In a BLSR, under normal circumstances, the protection fiber is unused and this is beneficial to ISP’s since they can use the protection fiber to send lower priority traffic (using protection bandwidth) like data traffic and voice traffic.

There are two architectures for BLSRs: The four-fiber BLSR and the two-fiber BLSR. In a four-fiber BLSR, two fibers are used as working fibers and the other two are used as protection fibers, to be utilized in the case of a failure. Four-fiber BLSRs use two types of protection mechanisms during failure recovery, namely ring and span switching. In span switching, when the source or destination on a link fails, traffic gets routed onto the protection fiber between the two nodes on the same link and when a fiber or cable cut occurs, service is restored using the ring switching mechanism.

In a two-fiber BLSR, the protection fibers are contained within the working fibers (like a four-fiber BLSR) and both the fibers are used to carry working traffic whilst keeping only half the capacity on each fiber for protection purposes. Two-fiber BLSRs also benefit from the ring
switching but cannot perform span switching like a four-fiber BLSR.

Due to its efficiency in protection, BLSRs are widely deployed in long haul and interoffice networks, where the traffic pattern is more distributed than in access networks. Most metro carriers have deployed two-fiber BLSRs, while many long-haul carriers have deployed four-fiber BLSRs since they can handle more load than two-fiber BLSRs.

**Mesh-based protection**

The techniques mentioned above for SONET and WDM networks can also be applied to mesh network architectures provided there are ring decompositions for the mesh architectures; and use well defined protection-switching schemes to restore service when a failure occurs. The three most notable ring-based protection techniques for mesh networks are ring covers, cycle double covers and p-cycles (pre-configured protection cycles).

The main goal of the ring cover technique is to find a set of rings that covers all the network links and then use these rings to protect the network against failures. Some network links in the ring cover might get used in more than one ring which can cause additional redundancy in the network and because of this reason, scaling down redundancy is the primary focus of this technique.

The cycle double covers technique provides one protection fiber for each working fiber (like in SONET rings) keeping 100% redundancy. This technique was initially proposed to remove the additional redundancy issue caused by the ring cover scheme.

The p-cycle technique is based on the property of a ring to protect not only its own links, but also any possible links connecting two non-adjacent ring nodes called chordal links. By doing this, p-cycles reduce the redundancy required to protect a mesh network against link failure. There are two types of p-cycles namely link p-cycles and node p-cycles. Link p-cycles protect all channels on a link whereas a node p-cycle protects all the connections traversing a node.

Another technique called the generalized loopback technique can be included under ring-based approaches. Although it is not strictly considered as one of the mesh-based ring protection techniques, its usage of a loopback operation is similar to the APS operation in rings to switch the signal from working to the redundant capacity.
Link protection in the Client/Service Layer

Protection in Ethernet
Ethernet links use link aggregation as a mechanism to recover from failures. Even when a link fails, its link capacity gets reduced but the communication system keeps working without interruptions in data flow. Other terms used to describe link aggregation include IEEE 802.1ax (formerly known as 802.3ad), link bundling or NIC teaming.

Protection in IP
In recent years, packet based networks made a big leap and almost every single service provided (voice, IP-TV, etc.) is IP based. This is due to the reason that the IP layer has long provided best-effort services.

IP uses dynamic, hop-by-hop routing of packets and if there is a link failure, the routing protocols (OSPF or IS-IS) operates in a distributed manner and updates the routing table at each router in the domain. This process can get slow and cause heavy delays in the network. In order to avoid slow recovery, every IP link can be protected using protocols at the lower levels which will help the IP links to recover by itself instead of waiting for the IP routing table to change. For example, IP links can be realized by protected MPLS using Label Switched Paths – LSPs (IP over MPLS).

Protection in MPLS Networks
MPLS based networks use fast re-route as its network resiliency mechanism. In MPLS fast re-route, MPLS data can be directed around a link failure without the need to perform any signaling when a failure is detected. One form of fast re-route is called Link Protection. In this protection, an LSP tunnel is set up through the network to provide a backup for a vulnerable physical link. The LSP provides a parallel virtual link. When the physical link fails, the upstream node switches traffic to the virtual link so that data continues to flow with a minimal disruption. The capacity of the backup LSP should be sufficient to carry the protected LSPs. Depending on the LSPs, the capacity needs to be configured.

Optical Link Design
The optical link design essentially is putting the various optical components so that information can be transmitted satisfactorily. The satisfactoriness of the transmission can be defined in terms
The user generally specifies the distance over which the information is to be sent and the data rate to be transmitted. The Designer then has to find the specification of the system components. The designer generally has to define some additional criteria either as per the standards or as per the user specifications.

The Design criteria are given in the following.

- **Primary Design Criteria**
  - Data Rate
  - Link length

- **Additional Design Parameters**
  - Modulation format eg: Analog/digital: Depends upon the type of signals user want to transmit. For example if it is a TV signal, then may be analog transmission is more suited as it requires less bandwidth and better linearity. On the other hand if data or sampled voice is to be transmitted, digital format may be more appropriate.
  - The digital signals have to be further coded to suite the transmission medium and also for error correction.
  - System fidelity: BER, SNR
    - The system fidelity defines the correctness of the data received at the receiver.
    - For digital transmission it is measured by the Bit Error Ratio (BER). The BER is defined as
      \[
      \text{BER} = \frac{\text{Number of bits in error}}{\text{Total Number of bits transmitted}}
      \]
      In optical system the BER has to be less than \(10^{-9}\).
    - For analog system the quality parameter is the Signal-to-noise (SNR) ratio. Also there is a parameter called the inter-modulation distortion which describes the linearity of the system.

- **Cost**: Components, installation, maintenance
Cost is one of the important issues of the link design.

The cost has three components, components, installation and maintenance.

The component and the installations cost are the initial costs. Generally the installation cost is much higher than the component cost for long links. This is especially true for laying the optical cable. It is therefore appropriate to lay the cables keeping in view the future needs.

The optical link is supposed to work for at least 25 years. The maintenance costs are as important as the initial cost. An initial cheaper system might end up into higher expenses in maintenance and therefore turn out to be more expensive as a whole.

- Upgradeability
  - The optical fiber technology is changing very rapidly and the data rates are increasing steadily.
  - The system should be able to adopt new technology as it should be able to accommodate higher data rates with least possible changes.

- Commercial availability
  - Depending upon which part of the world one is, the availability of the components and the systems may be an issue.

Here we discuss design of a simple point-to-point optical link. A simple point to point link is shown in the following figure.

The link has primarily 3 components to design

1. Optical Transmitter.
2. Optical Fiber
3. Optical receiver
Two calculations are carried out in the link design
1. Power budget calculation (SNR related)
2. Rise Time budget calculation (Distortion related)

The figure below shows the power loss model of an optical fiber link. The power is lost in various components like, fiber, connectors, splicing.

![Fiber Loss Model Diagram]

The fiber loss depends upon the wavelength and also the physical conditions of the fiber. The fiber loss is generally higher than that the specified by the manufacturers. This is primarily due to micro-bending of the fiber. Also the micro-bending loss is higher for 1550nm compared to 1310nm. Therefore the overall loss could be higher at 1550nm than at 1310nm, although intrinsically silica glass has minimum loss at 1550nm. Typical loss ate 1550nm may lie in the range 0.4-0.5 dB/km. The splice loss could be between 0.05-0.1 dB per splice. The connector loss is higher and could be 0.2-0.3 dB per connector.

**Power Budget Calculation**

Let \( P_s \) = Power from the Transmitter in dBm

\( P_r \) = Sensitivity of receiver in dBm for given BER

Maximum permissible loss : \( \alpha_{\text{max}} = P_s - P_r \)

Also,

\[
\alpha_{\text{max}} = \alpha_{\text{fiber}} + \alpha_{\text{conn}} + \alpha_{\text{splice}} + \alpha_{\text{syst}}
\]

\[
\Rightarrow \alpha_{\text{fiber}} = \alpha_{\text{max}} - (\alpha_{\text{conn}} + \alpha_{\text{splice}} + \alpha_{\text{syst}})
\]

**Power Limited Link Length**

\[
L_{P_{\text{max}}} = \frac{\alpha_{\text{fiber}}}{\text{Loss / Km}}
\]
Beyond this distance the SNR is below the acceptable limit. Hence, this distance is called Power Limited Link Length.

Rise Time Budget Calculation

Rise time analysis gives effective bandwidth of the link.

\[ t_{sys} = \left( t_{tx}^2 + D^2 \sigma_L^2 L^2 + t_{rx}^2 \right)^{1/2} \]

For satisfactory operation of the link

\[ t_{sys} \leq 0.7T_b \]

Rise time limited link length

\[ L_{RT\text{max}} = \frac{1}{D\sigma_L} \left\{ (0.7T_b)^2 - (t_{tx}^2 + t_{rx}^2) \right\}^{1/2} \]

Rise time of a system or component = 1/bandwidth

Here,

\[ t_{sys} = \text{Total system rise time.} \]
\( t_{t,x} = \) Transmitter rise time

\( t_{r,x} = \) Receiver rise time.

\( D = \) Dispersion of the fiber

\( \sigma_\lambda = \) Spectral width of the transmitter

\( L = \) Length

\( T_b = \) Data bit duration \( = \frac{1}{\text{Data Rate}} \)

In the link design two lengths, the power budget length \( L_{P_{\text{max}}} \) and the rise time budget length \( L_{R{T}_{\text{max}}} \) are calculated. The repeater has to be installed at a distance \( \min(L_{P_{\text{max}}}, L_{R{T}_{\text{max}}}) \).

Generally, the links are power limited and the repeaters are installed at \( L_{P_{\text{max}}} \). Typical repeater length is about 50-60 km in practice.