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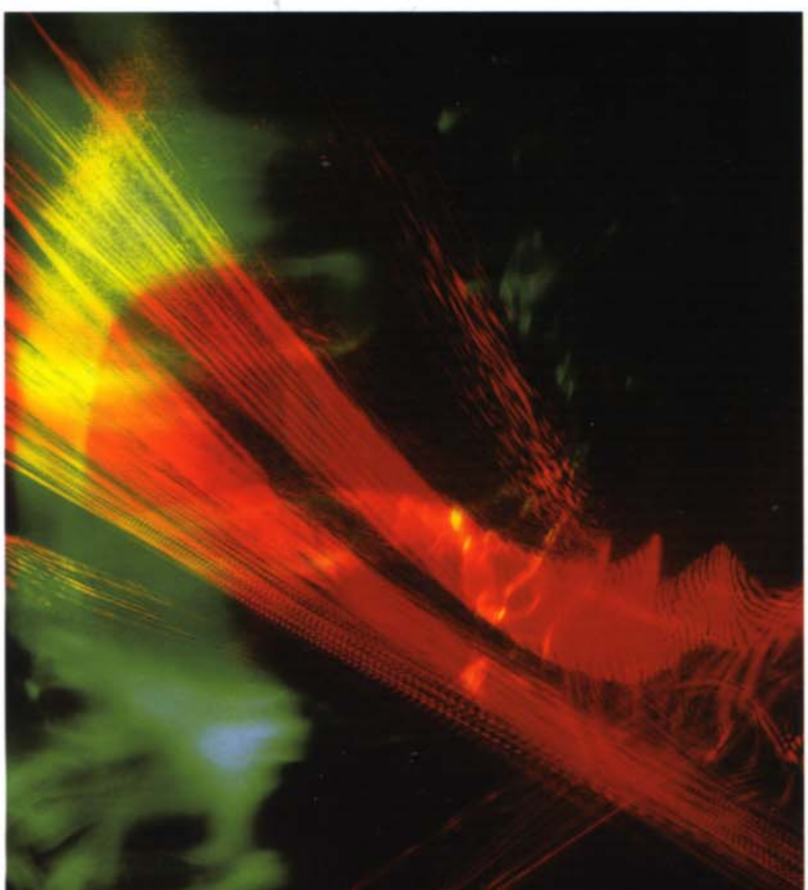
# The Optics Encyclopedia

Basic Foundations
and Practical Applications



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# Optoelectronics

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**Abstract**
It is useful to view today's optoelectronics in terms of various functional categories, most important of which are the generation of light, modulation of light, transmission of light and its connection between devices, amplification of light, switching of light, isolation of light, filtering of light, wavelength multiplexing and demultiplexing of light, and detection of light. The corresponding devices that implement these functions are light emitters (or light sources), modulators, waveguides and connectors, optical amplifiers, optical switches, optical isolators, optical filters, multiplexers and demultiplexers, and detectors. This introductory article reviews the principles of operation and characteristics of a number of selected devices to provide a general introduction to the field of optoelectronics with an emphasis on optical communications – a major area of application.

**Keywords**
coherent and incoherent sources; lasers; waveguides; optical fibers; connectors; light modulation; photodetectors; integrated optics; optoelectronic systems; optical communications.

## 1 Introduction

Optoelectronics is an evolving discipline that describes phenomena and applications using electronics *and* optics, or electrons *and* photons; a good example is a laser diode that converts an electric current at its input into a coherent beam of photons at its output. A major historical milestone in optoelectronics is the development of heterostructure laser diodes in the early 1960s that eventually allowed small-scale semiconductor lasers to be manufactured in late 1970s. Over the last two decades, there have been tremendous advances in optoelectronics driven primarily by the enormous growth in optical communication networks. While optical communications is obviously one of the most significant uses of optoelectronics, other applications have also been developing and serving other industries and markets. (The consumer is already familiar with CD and DVD players, flat-panel displays, digital and video cameras, infrared binoculars, etc.) There is no clear distinction between optoelectronics and photonics, though the latter would encompass substantial optics. The term *photonics* grew from envisaging and realizing applications that involve photons only without necessarily relying on electronics.

It is useful to view today's optoelectronics in terms of various functional categories, most important of which are the (1) generation of light, (2) modulation of light, (3) transmission of light and its connection between devices, (4) amplification of light,

(5) switching of light, (6) isolation of light, (7) filtering of light, (8) wavelength multiplexing and demultiplexing of light, and (9) detection of light. The corresponding devices that implement these functions are light emitters (or light sources), modulators, waveguides and connectors, optical amplifiers, optical switches, optical isolators, optical filters, multiplexers and demultiplexers, and detectors. These devices are shown as functional blocks in Fig. 1. An externally modulated optical communications system that incorporates some of these functionalities is schematically illustrated in Fig. 2. In the latter example, a laser diode generates a continuous wave light at 1550 nm with a narrow spectrum. The light is externally modulated by an electro-optic (EO) modulator. The modulator modulates the light passing through it according to the encoded information applied to its electrical input terminal. The optical signal in the form of pulses is fed into an optical fiber for transmission towards its destination. The wavelength of 1550 nm is preferred for long-haul communications because the attenuation along the optical fiber is least at this wavelength. Optical switches enable the optical path to be switched at various locations as desired by the user; for example, if there is a break in the fiber, the optical switch in Fig. 2 will switch the optical path to the back-up link. Optical amplification is typically used to amplify an optical signal that has been attenuated as a result of being guided along a transmission medium such as an optical fiber. An optical isolator allows the optical signal to travel only in one direction and is useful in preventing the amplified signal from traveling back to the transmitter. An optical coupler allows light in one fiber to be coupled into another fiber. An optical filter allows either a given wavelength to pass through (such as the 1550-nm wavelength) or blocks the passage of a certain wavelength (such as the 980-nm pump wavelength of an Er-doped fiber amplifier) by reflecting it. Various optical connectors (not shown in Fig. 2) are obviously needed to connect the devices and components to each other. Optical connectors, although simple in functionality, play an undeniably important role in the overall optoelectronic system design since various devices and components have to be connected together efficiently and economically, and without failure. For example, an inefficient connection system may lead to an additional use of optical amplifiers to correct the mistake. In optical communications, typically, various devices are connected through optical fibers and cables using connectors and splices. The connector and splice technology have been, by and large, standardized to facilitate the rapid and easy connection of fibers and cables to each other.

While the above simple function-based classification is convenient, it is not necessarily always sufficient. For example,

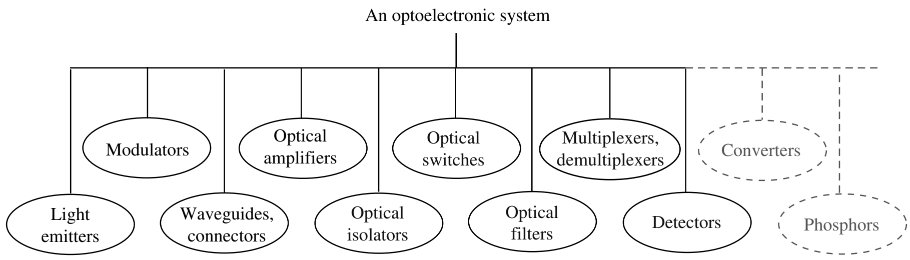


**Fig. 1** A variety of optoelectronic devices can be combined to build an optoelectronic system

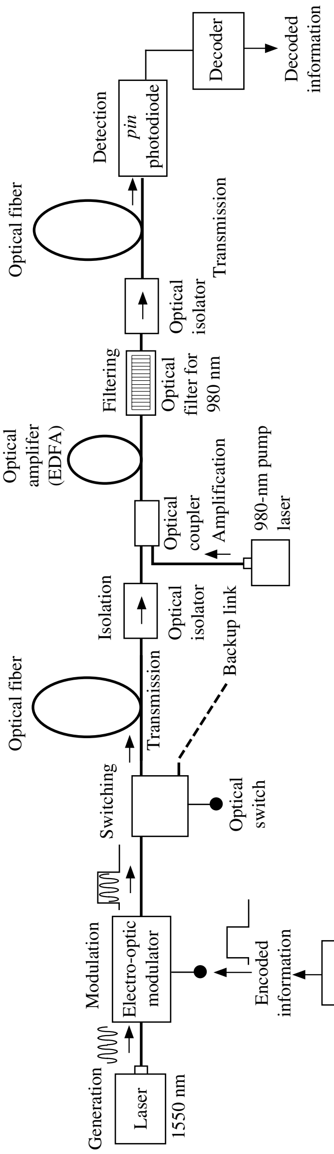


**Fig. 2** A simplified schematic illustration of an externally modulated optical communications system

we can also introduce other functional categories such as *light conversion* or *light storage*; in the former, the wavelength is changed (e.g., by second harmonic generation), whereas in the second case, the light is stored (which may involve conversion) until it is needed and then "let" out; stimulated phosphors are good examples of this, but there is a change in the wavelength. An alternative classification scheme is also possible, for example, based on the physical process that is exploited in the optoelectronic device rather than what the device does. (Optoelectronics engineers are more interested in the function of the device than the physical process that enables that function.) It is also possible to divide optoelectronics into categories based on end-uses or applications such as optical communications, optical information storage, metrology, medical imaging, medical diagnosis, laser surgery, holography, and so on, but not many optoelectronics books take that approach in describing the subject. Optoelectronics is generally taught as an overlap field between physics, electrical engineering, and materials science, though each discipline has its own slightly different description (and opinion) of the subject.

## 2
## Solid-state Emitters

### 2.1
### Light-emitting Diodes

A light-emitting diode (LED) is essentially a *pn* junction diode typically made from a direct bandgap semiconductor, for example, GaAs, in which the electron–hole pair (EHP) recombination results in the emission of a photon. The emitted photon energy $h\upsilon$ is approximately equal to the bandgap energy $E_g$. Figure 3(a) shows the energy band diagram of an unbiased $pn^+$ junction device in which the *n*-side is more heavily doped than the *p*-side. (The superscript "+" on *n* or *p* indicates heavy doping.) The Fermi-level $E_F$ is uniform through the device, which is a requirement of equilibrium with no applied bias. The depletion region extends mainly into the *p*-side. There is a potential energy (PE) barrier $eV_o$ from $E_c$ on the *n*-side to $E_c$

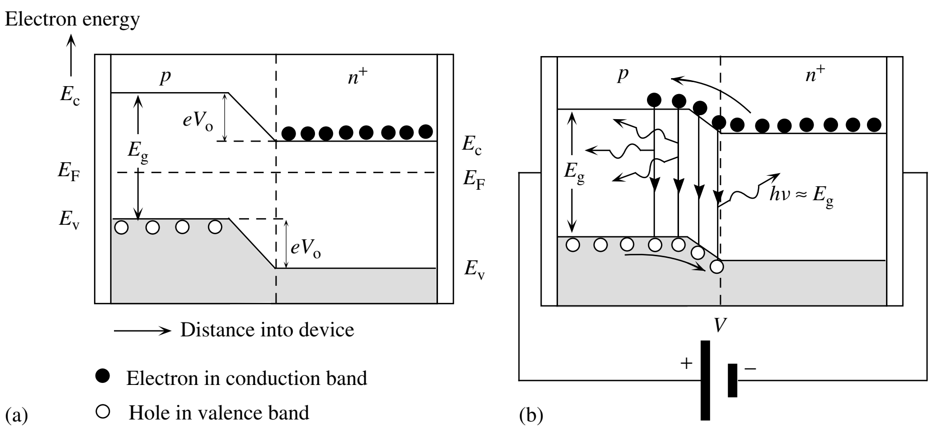


**Fig. 3** Energy band diagram of a *pn* (heavily *n*-type doped) junction. (a) No bias voltage; (b) With forward bias *V*

on the $p$-side where $V_o$ is the built-in voltage. The PE barrier $eV_o$ prevents the diffusion of electrons from the $n$-side to the $p$-side.

When a forward bias $V$ is applied, the built-in potential $V_o$ is reduced to $V_o - V$ which then allows the electrons from the $n^+$ side to diffuse, that is, become injected, into the $p$-side as depicted in Fig. 3(b). The hole injection component from $p$- into the $n^+$-side is much smaller than the electron injection component from the $n^+$ to $p$-side. The recombination of injected electrons in the depletion region and within a volume extending over the electron diffusion length in the $p$-side leads to photon emission. The phenomenon of light emission from EHP recombination as a result of minority carrier injection is called *injection electroluminescence*. Due to the statistical nature of the recombination process between electrons and holes, the emitted photons are in random directions; they result from spontaneous emission processes. The LED structure has to be such that the emitted photons can escape the device without being reabsorbed by the semiconductor material. This means the $p$-side has to be sufficiently narrow or we have to use *heterostructure* devices as discussed below.

The external efficiency $\eta_{\text{external}}$ of an LED quantifies the efficiency of conversion of electrical energy into an emitted external optical energy. It incorporates the internal efficiency of the radiative recombination process and the subsequent efficiency of photon extraction from the device. The input of electrical power into an LED is simply the product ($IV$) of the diode current $I$ and the diode voltage $V$. If $P_{\text{out}}$ is the optical power emitted by the device, then the external efficiency is $P_{\text{out}}/(IV)$, and some typical values are listed in Table 1. For indirect bandgap semiconductors, $\eta_{\text{external}}$ is generally less than 1%, whereas for direct bandgap semiconductors with the right device structure, $\eta_{\text{external}}$ can be substantial (>10%). Table 2 summarizes typical wavelength ranges for the

**Tab. 1** Selected LED semiconductor materials, wavelengths of emission, and typical external quantum efficiencies in commercial LEDs. Optical communication channels are at 850 nm (local network), and at 1.3 and 1.55 μm (long distance). D = direct, I = Indirect bandgap. $\eta_{\text{external}}$ is typical and may vary substantially depending on the device structure

| *Semiconductor (active layer)* | *D or I* | *λ [nm]* | $\eta_{external}$ *[%]* | *Comment* |
|---|---|---|---|---|
| GaAs | D | 870–900 | 10 | Infrared (IR) |
| $Al_xGa_{1-x}As$ ($0 < x < 0.4$) | D | 640–870 | 3–20 | Red to IR |
| $In_{1-x}Ga_xAs_yP_{1-y}$ ($y \approx 2.20x$, $0 < x < 0.47$) | D | 1–1.6 μm | >10 | LEDs in communications |
| InGaN alloys | D | 430–460 | 1–2 | Blue |
| | | 500–530 | 3–5 | Green |
| InGaN/GaN quantum well | D | 450–530 | >5 | Blue–green |
| SiC | I | 460–470 | 0.02 | Blue. Low efficiency |
| $In_{0.49}Al_xGa_{0.51-x}P$ | D | 590–630 | 1–10 | Amber, green, red |
| $GaAs_{1-y}P_y$ ($y < 0.45$) | D | 630–870 | <1 | Red–IR |
| $GaAs_{1-y}P_y$ ($y > 0.45$) (N or Zn, O doping) | I | 560–700 | <1 | Red, orange, yellow |
| GaP (Zn–O) | I | 700 | 2–3 | Red |
| GaP (N) | I | 565 | <1 | Green |

**Tab. 2** Wavelength ranges and colors as usually specified for LEDs

| | | | | | |
|---|---|---|---|---|---|
| Color | Blue | Emerald green | Green | Yellow | Amber |
| $\lambda$ (nm) | $\lambda < 500$ | 530–564 | 565–579 | 580–587 | 588–594 |
| Color | Orange | Red–orange | Red | Deep red | Infrared |
| $\lambda$ (nm) | 595–606 | 607–615 | 616–632 | 633–700 | $\lambda > 700$ |

apparent colors of various consumer LEDs. (Color perception is a difficult topic and the table only indicates "typical values" as quoted by various manufacturers of LEDs and as perceived by an average person.)

A junction between two different bandgap semiconductors is called a *heterojunction*. A semiconductor device structure that has junctions between different bandgap materials is called a *heterostructure device*. LED constructions for increasing the intensity of the output light make use of the double heterostructure. Figure 4(a) shows a double-heterostructure (DH) device based on two junctions between different semiconductor materials with different bandgaps. In this case, the semiconductors are AlGaAs with $E_g \approx 2$ eV and GaAs with $E_g \approx 1.4$ eV. The double heterostructure in Fig. 4(a) has an $n^+p$ heterojunction between $n^+$-AlGaAs and *p*-GaAs. There is another heterojunction between *p*-GaAs and *p*-AlGaAs. The *p*-GaAs region is a thin layer, typically a fraction of a micron and is lightly doped.

A highly simplified energy band diagram for the whole device in the absence of an applied voltage is shown in Fig. 4(b). The Fermi-level $E_F$ is continuous through the whole structure. There is a PE barrier $eV_o$ for electrons in the conduction band (CB) of $n^+$-AlGaAs against diffusion into *p*-GaAs. There is a bandgap change at the junction between *p*-GaAs and *p*-AlGaAs which results in a step change $\Delta E_c$ in $E_c$ between the two CBs of *p*-GaAs and *p*-AlGaAs. This $\Delta E_c$ is effectively a *PE barrier* that prevents any electrons in the CB of *p*-GaAs from passing to the CB of *p*-AlGaAs. (There is also a step change $\Delta E_v$ in $E_v$ but this is small and is not shown.)

When a forward bias is applied, most of this voltage drops between the $n^+$-AlGaAs and *p*-GaAs, and reduces the PE barrier $eV_o$, just as in the normal *pn* junction. This allows electrons in the CB of $n^+$-AlGaAs to be injected into the CB of *p*-GaAs as shown in Fig. 4(c). These electrons, however, are *confined* to the CB of *p*-GaAs since there is a barrier $\Delta E_c$ between *p*-GaAs and *p*-AlGaAs. The wide bandgap *p*-AlGaAs layers therefore act as confining layers that restrict injected electrons to the *p*-GaAs layer. The recombination of injected electrons and holes already present in this *p*-GaAs layer results in spontaneous photon emission. The *p*-GaAs layer is called the *active layer* inasmuch as this is where light is generated. Since the bandgap $E_g$ of AlGaAs is greater than GaAs, the emitted photons do not get reabsorbed as they escape the active region and can reach the surface of the device as depicted in Fig. 4(d). Since light is also not absorbed in *p*-AlGaAs, it can be reflected to increase the light output.

The spectrum of the emitted radiation is determined by the energy spread of the electrons in the conduction band (CB) and the energy spread of the holes in the valence band (VB) in the

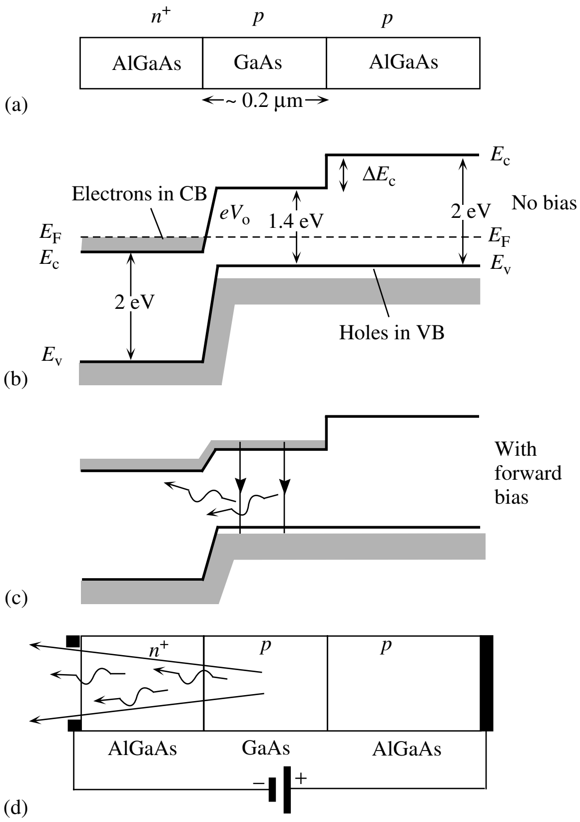


**Fig. 4** A double-heterostructure LED. (a) a double-heterostructure diode has two junctions that are between two different bandgap semiconductors (GaAs and AlGaAs); (b) a simplified energy band diagram with exaggerated features. $E_F$ must be uniform; (c) forward-biased simplified energy band diagram; (d) forward-biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device

active region. Since the energy spread in each case is $\sim 2kT$ (where $k$ is the Boltzmann constant and $T$ is the temperature), the spectral linewidth of the emission corresponds to a photon energy spread of a few $kT$. As the temperature increases, the linewidth $\Delta\lambda$ gets wider and the peak emission wavelength shifts to longer wavelengths, since the bandgap $E_g$ decreases with temperature as apparent in Fig. 5.

## 2.2 Semiconductor Laser Diodes

### 2.2.1 Double-heterostructure Laser Diodes

A laser diode is a semiconductor diode which emits *coherent radiation* in contrast to an LED which emits incoherent radiation. Laser diodes operate on the principle of stimulated emission resulting from photon-induced direct recombination of

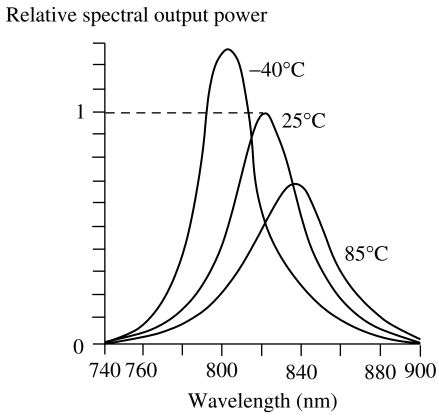


**Fig. 5** The output spectrum from an AlGaAs LED. Values normalized to peak emission at 25 °C

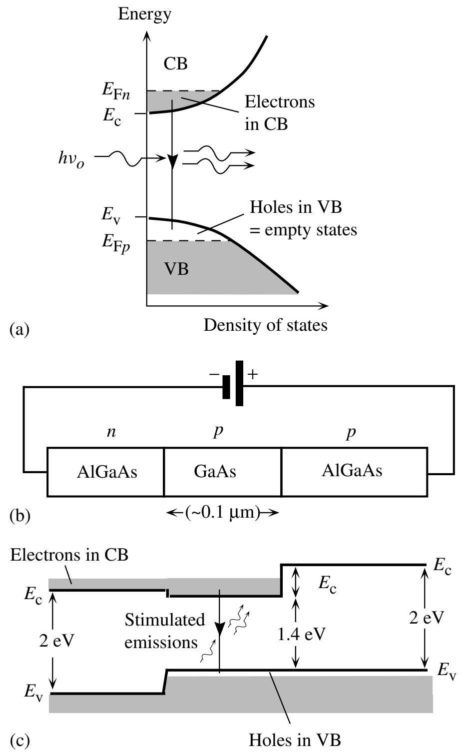


**Fig. 6** The principle of operation of the double-heterostructure laser diode. (a) The density of states and energy distribution of electrons and holes in the conduction and valence bands in the active layer, and photon-stimulated electron and hole recombination; (b) a double-heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs); (c) a simplified energy band diagram under a large forward bias. Lasing recombination takes place in the *p*-GaAs layer, the *active layer*

injected electrons and holes under forward bias, as illustrated in Fig. 6(a). All practical semiconductor laser diodes are either based on the DH or on quantum wells (QWs). A highly simplified energy band diagram of a forward-biased DH laser diode is shown in Fig. 6(b) and (c) and is similar to the LED diagram in Fig. 4. In this case, the semiconductors are AlGaAs with $E_g \approx 2$ eV and GaAs with $E_g \approx 1.4$ eV. The *p*-GaAs region is a thin layer, typically 0.1 to 0.2 μm, and constitutes the active layer in which stimulated emissions and hence optical amplification take place. Both *p*-GaAs and *p*-AlGaAs are heavily *p*-type doped and are degenerate with the Fermi level in the VB. When a sufficiently large forward bias is applied, $E_c$ of *n*-AlGaAs moves above $E_c$ of *p*-GaAs which leads to a large injection of electrons from the CB of *n*-AlGaAs into the CB of *p*-GaAs as shown in Fig. 6(c). These electrons, however, are *confined* to the CB of *p*-GaAs since there is a PE barrier $\Delta E_c$ between *p*-GaAs and *p*-AlGaAs due to the change in the bandgap. *Carrier confinement* is the restriction of injected charge carriers to a small volume to increase the carrier concentration. A *confining layer* is a layer with a wider bandgap than the active layer, and adjacent to it, to confine the injected minority carriers to the active layer.

The *p*-GaAs layer is degenerately doped. Thus, the top of its VB is full of holes, or it has all the electronic states *empty* above the Fermi-level $E_{Fp}$ in this layer as shown in

Fig. 6(a). The large forward bias injects a very large concentration of electrons from *n*-AlGaAs into the CB of *p*-GaAs. Consequently, as shown in Fig. 6(a), there is a large concentration of electrons in the CB and totally empty states at the top of the VB, which means that there is a *population inversion*. An incoming photon with an energy $h\upsilon_o$ (where $h$ is Planck's constant and $\upsilon_o$ is the photon frequency) just above $E_g$ can stimulate a conduction electron in the *p*-GaAs layer to fall down from the CB to the VB and emit a photon by stimulated emission as depicted in Fig. 6(a). Such a transition is a photon-stimulated electron–hole recombination, or a lasing recombination. Thus, an avalanche of stimulated emissions in the active layer provides an optical amplification of photons with energy $h\upsilon_o$ in this layer. The amplification depends on the extent of population inversion and hence on the diode forward current. There is a *threshold current* $I_{th}$ below which there is no stimulated emission and no optical amplification as illustrated in Fig. 7. Any emission below $I_{th}$ is due to spontaneous emission and the device operates as an LED. Figure 7 compares the output characteristics of a laser diode and an LED.

To construct a semiconductor laser with a self-sustained lasing emission, we have to incorporate the active layer into an optical cavity. The optical cavity with reflecting ends reflects the coherent photons back and forward, and encourages their constructive interference within the cavity. This leads to a build-up of high-energy electromagnetic (EM) oscillations in the cavity. Some of this energy is tapped out by having one end of the cavity as partially reflecting. For example, one type of optical cavity has a dielectric mirror at one end of the crystal and has the other crystal-end polished. Further, wider bandgap semiconductors generally have lower refractive indices, which means that AlGaAs has a lower refractive index than GaAs. The change in the refractive index defines an optical dielectric waveguide that confines the photons to the active region of the optical cavity and thereby reduces photon losses and increases the photon concentration. This increase in the

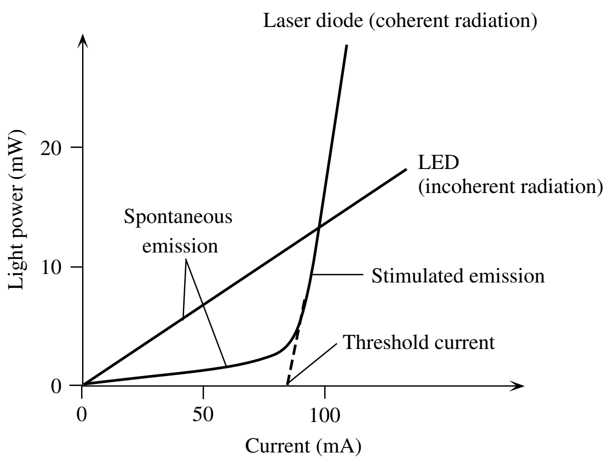


**Fig. 7** Typical optical power output vs. forward current for an LED and a laser diode

photon concentration increases the rate of stimulated emissions and the efficiency of the laser.

Buried double-heterostructure laser diode is a good example of a double-heterostructure semiconductor laser device that has its active region "buried" within the device in such a way that it is surrounded by low refractive index materials rendering the active region as a waveguide as shown in Fig. 8. Inasmuch as the active layer is surrounded by a lower index AlGaAs, it behaves as a dielectric waveguide and ensures that the photons are confined to the active or the optical gain region, which increases the rate of stimulated emission and hence the efficiency of the diode. Since the optical power is confined to the waveguide defined by the refractive index variation, these diodes are said to be *index guided*. Further, if the buried heterostructure has the right dimensions compared with the wavelength of the radiation, then only the fundamental mode can exist in this waveguide structure as in the case of dielectric waveguides. This would be the case in a *single-mode laser diode*.

The laser diode heterostructures based on GaAs and AlGaAs are suitable for emissions around 900 nm. For operation in the optical communication wavelengths of 1.3 and 1.55 μm, typical heterostructures are based on InP (substrate) and quarternary alloys InGaAsP where InGaAsP alloys have a narrower bandgap than that of InP and a greater refractive index. The composition of the InGaAsP alloy is adjusted to obtain the required bandgap for the active and confining layers.

### 2.2.2 Quantum Well and Quantum Dot Lasers

A quantum well (QW) device has an ultra thin, typically less than 20 nm, narrow bandgap semiconductor, such as GaAs, sandwiched between two wider bandgap semiconductors, such as AlGaAs which is a *heterostructure device* as shown in Fig. 9(a). Since the bandgap, $E_g$, changes at the interface, there are discontinuities in $E_c$ and $E_v$ at the interfaces. These discontinuities, $\Delta E_c$ and $\Delta E_v$, depend on the semiconductor materials and their doping. In the case of GaAs/AlGaAs heterostructure, which is shown in Fig. 9(b), $\Delta E_c$ is greater than $\Delta E_v$. Because of the PE barrier, $\Delta E_c$, conduction electrons in the thin GaAs layer are confined in the $z$-direction. This confinement length $d$ is so small that we can treat the electron as in a one-dimensional PE well in the $z$-direction, but as if it were free in the $xy$ plane. The electrons in the CB of GaAs form a two-dimensional (2-D) electron gas. The conduction electron in the GaAs well has

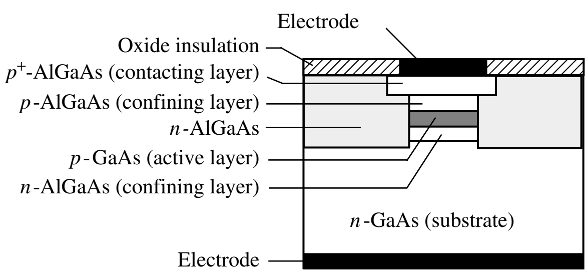


**Fig. 8** Schematic illustration of the cross sectional structure of a buried heterostructure laser diode

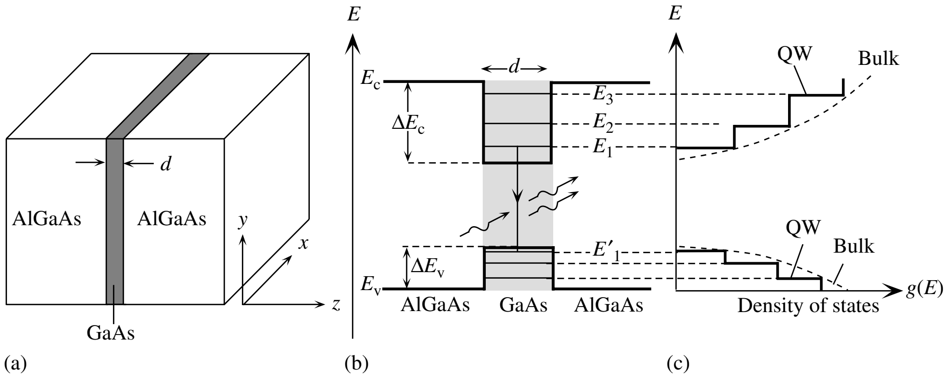


**Fig. 9** A quantum well (QW) device. (a) Schematic illustration of a QW structure in which a thin layer of GaAs is sandwiched between two wider bandgap semiconductors (AlGaAs); (b) the conduction electrons in the GaAs layer are confined (by $\Delta E_c$) in the *z*-direction to a small length *d* so that their energy is quantized; (c) the density of states of a two-dimensional QW. The density of states is constant at each quantized energy level

the allowed energies $E_1$, $E_2$, $E_3 \ldots$ above $E_c$ and the hole energies are at $E'_1$, $E'_2$ $E'_3 \ldots$ below $E_v$, due to the quantization in the $z$-direction (the energy due to electron motions in the $x$ and $y$ directions are small and add onto $E_1, E_2, E_3, \ldots$). The density of electronic states for the two-dimensional electron system is not the same as that for the bulk semiconductor. For a given electron concentration $n$, the density of states $g(E)$, that is, the number of quantum states per unit energy per unit volume is constant and does not depend on the energy. The density of states for the confined electron and that in the bulk semiconductor are shown schematically in Fig. 9(c). $g(E)$ is constant from $E_1$ until $E_2$ where it increases as a step and remains constant until $E_3$, where again it increases as a step by the same amount and at every value of $E_n$. Density of states in the VB behaves similarly. Since there is a finite and substantial density of states at $E_1$, the electrons in the CB do not have to spread far in energy to find states. In the bulk semiconductor, on the other hand, the density of states at $E_c$ is zero and increases slowly with energy (as $E^{1/2}$) which means that the electrons are spread more deeply into the CB in search for states. A large concentration of electrons can easily occur at $E_1$ whereas this is not the case in the bulk semiconductor. Similarly, the majority of holes in the VB will be at $E'_1$ since there are sufficient states at this energy. Under a forward bias, electrons are injected into the CB of the GaAs layer, which serves as the active layer. The injected electrons readily populate the ample number of states at $E_1$, which means that the electron concentration at $E_1$ increases rapidly with current and hence population inversion occurs quickly without the need for a large current to bring in a great number of electrons. Stimulated transitions of electrons from $E_1$ to $E'_1$ lead to a lasing emission. The threshold current density for population inversion and hence lasing emission is markedly reduced when compared to that of a DH laser, by almost a factor of 10. *Multiple quantum well* (MQW) lasers have more than one QW and the QWs form a periodic structure as in Fig. 10. The smaller bandgap layers are the active layers where electron confinement

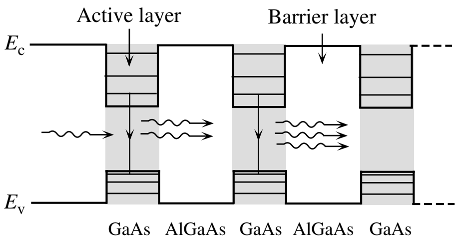


**Fig. 10** A multiple quantum well (MQW) structure. Electrons are injected by the forward current into active layers which are quantum wells

and lasing transition take place whereas the wider bandgap layers are the barrier layers. Many commercially available laser diodes are currently MQW devices.

Currently, there is much interest in developing *quantum dot* (QD) lasers. A QD is a crystal that is so tiny in all dimensions that the conduction electrons are confined in the $x$-, $y$- and $z$-directions. The electron energy in the QD is quantized in a similar fashion to the electron energy in a finite three-dimensional PE well that is well described in quantum mechanics. Quantum effects become apparent when the crystal size is several nanometers, typically less than 10 nm. Electron quantization effects associated with tiny microcrystals of II–VI semiconductors (such as CdS, CdSe, ZnS, etc.) in glasses are well documented. InAs quantum dots of the order of 10 nm in dimension can form in a self-organized fashion when InAs is being grown on GaAs substrates. The strain mismatch between the two crystals forces the InAs to cluster together into a tiny crystal. The preparation of technologically useful QDs is still under intense research. QD lasers have a number of distinct theoretical advantages. Compared with QW lasers, QD lasers have the lowest threshold current densities and have the narrowest spectral emission spectrum. Further, the threshold current for a QD laser is expected to show very little temperature dependence compared with QW lasers. An InAs QD laser emitting near 1.3 μm with a threshold current as low as 24 A $cm^{-2}$ has already been demonstrated; current extensive research and development will undoubtedly bring QD lasers into viable commercialization in the future.

### 2.2.3 Single Frequency Lasers

Ideally, the output spectrum from a laser device should be as narrow as possible, which generally means that we have to allow only a single mode to exist and also reduce cavity losses from end reflections in a Fabry–Perot cavity-based laser. There are a number of device structures that operate with an output spectrum that has a high modal purity. One of the most important semiconductor single-mode lasers is the distributed feedback (DFB) laser. In a Fabry–Perot cavity laser, the crystal faces provide the necessary optical feedback into the cavity to build up the photon concentration. In a DFB laser, as shown in Fig. 11(a), there is a corrugated layer, called the *guiding layer*, next to the active layer; radiation spreads from the active layer to the guiding layer. These corrugations in the refractive index act as optical feedback over the length of the cavity by producing partial reflections. Thus optical feedback is *distributed* over the cavity length. In the DFB structure, traveling waves are reflected partially and periodically as they propagate. The left and right traveling waves can only coherently couple to set up a mode if their frequency is related to the corrugation periodicity $\Lambda$, taking into account that the medium alters the wave-amplitudes via optical gain. The allowed DFB modes are not exactly at Bragg wavelengths but are symmetrically placed at about $\lambda_B$. The relative threshold gain for higher modes is so

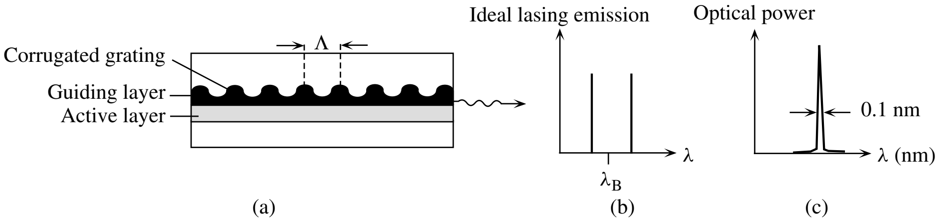


**Fig. 11** (a) Distributed feedback (DFB) laser structure; (b) ideal lasing emission output; (c) typical output spectrum from a DFB laser

large that only the lowest mode effectively lases. A perfectly symmetric device has two equally spaced modes placed around $\lambda_B$ as shown in Fig. 11(b). In reality, either inevitable asymmetry introduced by the fabrication process, or asymmetry introduced on purpose, leads to only one of the modes to appear as shown in Fig. 11(c). There are various commercially available single-mode DFB lasers in the market with spectral widths of ~0.1 nm at the communications channel of 1.55 μm.

### 2.2.4 Vertical Cavity Surface Emitting Lasers (VCSELs)

Vertical cavity surface emitting lasers (VCSELs) have the optical cavity axis along the direction of current flow rather than perpendicular to the current flow as in conventional laser diodes. The active region length is very short compared with the lateral dimensions so that the radiation emerges from the "surface" of the cavity rather than from its edge as shown in Fig. 12. The reflectors at the ends of the cavity are dielectric mirrors made from alternating high and low refractive index quarter-wave thick multilayers. Such dielectric mirrors provide a high degree of wavelength-selective reflectance at the required free surface wavelength $\lambda$ if the thicknesses of alternating layers $d_1$ and $d_2$ with refractive indices $n_1$ and $n_2$ are such that $n_1 d_1 + n_2 d_2 = (1/2)\lambda$ which

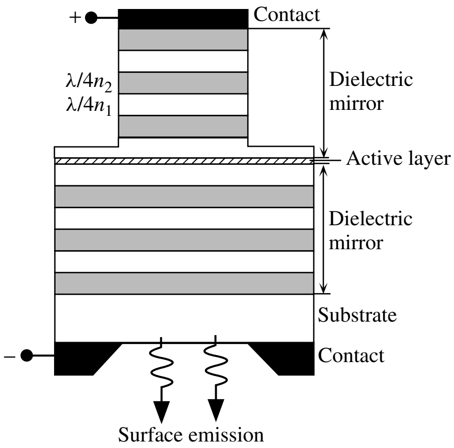


**Fig. 12** A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL)

then leads to the constructive interference of all partially reflected waves at the interfaces. Since the wave is reflected because of a periodic variation in the refractive index as in a grating, the dielectric mirror is essentially a distributed Bragg reflector. High reflectance end mirrors are needed because the short cavity length reduces the optical gain of the active layer. There may be 20 to 30 or so layers in the dielectric mirrors to obtain the required reflectance (~99%). The whole optical cavity looks "vertical" if we keep the current flow the same as in a conventional laser diode cavity. The active layer is generally very thin (<0.1 μm) and is likely to be a MQW for improved threshold current. The required semiconductor layers are grown by epitaxial growth on a suitable substrate that is transparent in the emission wavelength. For example, a 980-nm emitting VCSEL device has InGaAs as the active layer to provide the 980-nm emission, and a GaAs crystal is used as substrate that is transparent at 980 nm. The dielectric mirrors are then alternating layers of AlGaAs with different compositions and hence different bandgaps and refractive indices. The top dielectric mirror is etched after all the layers have been epitaxially grown on the GaAs substrate. The vertical cavity is generally circular in its cross section so that the emitted beam has a circular cross section which is an advantage. The height of the vertical cavity may be as small as several microns. Therefore, the longitudinal mode separation is sufficiently large to allow only one longitudinal mode to operate. However, there may be one or more lateral (transverse) modes depending on the lateral size of the cavity. In practice, there is only one lateral mode (and hence one mode) in the output spectrum for cavity diameters less than ~8 μm. Various VCSELs in the market have several lateral modes but the spectral width is still only ~0.5 nm, substantially less than a conventional longitudinal multimode laser diode. With cavity dimensions in the microns range, such a laser is referred to as a *microlaser*. One of the most significant advantages of microlasers is that they can be arrayed to construct a matrix emitter, which is a broad area surface emitting laser source. Such laser arrays have important potential applications in optical interconnect and optical computing technologies. Further, such laser arrays can provide a higher optical power than that available from a single conventional laser diode. Powers reaching a few watts have been demonstrated using such matrix lasers.

## 3
## Optical Fibers as Waveguides

### 3.1
### Step-index Optical Fiber Fundamentals

The most important optical waveguide is probably the optical fiber that serves as the backbone of optical communications. It is the most widely used waveguide "transporting" light from one point to another. An optical fiber is a thin cylindrical glass fiber, perhaps 100 microns or so in total thickness (as thin as hair), that acts as a dielectric waveguide, that is, guiding light from one end of the guide to the other. An optical fiber has a core region of higher refractive index $n_1$ and a surrounding region, *cladding*, of lower refractive index $n_2$, which "clads" the core as depicted in Fig. 13. In the case of a step-index fiber, the change in the refractive index from the core to the cladding occurs as a step and typically this change is very small (less than 1%). The normalized refractive index difference $\Delta$ is defined by $\Delta = (n_1 - n_2)/n_1$ and is less than 0.01. Waveguides that have a very small normalized refractive difference between the core and the cladding are called *weakly guiding waveguides*. The core region must have as low optical attenuation as possible to allow the transmission of light through the optical fiber.

Light entering the fiber can only propagate along the fiber as certain distinct electric field patterns across the fiber, each of which is a distinct *mode* of the fiber. Each mode of an optical fiber is a distinct transverse (to the waveguide axis) electric field pattern that can propagate and hence be guided along the waveguide. These modes

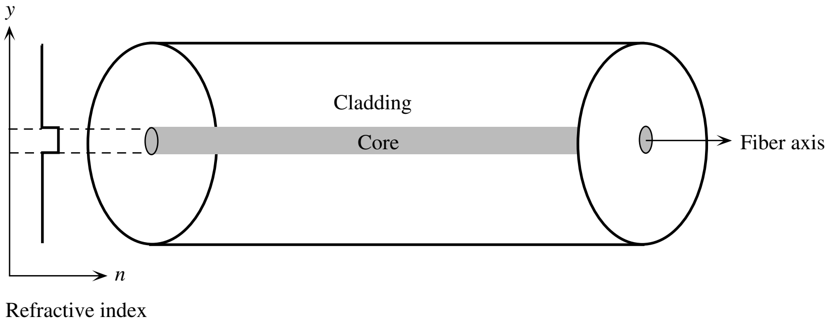


**Fig. 13** A step-index optical fiber

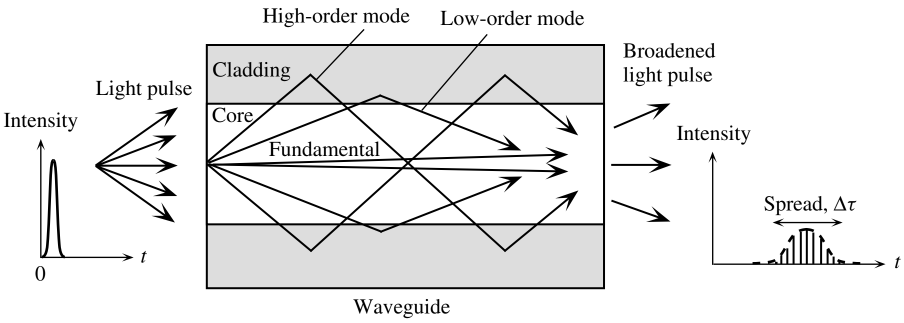


**Fig. 14** Schematic illustration of light propagation in an optical waveguide. Light pulse entering the waveguide breaks up into various modes which then propagate at different group velocities down the guide. At the end of the guide, the modes combine to constitute the output light pulse which is broader than the input light pulse

are allowed traveling EM field patterns that satisfy Maxwell's equations with the given waveguide boundary conditions. We can intuitively represent each mode as two oppositely zigzagging rays that travel along the guide by total internal reflection (TIR) at the core-cladding boundary as illustrated in Fig. 14. Notice that the TIR does not occur exactly at the interface because the ray penetrates the cladding a little (by a distance called the *penetration depth* $\delta$) due to the existence of an evanescent wave in the cladding. Rays in Fig. 14 have to satisfy the TIR condition at the core-cladding interface as well as a waveguide condition that leads to propagation along the guide. These zigzagging waves cannot interfere destructively and cancel each other in the core if they are to propagate; they have to interfere constructively which means that only certain modes can exist. These modes are typically labeled and identified by sets of integers, for example, $l$ and $m$ for step-index fibers. In simple ray terms, the order (magnitudes of $l$ and $m$) of a mode is related to the angle of incidence at the core-cladding boundary and the order increases as this angle decreases; the lowest-order mode, the "axial" or the fundamental mode, has an incidence angle of nearly 90°.

Each mode in a step-index fiber is an allowed propagating electric field distribution $E_{lm}(r, \phi)$ that propagates with its own

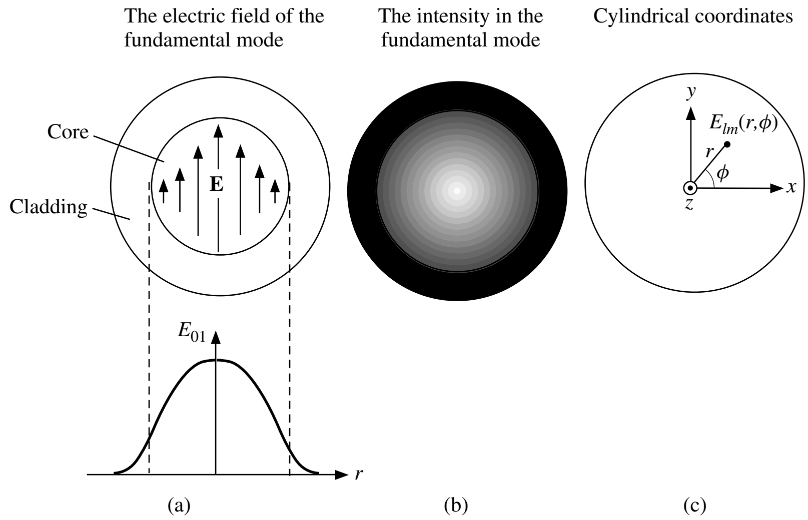


**Fig. 15** The electric field distribution of the fundamental mode ($l = 0$ and $m = 1$) in the transverse plane to the fiber axis $z$

particular propagation constant $\beta_{lm}$ (wave number) along the $z$-axis. This is depicted in Fig. 15 for the fundamental mode, $l = 0$, $m = 1$. This mode has a cylindrically symmetric field distribution about the fiber axis and is the most important mode in optical communications. Since each mode has a different propagation constant, the modes propagate with different group velocities along the fiber. (This is apparent in Fig. 14 where the modes have different effective velocities along the fiber.)

An important characteristic waveguide parameter is the $V$-number or normalized frequency, which determines the nature of propagation of EM waves along the guide. For a step-index fiber, it is defined by

$$V = (2\pi a/\lambda)[n_1^2 - n_2^2]^{1/2}$$
$$\approx (2\pi a/\lambda)[2n_1^2\Delta]^{1/2}$$

where $a$ is the core radius and $\lambda$ is the free space wavelength of the radiation. When $V < 2.405$, then only one mode, the *fundamental mode*, can propagate and the fiber is called a *single-mode fiber* (SMF). When $V > 2.405$, then the fiber becomes a multimode fiber (MMF) and the number of modes increases sharply with $V$. The cut-off wavelength $\lambda_c$ corresponds to that wavelength which makes $V = 2.405$. If the wavelength of the light is longer than $\lambda_c$, then the fiber operates as a single-mode fiber.

The *acceptance angle*, or the maximum acceptance angle, $\alpha_{max}$, as illustrated in Fig. 16, is the largest possible light launch angle from the fiber axis. Light waves within the acceptance angle that enter the fiber become guided along the fiber core. The acceptance angle defines an *acceptance cone* about the fiber axis as depicted in Fig. 16. The *numerical aperture* (NA) is another characteristic of an optical fiber that depends on the refractive indices of the core and the cladding, and measures the light gathering ability of the core. The NA is defined by

$$\text{NA} = [n_1^2 - n_2^2]^{1/2}$$

and $\alpha_{max}$ is given by

$$\sin\alpha_{max} = \frac{[n_1^2 - n_2^2]^{1/2}}{n_o} = \frac{\mathrm{NA}}{n_o}$$

where $n_o$ is the refractive index of the medium from which light is launched into the fiber.

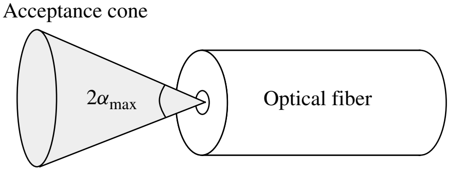


**Fig. 16** The acceptance cone and the maximum acceptance angle $\alpha_{max}$

A graded index (GRIN) optical fiber has a core refractive index that is graded gradually, that is, changes continuously, towards the cladding. Figures 17(a), (b), and (c) summarize the index profiles and light propagation in single-mode and multimode step-index fibers, and graded index fibers (GIFs). Typically, in a GIF, the refractive index profile is approximately parabolic to minimize modal dispersion to a virtually innocuous level. All different mode rays in the GIF arrive at the same time; compare Figs. 17(b) and (c). The intuitive reason for this is that the velocity along the ray path, $c/n$, is not constant and increases as the ray is farther away from the center. A ray such as 2 that has a

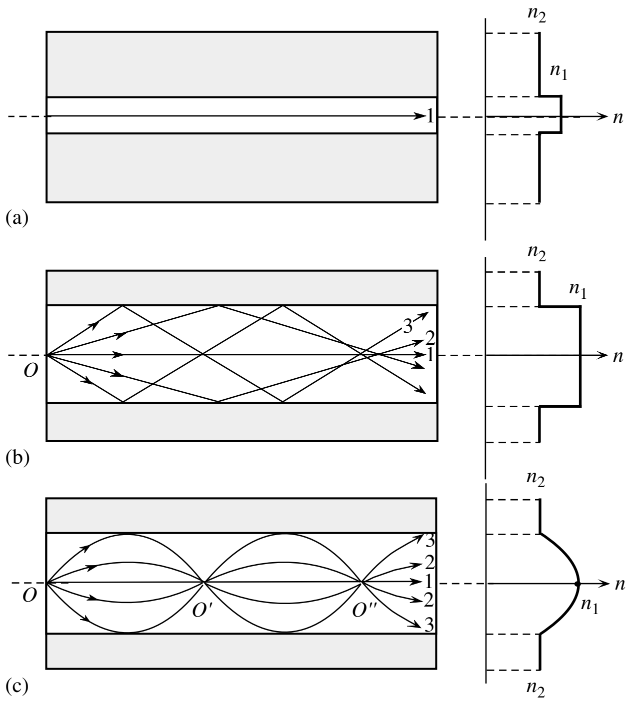


**Fig. 17** (a) Single-mode step-index fiber (SMF). There is only an axial ray; (b) multimode step-index fiber (MMF). Ray paths are different so that rays arrive at different times; (c) graded index fiber (GIF). Ray paths are different but so are the velocities along the paths so that all the rays arrive at the same time

longer path than ray 1 then experiences a faster velocity during a part of its journey to enable it to catch up with ray 1. Similarly, ray 3 experiences a faster velocity than ray 2 during part of its propagation to catch up with ray 2 and so on.

## 3.2 Dispersion in Optical Fibers

Dispersion in fiber optics is the spread in time $\Delta\tau$, known as temporal broadening, of a very short optical pulse as it propagates along the fiber as schematically depicted in Fig. 14. The temporal broadening is due to the different propagation characteristics of different wavelength components of light that are coupled into the fiber and propagate along the guide. The *group delay time* $\tau$ is the time it takes for a very short light pulse of a particular mode of given wavelength to travel from the input to the output of the fiber; a "delay time" from the fiber's input to output. The temporal spread in $\tau$, $\Delta\tau$ is called *dispersion*. Owing to the dispersion effect, there is an upper limit for the rate at which we can transmit light pulses along a fiber, that is, there is a maximum bandwidth and maximum bit-rate. Each mode in the waveguide has a different propagation constant so that at the end of the fiber, the modes arrive at different times and constitute an output pulse that is broadened in time as illustrated in Fig. 14. Modal dispersion increases with the fiber length and the normalized refractive index difference $\Delta$. It is zero in an SMF that allows only one mode, the fundamental mode, to propagate. Multimode step-index fibers suffer from modal dispersion, which limits their use to local area networks.

*Waveguide dispersion* is the dispersion that arises because of the wavelength dependence of the $V$-number, which determines the propagation constant inside the guide. As the radiation fed into the core has a finite range of wavelengths, $\Delta\lambda$, the $V$-number is not constant, which leads to fundamental modes with different wavelengths that propagate at different velocities. Waveguide dispersion results from the guiding properties of the dielectric structure, and it has nothing to do with the frequency (or wavelength) dependence of the refractive index.

*Material dispersions* occur as a result of the variation of the refractive index $n_1$ of the core glass with the wavelength of light coupled into the fiber. The propagation velocity of the guided wave along the fiber core depends on $n_1$ which in turn depends on the wavelength. Its manifestation is the result of no practical light source being perfectly monochromatic in that there are waves in the guide with various free space wavelengths, that is, a range of $\lambda$ values.

*Profile dispersion* is the broadening of a propagating optical pulse in a fiber as a result of the group velocity of the fundamental mode also depending on the refractive index difference $\Delta$, that is, $\Delta = \Delta(\lambda)$. If $\Delta$ changes with wavelength, then different wavelengths from the source would have different group velocities and experience different group delays leading to pulse broadening.

*Chromatic dispersion* is the time spread of a propagating optical pulse in an optical guide due to the wavelength dependence of all the guide properties. It includes waveguide, material, and profile dispersions added together. Chromatic dispersion is normally quoted as dispersion in picosecond per nanometer of input light linewidth and per kilometer of fiber, for example, 10 ps $\text{nm}^{-1}\,\text{km}^{-1}$. For an input laser of linewidth 0.1 nm and for a fiber of 100 km, chromatic dispersion is 100 ps.

*Polarization mode dispersion* arises when the fiber is not perfectly symmetric and homogeneous, that is, the refractive index is *not isotropic*. When the refractive index depends on the direction of the electric field, the propagation constant of a given mode depends on its polarization. Polarization mode dispersion depends on the extent of anisotropy in the refractive index, which is kept minimum by various manufacturing procedures (such as rotating the fiber during drawing, etc.). Typically, polarization mode dispersion is less than a fraction of a picosecond per kilometer of fiber. However, this type of dispersion does not scale linearly with fiber length $L$; in fact, the dispersion scales roughly as $L^{1/2}$ and the polarization mode dispersion in current fibers is typically 0.05–0.5 ps $km^{-1/2}$.

*Self-phase modulation dispersion* is the temporal spreading of a propagating light pulse due to the dependence of the refractive index on the light intensity; a consequence of the nonlinear properties of glasses at high fields or large light intensities. When the propagating light pulse is very intense, the small changes in the index can lead to this type of dispersion.

In most applications, optical fibers carry digital information and what is of significance is the maximum rate at which bits can be sent, the maximum bit-rate $B$. The latter quantity depends inversely on the dispersion $\Delta\tau$ of the fiber. The dispersion itself depends on the linewidth $\Delta\lambda$ of the input light, the length of the fiber $L$, and the mechanisms that are causing the dispersion as summarized above. To achieve high bit rates, the dispersion has to be minimized. In the late eighties and early nineties, there was a drive to shrink $\Delta\lambda$ by using narrow laser linewidths, and to minimize the inherent dispersion in the fiber by trying different waveguide geometries (index profiles) and by accurately controlling the manufacturing processes. The recent trend however, has been the control of dispersion by dispersion-compensating fibers. The fiber for use is produced with some chromatic dispersion, for example, $+10$ ps $nm^{-1}$ $km^{-1}$ and dispersion is allowed to build upto say, $\Delta\tau_1$ over a certain length, $L_1$. Then, dispersion $\Delta\tau_1$ is "cancelled" by using a second fiber, called *compensating fiber*, that has negative dispersion characteristics with respect to the first, that is, modes that travel fast in the first fiber are slow in the second fiber. The introduction of dense wavelength division multiplexing (DWDM) has led to certain requirements not only on the magnitude of dispersion but also on its dependence on the wavelength ("dispersion slope"). Consequently, dispersion management in fibers is one of the most active areas of current research development.

The dispersion shifted fiber is a fiber in which the chromatic dispersion characteristic (dispersion vs wavelength) has been shifted to longer wavelengths by adjusting the waveguide dispersion by appropriately changing the waveguide geometry or the refractive index profile. Zero dispersion shifted fiber has its chromatic dispersion zero at around 1550 nm. Nonzero dispersion shifted fiber is designed for use with WDM (wavelength division multiplexing) and has its chromatic dispersion zero outside the Er-doped amplifier band, 1525 to 1620 nm.

## 3.3 Attenuation in Optical Fibers

As light propagates through an optical fiber, it becomes attenuated by a number of processes that depend on the wavelength of light. Attenuation is the decrease in the optical power of a traveling wave, or a guided wave in a dielectric waveguide, in the direction of propagation due to scattering and absorption. Scattering is a process by which the energy from a propagating EM wave is redirected as secondary EM waves in various directions away from the original direction of propagation. Rayleigh scattering of waves in a medium arises whenever there are small inhomogeneous regions in which the refractive index is different from that of the medium (which has some average refractive index). This means a local change in the relative permittivity and polarizability. The result is that the small inhomogeneous region acts like a small dielectric particle and scatters the propagating wave in different directions. In the case of optical fibers, dielectric inhomogeneities arise from fluctuations in the relative permittivity that is part of the intrinsic glass structure. As the fiber is drawn by freezing a liquid-like flow, random thermodynamic fluctuations in the composition and structure that occur in the liquid state become frozen into the solid structure. Consequently, the glass fiber has small fluctuations in the relative permittivity, which leads to Rayleigh scattering. Nothing can be done to eliminate Rayleigh scattering in glasses, as it is part of their intrinsic structure. Rayleigh scattering decreases as $\lambda^4$ and depends on the extent of "structural randomness" in the glass structure.

In conventional fibers, there is a marked attenuation peak centered at around 1.4 μm as apparent in Fig. 18. This attenuation region arises from the presence of hydroxyl ions as impurities in the glass structure inasmuch as it is difficult to remove all traces of hydroxyl (water) products during fiber production. Further, hydrogen atoms can easily diffuse into the glass structure at high temperatures during production, which leads to the formation of hydrogen bonds in the silica structure and $OH^-$ ions. Absorption of energy is mainly by the stretching vibrations of the $OH^-$ bonds within the silica structure that has a fundamental resonance in the infrared region (beyond 2.7 μm) but overtones or harmonics at shorter wavelengths (or higher frequencies). The first overtone at around 1.4 μm is the most significant. The

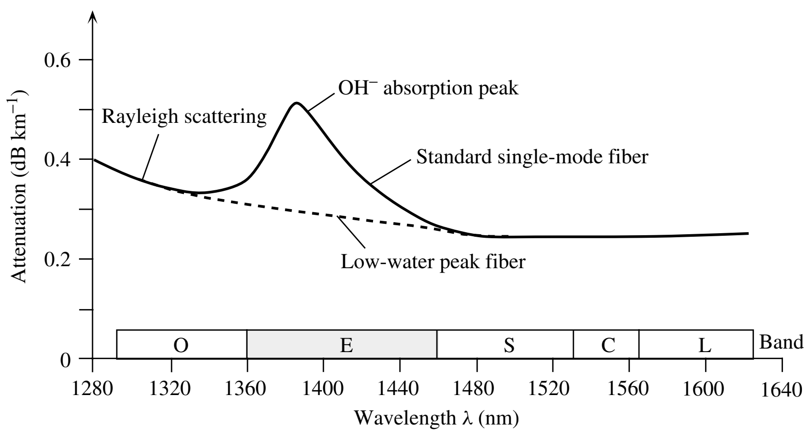


**Fig. 18** Attenuation in a standard single-mode optical fiber and also in a newly developed low-water peak fiber. (Lucent; Lindstrom, A. (2002), Optical fiber: where is it headed?, *Photonics Spectra*, Vol. 36. Pittsfield, MA: Laurin Publishing Company, pp. 68–72)

$OH^-$ peak at 1.4 μm has prevented the use of the E-band in optical communications. However, recent developments in fiber manufacturing have almost totally eliminated the water peak as apparent in the attenuation versus wavelength characteristic of a low-water peak fiber, newly developed by Lucent, in Fig. 18.

*Bending losses* arise whenever a fiber is bent. *Microbending loss* occurs typically whenever the radius of curvature of the bend is microscopically sharp, typically less than 0.1 to 1 mm. It is due to a sharp local bending of the fiber, for example, due to a ''kink'' in the fiber that may occur during cabling, which changes the guide geometry and refractive index profile locally, and which therefore leads to some of the light energy being radiated away from the guiding direction. The bending loss increases exponentially as the radius of curvature decreases, that is, as the bend becomes sharper. *Macrobending loss* is the attenuation in the fiber when the fiber's direction is bent from a straight line over macroscopic distances, typically when the radius of curvature is greater than ~1 mm, for example, when the fiber cable is curved around a corner. Bending losses are normally ignored when the bend radius is more than 100 mm or so.

## 3.4 Cables

Optical fibers are always cabled in use, that is, they are surrounded by other material for protection. A bare fiber can easily ''crack'' and break when it is bent or stretched. The fracture is usually a brittle fracture that initiates at a flaw, such as a microcrack, on the fiber surface. It is therefore essential to protect the fiber by cabling it, which makes it easier to handle. As much as possible, the cable prevents the fiber from experiencing crushing and tensile forces that would otherwise damage the fiber. The cable also protects the fiber from heat, cold, moisture, and various species of chemicals that may be present in the atmosphere. An optical cable can carry one to hundreds of fibers. Usually, the fibers are placed in a cushioned or buffered tube inside the cable as depicted in Fig. 19. There are various types of cables in the market, each with its own particular design and structure that depends on its use, for

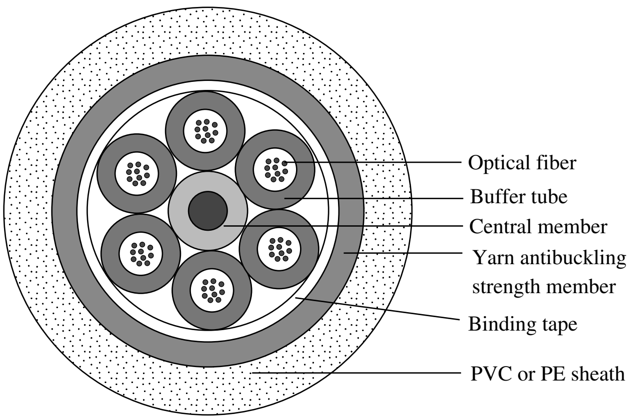


**Fig. 19** A schematic sketch (not to scale) of a typical indoor stranded loose tube cable carrying many individual fibers

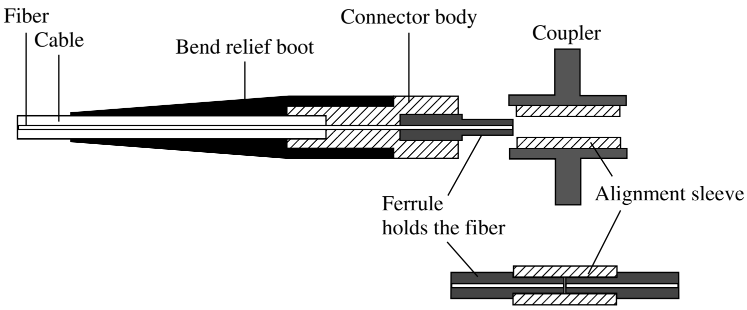


**Fig. 20** A typical connector

example, indoor, outdoor, underground, or submarine applications.

## 3.5 Connectors and Splices

In many optoelectronic applications, we have to connect optical fibers or cables. Connectors are primarily mechanical devices that temporarily bring fiber ends together to couple light from one to the other; an example is shown in Fig. 20. The connection is temporary because the connector can be "unplugged." The connector may contain an optical component such as a lens, or lenses, to couple the light from one fiber to the other.

A splice is a permanent connection between two fibers, usually achieved by aligning the fibers and then fusing the two glasses to each other at a high temperature in an electrical arc between two electrodes. Whenever two fibers are to be connected permanently, for example, when laying down additional fiber or repairing a broken fiber, they are always spliced. Splicing is achieved by an instrument called the *fusion splicer*.

One of the most important characteristics of connectors and splices is their attenuation, that is, how much light is lost through the connection. There are various reasons for the attenuation, the most significant are misalignment of fibers, mismatch of core areas, mismatch in the NAs, dead space between fibers, fiber-end reflections, extraneous materials such as dirt or grease on the fibers, and so on. Splices normally have much lower attenuation than connectors and are therefore preferred whenever the connection can remain permanently. An important characteristic of a connector is its *insertion loss*, that is, its attenuation. Typically a splice will have an insertion loss less than 0.1 dB. On the other hand, mechanical connectors tend to have substantially higher losses that typically range from 0.2 dB to 1 dB, depending on the type of connector. An ST (straight tip) connector for an SMF would have a loss of about 0.40 dB.

# 4 Optical Amplifiers

An Optical amplifier is an amplifier that amplifies an optical signal, that is, light. A common type of optical amplifier is an *erbium ion doped optical fiber amplifier* (EDFA), in which erbium ions in the glass are pumped to an excited state by using a laser diode (or an LED) at 980 nm. This pumping leads to a population inversion of Er-ions that corresponds to a narrow wavelength range of around 1550 nm, which is the long-haul communications wavelength. Figure 21 illustrates schematically how EDFAs are used in communications.

An *optical semiconductor amplifier* is a semiconductor laser structure that can be used as an optical amplifier that amplifies light waves passing through its active region. Light to be amplified is made to enter the active region of the laser semiconductor diode and the active region is pumped with a sufficiently large diode current just as in a normal laser diode. The wavelength of radiation to be amplified must be within the optical gain bandwidth of the laser. Such a device would not be a laser oscillator, emitting lasing emission without an input, but an optical amplifier with input and output ports for light entry and exit. In the traveling wave semiconductor laser amplifier, as in Fig. 22(a), the ends of the optical cavity have antireflection (AR) coatings so that the optical cavity does not act as an efficient optical resonator, a condition for laser oscillations. Light, for example, from an optical fiber is coupled into the active region of the laser structure. As the radiation propagates through the active layer, optically guided by this layer, it becomes amplified by the induced stimulated emissions, and leaves the optical cavity with a higher intensity. The Fabry–Perot laser amplifier, as shown in Fig. 22(b), is similar to the conventional laser oscillator, but is operated below the threshold current for lasing oscillations; the active region has an optical gain but not sufficient to sustain a self-lasing output. Light passing through such an active region will be amplified by stimulated emissions, but because of the presence of an optical resonator, there will be multiple

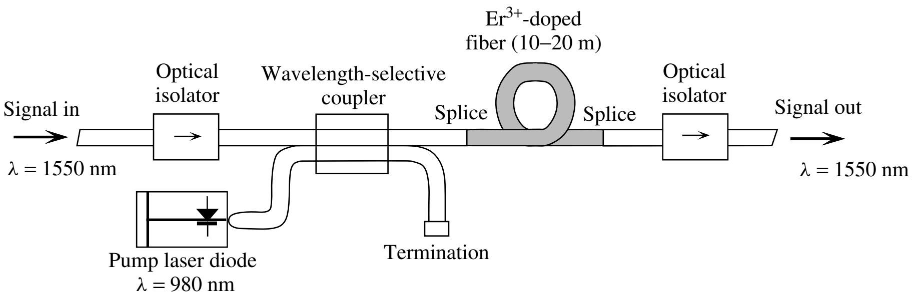


**Fig. 21** Er-doped optical fiber amplifiers are widely used for optical amplification

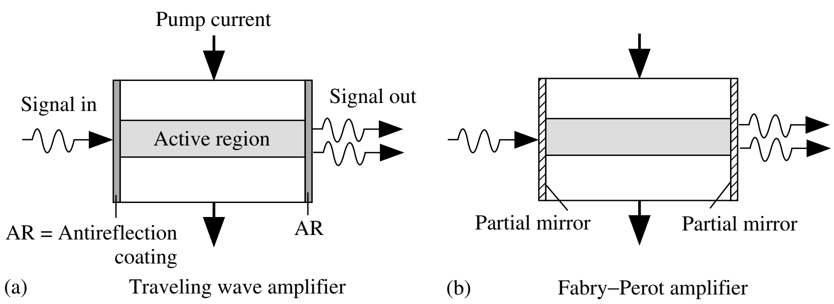


**Fig. 22** Simplified schematic illustrations of two types of laser amplifiers

internal reflections. These multiple reflections lead to the gain being highest at the resonant frequencies of the cavity within the optical gain bandwidth. Optical frequencies around the cavity-resonant frequencies will experience higher gain than those away from resonant frequencies. Although the Fabry–Perot laser amplifier can have a higher gain than the traveling wave amplifier, it is less stable.

A *Raman fiber amplifier* is a fiber amplifier that is based on the stimulated Raman scattering effect. In Raman scattering, a light wave of frequency $\upsilon_P$ is scattered from the molecular vibrations in a medium as a result of which its frequency is downshifted to $\upsilon_S$. This is an inelastic interaction and depends on the nonlinear dielectric behavior of the medium. The change in the photon energy from $h\upsilon_P$ to $h\upsilon_S$ excites the molecular vibrations in the interaction region by a phonon energy, that is, $h\upsilon_R$ where $\upsilon_R$ is the Raman shift frequency, a resonance frequency associated with molecular oscillations of the medium. The photon $h\upsilon_S$ is called the *Stokes photon*, and the downshift in the frequency is called the *Stokes shift*. For silica, $\upsilon_R$ is not actually a single frequency but a range of frequencies, a "band," with a peak at about 13 to 14 THz. Suppose that we send a pump laser beam at frequency $\upsilon_P$ into a fiber to excite the molecular vibrations, and suppose that the pump beam is very intense. (In practice, this would be something like 1 W fed into an SMF). If the relatively weak incoming signal has a frequency $\upsilon_S$, then it can *stimulate* the Stokes shift and hence extract energy from the pump beam to add to itself. The result is an optical amplification of the signal at $\upsilon_S$. Since the discovery of the EDFA, the interest in Raman fiber amplifiers has somewhat waned due to long fiber lengths and high pump powers that are required to achieve acceptable optical gains. One of their advantages is that they have a wide optical bandwidth, and unlike EDFA they are not restricted to the 1550-nm range.

## 5 Modulators

It is possible to modulate the intensity of light *directly* by modulating the driving current of a light emitter such as an LED or a laser diode. In direct modulation, the intensity of light generated is controlled by an electrical signal. Direct modulation is widely used in optical communications. There are certain drawbacks to direct modulation. It is not possible to obtain high-speed modulation, typically more than ~10 GHz. The reason is that the modulation is limited by the relaxation time associated with the charge carriers and photons. Secondly, modulation introduces *chirping* in which the frequency of the light pulse varies over the duration of the signal.

External modulation involves modulating a characteristic of light, such as intensity, phase, frequency, or direction, as the light passes through the modulator. There are various types of modulators based on the physical effect utilized, most important of which are the *electro-optic* (*EO*), *acousto-optic* (AO), *magneto-optic,* and multiple quantum well (MQW) based *electro-absorption* (EA) modulators.

### 5.1 Electro-optic Modulators

Electro-optic effects refer to changes in the refractive index of a material induced by the application of an external electric field, which therefore "modulates" the optical properties; the applied field is not the electric field of any light wave, but a separate external field. We can apply such an external field by placing electrodes on opposite faces of a crystal and connecting these electrodes to a battery. The presence of such a field distorts the electron motion in the atoms or molecules of the substance, or distorts the crystal structure resulting in changes in the optical properties. For example, an applied external field can cause an optically isotropic crystal such as GaAs to become birefringent. In this case, the field induces principal axes and an optic axis. Typically, changes in the refractive index are small. The frequency of the applied field has to be such that the field appears static over the time scale it takes for the medium to change its properties, that is, to respond, as well as for any light to cross the substance. The EO effects are classified according to first and second order effects. If we were to take the refractive index $n$ to be a function of the applied electric field $E$, that is, $n = n(E)$, we can of course expand this as a Taylor series in $E$. The new refractive index $n'$ would be

$$n' = n + a_1 E + a_2 E^2 + \cdots$$

where the coefficients $a_1$ and $a_2$ are called the *linear* EO effect and *second* order EO effect coefficients respectively. Although we would expect even higher terms in the expansion of the above equation, these are generally very small and their effects negligible within most highest practical fields. The change in $n$ due to the first $E$ term is called the *Pockels effect*. The change in $n$ due to the second $E^2$ term is called the *Kerr effect*, and the coefficient $a_2$ is generally written as $\lambda K$ where $K$ is called the *Kerr coefficient*. Thus, the two effects are summarized by

$$\Delta n = a_1 E$$

and

$$\Delta n = a_2 E^2 = (\lambda K) E^2$$

*All* materials exhibit the Kerr effect. It may be thought that we will always find some (nonzero) values for $a_1$ for all materials but this is not true and only certain crystalline materials exhibit the Pockels effect. Thus $a_1 = 0$ for all noncrystalline materials (such as glasses and liquids). Similarly, if the crystal structure has a center of symmetry, then $a_1$ is again zero. Only crystals that are *noncentrosymmetric* exhibit the Pockels effect. For example, an NaCl crystal (centrosymmetric) exhibits no Pockels effect but a GaAs crystal (noncentrosymmetric) does.

One of the simplest examples of Pockels effect in an optoelectronic application is the polarization modulator shown in Fig. 23, where an embedded waveguide has been fabricated by implanting an $LiNbO_3$ substrate with Ti atoms, which increases the refractive index. Two coplanar strip electrodes run along the waveguide and enable the application of a transverse field $E_a$ to the light propagation direction $z$. The external modulating voltage $V(t)$ is applied between the coplanar drive electrodes, and by virtue of the Pockels effect, induces a change $\Delta n$ in the refractive index and hence, a voltage-dependent phase shift through the device. We can represent light propagation along the guide in terms of two orthogonal modes, $E_x$ along $x$ and $E_y$ along $y$. These two modes experience symmetrically opposite phase changes. The phase shift $\Delta\phi$ between the $E_x$ and $E_y$ polarized waves is proportional to the refractive index change, hence to the applied field. However, the applied field is not uniform between the electrodes, and further, not all applied field lines lie inside the waveguide. The EO effect takes place

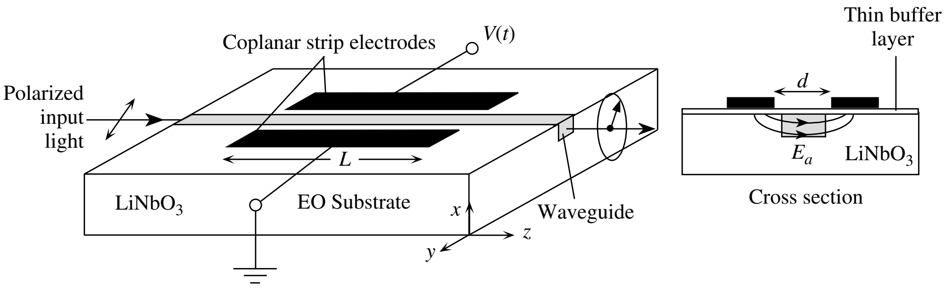


**Fig. 23** Integrated transverse Pockels cell phase modulator in which a waveguide is diffused into an electro-optic (EO) substrate. Coplanar strip electrodes apply a transverse field $E_a$ through the waveguide. The substrate is an *x*-cut LiNbO3 and typically there is a thin dielectric buffer layer (e.g., ~200-nm-thick $SiO_2$) between the surface electrodes and the substrate to separate the electrodes away from the waveguide

over the spatial overlap region between the applied field and the optical fields. Nonetheless, $\Delta\phi$ is proportional to $V/d$ (apparent applied field) and the length $L$ of the channel (Fig. 23) through the relevant Pockels coefficient $r$. The device is a *phase modulator*; $\Delta\phi$ is modulated by $V(t)$. For example, if the voltage induces a phase change of $\pi/2$, then a linearly polarized light at an angle 45° to the $x$-axis can be converted into a circularly polarized light as depicted in Fig. 23. The voltage that is necessary to induce a half-wave phase shift ($\Delta\phi = \pi$) is called the *half-wave voltage*, $V_{\lambda/2}$. At $\lambda = 1.5$ µm, for an $x$-cut $LiNbO_3$ modulator as in Fig. 23 with $d \approx 10$ µm, $V_{\lambda/2}L \approx 35$ V·cm. For example, a modulator with $L = 2$ cm has a half-wave voltage $V_{\lambda/2} = 17.5$ V. By comparison, for a $z$-cut $LiNbO_3$ plate, that is, for light propagation along the $y$-direction and $E_a$ along $z$, the relevant Pockels coefficients are much greater, which leads to $V_{\lambda/2}L \approx 5$ V·cm.

The Mach–Zehnder modulator is a lithium niobate–based EO device whose light transmittance is controlled by an applied external voltage. It uses the Pockels effect of $LiNbO_3$ and the interference of two waves that have a relative phase difference, induced by an applied external voltage. It converts the induced phase shift by an applied voltage to an amplitude variation by using an interferometer, a device that interferes two waves of the same frequency but different phase. As shown in Fig. 24, the device has implanted single-mode waveguides in an $LiNbO_3$ (or other EO) substrate in the geometry shown in Fig. 24. The waveguide at the input branches out at $C$ to two arms $A$ and $B$ and these arms are later combined at $D$ to constitute the output. The splitting at $C$ and combining at $D$ involve simple Y-junction waveguides. In the ideal case, the power is equally split at $C$ so that the field is scaled by a factor $\sqrt{2}$ going into each arm. The structure acts as an interferometer because the two waves traveling through the arms $A$ and $B$ interfere at the output port $D$ and the output amplitude depends on the phase difference (optical path difference) between the $A$ and $B$ branches. Two back-to-back identical phase modulators enable the phase changes in $A$ and $B$ to be modulated. Notice that the applied field in branch $A$ is in the opposite direction to that in branch $B$. The refractive index changes are therefore opposite, which means that

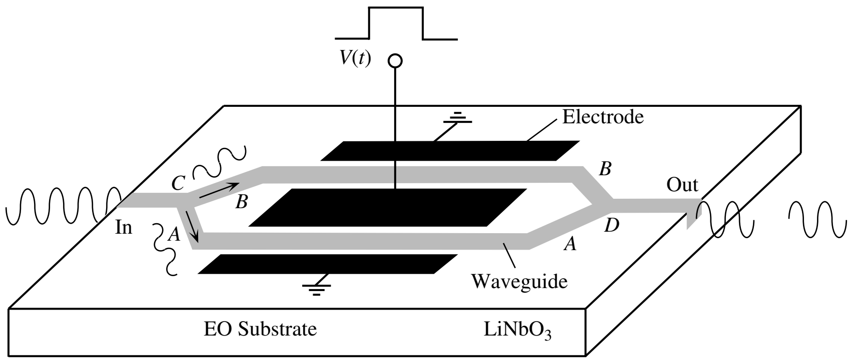


**Fig. 24** An integrated Mach–Zehnder optical intensity modulator. The input light is split at *C* into two coherent waves *A* and *B*, which are phase shifted by the applied voltage, and then the two are combined again at *D* at the output

the phase changes in arms *A* and *B* are also opposite. For example, if the applied voltage induces a phase change of $\pi/2$ in arm *A*, this will be $-\pi/2$ in arm *B* so that *A* and *B* would be out of phase by $\pi$. These two waves will then interfere destructively and cancel each other at *D*. The output intensity would then be zero. Since the applied voltage controls the phase difference between the two interfering waves *A* and *B* at the output, this voltage also controls the output light intensity, though the relationship is not linear. It is apparent that the relative phase difference between the two waves *A* and *B* is therefore doubled with respect to a phase change $\phi$ in a single arm. We can predict the output intensity by adding waves *A* and *B* at *D*. The power transfer is zero when the phase difference $\phi$ is $\pi/2$, as expected. In practice, the Y-junction losses and uneven splitting result in a less-than-ideal performance; *A* and *B* do not totally cancel out when $\phi = \pi/2$.

There are of course other types of EO modulators based on the Pockels effect. There are Kerr effect modulators as well. For further reading, the reader is referred to the references.

## 5.2
## Acousto-optic Modulators

Acousto-optic modulators are based on the photoelastic effect in which an induced strain (*S*) in a crystal changes its refractive index *n*. The strain changes the density of the crystal and distorts the bonds (and hence the electron orbits), which leads to a change in the refractive index *n*. The strain and refractive index relationship is quite complicated, because we must consider the effect of a strain *S* along one direction in the crystal on the induced change in *n* for a particular light propagation direction and some specific polarization. To a first order, we can take the photoeleastic effect to be linear; the induced change $\Delta n$ is proportional to the magnitude of the induced strain *S*.

We can generate traveling acoustic or ultrasonic waves on the surface of a piezoelectric crystal (such as $LiNbO_3$) by attaching interdigital electrodes onto its surface, as shown in Fig. 25, and applying a modulating voltage at radio frequencies (RF). The *piezoelectric effect* is the phenomenon of generation of strain in a crystal by the application of an external electric field. The modulating voltage at

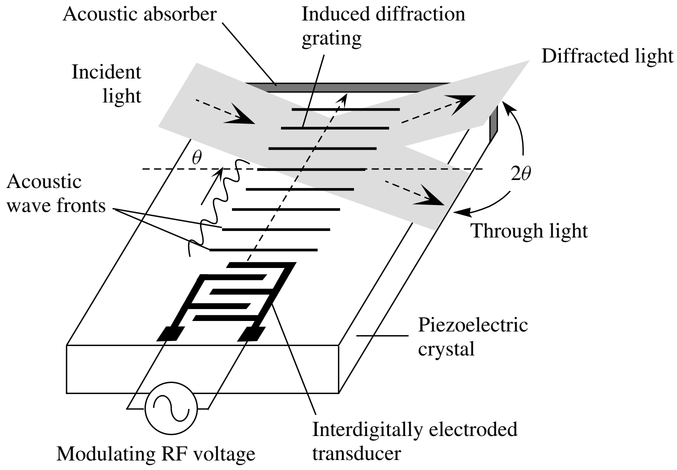


**Fig. 25** Traveling acoustic waves create a harmonic variation in the refractive index, and thereby create a diffraction grating that diffracts the incident beam through an angle $2\theta$

electrodes will therefore generate a *surface acoustic wave* (SAW) via the piezoelectric effect. These acoustic waves propagate by rarefactions and compressions of the crystal surface region which lead to a periodic variation in the density and hence a periodic variation in the refractive index in synchronization with the acoustic wave amplitude. The result is that a kind of "diffraction grating" is set up near the surface of the crystal by the acoustic wave. This acoustically induced diffraction grating diffracts the optical beam and allows the angle and intensity of the diffraction to be modulated by the amplitude and frequency of the applied RF signal. There is a change in the frequency of the diffracted beam by an amount that corresponds to the phonon (acoustic) frequency.

### 5.3 Multiple Quantum Well Modulators

Electro-absorption is the induced absorption of light in a device as a result of applying (or changing) an electric field within the device. There are fundamentally three types of EA processes. In the *Franz–Keldysh* process, a strong applied field modifies the photon-assisted probability of an electron tunneling from the VB to the CB and thus corresponds to an effective reduction in the "bandgap energy." It was first observed for CdS in which the absorption edge was observed to shift to lower energies with the applied field, that is, photon absorption shifts to longer wavelengths with the applied field. The effect is normally quite small but nonetheless observable. In this type of modulation, typically, the wavelength is chosen to be slightly smaller than the bandgap wavelength so that absorption is negligible. When a field is applied, absorption is enhanced by the Franz–Keldysh effect.

In *free carrier absorption*, the concentration of free carriers $N$ in a given band is changed (modulated), for example, by an applied voltage, to change the extent of photon absorption. The absorption coefficient is proportional to $N$ and to the light wavelength λ raised to some power, typically 2 to 3.

In the confined Stark effect, the applied electric field modifies the energy levels in a QW, for example, the energy level corresponding to $E_1$ in Fig. 9(b) is altered by the field. The field reduces the energy levels by an amount proportional to the square of the applied field. A MQW *pin* device has MQWs in its intrinsic layer between the *p* and *n* layers as shown in Fig. 26. Without any applied bias, light with photon energy just less than the QW exciton excitation energy, for example, from $E_1'$ to $E_1$ in Fig. 9(b), will not be significantly absorbed. When a field is applied, the energy levels are lowered and the incident photon energy is now sufficient to excite an electron–hole pair in the QWs. The relative transmission decreases with reverse bias $V_r$ applied to the *pin* device. Such MQW *pin* devices are usually not very useful in the transmission mode because typically the substrate material is such that it absorbs the light (for example, GaAs/AlGaAs MQW *pin* would be grown on a GaAs substrate that would absorb the radiation that excites the QWs; see Fig. 9). Thus, a

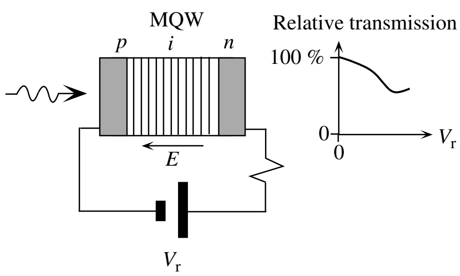


**Fig. 26** A schematic illustration of an MQW modulator based on the quantum confined Stark effect. The *i*-region has MQWs. The transmitted light intensity can be modulated by the applied reverse bias $V_r$ to the *pin* device, because the electric field $E_z$ modifies the absorption spectrum

"mirror" would be needed to reflect the light back before it reaches the substrate; such devices have indeed been fabricated.

## 6 Optical Switches, Multiplexers, and Isolators

The optical modulators discussed in Sect. 5 can also be used to switch light, that is, change the light output of the modulator from "transmission" to almost "no transmission." Such an action would constitute a simple optical switch because the passage of light through the device is either "on" or "off," depending on an independent control signal. In general, one can distinguish between two types of optical switching operations. In one type of optical switching, the action of the device on light corresponds to either one of the digital logical states, "0" or "1." Such optical devices would constitute the building blocks of an optical digital signal processor, an optical computer. In another type of optical switching, the switch redirects the optical signal from one optical path to another. The latter is the type of optical switching that is widely encountered in optoelectronic systems. A multiplexer is a device that combines two or more signals into a single output (two or more inputs are switched into a single output).

Many optoelectronic systems rely extensively on optical switches that can switch the signal from one optical path to another. Figure 27(a) illustrates how a simple 4 × 4 *optical cross-connect* (optical crossbar) *switch* can switch the light from any input fiber to any output fiber depending on the electrical control signal. (Practical cross-connect switches have more input–output connections.) The output of each input fiber is converted to an electrical signal (via

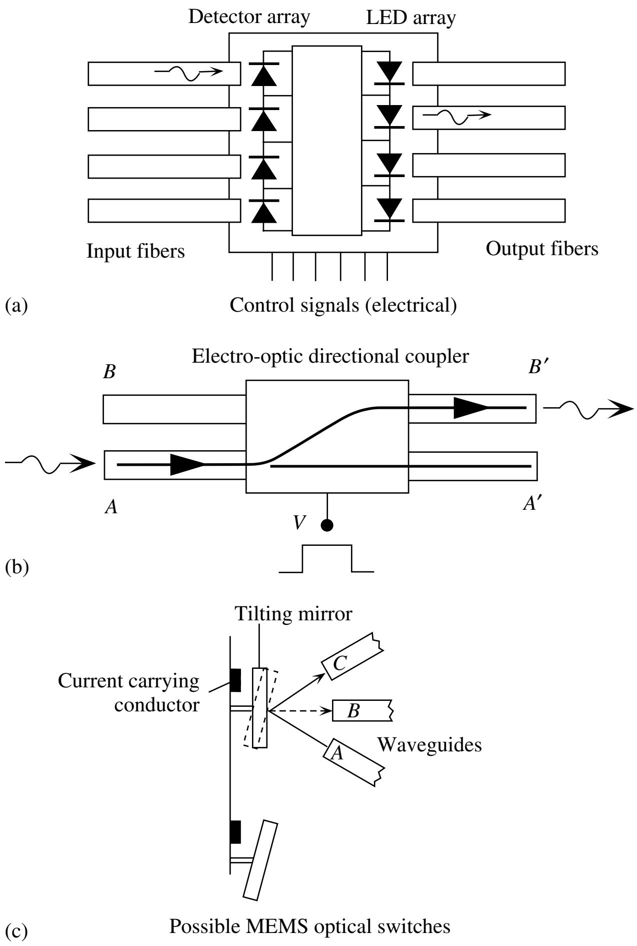


**Fig. 27** (a) A cross-connect switch or crossbar switch; (b) an electro-optic directional coupler; (c) MEMS optical switch

photodetectors) and then a programmed logic circuit drives LEDs (or laser diodes) that emit light into the appropriate output fibers. This type of switch is limited by the electronic speed with which the detector can respond, and the light emitters can be driven; depending on the semiconductors used, typical speeds are less than a few $\mathrm{Gb\,s^{-1}}$.

*Electro-optic directional couplers* provide a convenient and fast means of switching (coupling) an optical signal from one waveguide ($AA'$) to another ($BB'$) by the application of an electrical signal $V$ as depicted in Fig. 27(b); light at the input into guide $A$ is switched to $B'$ at the output. A number of these EO directional couplers connected together can obviously switch an optical signal between various optical paths.

*Opto-mechanical switches* rely on a mechanical motion that moves one guide to line up with another guide and thereby change the optical path; these switches are limited by the speed of mechanical motion. The mechanical motion may be implemented by an EM relay for example, in which case the speed would be of the order of milliseconds. By having tiny electromechanical structures, however, it is possible to construct fast and reliable switches. The tiny electromechanical structures are called *micro-electro-mechanical systems* (MEMS) that are fabricated by various semiconductor fabrication techniques that use special lithographic processes. Figure 27(c) illustrates how an MEMS optical switch can tilt a mirror and thereby deflect an optical signal from one guide to another. Such MEMS-based switches are fast (microseconds) and reliable.

An important operation that is the cornerstone of today's optical communications is the multiplexing and demultiplexing of optical signals. In WDM, $N$ optical signals (each one a channel) at various wavelengths $\lambda_1, \lambda_2, \ldots \lambda_N$, are multiplexed into a single fiber. At the destination, a demultiplexer has to separate out the $N$ channels based on their wavelengths. The multiplexing procedure may be as simple as focusing the $N$ channels into the input of a single fiber, but the demultiplexing procedure needs a "demultiplexing device" that will deflect or diffract light by an angle based on its wavelength. Prism- or diffraction grating–based demultiplexers, as shown in Fig. 28, are available; in principle, they can also work as multiplexers, multiplexing $N$ different wavelength channels into a single fiber.

*Optical isolators* are useful devices that allow light to pass in one direction and not in the opposite direction. For example, a sensitive laser diode connected to a fiber can be isolated from reflected or scattered light traveling in the fiber towards the laser by using an optical isolator. Many commercial optical isolators are based on using a simple polarizer and a Faraday rotator, a device that utilizes the Faraday effect. In the latter effect, the optical field **E**, or the polarization of light passing through a medium is rotated by an applied magnetic field **B** placed in the medium. The rotation $\theta$ of polarization depends only on the direction of **B**. The direction of light propagation in a Faraday rotator

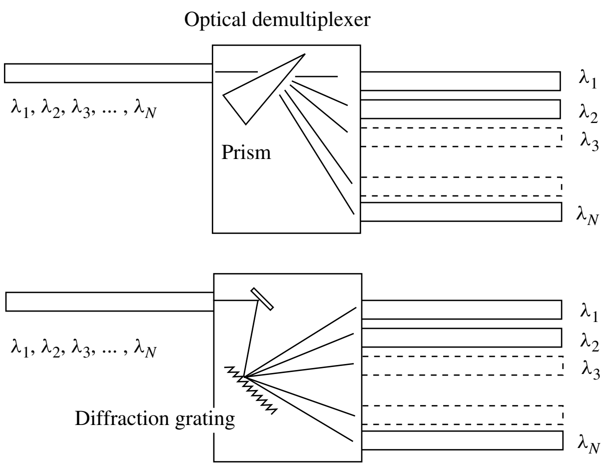


**Fig. 28** Demultiplexers based on using a prism and a diffraction grating

(a medium in a magnetic field) does *not* change the absolute sense of rotation of $\theta$. If we reflect the light to pass through the medium again, the overall rotation increases to $2\theta$, the polarization rotation in the reverse direction does not cancel that in the forward direction but adds to it. (This effect is distinctly different from optical activity.) Suppose that we use a polarizer and a Faraday rotator in series between the laser diode in the above example and the fiber. The forward going light from the laser will first pass through the polarizer, become polarized, and it will then pass though the rotator once. Its polarization would be rotated by $\theta$. But any reflected wave will pass through the rotator twice and thus have its polarization rotated by $2\theta$. It then cannot pass through the polarizer and return to the laser.

## 7 Photodetectors

### 7.1 Fundamental Definitions and Characteristics

Photodetectors convert an incident light signal into an electrical signal such as voltage or current. In many photodetectors such as photoconductors and photodiodes, this conversion is typically achieved by the creation of free EHPs by the absorption of photons, that is, the creation of electrons in the CB and holes in the VB. The free carriers that are photogenerated drift in the detector due to the presence of an applied field ($E$) and thereby generate an external current, called the *photocurrent* $I_{ph}$, and eventually the carriers are collected by the battery. The basic principle of photodetector operation is shown in Fig. 29 where the detector is a simple photoconductor with electrodes. If the absorbed photon generates one EHP as in Fig. 29, and both carriers are collected, then the total charge $Q$ collected in the external circuit is $e$, the electronic charge.

Two most important photodetectors are the *pin* and the *avalanche photodiode* (APD), which are described below. There are a number of important detector quantities that characterize the photodetector performance.

*Internal quantum efficiency* (*QE*) *of a photodetector* is the number of free EHPs photogenerated per absorbed photon; this is not per incident photon on the device. Inasmuch as internal QE is defined in terms of per absorbed photon, it is greater than external QE, which is defined in terms of per incident photon; not all incident photons are absorbed.

The QE $\eta$ of a detector, or external QE, is defined as the number of free EHPs collected per incident photon. Not all the incident photons are absorbed to create *free* EHPs that can be collected and used to give rise to a photocurrent. The efficiency of the conversion process of received photons to free EHPs is measured by the above QE definition. The measured photocurrent $I_{ph}$ in the external circuit is due to the flow of electrons per second to the terminals of the photodiode. The number of electrons

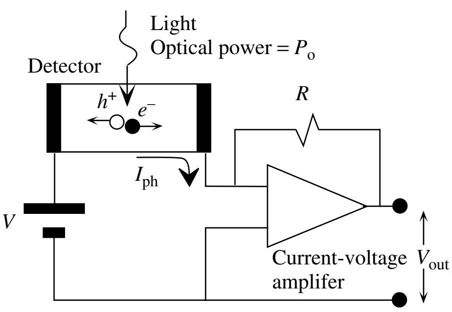


**Fig. 29** A schematic diagram illustrating the basic principle of operation of a photodetector

collected per second is $I_{ph}/e$. If $P_o$ is the incident optical power, then the number of photons arriving per second is $P_o/h\upsilon$. Then the QE $\eta$ can also be defined by

$$\eta = \frac{I_{ph}/e}{P_o/h\upsilon}$$

where $h$ is the Planck's constant, $e$ is the electronic charge, and $\upsilon$ is the frequency of light. Not all of the absorbed photons may photogenerate free EHPs that can be collected. Some EHPs may disappear by recombination without contributing to the photocurrent or become immediately trapped. Further, if the semiconductor thickness for absorbing the light is comparable with the penetration depth ($1/\alpha$, where $\alpha$ is the absorption coefficient of the material), then not all the photons will be absorbed. The device QE is therefore always less than unity. It depends on the absorption coefficient of the semiconductor at the wavelength of interest and on the structure of the device. QE can be increased by reducing the reflections at the semiconductor surface, increasing absorption within the depletion layer, and preventing the recombination or trapping of carriers before they are collected.

The responsivity is the photocurrent generated by a photodetector per unit incident optical power. It depends on the QE and the wavelength of the incident radiation. The responsivity $R$ of a detector characterizes its performance in terms of the photocurrent generated ($I_{ph}$) per incident optical power ($P_o$) at a given wavelength by

$$R = \frac{\eta e}{h\upsilon}$$

where $\eta$ is the QE that depends on the light wavelength $\lambda$, and $\upsilon$ is the light frequency. The responsivity therefore clearly depends on the wavelength. $R$ is also called the *spectral responsivity* or *radiant sensitivity*. The $R$ versus $\lambda$ characteristics represent the spectral response of the photodiode and is generally provided by the manufacturer. Ideally, with a QE of 100% ($\eta = 1$), $R$ should increase with $\lambda$ upto $\lambda_g$ as depicted in Fig. 30. In practice, QE limits the responsivity to lie below the ideal photodiode line with upper and lower wavelength limits as shown for two typical Si photodiodes in Fig. 30. The QE of a well-designed Si photodiode in the wavelength range 700 to 900 nm can be close to 90 to 95%.

## 7.2 pin Photodiode

Figure 31(a) shows the schematic diagram of a silicon *pin* photodiode that has a thin heavily doped *p*-type Si ($p^+$; superscript "+" indicates heavy doping), a wide intrinsic region ($i$), and a heavily doped *n*-type region ($n^+$). The intrinsic layer has a much smaller doping than both $p^+$ and

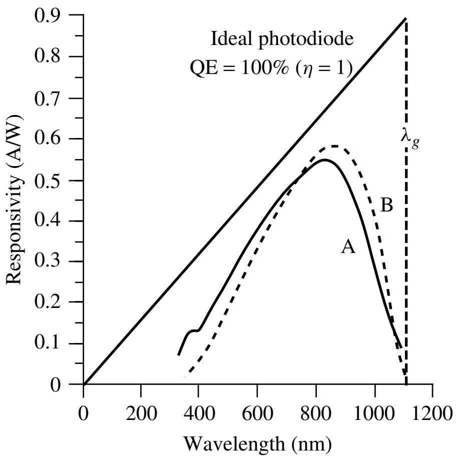


**Fig. 30** Responsivity ($R$) versus wavelength ($\lambda$) for an ideal photodiode with QE = 100% ($\eta = 1$) and for two typical commercial Si *pin* photodiodes with different structures; A is designed to be sensitive in the UV region and has a quartz window to pass the UV radiation

$n^+$ regions and is much wider than these regions, typically 5 to 50 μm, depending on the particular application. Figures 31(b) and (c) show the net space charge density and the internal field across the whole device. There is a uniform built-in field $E_o$ in the *i*-Si layer from the exposed positive donor ions in the $n^+$-region to exposed negative acceptor ions in the $p^+$-region as illustrated in Fig. 31(c). The *pin* detector is normally reverse biased with a voltage $V_r$ as shown in Fig. 31(d). The applied field drops across the resistive *i*-region and increases the built-in field to $E = E_o + V_r/W$ where $W$ is the width of the *i*-region. When a photon with an energy greater than the bandgap energy $E_g$ is incident, it becomes absorbed in the *i*-region ($p^+$-region is very thin) to photogenerate a free EHP, that is, an electron in the CB and a hole in the VB. Usually, the energy of the photon is such that photogeneration takes place in the *i*-layer. The field $E$ in the *i*-layer then separates the EHP and drifts them in opposite directions until they reach the neutral regions as indicated in Fig. 31(d). Drifting carriers generate a photocurrent $I_{ph}$, in the external circuit that provides the electrical signal. The *pin* photodiode structure shown in Fig. 31(a) is, of course, idealized. In reality, the *i*-Si layer will have some small doping. For example, if the sandwiched layer is lightly *n*-type doped, it is labeled as a $\upsilon$-layer and the structure is $p^+ \upsilon n^+$. The sandwiched $\upsilon$-layer becomes a depletion layer with a small concentration of exposed positive donors. The field then is not entirely uniform across the photodiode. The field is maximum at the $p^+\upsilon$ junction and decreases slightly across $\upsilon$-Si to reach the $n^+$ side. As an approximation, we can still consider the $\upsilon$-Si layer as an *i*-Si layer.

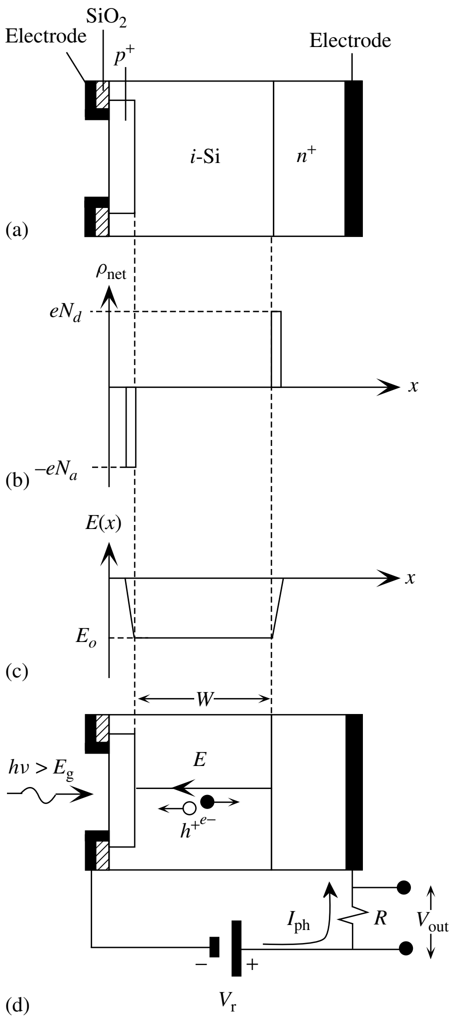


**Fig. 31** (a) The schematic structure of an idealized *pin* photodiode; (b) the net space charge density across the photodiode; (c) the built-in field across the diode; (d) the *pin* photodiode in photodetection is reverse biased

The *pin* photodiodes have a number of distinct advantages over the ordinary *pn* junction photodiodes. Having a wider depletion region, they have relatively better quantum efficiencies. The depletion layer capacitance is much smaller than the *pn* junction depletion layer capacitance and relatively independent of the reverse bias. Consequently, the *RC* time constant associated with the depletion layer capacitance *C* is small if the external resistance *R* is small as shown in Fig. 31(d). Further, a higher reverse bias voltage can be applied to a *pin* diode than to a *pn* junction without breakdown. The speed of a *pin* photodiode is normally limited by the transit time of the slowest photogenerated charge carriers. The speed improves with reverse bias until the carrier drift velocities saturate at the highest fields. The *pin* photodiode is probably one of the most popular photodetectors used in optoelectronic applications due to its fast speed and good responsivity.

## 7.3
## Avalanche Photodiode

Avalanche photodiodes (APDs) are widely used in various optoelectronic applications, particularly optical communications, due to their high speed and internal gain. A simplified schematic diagram of an Si *reach-through* APD is shown Fig. 32(a) The $n^+$-side is thin and it is the side that is illuminated through a window. There are three *p*-type layers of different doping levels next to the $n^+$-layer to suitably modify the field distribution across the diode. The first is a thin *p*-type layer and the second is a thick slightly *p*-type doped (almost intrinsic) $\pi$-layer, and the third is a heavily doped $p^+$-layer. The diode is reverse biased to increase the fields in the depletion regions. The net space charge distribution across the diode due to exposed dopant ions is shown in Fig. 32(b). Under zero bias, the depletion layer in the *p*-region (between $n^+p$) does not normally extend across this layer. But when a sufficient reverse bias is applied, the depletion region in the *p*-layer widens to *reach-through* to the $\pi$-layer (and hence the name *reach-through*). The field extends from the exposed positively charged donors in the thin depletion layer in $n^+$ side, all the way to the exposed negatively charged acceptors in the thin depletion layer in $p^+$-side.

The variation in the field across the diode is shown in Fig. 32(c). The field lines start at positive ions and end at negative ions that exist through the $p$, $\pi$, and $p^+$ layers. This means that $E$ is maximum at the

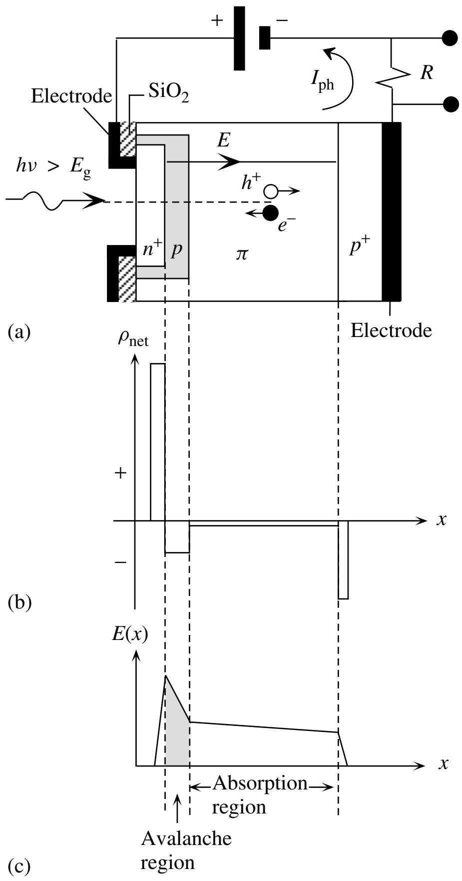


**Fig. 32** (a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain; (b) the net space charge density across the photodiode; (c) the field across the diode and the identification of absorption and multiplication regions

$n^+p$ junction, and then decreases slowly through the $p$-layer. Through the $\pi$-layer, it decreases only slightly as the net space charge density here is small. The field vanishes at the end of the narrow depletion layer in the $p^+$ side.

The absorption of photons and hence photogeneration takes place mainly in the long $\pi$-layer. The nearly uniform field here separates the EHPs and drifts them at velocities near saturation towards the $n^+$- and $p^+$-sides respectively. When the drifting electrons reach the $p$-layer, they experience even greater fields and therefore acquire sufficient kinetic energy (greater than $E_g$) to *impact-ionize* some of the Si covalent bonds and release EHPs. These generated EHPs themselves can also be accelerated by the high fields in this region to sufficiently large kinetic energies to further cause impact ionization and release more EHPs, which leads to an avalanche of impact ionization processes. Thus, from a single electron entering the $p$-layer, one can generate a large number of EHPs, all of which contribute to the observed photocurrent. The photodiode possesses an *internal gain mechanism* in that a single photon absorption leads to the generation of a large number of EHPs. The photocurrent in the APD, in the presence of avalanche multiplication, therefore corresponds to an effective QE in excess of unity. The reason for keeping the photogeneration within the $\pi$-region and reasonably separate from the avalanche $p$-region is that avalanche multiplication is a statistical process and hence leads to carrier generation fluctuations which lead to *excess noise* in the avalanche multiplied photocurrent. This is minimized if impact ionization is restricted to the carrier with the highest impact ionization efficiency, which in Si is the electron.

### 7.4 Heterojunction Avalanche Photodiodes

III–V compound-based heterojunction APDs have been developed for use at the communications wavelengths of 1.3 μm and 1.55 μm. As in the reach-through Si APD, the absorption or photogeneration region is separated from the avalanche or multiplication region which allows the multiplication to be initiated by one type of carrier. The *separate absorption and multiplication* (SAM) APD is typically a heterostructure, as shown in Fig. 33, (e.g., InGaAs-InP) with different bandgap materials to separate absorption and multiplication. InP has a wider bandgap than InGaAs and the $p$- and $n$-type doping of InP is indicated by capital letters, $P$ and $N$. The main depletion layer is between $P^+$-InP and $N$-InP layers, and is within the $N$-InP. This is where the field is greatest and therefore it is in this $N$-InP layer where avalanche multiplication takes place. With sufficient reverse bias, the depletion layer in the $n$-InGaAs reaches through to the $N$-InP layer. The field in the depletion layer in $n$-InGaAs is not as great as that in $N$-InP. Although the long wavelength photons are incident onto the InP side, they are not absorbed by InP since the photon energy is less than the bandgap energy of InP ($E_g = 1.35$ eV). Photons pass through the InP layer and become absorbed in the $n$-InGaAs layers. The field in the $n$-InGaAs layer drifts the holes to the multiplication region where impact ionization multiplies the carriers. The real device is more complicated than this simple description. Photogenerated holes drifting from $n$-InGaAs to $N$-InP become trapped at the interface because there is a sharp increase in the bandgap and a sharp change $\Delta E_v$ in $E_v$ (VB edge) between the two semiconductors, and holes

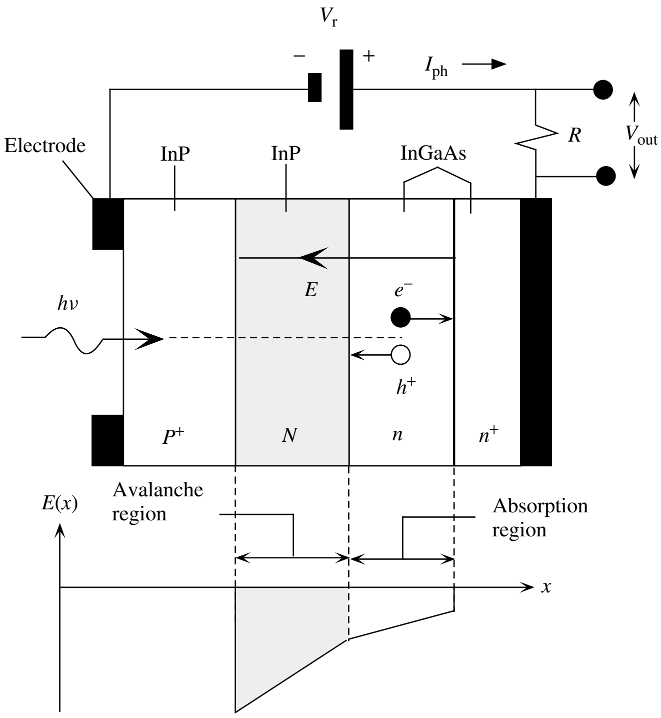


**Fig. 33** Simplified schematic diagram of a separate absorption and multiplication (SAM) APD using a heterostructure based on InGaAs-InP. *P* and *N* refer to *p*- and *n*-type wider bandgap semiconductor

cannot easily surmount the PE barrier $\Delta E_V$. This problem is overcome by using thin layers of *n*-type InGaAsP with intermediate bandgaps to provide a graded transition from InGaAs to InP. Effectively, $\Delta E_V$ is broken up into multiple steps. These devices are called *separate absorption, grading,* and *multiplication* (SAGM) APDs. Both the InP layers are grown epitaxially on an InP substrate. The substrate itself is not directly used to make the *PN* junction in order to prevent crystal defects (for example, dislocations) in the substrate appearing in the multiplication region and hence deteriorating the device performance.

## 8
## Integrated Optics and Optoelectronics

Integrated circuits that revolutionized the electronics industry are based on incorporating millions of transistor switches into a single monolithic device called the integrated circuit (IC). A *monolithic* circuit has all the devices manufactured on the same crystal whereas a *hybrid* circuit has devices that are not integrated into a single crystal but typically placed and interconnected on a separate substrate. In an IC, a single crystal of silicon is used as the substrate and the devices are incorporated onto this substrate using the planar fabrication technology. The counterpart of this technology in optoelectronics is *Integrated Optics* in which two or more optical and/or optoelectronic functionalities are integrated onto a single substrate to form an integrated optical or optoelectronic circuit; a planar assembly of devices that forms an *integrated optic device* or an *optoelectronic integrated circuit* (OEIC), which is a more common term in optoelectronic engineering. Figure 23 shows one of the simplest integrated optoelectronic devices, an integrated Pockels cell phase modulator. There is a single electro-optic substrate, $LiNbO_3$, onto which a waveguide has been implanted and coplanar strip electrodes have been placed to apply an electric field and hence modify the refractive index of the waveguide. There are two functionalities: waveguiding and the electro-optic effect. This is therefore an integrated transverse Pockels phase modulator. (The adjective "integrated" sometimes is also used with a device that has a single functionality if the device has been fabricated using the planar technology on single substrates that can accommodate further devices.). Figure 24 shows an integrated Mach–Zehnder optical intensity modulator. In the latter case two waveguides have been embedded and there are three electrodes. It is clear that in principle, with the right choice of the substrate material, one should be able to achieve sophisticated integrated optic devices that can carry out quite complicated operations, analogous to ICs in the sixties. To date, however, the commercial integrated optoelectronic devices have integrated only a small number of devices. It should be apparent that since integrated optical circuits handle photons these photons have to be coupled into the integrated optic device, guided and manipulated, from one device to another within the monolithic assembly. Thus, a key element in an integrated optical circuit is the integrated optical waveguide. There are various possible waveguide structures one can use depending on the required application. At present there are essentially two important classes of substrates that are commonly used in integrated optoelectronics. The $LiNbO_3$ (as in Figures 23 and 24) substrates are used for various electro-optic based functionalities. OEICs that use lasers and photodetectors are based on III–V semiconductors such as GaAs or InP as substrates. III–V compounds (Sect. 2) are the materials of choice for fabricating LEDs and semiconductor laser diodes as well as detectors (Sect. 7) for optical communications.

Integrated optoelectronic circuits have a number of distinct advantages over those circuits that are based on connecting discrete optoelectronic devices. The reduction in *RC* time constants in integrated optoelectronic circuits leads to an increase in the electrical bandwidth, and thus to a higher modulation frequency. The small size of the integrated optoelectronic circuit implies smaller lengths and widths that translate to smaller external voltages for applying the necessary electric field for electro-optic effects. When properly designed and fabricated, the final integrated optoelectronic device is free from alignment problems. As in the case of ICs, integrated optical and optoelectronic circuits offer cost-effective mass production of reliable devices.

The goal of developing commercial integrated optical and optoelectronic circuits took an enormous importance with the development and commercialization of affordable small semiconductor lasers. Over the last two decades, a variety of integrated optic devices have been demonstrated and developed some examples of which are integrated optical switches, multiplexers and demultiplexers, modulators, erbium-doped waveguide amplifier arrays, DFB laser arrays, tunable lasers, multiwavelength lasers and so on. The rapid growth of optical communications in the last two decades has demanded ever-increasing levels of integration. For example, it is possible to fabricate an OEIC that functions as a multiwavelength transmitter based on integrating an array of lasers that can be modulated, a coupler and an optical amplifier. Such an OEIC is obviously very useful as a transmitter for wavelength division multiplexed (WDM) optical communications.

## 9 Optoelectronic Systems

Combinations of various optoelectronic devices can lead to the implementation of quite impressive and sophisticated optoelectronic systems. Typically, an optoelectronic system may contain not only conventional optoelectronic devices (e.g., lasers, modulators, fiber, photodetectors) but also purely optical components (e.g., polarizers, filters, etc.) and purely electronic devices (e.g., amplifiers, encoders, A/D, D/A converters, power supplies, etc).

A simplified block diagram of a WDM optical communication system is shown in Fig. 34. *N* optical information channels are generated by modulating *N* light waves, each with a different wavelength from $\lambda_1$ to $\lambda_N$. The *N* optical channels are then multiplexed into a single fiber for transmission. Optical amplifiers are used at various points along the transmission medium to amplify the attenuated signal. If a particular information channel, for example, the third channel at $\lambda_3$, needs to be dropped and another information channel (at the same wavelength) needs to be added, this can be done by using a *wavelength add/drop multiplexer*. The new channel is labeled as $\lambda_{3'}$. At the destination, the optical signal has to be separated into its constituent *N* channels by a wavelength demultiplexer. Each channel is then fed into a receiver, which like the transmitter can be quite complicated in terms of electronics.

An examination of the WDM system in Fig. 34 illustrates a number of important basic functions: (1) generation of different wavelengths of light each with a narrow spectrum to avoid any overlap in wavelengths; (2) modulation of light without wavelength distortion, that is, without chirping (variation in the frequency of light due to modulation); (3) efficient coupling of different wavelengths into a single transmission medium; (4) optical amplification of all the wavelengths by an amount that compensates for attenuation in the transmission medium, which depends on the wavelength; (5) dropping and adding channels when necessary during transmission; (6) demultiplexing the wavelengths into individual channels at the receiving end; and (7) detecting the signal in each channel. To achieve an acceptable bandwidth, we need to dispersion-manage the fiber (use dispersion compensation fibers); and to reduce cross talk and unwanted signals, we have to use optical filters to block or pass the required wavelengths. We need various optical components to connect the devices together and implement the whole system.

Channel density is an important quantity in designing WDM systems. It is usually measured in terms of frequency spacing between two neighboring optical channels. If the frequency spacing $\Delta\upsilon$ is less than 200 GHz, then WDM is called *dense wavelength division multiplexing* and is denoted as DWDM. At present, DWDM stands typically at 100 GHz separated channels,

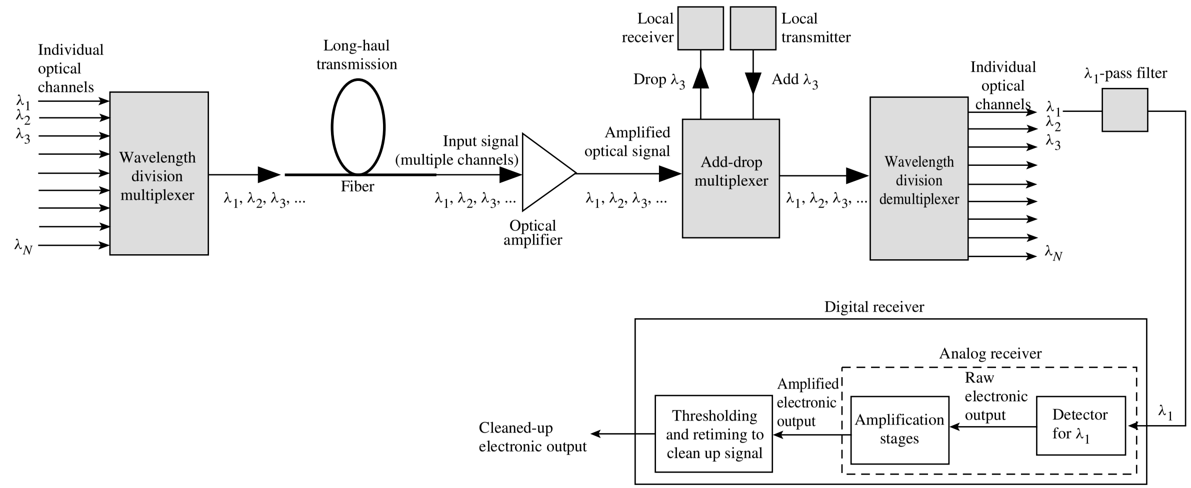


**Fig. 34** Wavelength division multiplexing, an example of an optoelectronic system

which is equivalent to a wavelength separation of 0.8 nm. DWDM imposes stringent requirements on lasers and modulators used for generating the optical signals. It is not possible to tolerate even slight shifts in the optical signal frequency when channels are spaced closely. As the channel spacing becomes narrower as in DWDM, one also encounters various other problems not present previously. For example, any nonlinearity in a component carrying the channels can produce intermodulation between channels, an undesirable effect. Thus, the total optical power must be kept below the onset of nonlinearity in the optical amplifiers within the WDM system. Further, the nonlinearity of optical fiber at high optical powers leads to a phenomenon called *four-photon mixing*. Consider three optical signals at $\upsilon_1$, $\upsilon_2 = \upsilon_1 + 100$ GHz, $\upsilon_3 = \upsilon_1 + 200$ GHz. The nonlinearity in the optical fiber mixes signals to generate a new signal at $\upsilon_4 = \upsilon_1 + \upsilon_2 - \upsilon_3 = \upsilon_1 - 100$ GHz, on top of the channel below $\upsilon_1$. Four-photon mixing thus adds noise to the communication system.

There are limits to how much optical power can be efficiently transmitted in a fiber. The optical power transmitted through a fiber does not increase linearly with the input power when the latter is sufficiently high to cause stimulated Brillouin scattering (SBS). Interaction of the photons with acoustics phonons in the fiber generates a periodic variation in the refractive index, which in turn reflects some of the power back. The effect increases as the input light power increases and the spectral width of the input light becomes narrower. The onset of SBS depends not only on the fiber type and core diameter, but also on the linewidth $\Delta\lambda$ of the laser output spectrum. SBS is enhanced as the laser linewidth $\Delta\lambda$ is narrowed or the light pulse is lengthened. For example, for a directly modulated laser diode emitting at 1550 nm into an SMF, the onset of SBS is expected to occur at power levels greater than 20 to 30 mW. In DWDM systems with externally modulated lasers, that is, narrower $\Delta\lambda$, the onset of SBS can be as low as $\sim$10 mW. SBS is an important limiting factor in transmitting high power signals in WDM systems.

The WDM example in Fig. 34 is one of many examples on optoelectronic systems. The complexity of such systems depends not only on whether individual optoelectronic devices can efficiently implement the required function, but also on the availability of various optical components that are needed to properly interconnect the devices. Optoelectronics today is an interdisciplinary activity. Advances at the device level are enabling systems that would have been thought impossible a couple of decades ago (DWDM being an excellent example).

## Glossary

**Acceptance Angle:** The largest possible angle with respect to the fiber axis for launching light into the fiber.

**Acousto-optic (AO) Modulator:** A photoelastic effect–based device that can deflect light when a suitable radio frequency signal is applied to it.

**Avalanche Photodiode (APD):** Photodetector that has internal gain due to the impact ionization multiplication of photogenerated carriers so that the quantum efficiency is normally more than unity.

**Chromatic Dispersion:** The temporal spread of a propagating optical pulse in an optical guide due to the wavelength dependence of all the guide properties. It includes waveguide, material, and profile dispersions added together.

**Cladding:** A medium of lower refractive index surrounding a core of higher refractive index that guides light; cladding confines the light to the core.

**Compensating Fiber:** A length of fiber that is connected (spliced) to a transmission fiber whose chromatic dispersion is to be reduced. Compensating fiber has dispersion characteristics that nearly cancel the dispersion in the transmission fiber.

**Connector:** A convenient mechanical device that is attached to the end of a fiber that connects to another such device and thereby connects fibers together.

**Core:** The central region of an optical fiber that has a higher refractive index than the surrounding cladding region, and guides light along the fiber.

**Demultiplexer (DMUX):** A device that is able to separate a multiplexed signal into its original component channels.

**Dense Wavelength Division Multiplexing (DWDM):** The transmission of many channels of information that are closely spaced in wavelength along the same fiber. The channels are transmitted at wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_N$, which are separated in frequency by 200 GHz, or wavelengths separated by 1.6 nm if the wavelengths are in the 1550-nm window.

**Dispersion:** Dispersion in optical fiber refers to the spread in time, known as temporal broadening, of an infinitesimally thin optical pulse as it propagates along the fiber.

**Dispersion Shifted Fiber:** A fiber whose wavelength for zero chromatic dispersion has been shifted to the 1550-nm region; not useful in WDM optical systems.

**Distributed Feedback (DFB) Laser:** A "single frequency" laser, that is, a laser with a very narrow output spectrum, in which the optical feedback in the cavity occurs distributively over the cavity length due to a periodic corrugation in the cavity; such corrugation forms a periodic change in the refractive index and hence forms a grating.

**Double Heterostructure (DH):** A structure in which a semiconductor layer is sandwiched by two wider bandgap semiconductor layers. There are two heterojunctions since the narrow bandgap semiconductor makes junctions with its two wider bandgap neighbors, hence the name double heterostructure. DH junctions are useful in confining injected minority carriers in the narrow bandgap layer.

**Electro-absorption:** The absorption of photons with energies slightly less than the bandgap energy as a result of the application of an electric field.

**Electro-optic Effect:** Changes in the refractive index of a material induced by the application of an external electric field, which therefore "modulates" the optical properties.

**Electro-optic Modulator:** A device that modulates a characteristic of light such as its intensity or phase in response to an electrical signal by virtue of the electro-optic effect.

**Erbium Doped Optical Fiber Amplifier (EDFA):** An optical amplifier made from a glass fiber whose core has been doped with $Er^{3+}$ ions; the latter are pumped to an excited state by using a laser diode (or an LED) at 980 or 1480 nm.

**Faraday Effect:** A physical phenomenon in which the plane of polarization of a propagating light wave in a medium is rotated by placing a magnetic field into that medium. The amount of rotation depends on the material and is proportional to the applied magnetic field and the length of the medium.

**Franz–Keldysh Effect:** Electric field induced absorption of light with photon energies slightly less than the bandgap in a semiconductor due to the modification of the energy band edge by the applied field.

**Graded Index (GRIN) Optical Fiber:** A fiber that has a core refractive index that is graded gradually, changes continuously, towards the cladding. Typically in a graded index fiber, the refractive index profile is approximately parabolic to minimize modal dispersion.

**Injection Electroluminescence:** Light emission by radiative recombination of an electron and a hole that have been injected by an electrical current into a semiconductor device such as an LED.

**Integrated Optics or Optoelectronics:** A monolithic optical or optoelectronic circuit in which two or more optical and/or optoelectronic functionalities are integrated planarly into a single substrate to form an integrated optic (or optoelectronic) device.

**Kerr Effect:** A second order effect exhibited by all materials in which the change in the refractive index is proportional to the square of the applied electric field.

**Laser Diode:** A semiconductor diode, usually a heterostructure device, that emits coherent radiation, a lasing output, when the current through it exceeds the threshold current to achieve the necessary population inversion for stimulated emission.

**Light-emitting Diode (LED):** Usually a *pn* junction diode type device that emits light by the spontaneous emission of photons through injection electroluminescence when it is forward biased.

**Mach–Zehnder Modulator:** A lithium niobate device whose light transmittance is controlled by an applied external voltage; it is based on interfering two waves passing through the crystal in such a way that their phase difference can be controlled by the Pockels effect.

**Modal Dispersion:** Dispersion due to the propagation of an optical signal along a multimode fiber as different modes of radiation with each having its own propagation velocity. These modes arrive at different delay times and cause the optical pulse to broaden. Modal dispersion is absent in single-mode fibers.

**Modulator:** A device that changes a characteristic of light, such as its intensity, phase, polarization, or direction, passing through it in response to an electrical input signal.

**Multimode Fiber (MMF):** A fiber in which light propagates as many modes.

**Multiple Quantum Well (MQW):** A superlattice that is formed by many quantum wells; many alternating thin layers of narrow bandgap semiconductors separated by higher bandgap semiconductors.

**Multiplexer (MUX):** A device where two or more signals (channels) are combined into a single output.

**Nonzero Dispersion Shifted Fiber:** A fiber whose wavelength of zero chromatic dispersion has been shifted to be just outside the Er-doped fiber amplifier region (1525 to 1620 nm).

**Numerical Aperture (NA):** A characteristic parameter of an optical fiber that depends on the refractive indices of the core and the cladding, and measures light gathering ability of the core.

**Optical Amplifier:** An amplifier that amplifies an optical signal, namely, light.

**Optical Fiber:** A thin glass–based cylindrical optical waveguide whose core region has a higher refractive index and thereby guides light. Signals in optical communications are transmitted through optical fibers.

**Optical Fiber Mode:** A distinct electric field pattern that is allowed to exist in the fiber and propagate along the fiber without attenuation if the fiber is lossless.

**Optical Isolator:** A device that allows light to pass in one direction and not in the opposite direction.

**Optical Semiconductor Amplifier:** A semiconductor laser structure that can be used as an optical amplifier that amplifies light waves passing through its active region.

**Optical Switch:** A device that can be actuated by an external signal to switch an optical signal from one optical path to another, or can be actuated to either transmit or not transmit light.

**Photodetector:** An optoelectronic device that converts an incident optical signal to an electrical signal, usually a photocurrent.

***pin* Photodiode:** A photodetector that has the structure, $p^+$/intrinsic/$n^+$ with a relatively thick intrinsic (depletion) region where the electric field is relatively uniform and where photogeneration takes place for efficient charge collection and high quantum efficiency.

**Pockels Effect:** An effect exhibited by noncentrosymmetric crystals in which the change $\Delta n$ in the refractive index is linearly proportional to the applied electric field $E$; if $\Delta n$ is positive for a field in a certain direction, reversing the field results in a negative $\Delta n$.

**Quantum Dot (QD):** A crystal that is so small (for example, a crystal that is several nanometers) that the electrons and holes in the crystal are confined in three dimensions and exhibit quantum effects such as quantized energies in all directions.

**Quantum Efficiency:** A quantity that describes the efficiency of conversion in the photodetection process from collected photons to detectable charge carriers; number of free electron–hole pairs collected per incident photon.

**Quantum Well (QW):** A heterostructure that has an ultra thin, typically less than 20 nm, narrow bandgap semiconductor, such as GaAs, sandwiched between two wider bandgap semiconductors, such as AlGaAs. The electrons and holes in the thin narrow bandgap layer exhibit quantum effects along the direction perpendicular to the layers ($z$-direction) and have quantized energies similar to an electron in a finite one-dimensional potential energy well; energy is not quantized for motion in the $xy$ plane.

**Raman Fiber Amplifier:** Is a fiber based optical amplifier in which energy is transferred from a powerful pump radiation fed into a fiber to a weak propagating signal as a result of nonlinear frequency mixing; the result is an optical amplification. The pump frequency is higher than the signal frequency by a phonon frequency of the medium.

**Responsivity, Radiant Sensitivity:** A characteristic property of a photodetector that indicates how responsive the detector is at a certain wavelength by measuring the photocurrent generated per incident optical power.

**Separate Absorption and Multiplication (SAM) APD:** A heterostructure avalanche photodetector with different bandgap materials to separate absorption and multiplication processes to reduce the excess avalanche multiplication noise.

**Single-mode Fiber (SMF):** A fiber in which only the fundamental mode can propagate; the fiber has a $V$-number, $V < 2.405$ at the operating wavelength.

**Single-mode Waveguide:** A waveguide that can carry only the *fundamental mode* (lowest mode) of radiation within the wavelength range of interest, that is, wavelengths longer than the critical cut-off wavelength.

**Splice:** A permanent connection between two fibers achieved by aligning the fibers and then fusing the two glasses to each other at a high temperature in an electrical arc between two electrodes.

**Threshold Current:** The minimum current that must be passed through a laser diode to obtain coherent output radiation that exceeds the spontaneous radiation output. More strictly, it is the minimum current for self-sustaining lasing oscillations in the laser diode.

**Vertical Cavity Surface Emitting Laser (VCSEL):** A small semiconductor laser that has the optical cavity axis along the direction of current flow rather than perpendicular to the current flow as in conventional laser diodes. The active region length is very short compared with the lateral dimensions so that the radiation emerges from the "surface" of the cavity rather than from its edge.

***V*-number:** A dimensionless quantity that is a characteristic of a dielectric waveguide which determines the nature of propagation of EM waves along the guide. For a step-index fiber, it is defined by $V = (2\pi a/\lambda)[n_1^2 - n_2^2]^{1/2}$, where $a$ is the core radius, $\lambda$ is the free space wavelength of the radiation to be guided, and $n_1$ and $n_2$ are the refractive indices of the core and cladding respectively. If $V < 2.405$, only the fundamental mode can propagate.

**Wavelength Add/Drop Multiplexer (WADM) or Optical Add/Drop Multiplexer (OADM):** A multiplexer that is able to selectively take out, that is, remove, a signal at a specified wavelength $\lambda_s$ from wavelength division multiplexed signals propagating along a fiber, and then add new or different information at the same wavelength $\lambda_s$ into the fiber, in the same direction.

**Wavelength Division Multiplexing (WDM):** Multiplexing of different channels of information along the same fiber at different wavelengths.

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