CHAPTER 6

LIGHT SOURCES

6.1 INTRODUCTION

There are many types of light source. The sun and light from burning torches were the first light sources used to study optics. As a matter of fact, light emanating from certain (exited) matter (e.g., iodine, chlorine, and mercury ions) still provides reference points in the optical spectrum.

One of the key components in optical communication is the monochromatic light source. In optical communications, light sources must be compact, monochromatic, stable, and long lasting (many years). In practice, there are no monochromatic light sources; there are merely light sources that generate light within a very narrow band of wavelengths. The light sources used in spectrography are neither practical nor economical in communications. Stability of a light source implies constant intensity level (over time and temperature variations) and constant wavelength (no drifts).

Solid-state technology has made it possible to have such optical sources of light. There are two different types of light source. The first type transmits a *continuous wave* (CW). Continuous emitting lasers and light-emitting diodes (LEDs) are examples of CW light sources. This type of light source requires an external modulator at its optical output. In this arrangement, an electrical signal representing a data stream acts on the modulator that modulates the light passing through. The second type transmits *modulated light*; that is, no external modulator is necessary. This type receives an electrical data stream that directly modulates the light source. Lasers and LEDs are examples of modulated light sources.

In this chapter, we examine two popular light sources, *light-emitting diodes* and *semiconductor lasers*.

6.2 LIGHT-EMITTING DIODES

In certain semiconductors, during the recombination process of electrons with holes at the junction of n-doped and p-doped semiconductors, energy is released in the form of light. The excitation takes place by applying an external voltage and the recombination may be spontaneous, or it may be stimulated as another photon.

An LED is a monolithically integrated p–n semiconductor device (a diode) that emits light when voltage is applied across its two terminals. The LEDs used in communications are constructed to allow light to emerge from the device edge (Figure 6.1). This facilitates coupling the LED light with a fiber. Since, however, LEDs transmit light within a relatively wide cone, their application in optical transmission is limited. Currently, sophisticated doping structures are used to increase the switching speed and narrow the optical spectrum of the LED.

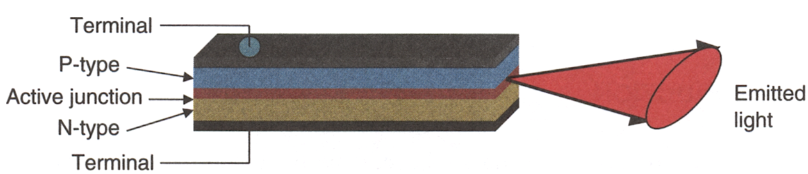

Figure 6.1 An LED is a p–n semiconductor device that emits light when a voltage is applied across its two terminals.

6.2.1 Switching Speed and Output Power

The *switching speed* of an LED depends on the recombination rate, R, expressed by

$$R = \frac{J}{de}, \tag{6.1}$$

where J is the current density (A /m^2), d is the thickness of the recombination region, and e is the electron charge.

The *output power* of an LED is expressed by

$$P_{\text{out}} = \left[\frac{\eta hc}{e\lambda}\right] I, \tag{6.2}$$

where I is the LED drive current (A), η is the quantum efficiency (relative recombination/total recombination), h is Planck's constant, e is the electron charge, and λ is the wavelength of light.

6.2.2 Output Optical Spectrum

The output optical spectrum of LEDs is the range of emitted wavelengths. This depends on the absolute junction temperature (i.e., the range widens as temperature increases) and on the emission wavelength λ

$$\Delta\lambda = 3.3 \left(\frac{kT}{h}\right)\left(\frac{\lambda^2}{c}\right), \tag{6.3}$$

where T is the absolute temperature at the junction, c is the speed of light, k is Boltzmann's constant, and h is Planck's constant.

Temperature has an adverse effect on the stability of an LED device. As temperature rises, its spectrum shifts and its intensity decreases, as shown in Figure 6.2.

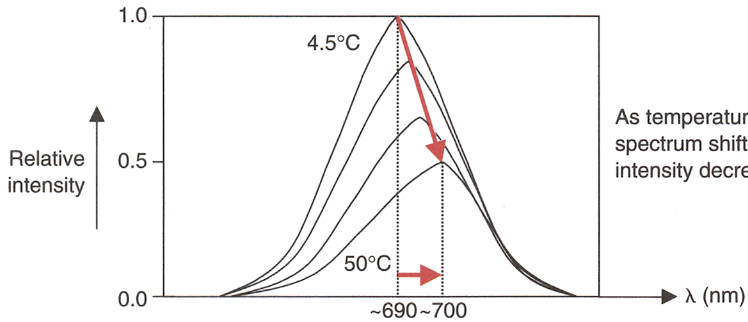

Figure 6.2 The spectral output of LEDs in the range of emitted wavelengths depends on the absolute junction temperature.

6.2.3 Input–Output Response

An LED, being a diode, behaves like one, and its *I*–*V* characteristic has a similar profile. Because its output optical power depends on the current density, which depends on the applied voltage and electron concentration, a similar response would be expected and indeed is observed. However, a threshold is defined, below which the optical power is negligible (Figure 6.3).

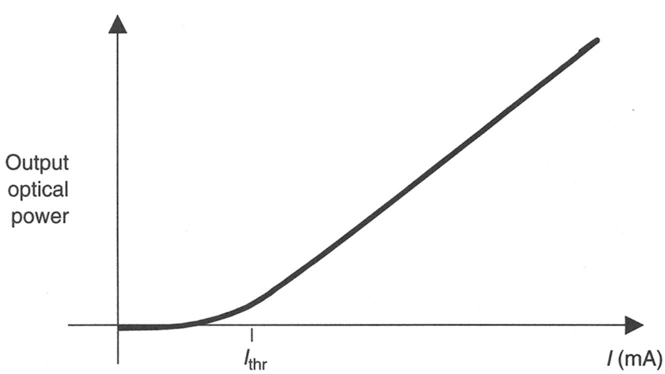

Figure 6.3 An LED behaves like a diode.

6.2.4 Modulation Response

The modulated current density J is expressed by

$$J = J_0 + J_0 m_j \exp(j\omega t) \tag{6.4}$$

where J_0 is the steady-state current density, m_j is the modulation depth, and ω is the modulation frequency. This current modulates the electron density difference through the junction, $\Delta n = n - n_0$ (n_0 is the electron density at equilibrium with no bias current) as

$$\Delta n = N_0\{1 + M_N \exp[j(\omega t - \theta)]\}, \tag{6.5}$$

where N_0 is the electron density at steady state, M_N is the electron modulation depth, and θ is the phase shift.

From the differential $d(\Delta n)/dt$, the output power modulation index I_M is derived in terms of the output modulation response, M_N:

$$I_M = M_N e^{-j\theta} = \frac{m_j}{1 + j\omega\tau_r} \tag{6.6}$$

where τ_r is the electron–hole recombination time. Comparing the modulation response with a first-order low-pass filter (LPF), it is concluded that the transfer functions are identical. Thus, the modulation response may be studied like an LPF, from which the 3-dB modulation bandwidth is derived:

$$\omega_{3dB} = \frac{1}{\tau_r}. \tag{6.7}$$

6.2.5 Conclusions

- The LED bandwidth depends on the device material.
- The LED amplitude depends on the current density (i.e., on the operating V–I point).
- The LED amplitude and spectrum depend on temperature.
- LEDs are relatively slow devices (<1 Gb/s).
- LEDs exhibit a relatively wide spectral range.
- LEDs are inexpensive.
- LEDs transmit light in a relatively wide cone.
- LEDs are suitable sources for multimode fiber communications.

6.3 LASERS

Laser stands for **l**ight **a**mplification by **s**timulated **e**mission **r**adiation. It has been found that some elements in gaseous state (e.g., He–Ne) and others in crystals (e.g., ruby with 0.05% chromium) absorb electromagnetic energy (light) and remain in a semistable, high-energy excited state.

Lasers take advantage of stimulated emission. Some photons traveling through the excited medium interact with electrons and holes in the recombination region. A cascaded and rapid process is thus triggered, by which excited atoms drop from their high-energy state to a low-energy state by releasing energy in the form of light; that is, a single photon causes many. Emitted photons enter a region known as the cavity. The emitted photons (in phase) are reflected back and forth in the cavity to form a strong *coherent* monochromatic beam; photons traveling in other directions are eventually lost through the walls of the cavity.

The back-and-forth reflection of photons within a frequency-selective mechanism, such as a cavity with specific dimensions or a *grating*, results in an optical output with a narrow spectrum and a large positive gain. This is explained as follows. As energy is pumped in, the lost photons are replenished, optical feedback creates resonance, the optical gain reaches a threshold, and the lasing process starts. However, the dimensions of the cavity structure (which has a dielectric constant greater than air) must be precise in wavelength multiples. Remember that owing the dielectric constant, an imprecision of few angstroms of semiconductor material in the cavity is equivalent to millimeters in an air cavity.

Typically, the large positive gain of lasers depends on semiconductor materials and their composition, semiconductor structure, pumped energy, and feedback mechanism. Taking advantage of stimulated emission, and keeping the gas or crystal continuously in a high energy state by pumping photonic energy into it (or applying a voltage), a continuous or a pulsating coherent light amplification mechanism is achieved (see Section 6.3.1). Lasers that support a *single transverse mode* are known as *single-mode lasers* (whether they oscillate in a single or multiple longitudinal mode). Those that support both a *single transverse mode* and a *single longitudinal mode* are known as *single-frequency lasers.* If they oscillate at *several frequencies simultaneously,* longitudinal or transverse, then they are called *multifrequency lasers.*

A laser oscillates at frequencies that have sufficient gain (or amplitude) to satisfy the *amplitude* and *phase condition.*

6.3.1 The Ruby Laser

The ruby laser (Figure 6.4) is a characteristic example. It consists of a rubidium rod that contains 0.05% chromium, which is wrapped around with a flash tube. The ruby–flash tube assembly is enclosed in a cylindrical reflector having a window at one end. Both ends of the ruby rod are cut parallel and polished. One end face is fully reflecting, while the other is partially reflecting. Part of the green-blue light from the flash tube excites the chromium atoms. Initially, spontaneous emission in the ruby radiates in all directions but shortly, after 0.5 ms, coherent radiation emerges through the window that may reach peak power at several kilowatts. The wavelength of this coherent light is about 694 nm, but its exact value depends on the length of the ruby rod (the recombination cavity) and the temperature of the rod.

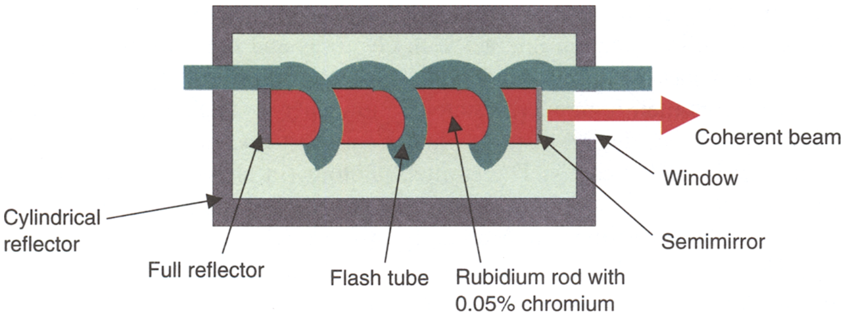

Figure 6.4 The ruby laser exemplifies the operation of a laser.

6.3.2 Semiconductor Lasers

Besides gases and rubidium, certain solid materials exhibit the same behavior. Examples include AlGaAs and InGaAsP. AlGaAs and InGaAsP are suitable because they can be cost-effectively manufactured, they generate light at wavelengths compatible with silica fiber, and they can be monolithically integrated with other optical components.

Semiconductor lasers are diodes constructed with the planar method: that is, by growing several thin layers of crystals with controlled consistency and doping on top of an InP substrate. The active layer of this structure, such as a straight channel of InGaAsP, is sandwiched between n- and p-type layers of InP, also known as cladding layers. When bias is applied, holes and electrons in the active region are excited. When they recombine, energy is released in the form of light. The wavelength of light depends on the energy band-gap of the active material. The active layer has a much higher refractive index than the cladding layers, and thus the cladding layers confine the electron holes and the photons in the active region.

Semiconductor lasers transmit coherent light within a very narrow cone, and thus the beam is more efficiently coupled to a fiber. In addition, they are directly modulated and thus better suited than LEDs to high bit rates and long fiber spans. However, direct modulation at very high bit rates (~10 Gb/s) may cause the laser to optically chirp, that is, to emit a form of wavelength jitter and noise. This occurs because the refractive index of the laser cavity depends on the drive current. Thus, as the drive current changes from a logic one to a logic zero and vice versa, the refractive index changes dynamically (effectively changing the resonant cavity characteristics), which causes a dynamic change in the wavelength, hence *optical chirping*. Optical chirping may be viewed as a spectral line that jitters about the central wavelength. Chirping is avoided if external modulation is used. In this case, the laser emits a continuous wave, thus avoiding the broadening of the line width. Because lasers and modulators can be made with In + Ga + As + P, both laser and modulator can be monolithically integrated on an InP substrate to yield a compact device.

The semiconductor laser designer is challenged to integrate key optical elements (cavity, filter, excitation region, reflectors, etc.) in a device that is very small, monolithic, efficient, almost monochromatic, and stable.

Wavelength and signal amplitude stability of semiconductor lasers are important to efficient and reliable transmission. Stability depends on materials, bias voltage, and temperature. Frequency stabilization is usually established by using thermoelectric cooling techniques that keep the temperature stable within a fraction of a degree centigrade. However, this adds to the cost structure and power consumption of the device, and efforts are made to design "cooler" devices.

Monolithic laser devices have been manufactured for a wide range of applications. Depending on usage, device efficiency, and cost, semiconductor lasers are designed for specific wavelength ranges and for specific modulation rates, such as low-cost broadband transmitters in the range of 45–622 Mb/s and ultrafast transmitters that are modulated to rates greater than 20 Gb/s. Moreover, there are two major laser categories, the *fixed frequency* and the *tunable* laser.

Semiconductor lasers have at minimum:

- An optical waveguide (to limit light in a single direction)
- An active region (where stimulated emission takes place)
- Optical feedback (a cavity in which light bounces back and forth for gain and filtering purposes)

In the following sections, we examine these components.

6.4 MONOLITHIC FABRY–PEROT LASERS

Monolithic semiconductor lasers with a resonance mechanism (or optical feedback) based on the Fabry–Perot principles are constructed with the planar method; that is, growing three-dimensional (3-D) layers of crystals with controlled consistency and doping. A simplified structure of a semiconductor laser source based on the Fabry–Perot principle is shown in Figure 6.5. This structure combines a semiconductor material in the form of a straight channel (p-type AlGaAs), which is both the active region (for stimulated emission) and the optical waveguide (to guide photons in one direction). Both ends of the channel are carefully cleaved to act as mirrors with a reflectivity

$$R = \left(\frac{n-1}{n+1}\right)^2,$$

where n is the refractive index of the active medium. The actual laser structure is very complex and has many layers (typically, > 10); in this structure, a Fabry–Perot etalon is incorporated.

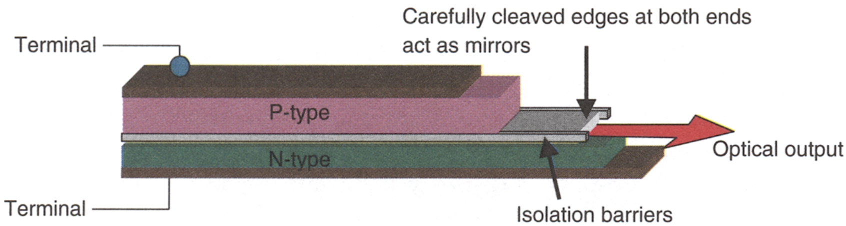

Figure 6.5 Laser structure based on the Fabry-Perot principle.

By controlling 3-D geometry, semiconductor composition, and doping, one obtains the desired optical gain, optical feedback (resonance), and filtering.

The exact structure of the Fabry–Perot lasers varies among manufacturers. A complete description of these lasers is beyond our purpose.

Fabry–Perot lasers can generate several longitudinal frequencies (modes) at once. The semiconductor laser material, the frequency spacing, and the Fabry–Perot laser length determine the range of frequencies. The bias current determines the threshold frequency.

6.5 MONOLITHIC BRAGG LASERS

Cleaved edges in the Fabry–Perot structure (Figure 6.5) resulted in laser light with an insufficiently narrow line width. Narrower line widths may be accomplished by employing Bragg gratings to act as reflectors. Bragg grating is achieved by periodically varying the index of refraction (or the doping of the material: see dark/light blue regions in Figure 6.6). Such a laser is called a distributed Bragg reflector (DBR). The simplified diagram illustrates the applicability of the Bragg grating (for feedback) at either side of a laser cavity (active region) and the optical waveguide.

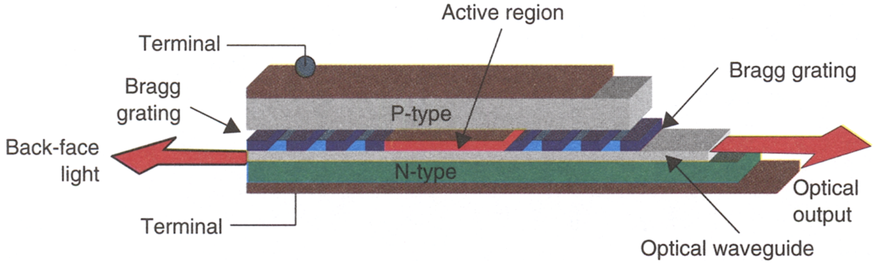

Figure 6.6 Bragg gratings may be used as frequency-selective reflectors in semiconductor lasers.

6.6 DISTRIBUTED-FEEDBACK LASERS

Distributed-feedback (DFB) lasers are monolithic devices that have an internal structure based on InGaAsP waveguide technology and an internal grating (typically at the interface of the n-InP substrate and n-InGaAsP layers) to provide feedback at a fixed wavelength, determined by the grating pitch. DFBs are an extension of the electroabsorption-modulated lasers and take their name from their structure. The DFB structure may be combined with multiple quantum well (MQW) structures to improve the line width of the produced laser light (as narrow as few hundred kilohertz). MQWs have a structure similar to diode structure, but the active junction is only a few atomic layers thick—see Section 6.7). The resonant cavity may be of the Mach–Zehnder or the Fabry–Perot type.

DFB lasers are reliable sources with center frequencies in the region around 1310 nm, and also in the 1520–1565 nm range; the latter makes them compatible with erbium-doped fiber amplifiers and excellent sources in dense wavelength division multiplexing (DWDM) applications.

A complete DFB laser device contains other components necessary to stabilize the center frequency and maintain a constant uniform amplitude. For example, a photodiode monitors the laser output; a thermoelectric cooler (TEC) or heat pump and a heat sink control the junction temperature of the laser chip; and feedback circuitry controls its output to constant level and frequency. A complete DFB laser packaged device may contain more components aimed at stabilizing the center frequency and maintaining constant amplitude. For example, a device may include a 5% power reflector in conjunction with a photodiode ([a positive intrinsic negative photodiode (PIN) or an avalanche photodetector (APD)] to monitor the laser output and a feedback circuit to control the output power. Another device may include a thermoelectric cooler and heater (TEC) and a heat sink to control the temperature constant to 25°C over the package temperature range, −20 to 65°C. However, the internal package structure and components are not standard; there is variation from manufacturer to manufacturer.

6.7 SEMICONDUCTOR QUANTUM WELL LASERS

Semiconductor QWLs are diode lasers (see Figure 6.1) with a very thin active junction layer (50–100 Å or 7–10 atomic layers), whereas conventional diode lasers have a tenfold or larger active layer. The active region is a GaAs (quantum well) layer sandwiched between a p-type $Al_xGa_{1-x}As$ layer and an n-type $Al_yGa_{1-y}As$ layer. Very thin layers are typically grown by means of the molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) methods. To visualize such a device, think of a thick n-type GaAs substrate with a stack of 40 alternating p- or n-type AlGaAs and quantum well GaAs structures, topped by a last p-type GaAs thick layer. That is, GaAs*/n-AlGaAs/GaAs/p-AlGaAs/GaAs/· · ·/p-AlGaAs/GaAs*; where GaAs* indicates thick substrate layers. This structure is again sandwiched between two metallic electrode layers where the bias voltage is applied (the ground potential is connected with the n-type GaAs*).

The extremely thin active layer of the QWL has some very interesting properties. It constrains electron–hole pairs to move in an almost horizontal plane that is found in a narrow energy gap between the p- and n-layers, and the recombination properties are best studied with quantum mechanical theory (hence the name of this laser type). In addition, the narrow layer guides released photons in a similar manner to a single-mode fiber. The result is that when a bias current excites the active region, small currents produce large amounts of coherent light within a narrow line width, and this is a significant advantage of the QWLs. More complex structures with multiple quantum wells produce *multiple quantum well lasers* (MQWL or MQW).

6.8 VCSEL LASERS

Fabry–Perot devices, DFBs, and DBRs typically require substantial amounts of current to operate, in the order of tens of milliamperes. Moreover, their output beam has an elliptical cross section, typically an aspect ratio of 3:1, which does not match the cylindrical cross section of the fiber core. Thus, a noncylindrical beam may require additional optics. A structure that produces a cylindrical beam is known as vertical-cavity, surface-emitting laser (VCSEL). This laser consists of a vertical sandwich of a p-type multilayer, an active region, and an n-type multilayer (Figure 6.7). The p-type and n-type multilayers (40–60 quarter-wavelength layers) comprise Bragg reflectors (DBR) that are made with In + Ga + As + (Al or P), depending on the wavelength desired. For example, In + Ga + As + P is used for lasers in the wavelength window from 1300 nm to 1550 nm. These layers are made with epitaxial growth followed by planar processing. Clearly, the foregoing description is very general; the exact process and consistency of the multilayers and the overall device is manufacturer dependent (and proprietary).

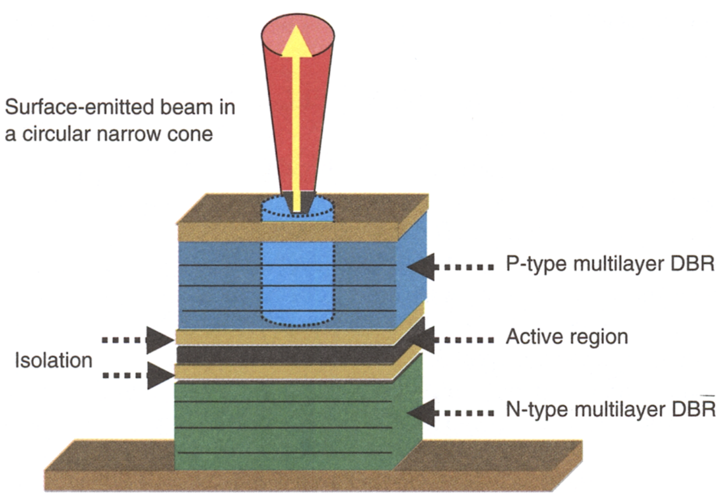

Figure 6.7 A simplified VCSEL structure.

The VCSEL structure is very compact and can easily incorporate MQWs, since the latter are made from the same elements and with a similar (multilayer) structure, thus increasing the efficiency of the laser device. VCSEL devices may be made to form a matrix of lasers, each at different wavelength. Such a device, combined with other optical components and detectors in a matrix configuration, opens the possibility of some interesting devices, such as space optical switches.

6.9 MONOLITHIC TUNABLE LASERS

Tunable lasers enable a device to emit light at specific selectable wavelengths. In wavelength division multiplexing (WDM), this represents a desirable feature if wavelength selectability is accomplished at a low cost. Tunable lasers have numerous other applications in medicine, chemistry, environmental monitoring, and agriculture.

Integrated monolithic multistage tunable lasers are devices in which the laser, filtering, amplification, and modulation functions are all integrated. The modulator is of the electroabsorption (EA) type, and filtering is typically of the Bragg type. However, because of their compactness, these devices may exhibit parasitic coupling that may degrade the quality of the wavelength produced. The primary two undesirable couplings are electrical cross-talk and optical cross-talk. Parasitic coupling is addressed with careful design. Other degradations that also depend on device design are chirp, linewidth broadening, wavelength shift due to temperature, and diminution of long-term stability.

There are two categories of monolithic tunable lasers: *single-frequency* and *multifrequency* lasers. Tunability may be accomplished electrically, mechanically (by trimming), or by controlling the temperature (a change of a few degrees is sufficient to tune the laser to another wavelength channel).

6.9.1 Single-Frequency Lasers

Single-frequency lasers are tuned by controlling the refractive index. In this case, the index of refraction in the lasing cavity is varied so that the peak transmissivity of the intracavity filter shifts to vary the wavelength. Changing the refractive index is equivalent to increasing the length of a free space cavity.

The DBR tunable lasers are in this category.

6.9.2 Multifrequency Lasers

Multifrequency lasers are classified as *integrated cavity lasers* or as *arrayed lasers. Integrated cavity lasers* have an integrated cavity that serves both as a filter and as a multiport optical power combiner (multiplexer). The laser is also integrated with optical amplifiers.

Arrayed lasers are integrated arrays of individually tuned frequency lasers. The outputs are combined to produce a range of desired frequencies. The distributed feedback (DFB) arrays are in this category. An array of DFB lasers may also be used as a wavelength-selectable device. In this case, several DFB lasers are monolithically integrated, each generating a different wavelength. Then, one of the DFBs is selected and generates the wavelength of interest. If each DFB has its own modulator, a multiwavelength source is generated.

6.10 OPTICAL COMB GENERATORS

An optical comb generator is a device that generates a predetermined range of $2K + 1$ distinct wavelengths with a predetermined spacing Ω when an angle modulated optical signal $Y(t)$ is applied, described by

$$Y(t) = A_S \cos(\omega t + m \sin \Omega t), \tag{6.8}$$

where A_S is the signal amplitude, ω is the optical frequency, m is the modulation index, and Ω is the modulation frequency. This relationship indicates that the power of the applied signal $Y(t)$ spreads across a spectrum of several frequencies that consist of the fundamental frequency and sidebands.

The total number of components depends on the value of m. For example, for $m = 3$ there are seven terms; one fundamental and three sidebands on each side.

The output spectrum of a comb is described by

$$S(f) = \Sigma A_k \delta(f - k\Omega),\ -K < k < K, \tag{6.9}$$

where A_k is the amplitude of the kth component and $\delta(f - k\Omega)$ is the frequency member of the comb represented by a delta function. Ideally, all A_k values should be identical; in reality, they are not, owing to an amplitude modulation (filtering) effect. Multifrequency tunable lasers are comb generators (see Figure 6.8).

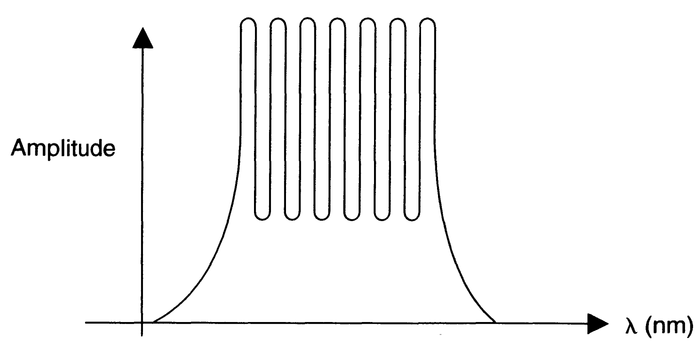

Figure 6.8 Comb generators have an output spectrum that looks like a comb.

6.11 CHIRPED-PULSE LASER SOURCES

The chirped-pulse wavelength division multiplexing (CPWDM) method is another category of lasers that generates many wavelengths. Consider a very narrow pulse (femtoseconds wide) coupled in a dispersive fiber. Dispersion causes the pulse to be broadened to nanoseconds while spreading the spectral frequency content of the light, similar to Fourier process, which generates many frequency components from an impulse: the narrower the impulse, the more frequency components. This method is known as "chirping" (as in bird chirping). Now, consider a mode-locked laser source that emits a sequence of ultrashort pulses. Each pulse generates a set of pulsed frequencies in the time–spectrum continuum; each pulse is referred to as a *slice.* Now, time division multiplexed data (via a fast modulator) modulate the bits of every slice, and thus each frequency channel is modulated with different data.

6.12 MULTIFREQUENCY CAVITY LASERS

Multifrequency cavity lasers (MFLs) are complex devices that consist of a K-input, N-output port ($K \times N$) waveguide grating router (WGR) that may be integrated with several multiplexed wavelengths at each input port, as well as optical amplifiers at each output port. A multifrequency laser has a very wide spectrum, a spectrum that covers, for example, the C-band. Multifrequency lasers, used in conjunction with other components, generate a set of individual frequencies or a comb of frequencies. The wide spectrum (multiwavelength) source is passed through a fiber that is connected to one of the input ports of a WGR. The WGR is a generalized Mach-Zehnder interferometer that consists of an array of N input waveguides, an array of N output waveguides, a waveguide grating, and two free space regions (Figure 6.9).

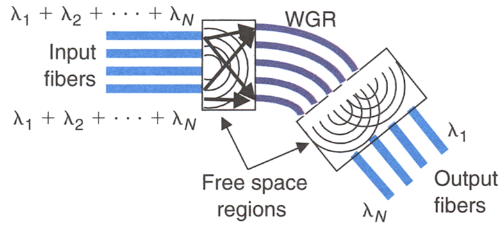

Figure 6.9 A waveguide grating router (WGR) is a generalized Mach–Zehnder interferometer.

An $N \times N$ WGR functions as follows. Optical signals consisting of many wave lengths at each input port are coupled via the first free space region into the wave guide grating. The waveguide grating consists of waveguides of different length and/or index of refraction. The optical path difference between neighboring waveguides ΔL causes a wavelength-dependent linear phase shift between them. It turns out that because of interference, light of a certain wavelength will couple to only one output port.

The number of ports N and the free spectral range (FSR) determine the optical channel spacing (CS)

$$\mathrm{CS} = \frac{\mathrm{FSR}}{N}, \tag{6.10}$$

where the FSR is determined by (n_g is the group index of refraction and λ is the wavelength):

$$\mathrm{FSR} = \frac{\lambda^2}{n_g \Delta L}. \tag{6.11}$$

However, the actual number of channels is constrained by the optical device technology (fiber type, resolution of transmitters and receivers, filter and amplifier characteristics), the maximum bit rate, and the optical power budget.

6.12.1 Advantages of WGRs

- Optical channel spacing is extremely accurate.
- There is low insertion loss.
- There is simultaneous operation of all wavelengths.
- WGRs can be tuned fast ($<$3 ns).
- WGRs are scalable ($N \times N$).
- Temperature variation shifts all wavelengths (entire comb), but CS remains the same.
- WGRs have broadcast capability.

6.12.2 Disadvantages of WGRs

- WGRs are not fiber based.
- They have a relatively large physical size.
- Proximity of integrated amplifiers causes electrical cross-talk to increase.
- As the number of channels increases, the optical channel spacing should be decreased, and thus, the size of the MFL increases, the intracavity loss increases, and device performance decreases.

6.13 MONOLITHIC DFB ARRAYS

To produce a range of desired wavelengths with small devices, DFB tuned laser arrays have been integrated in monolithic devices. In this arrangement, an independent filter, rather than a cavity with a waveguide grating, determines the wavelength of each individual DFB laser. All laser outputs are multiplexed and launched into the fiber.

The DFB laser, in a variation also known as electroabsorption modulated DFB laser (EML) is a device that potentially can be used as a low-cost, low-frequency chirp, and compact wavelength-selectable source. In addition to the array already discussed, widely tunable laser DFBs have been investigated. In this case, the tunable device is integrated with a semiconductor optical amplifier and an electroabsorption modulator.

6.13.1 Advantages of DFBs

- Integration yields small devices.
- Each DFB is modulated at very high speeds (short cavity) independently.
- Temperature variability is the same for all lasers in the device.

6.13.2 Disadvantages of DFBs

- Precise channel spacing because of variability of individual filters is difficult to obtain.
- Frequency shifts of lasers do not track each other and may drift into each other.
- Intrinsic losses, make integration of many channels difficult.
- DFBs require a fine period grating.
- Close proximity of integrated amplifiers increases electrical cross-talk.

6.14 MODULATORS

Optical modulators are integrated components designed to control the amount of continuous optical power transmitted in an optical waveguide. Thus, they are external modulators that are positioned in line with a CW laser source, as well as monolithically integrated with a laser source.

The semiconductor-type modulators (Figure 6.10) include the integrated Mach–Zehnder (M–Z), the electroabsorption MQW, and the electrorefraction modulator. The M–Z type consists of a Y-splitter junction, two phase modulators (typically made with InGaAsP), and a Y-combiner junction (Figure 6.10a). Thus, incoming optical power is split by the first Y-junction into two equal parts. One of the two parts is phase adjusted (by controlling the refractive index), and then the two parts recombine.

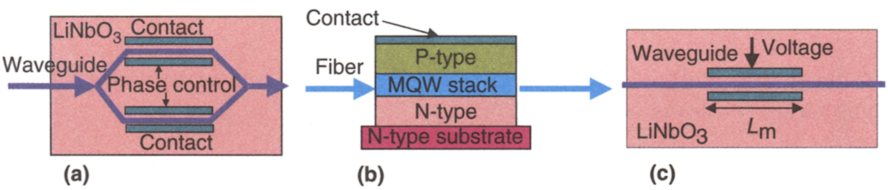

Figure 6.10 Principles of three different types of optical modulator: (a) Mach–Zehnder, (b) multiple quantum well (MQW), and (c) electrorefraction.

Based on the phase delay, light destructively or constructively interferes at the recombining Y-junction and an on or off signal is obtained at the output. These modulators actually function as on–off switches with the application of an on–off voltage.

MQW directional couplers operate on light absorption properties and are based on MQW semiconductor structures (Figure 6.10b). Light is absorbed when voltage is applied. Thus, electroabsorptive devices act as fast shutters and, when combined with DFB laser sources, form elegant integrated modulators.

The electrorefraction modulator directly controls the phase of an optical wave through it when a voltage is applied (Figure 6.10c).

Electroabsorption modulators are on–off optical devices. They display an almost logarithmic attenuation of optical power that depends on the voltage applied on them. They are sources of short optical pulses (and short duty cycle) and can generate bit rates in excess of 40 Gb/s. They exhibit modulation depths in excess of 45 dB. They are InGaAsP solid-state compact and stable devices and thus can easily be integrated with other optical devices (e.g., DFB lasers).

The major benefit of external modulators is that they have negligible chirp (phase jitter) compared with direct modulation. Chirp and fiber dispersion effects limit the transmission distance between source and detector. In addition, external modulators can modulate high optical power CW beams with depth greater than 20 dB.

As an optical (monochromatic) beam passes through a modulator, one of its properties changes: intensity, phase, frequency, or polarization.

The parameters that characterize the performance of optical modulators are:

- Modulation depth, η
- Bandwidth
- Insertion loss
- Degree of isolation
- Power

For **intensity modulators**, the *modulation depth* η is:

$$\eta = \frac{(I_0 - I)}{I_0}.$$

The *extinction ratio* is the maximum value of the ratio of η_{max} to η when the intensity of the transmitted beam is a minimum, I_{min}, and it is given by:

$$\eta_{max} = \eta(I_{min}).$$

For **phase modulators**, the *modulation depth* η is defined similarly, provided the intensity is related to phase: ($I = I(\phi)$).

For **frequency modulators**, an analogous figure of merit is used, namely, the maximum frequency deviation D_{max}, defined by:

$$D_{max} = \frac{|f_m - f_0|}{f_0},$$

where f_m is the maximum frequency shift of the carrier f_0.

The *degree of isolation*, in decibels, represents the maximum optical change produced by the modulator and is related to the extinction ratio [10 log(η)] or to the maximum frequency deviation (10 log D_{max}).

6.15 LASER MODULES

Laser modules are hermetically sealed packages that may contain several individual devices required to stabilize the frequency and power amplitude over a wide range of temperatures and over time (device aging). The components are as follows:

- A laser device (e.g., MQW, DFB), a Fabry–Perot etalon, or a Bragg filter (it may also be part of the laser device structure).
- A modulator device (internal to the laser or an external lithium niobate device).
- An internal optical isolator to suppress reflections of laser light at the interface (optical feedback) back into the laser device.
- A thermoelectric cooler (TEC) and a heat sink; the thermistor of the TEC monitors the temperature, which is controlled with a microprocessor acquisition circuit that adjusts the temperature to a constant level, typically 25°C.
- A photodiode (PIN or APD) that monitors the emission of laser light at the back face and controls the forward output optical power via an electronic circuit.
- A connectorized fiber pigtail that guides the laser output outside the hermetically sealed package to be coupled with the transmitting fiber; the pigtail may (or may not) be of the polarization-maintaining fiber (PMF) type.
- A semiconductor optical amplifier (SOA).

The actual internal structure of the laser module and its specifications vary with manufacturer and type, and according to the intended application.

In general, laser modules may operate in one of the wavelength ranges (e.g., about 1310 nm, or 1555 nm, etc.) and over the temperature range −40 to 65°C, at bit rates up to 10 Gb/s (or higher). They may have an optical power up to 40 mW or higher, and they require a single voltage (+5 V), or one voltage for the laser (+3.7 V), another for the modulator (depends on the type), and yet another for the thermoelectric heat pump (+5 V). The physical size of these modules, depending on type, is approximately $50 \times 15 \times 5$ mm^3; for larger assemblies the footprint may be approximately 120×100 mm^2. To avoid eye damage, laser users should not incur direct exposure to the laser beam.

6.16 SUPERCONTINUUM SOURCES: SPECTRUM SLICING

One technique for generating a number of wavelengths is based on a high-intensity light source and on the property of self-modulation in a highly nonlinear medium. The device, known as a supercontinuum generator, consists of a LiNb-based waveguide or a polarization-maintaining fiber (PMF) cascaded by a dispersion-shifted fiber (DSF) about 4 km long.

According to this technique, a continuous wave source enters a highly nonlinear medium, the supercontinuum generator, where the self-modulation phenomenon generates frequencies within the spectrum of the C-band. Subsequently, the supercontinuum of wavelengths (in the C-band) enters a wavelength demultiplexer (e.g., a grating). Now, each frequency that is obtained from the demultiplexer is individually modulated, and all modulated sources are multiplexed and coupled into one fiber.

EXERCISES

1. How many different types of light source are there?
2. To which type does a laser source belong?
3. Could an LED be classified as a diode device?
4. What is the effect of temperature on the stability of LED devices?
5. What fiber network applications are LEDs most suitable for?
6. Why must a laser cavity structure with a dielectric be precise in wavelength multiples?
7. What are the basic elements of a semiconductor laser?
8. A laser source needs to be modified with the minimum amount of chirping. What type of modulation should be used?
9. Name two different resonant cavity types used in monolithic semiconductor lasers.
10. What is the basic difference between a semiconductor QWL and a conventional semiconductor laser?
11. Name four advantages of the WGR devices.
12. EDFAs perform best in the 1350-nm range. True or false?