Chapter 33
Optical Communications

An important field of application of lasers is optical communications by means of glass fibers.

To transfer information over very large distances (e.g., around the world), radiation of a wavelength of 1.55 μm is most suitable by two reasons. First, glass fibers have the smallest loss of radiation in a wavelength band around 1.55 μm. Second, a glass fiber amplifier—the erbium-doped fiber amplifier—allows for amplification of laser radiation at 1.55 μm. A glass fiber with integrated light amplifier (installed every 100 km) can transport information over any distance on earth.

The transfer of optical waves over shorter distances (up to about 50 km) is possible with radiation at wavelengths around 1.32 μm. At this wavelength, the absorptivity of glass fibers is also small and the dispersion is zero (resulting in less distortion of optical pulses in comparison to pulses of 1.55 μm radiation). However, there is no efficient light amplifier available for 1.32 μm radiation.

In the past, the transfer rate increased more and more. The use of radiation at many wavelengths at the same time—corresponding to many frequency bands available for information transfer—and increase of the modulation bandwidth enhanced the transfer rate. For long-distance transfer of information via fiber-optic cable networks, a frequency band of about 5 THz is available; the width of the band corresponds to about 2.5% of an average frequency (about 200 THz) of radiation of the 1.55 μm band.

33.1 Principle of Optical Communications

The basis of optical communications is the guidance of light by means of optical fibers. The principle of optical communications is illustrated in Fig. 33.1. Light, coupled by means of a transmitter into a fiber, propagates through the fiber to a receiver. For long-distance transfer, the fiber contains laser amplifiers. The following components belong to an optical transfer system.
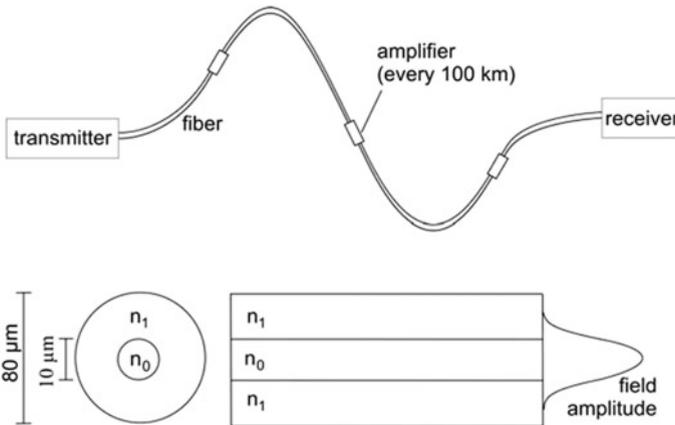
Fig. 33.1 Optical communications (*principle*) and glass fiber

- *Transmitter*. Laser + modulator + coupler.
- *Laser*. Quantum well laser, a heterostructure of $Ga_x In_{1-x} As_y P_{1-y}$ material on n-type or p-type InP, lattice matched for $y = 1.2x$. The laser wavelengths are 1.55 μm ($x = 0.42$) for long distance transmittance and 1.32 μm ($x = 0.27$) for transmittance up to about 50 km.
- *Receiver*. Photodetector + demodulator.

Of course, communication with free light waves is also possible. On earth, it is restricted because of damping of light in the atmosphere and because of the effort that is necessary for changing the propagation direction of light.
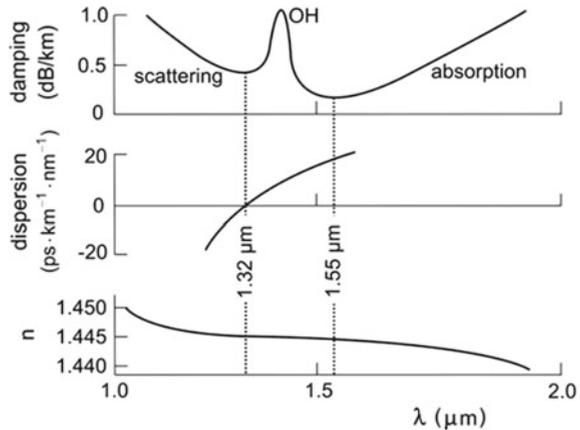
33.2   Glass Fiber

Glass fibers can be prepared with high accuracy from quartz glass. A glass fiber (Fig. 33.1) consists of two parts.

- *Core*. Diameter about 10 μm; SiO_2 doped with germanium; refractive index $n_0 = 1.52$.
- *Cladding (mantle)*. Diameter about 80 μm; SiO_2; $n_1 = 1.48$.

The basis of the guidance of light is the total reflection. The light is propagating in the 00 mode of a fiber (monomode fiber). The field distribution is Gaussian like. The amplitude of the field is large within the core and decreases exponentially in the mantle. Accordingly, a portion of the light is propagating in the core, another portion in the mantle. While a Gaussian beam in free space is always divergent, a Gaussian like beam in a fiber remains confined.

Fig. 33.2 Damping, dispersion and refractive index of light in a glass fiber

Light in a glass fiber experiences damping (Fig. 33.2, upper part). The damping has two minima at slightly different wavelengths.

- 1.32 μm; damping 0.4 dB/km.
- 1.55 μm; damping 0.2 dB/km.

Toward small wavelengths, the damping increases because of Rayleigh scattering. This is a consequence of small irregularities at the interface between core and mantle. Toward large wavelengths the damping increases due to absorption caused by lattice vibrations (phonons) in glass. OH impurities in glass are responsible for an absorption line near 1.4 μm. The OH concentration (5 ppm) in a glass fiber corresponds to 1 OH group per 2×10^8 SiO_2 molecules.

33.3 Pulse Distortion Due to Dispersion

A light pulse propagating in a fiber is damped and changes its shape. This is due to dispersion (Fig. 33.2, center). The dispersion is zero at 1.32 μm. It has a value of about 15 ps per km and nm at 1.55 μm. The dispersion relation of light in an isotropic medium (refractive index n) is

$$\omega = v_{ph}k = \frac{c}{n}k, \tag{33.1}$$

where ω is the angular frequency, v_{ph} the phase velocity, and k the wave vector. The refractive index of SiO_2 glass (Fig. 33.2, lower part) shows in the near infrared a weak decrease with increasing wavelength and a point of inflection at 1.32 μm. We can write the dispersion relation in the form

$$k = \frac{\omega}{c} n. \tag{33.2}$$

To determine the influence of dispersion of glass on the propagation of light pulses, we calculate the group velocity

$$v_g = \frac{d\omega}{dk} = \frac{1}{dk/d\omega} = \frac{c}{n + \omega dn/d\omega}. \tag{33.3}$$

Propagation of a pulse over a distance L takes the time

$$\tau_g = L/v_g. \tag{33.4}$$

A light pulse has a frequency width $d\omega$ (determined by the pulse duration). Because of dispersion, the relative difference of the time of flight of light of a frequency ω and a frequency $\omega + d\omega$ is

$$\begin{aligned} \beta_2 &= \frac{1}{L}\frac{d\tau_g}{d\omega} = \frac{d}{d\omega}\left(\frac{1}{g_g}\right) \\ &= \frac{d}{d\omega}\left(\frac{n}{c} + \frac{\omega}{c}\frac{dn}{d\omega}\right) = \frac{2}{c}\frac{dn}{d\omega} + \frac{\omega}{c}\frac{d^2n}{d\omega^2}. \end{aligned} \tag{33.5}$$

The first term of β_2 describes a delay of a pulse and the second term a distortion of the shape of the pulse. The unit of β_2 is $\text{s m}^{-1}\,\text{Hz}^{-1}$.

33.4   Erbium-Doped Fiber Amplifier

In a long distance fiber cable, an erbium-doped fiber amplifier (EDFA) compensates damping of radiation.

Light is amplified (Fig. 33.3) by stimulated transitions in Er^{3+} ions that are pumped with radiation of a semiconductor laser (wavelength 1,480 nm or 980 nm). The erbium-doped glass amplifier can amplify radiation in the range of 1,520–1,560 nm. The relative bandwidth ($\delta\nu/\nu \sim 2.6\%$) corresponds to a bandwidth $\delta\nu \sim 5\,\text{THz}$ at the frequency $\nu \sim 2 \times 10^{14}\,\text{Hz}$. Thus, the band available near 200 THz for optical communications has a width of about 5 THz. The mechanism of gain of radiation in an erbium fiber is discussed in Chap. 18; *see*, particularly, Fig. 18.1.

A fiber amplifier consists of an erbium-doped region of a long glass fiber cable. pump radiation of a semiconductor laser is coupled into a fiber via an optocoupler. An amplifier (length 30 m) has a gain factor of the order of 1,000 (gain 30 dB). In parallel to a a long-distance fiber cable, there is a current carrying cable delivering the electric energy necessary to operate the pump laser of the erbium-doped fiber amplifier.
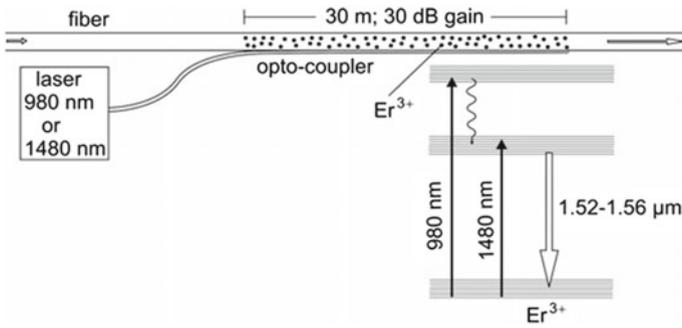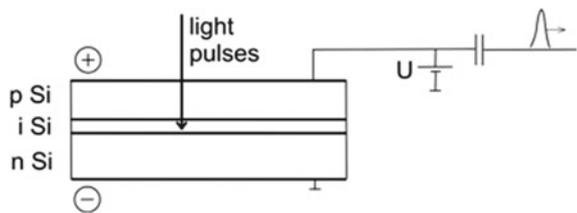
Fig. 33.3   Erbium-doped fiber amplifier (EDFA)

Fig. 33.4   Silicon pin photodiode

33.5   Detector

Photodiodes are suitable as detectors of radiation in optical communication systems. A silicon pin photodiode (Fig. 33.4) consists of a thin p-doped silicon layer, an intrinsic (1) silicon layer, and an n-doped silicon layer on an n-doped silicon substrate. A transparent metallic anode film on the p-doped silicon layer and a metal cathode on the backside of the substrate serve as metallic contacts. A light pulse traversing the anode film creates electron-hole pairs in the intrinsic layer. A static voltage across the photodiode accelerates electrons and holes, created by a light pulse, giving rise to an electric pulse that is registered electronically.

33.6   Transfer Rates

The transfer rates of large-distance communication systems increased permanently.

- Before 1996, a copper cable in the ocean reached a transfer rate of 280 Mbit/s (about 4,000 phone calls at the same time).
- 1996. An optical cable in the ocean (all-optical cable) reached 2.5 Gbit/s.
- Since 1999. Faster networks are in operation.

Transfer rates reached in the laboratory are:

- 1993. 10 Gbit/s. Limitation by the conversion of a light signal in an electric signal and vice versa. TDM, time division multiplexing.
- 2000. 1 Tbit/s; 16 channels (i.e., radiation at 16 wavelengths in parallel).
- 2001. 25 Tbit/s; 1,000 channels (=1,000 wavelengths in parallel); optical broadband fiber (DWDM, dense wavelength division multiplexing).

In comparison with copper cables (used in the ISDN, Integrated Services Digital Network; transfer rate 100 kHz) and coaxial cables (transfer rate 300 MHz), the glass fiber has a much larger bandwidth (5 THz). and allows therefore for a much larger transfer rate. A fiber with a transfer rate of 40 Gbit/s of light of a single frequency is presently the basis of the global network (i.e., the global system of mobile communication). Every year, the number of bytes transferred by the Internet doubles.

References [208–210, 276–282].

Problems

33.1 Estimate the electric power needed to maintain an optical fiber cable with 10 fibers that extends around the earth.