Optical Fibre Communications
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CHAPTER 1

Introduction to optical communications

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1.1 HISTORY AND METHODS OF OPTICAL COMMUNICATIONS

The transmission of information by means of light has a much longer history than electrical communications. At the end of the sixth century B.C. Aeschylus mentioned passing the news on of Troys downfall by fire signals via a long chain of relay stations from Asia Minor to Argos. In the second century B.C. Polybius described an arrangement by which the whole Greek alphabet could be transmitted by fire signals using a two-digit, five-level code.[1] To our knowledge this was the first optical communications link which allowed the transmission of messages not previously agreed upon. At the end of the eighteenth century A.D. the optical telegraph by Claude Chappe allowed the transmission of a signal over the 423 km distance from Paris to Strasbourg within a time of six minutes.[2] Chappe's telegraph used movable signal elements which were observed from the subsequent relay station by telescopes. In the middle of the nineteenth century, optical telegraphy was replaced by electrical telegraphy, which at this time allowed a faster signal transmission and required fewer skilled personnel.

However, although optical communication exhibited low practical importance in the next decades, its development proceeded. In 1880 Graham Bell reported the transmission of speech over a beam of light.[3] To modulate a beam of sunlight, Graham Bell used a diaphragm-mirror, against the back of which the speakers voice was directed. The beam was received upon a parabolic reflector, in the focus of which was placed a sensitive selenium photoresistor, connected with a battery and a telephone. Besides a number of other means for modulating a light beam, Bell had already proposed modulators based upon the Faraday effect and Kerr effect. In the first half of the twentieth century optical communications has been used only on a small-scale in mobile low-bandwidth and short-distance communication links.[4,5]

The situation changed rapidly with the invention of the laser. In 1958 Schawlow and Townes proposed the extension of the maser principle into the optical region;[6] in 1960 Maiman reported the generation of coherent light pulses by a ruby laser;[7]

and one year later Javan and coworkers realized a continuously operating helium–neon laser with a linewidth of only a few tens of kilohertz.[8] The availability of coherent light sources greatly stimulated the research into optical communications for the following reasons: the carrier frequencies between 10^{13} und 10^{15} Hz yield a high available bandwidth for signal transmission. To make use of this high available bandwidth it is necessary that the carrier bandwidth should not exceed the signal bandwidth by orders of magnitude. For example, if optical frequency multiplexing is used, the carrier wavelength spacing is determined by the carrier bandwidth if the carrier bandwidth is considerably larger than the signal bandwidth. Also in the case of time-division multiplexing over long transmission lines, a higher carrier bandwidth will result in a higher pulse spreading due to line dispersion. Since the relative bandwidth of incoherent light sources is usually of the order of a few per cent, the carrier bandwidth is higher by orders of magnitude than the signal bandwidth. The attempt to realize incoherent light sources with narrow spectral width is not the right way of solving these difficulties. On the one hand, the transmitted power would be greatly reduced by narrow-bandwidth optical filtering, and on the other hand, due to the fundamental differences in the statistical properties of coherent and incoherent light, a low optical carrier bandwidth also requires coherence in order to obtain a high signal-to-noise ratio.[9,10] We shall come back to this topic in Section 1.2.

A further advantage of laser light is its spatial coherence, which yields a lower beam divergence. This is advantageous not only for free-space communications but also for the coupling efficiency into optical beam waveguides. The reason is the following: an incoherent radiation source emits light in many radiation modes, the number of which is in the order of the ratio of the light-emitting area to the square of the light wavelength. As a result of this, the radiation source emits light in the hemisphere according to Lambert's cosine law. The reduction of the beam divergence is always connected with an inversely proportional increase of the beam diameter. The coherent laser light source, on the other hand, exhibits not only a low beam diameter but also a low beam divergence, especially if the laser oscillates in its fundamental transverse mode only. A further decrease of the beam divergence by optical means is also possible here. If a monomode optical beam waveguide is used in order to achieve maximum bandwidth, besides narrow spectral source width, transverse single-mode emission is also required in order to obtain a good coupling efficiency into the optical beam waveguide.

As is the case at radio frequencies, optical communications using wave propagation in free space as well as in light waveguides is possible. For atmospheric free-space optical transmission, several windows of high transparency exist in the visible-wavelength range and in some wavelength regions between 1 and 12 μm.[11–14] Unfortunately, the transmission loss is increased considerably by fog or precipitation. In addition, clear-weather changes in refractive index, caused by temperature gradients and turbulences in the air, degrade the transmission properties of atmospheric communication channels.[13,14] For all these regions, atmospheric optical transmission systems need a high transmitter power and a close repeater spacing. An interesting field of application of free-space optical communications are satellite links in outer space.[15] In satellite communications, the low beam divergence achievable with small antenna areas is advantageous.

Optical waveguides have been developed in order to avoid disturbances by the atmosphere. Whereas light waves in free space propagate in a straight line, waveguides in all practical cases are forced to follow a curved path as determined by the terrain contours and diverse physical obstacles. Miller has shown theoretically that for any electromagnetic waveguide having transverse planes in which the field is essentially equiphase, the minimum bending radius $R_{\min}$ and the maximum abrupt change $\delta_{\max}$ for a wavelength λ, a beam diameter $2a$, and for $\lambda < a$ are determined by[16]

$$R_{\min} = 2(a^3/\lambda^2) \tag{1.1}$$

$$\delta_{\max} = \tfrac{1}{2}(\lambda/a) \tag{1.2}$$

For a He–Ne-laser light beam with 0.6328 μm wavelength and a 1 mm beam diameter, $\delta_{\max} = 0.036°$ and $R_{\min} = 600$ m. It is clear that such a high minimum bending radius and low maximum abrupt angular change would impose severe restrictions on the path taken by an optical link and would also require high precision components and installation.

Lightwave guidance can be performed discontinuously or continuously. Discontinuous waveguides consist of a sequence of uniformly spaced irises or lenses (Figure 1.1).[17,18] An experimental light waveguide comprising 10 lenses within 1 km length and enclosing the light beam within a 10.2 mm aluminium pipe has been investigated by Goubeau and Christian.[18] In spite of the doubly-shielded light path, temperature-dependent inhomogeneities of the air caused beam deflections, making a remote lens adjustment necessary. A modified kind of lens waveguide is the tubular gas lens waveguide.[19] The gas lens is formed by blowing a cool gas through a warmer tube. The gas near the axis has a lower temperature and consequently a higher density and a higher refractive index than that near the walls. Therefore the tube acts as focusing lens. The use of gas lenses instead of glass lenses avoids reflection losses.

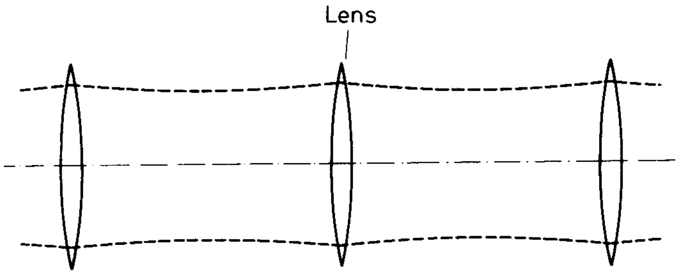

Figure 1.1 Lens waveguide

Early proposals for continuous light waveguides were hollow metallic and dielectric waveguides.[20,21] Since the attenuation of each mode in such waveguides is inversely proportional to the cube of the inner diameter, the inner diameter must not be too small. For a dielectric waveguide made of glass with a refractive index of 1.5, an inner diameter of 2 mm and a wavelength of 1 μm, Marcatili and Schmeltzer have calculated an attenuation of 1.85 dB/km for the EH_{11} mode, which doubled even for a bending radius of 10 km.[21] Although the hollow metallic waveguide turned out to be less sensitive to bending, the minimum radius is also in the order of tens of metres.

All the above concepts for optical waveguides suffered from the disadvantages of high precision requirements and consequently high manufacturing costs as well as high installation costs due to their large minimum curvatures. Their application only seemed to be appropriate for communication links with extremely high bandwidths. The breakthrough of guided optical communications came about with the development of the optical-fibre waveguides. The ability of a dielectric rod with a higher dielectric constant than its surrounding to guide electromagnetic waves had already been known for a long time. In 1910 Hondros and Debye solved Maxwell's equations for wave propagation in a circular dielectric rod.[22] First experimental investigations on radio-frequency electromagnetic wave propagation in a dielectric waveguide were published by Schriever in 1920.[23] Early applications of glass fibres in the optical region were to transport light or optical images across short distances.[24] Van Heel first suggested coating fibres with a layer of lower refractive index to ensure total reflection at the core-cladding interface and in this way to isolate optically individual fibres within a bundle from their neighbours.[25] The first suggestions to use fibres as a transmission medium for optical communications were made in 1966 by Kao and Hockham,[26] Werts,[27] and Boerner.[28] These authors proposed the use of glass fibres with a core of higher refractive index and a cladding

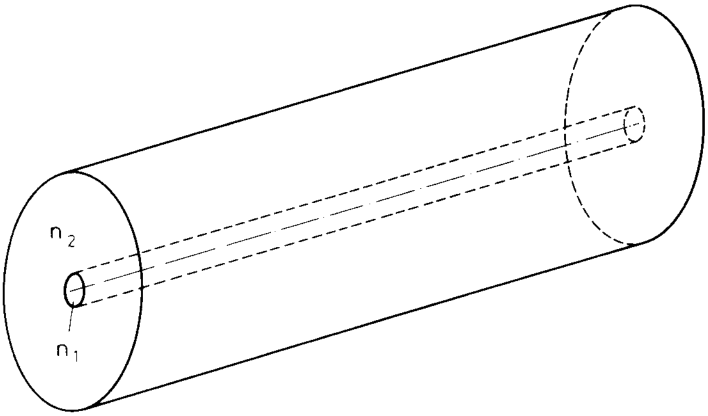

Figure 1.2. Fibre waveguide with a core of higher refractive index n_1 and a cladding of lower refractive index n_2

with lower refractive index (Figure 1.2). Such a fibre acts as an open optical waveguide. The electromagnetic field is guided only partially within the core region, whereas outside the core the electromagnetic field is evanescent in a direction normal to propagation. Among the electromagnetic field modes there is one, namely the HE_{11} which has no cutoff wavelength.[29] Only this HE_{11} mode can propagate in a fibre for wavelengths greater than the highest cutoff wavelength of the other modes. For a given core refractive index n_1, a cladding refractive index n_2 and the core diameter d, the vacuum cutoff wavelength λ_c for monomode operation is given by[29]

$$\lambda_c = \frac{\pi d}{2.405}(n_1^2 - n_2^2)^{1/2} \tag{1.3}$$

For $d = 5\ \mu m$, $n_1 = 1.5$ and n_2 smaller than n by 0.3%, for example, we obtain $\lambda_c = 0.758\ \mu m$. The bandwidth of an optical-fibre transmission link is limited by the fibre dispersion. The dispersion is usually measured by the broadening of a light pulse propagating across the fibre. In the monomode regime the dispersion is caused mainly by the wavelength dependence of the refractive index of the fibre material. The pulse dispersion depends on the wavelength and the spectral width of the optical source. For an optical source with a centre wavelength of 0.85 μm, single-mode fibres exhibit a pulse dispersion of 80 ps per kilometre fibre length and per nanometre spectral width of the optical source.[30] In the 1.27 μm wavelength region, monomode fibres exhibit a dispersion minimum[31] which is shifted into the wavelength region between 1.3 and 1.4 μm due to the geometric dispersion of the

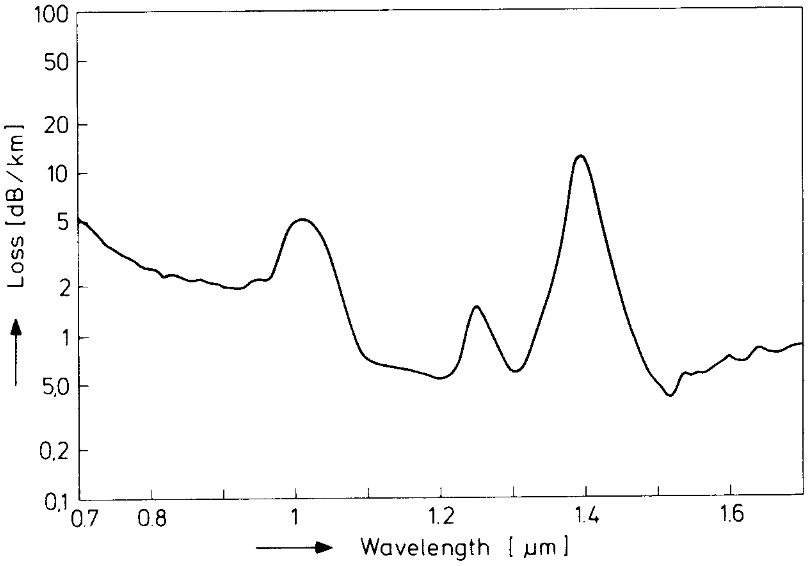

Figure 1.3. Loss spectrum of a single-mode silica fibre[33].

fibre guide.[32] With a germanium-doped silica glass fibre at the wavelength of 1.29 μm, a pulse broadening of only 4 ps nm^{-1} km^{-1} has already been measured.[33] There has been a great effort in the last ten years to reduce the fibre losses. When fibre attenuation values of only 20 dB/km were achieved with silica fibres by Kapron, Keck and Maurer in 1970, the barrier against the application of optical fibres in communication links was broken through.[34] At the beginning of 1978 the best measured attenuation values for silica-based monomode fibres were under 2 dB/km at 0.85 μm wavelength and under 0.5 dB/km at 1.3 μm wavelength.[33,35] Figure 1.3 shows the loss spectrum of a single-mode silica fibre. Compared with other light waveguides, optical fibres are inexpensive to manufacture. Since curvatures in the order of centimetres are allowed, the cabling of the fibres and the installation of fibre cables is as simple as that for electrical cables.

So far we have only referred to the monomode fibre waveguide. The monomode fibre exhibits minimum dispersion and therefore the highest transmission bandwidth. However, since optical fibres are a very inexpensive transmission medium, they also became interesting for lower-bandwidth applications. For these purposes fibre types which allow the propagation of many modes are of special interest. Figure 1.4 shows the three types of fibres mainly used in optical communications. Apart from the monomode fibre, these are the step-index multimode fibre and the graded-index multimode fibre. Whereas the monomode fibre exhibits core diameters in the order of 2 to 8 μm the step index multimode fibre has core diameters in the order of 50 μm. A large number of modes can propagate in such a fibre. Usually, many modes are excited by a light source at the fibre end, and due to fibre bendings mode conversion occurs along the fibre. The different group velocities of the modes yield a considerable broadening of transmitted light pulses, so that the

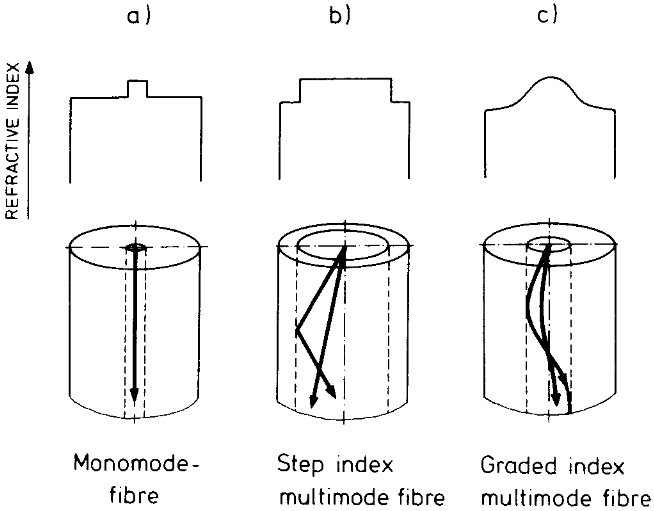

Figure 1.4. Tupes of fibres

bandwidth length product is in the order of 10 to 100 MHz km. For low-bandwidth optical links the multimode fibre has two advantages compared with the monomode fibre due to the higher core diameter. Firstly, the multimode fibre allows the use of incoherent optical sources, which could only be coupled with extremely low efficiency into monomode fibres. Secondly, the multimode fibre imposes lower tolerance requirements on fibre connectors. With a step-index multimode fibre consisting of a phosphosilicate core and a borosilicate cladding, an attenuation of 0.47 dB/km was achieved at 1.2 μm wavelength.[36]

The graded-index fibre exhibits no step-index change but a parabolic refractive index profile with its maximum in the fibre axis.[37,38] The graded index fibre also supports a great number of modes. Compared with the step-index multimode fibre it has the advantage of a low intermode dispersion. This is achieved by an appropriate choice of the refractive index profile which minimizes the group velocity difference of the different modes. This behaviour of graded-index multimode fibres can be easily understood using concepts of geometric optics. Figures 1.4b and 1.4c show the paths of light rays in the fibre cores. In the step-index fibre the light rays are straight within the core and are totally reflected at the core–cladding interface. Since the light velocity is constant within the core, rays intersecting a higher angle with the fibre axis consequently have a smaller velocity component in the fibre direction. In graded-index fibres the light rays follow curved paths. Rays running close to the fibre axis have a shorter path, but they pass through a region with a higher refractive index and therefore lower group velocity, compensating for the shorter path-lengths. Graded-index fibres use a parabolic index profile. The power law index for minimum dispersion depends on the fibre material. With a boron oxide–doped silica-graded index fibre with a power law index of 1.77 Cohen and coworkers[39] achieved an intermodal dispersion of only 170 ps km^{-1} and with a laser light source of 907.5 nm wavelength and approximately 2.5 nm spectral width, a total pulse spreading of 260 ps km^{-1}. An intermodal dispersion of only 150 ps km^{-1} was obtained with a germanium and boron oxide–doped silica fibre.[40] If a laser light source is also used with the best graded-index fibres, gigabit rates can be transmitted across distances of several kilometres.

Let us now turn again to the light sources for optical communications. In the last 20 years optical sources have also undergone a development similar to the optical transmission media from large and expensive devices to small and simply manufacturable ones. In the early stages of laser communication research, helium–neon, argon ion, CO_2 gas lasers and the neodymium doped YAG solid-state laser were interesting candidates for the optical sources in high-capacity optical communication links.[41] The helium–neon laser was the first highly developed CW laser and supplied output powers up to 100 mW at the 0.633 μm wavelength. The CO_2 laser has a high optical output power up into the kilowatt region and oscillates at the long wavelength of 10.6 μm. The long wavelength yields a low photon noise when cooled detectors are used. The CO_2 laser therefore is well suited for long-distance outer-space applications. For fibre-optic applications, gas lasers are in general too large, too expensive and suffer from low efficiency and the need for external modulation. Neodymium compound solid-state lasers are of some interest as sources for fibre-optic communications. When Danielmeyer and Weber[42] succeeded in 1972 in growing stoichiometric neodymium ultraphosphate crystals, a laser material with an optical gain 60 times higher than that of neodymium-doped YAG was available and the fabrication of small-dimension lasers became possible. Since then many stoichiometric neodymium laser materials with emission wavelengths between 1.0477 and 1.0641 μm, and in one case 1.32 μm, have been investigated.[43] In 1975 Burrus and Stone grew single-crystal neodymium-doped YAG fibres.[44] Using such a fibre 0.5 cm long and 80 μm in diameter, a room-temperature CW laser pumped from one end by a GaAs superluminescent diode was realized.[45] It has been estimated that with optimized mirrors an optical output of 1 mW could be achieved. Neodymium compound lasers have the advantages of a narrow spectral width and an emission wavelength close to the dispersion and attenuation minima of optical fibres. However, the need for an external pump and external modulation complicates their application.

Today the semiconductor injection laser is the most promising coherent light source for optical-fibre communications. Its main advantages are simple construction, small dimensions, high efficiency and direct modulation capability up into the GHz range. The semiconductor injection laser utilizes stimulated emission due to the recombination of carriers injected across a semiconductor *p–n* junction in forward direction. This principle was first suggested by Basov *et al.* in 1961.[46] Unfortunately, the germanium semiconductor material proposed by Basov is not suitable for this purpose, since as an indirect semiconductor it has too low an optical transition probability. Also in 1961, Bernard and Duraffourg derived the laser condition for semiconductor lasers.[47] Then, in 1962, lasing action was achieved with semiconductor injection lasers by three different research groups.[48–50] The first semiconductor injection lasers were made from gallium arsenide in the

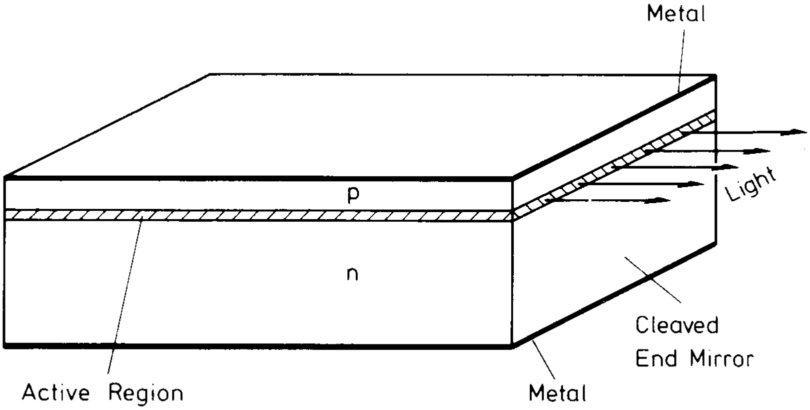

Figure 1.5. Semiconductor injection laser

form of a parallelepiped with a planar diffused *p–n* junction perpendicular to two opposite ends of the semiconductor crystal (Figure 1.5). If a current in forward direction is impressed, radiative carrier recombination occurs near the junction plane. The semiconductor material also exhibits optical gain for a sufficiently large injection current. Since the semiconductor crystal has a refractive index greater than that of air, the cleaved end faces of the crystal act as mirrors, so that the radiation is generated and amplified within a Fabry–Perot cavity. At a certain threshold level the round-trip gain exceeds the bulk and mirror losses for a certain mode and the laser starts to oscillate. The first injection lasers exhibited threshold current densities of up to 10^5 A cm^{-2} at 300 K so that room-temperature CW operation was impossible. In 1963, Kroemer suggested heterostructures in which the active region of the *p–n* junction was followed by a semiconductor layer with a higher band gap and a lower refractive index in order to provide better carrier and optical confinement, and hence to reduce the threshold current density.[51] In 1970 Hayashi and Panish built single-heterostructure lasers with room-temperature threshold current densities of 10^4 A cm^{-2} [52] and double-heterostructure lasers with a room-temperature threshold current density of only 1600 A cm^{-2}.[53,54] GaAs and $Ga_xAl_{1-x}As$ heterostructures fabricated by liquid-phase epitaxy were used in these cases. The narrow-gap active GaAs layer of the double heterostructure laser with a thickness considerably below 1 μm is bounded by two wide-gap layers of $Ga_xAl_{1-x}As$. The threshold current of injection lasers could be further reduced by the introduction of stripe geometry. Figure 1.6 shows the first stripe-geometry laser.[55] The active *p*–GaAs layer is sandwiched by two $Ga_xAl_{1-x}As$ layers. The stripe is etched in a thin SiO_2 layer deposited on the semiconductor crystal and forms a window for the metal contact. As a consequence, only the part of the active region under the stripe is pumped. With a laser length of 400 μm and a stripe width of 13 μm, Ripper and coworkers achieved threshold currents as low as 300 mA at room temperature.[55] Furthermore, with stripe-geometry lasers single

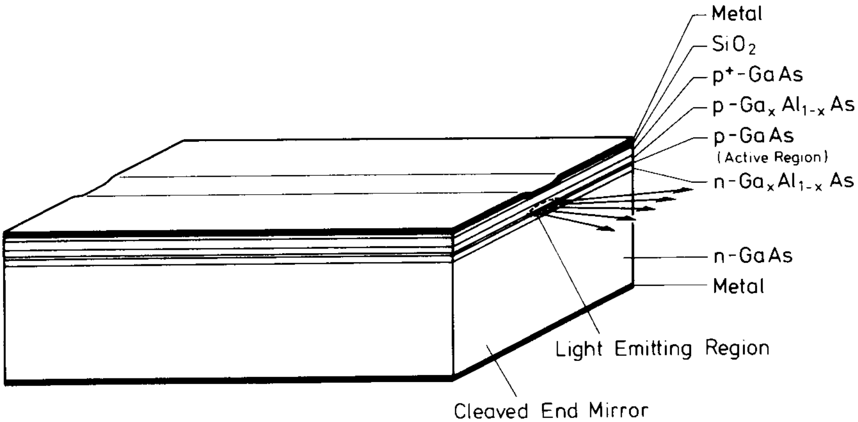

Figure 1.6. Stripe geometry double-heterostructure injection laser

tranverse-mode operation and single-frequency operation became feasible, whereas first injection lasers exhibited a broad multimode spectrum. Single transverse-mode operation is necessary for a good coupling efficiency into monomode fibres. The more severe demands of single-frequency operation must be met if a low pulse dispersion in single-mode fibres is required.

The first lasers for CW room-temperature operation exhibited lifetimes in the order of minutes only. Much technological effort has been undertaken to increase the laser lifetime to several 10^5 hours for CW room-temperature operation with light output powers of several milliwatts.[56] When CW lasers became available at the beginning of the 1970s, experimental investigation into the direct modulation capability at high modulation frequencies and high duty cycles started.[57] For high bit-rate digital communications from several 100 Mbit/s to the Gbit/s range, lasers must exhibit a narrow spectral bandwidth, no modulation distortions, and no high spectral broadening due to direct modulation.[58] Furthermore, the injection laser must not exhibit spontaneous fluctuations in the light intensity when it is biased above threshold.[59] The attempt to meet all these requirements led to the development of a variety of stripe-geometry structures, for example, the proton-bombarded,[60] the zinc-diffused stripe,[61] the stripe mesa,[62] the buried heterostructure,[63] the channelled substrate planar,[64] the transverse junction stripe[65] and the v-groove structure.[66] In some cases a direct modulation capability of up to 2 Gbit/s has been achieved.[58,63,64] Figure 1.7 shows the light output signal of a v-groove laser modulated with a 1 Gbit/s return-to-zero pcm signal.

The quarternary semiconductor material $Ga_xIn_{1-x}As_yP_{1-y}$ is now of growing interest for injection laser fabrication. Lasers with an emission wavelength in the 1.1 to 1.5 μm region can be realized with this material.[67] In this wavelength region one can take advantage of the dispersion and attenuation minima of optical fibres. The dynamic behaviour of $Ga_xIn_{1-x}As_yP_{1-y}$ injection lasers is identical to that of gallium arsenide injection lasers.[68,69]

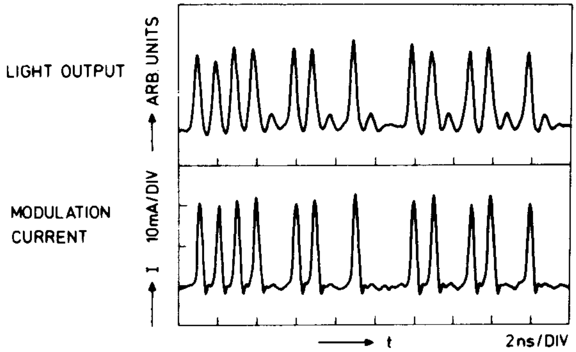

Figure 1.7. Light output signal and modulation current signal of a v-groove laser modulated with a 1 Gbit/s return-to-zero signal[66]

Apart from the semiconductor injection laser, another kind of semiconductor light emitting device, namely the light-emitting diode (LED), has gained importance as the light source for optical-fibre communications. In the LED, light is generated in the same way as in the laser diode, but since no optical feedback is introduced the LED produces incoherent light. The first gallium arsenide LED suitable for optical communications was made in 1962 by Keyes and Quist.[70] The spectral bandwidth of gallium arsenide LEDs is typically 300 Å i.e. higher by a factor of at least 20 than that of lasers. LEDs emit light into many spatial modes. Since the number of modes which can be coupled into a fibre approximately equals the number of modes which can propagate in the fibre, adequate coupling efficiency into the fibre can be achieved only if a multimode fibre is used. LEDs for fibre-optic communication must have a small light-emitting area of high radiance. Examples of such diodes are the Burrus diode[71] and the edge emitter diode.[72] The Burrus diode emits light from a small circular spot of approximately 50 μm diameter perpendicular to the junction plane, whereas the edge-emitter diode has a geometry similar to a stripe-contact laser and emits the light in the direction of the junction stripe. The superluminescent diode is a modified edge-emitter diode with a stripe long enough so that the spontaneously emitted light is considerably amplified by the stimulated processes, but it uses no optical feedback.[73] A lower spectral width (typically 100 Å) and a lower risetime (2 ns) can be achieved with superluminescent diodes than with ordinary LEDs.[74]

In the fibre-optic receiver, a photodetector with a sufficiently wide bandwidth and a high sensitivity is required. Semiconductor photodiodes meet these requirements for fibre-optic communications and have the additional advantages of small dimensions and simple construction.[75,76] The electron–hole pairs created in the depletion layer of a photodiode by absorption of photons give rise to a photocurrent. Since the photocurrent is proportional to the incident optical power, the photodiode acts as a quadratic detector. Silicon photodiodes are suitable for wavelengths up to 1 μm whereas germanium photodiodes can be used up to 1.5 μm. Figure 1.8a shows the cross section of a silicon PIN photodiode. The intrinsic region has a width in the order of 10 to 20 μm.

Avalanche photodiodes were first reported by Johnson in 1965[77] and allow a considerable signal amplification due to avalanche carrier multiplication when reverse biased between 100 and 300 V.[75–78] Figure 1.8b shows the cross section of a silicon avalanche photodiode. The electron–hole pairs are created in the drift region. Avalanche multiplication occurs in the depletion layer of the p–n^+ junction. Gain–bandwidth products greater than 200 GHz have been achieved with silicon avalanche photodiodes.[79] Unfortunately, due to the statistical nature of the avalanche process, the noise increases more strongly than by the square of the signal gain. If the signal amplification factor is M, the noise amplification equals M^{2+x}, where x depends on the diode. For silicon avalanche photodiodes, x usually equals between 0.2 and 0.5. An optimum gain for the photodiode can be determined by taking into account the noise of the following amplifier stage. The optimum design

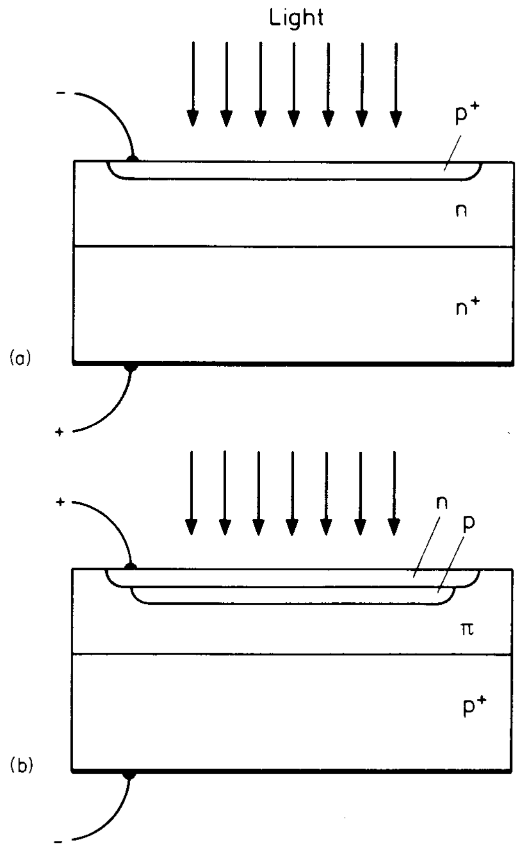

Figure 1.8. Cross sections of: (a) a silicon PIN photodiode; (b) a silicon avalanche photodiode

of the front-end amplifier has been studied by Personick.[80] Avalanche photodiodes have been developed using germanium[81] and InGaAsP[82,83] for the longer-wavelength region. However, germanium avalanche photodiodes suffer from a much higher dark current and a higher excess noise ($x \approx 1$) than silicon photodiodes. InGaAsP avalanche photodiodes are superior to germanium devices but at present are not competitive with silicon avalanche photodiodes. Therefore for the longer-wavelength region (1.1–1.3 μm), a combination of a PIN photodiode with a gallium arsenide field-effect transistor seems to be advantageous.[84] Since photodiodes are quadratic detectors, optical heterodyning to improve the detection sensitivity is possible in principle.[75] However, the spectral width and frequency stability of semiconductor injection lasers are not sufficient to use this method.[58]

Fibre-optic communication links exhibit a number of advantages compared with conventional cable transmission links. The bandwidth and repeater separation are higher than with coaxial cables. Furthermore, fibres are immune to inductive interference, and exhibit no crosstalk. Fibre cables also have a smaller diameter and a lower weight than coaxial cables.

In fibre-optic communications, analog as well as digital modulation is possible. However, for analog modulation a higher signal-to-noise ratio at the receiver is required and the linearity of injection lasers decreases at higher modulation frequencies.[58] For these reasons, analog links are limited to lower bandwidths and lower distances than digital links.

Figure 1.9 shows the block diagram of a typical digital fibre-optic link. The laser driver directly modulates the injection laser with the pcm signal. The APD is followed by the front-end amplifier, a filter for linear signal processing and noise bandwidth reduction, a nonlinear signal processing circuit and phase lock loop for clock extraction and the baseline regenerator and decision detector for signal regeneration.[85] Table 1.1 gives the data of some fibre-optic digital transmission experiments. The possibility of transmitting gigabit rates over fibre links has also stimulated the development of gigabit electronic circuits, necessary for transmitters and receivers.[87,96,97] For low-capacity, short-distance digital fibre-optic links with data rates up to 15 Mbit/s the electronic circuits for the transmitter as well as for the receiver have been monolithically integrated, each on a single chip.[98]

In future, fibre-optic links will find application in telephone networks. In a study by the British Post Office, the economic aspects of fibre-optic links for junction networks with bit rates of 2, 8 and 34 Mbit/s and trunk networks with 140, 280 and 565 Mbit/s were investigated.[99] As a result, the bit rate of 140 Mbit/s would most likely find application for trunk networks, followed by 8.448 Mbit/s (and 2.048 Mbit/s) for junction networks. Fibre-optic links for medium bit rates of

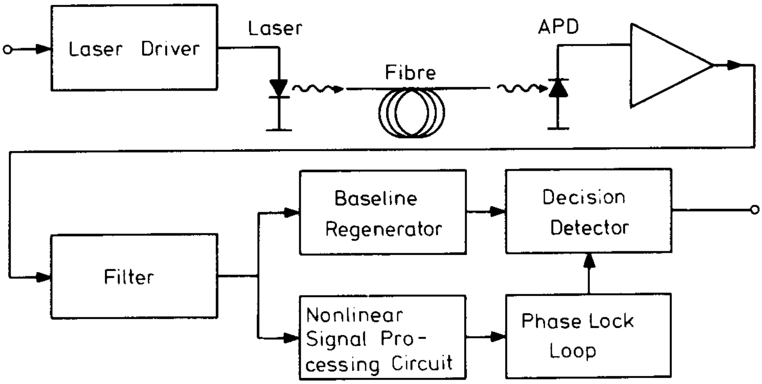

Figure 1.9. Block diagram of a digital fibre-optic link

Table 1.1 *Experimental digital fibre-optic transmission links*

Bit rate	Optical wavelength	Light source	Fibre	Detector	Power at the receiver for error rate 10^{-9}	Reference
10 Mbit/s	0.82 μm	GaAs-LED	6 km graded index	Si-APD	– 63.5 dBm	86
10 Mbit/s	0.85 μm	GaAs/GaAlAs-LD	13 km graded index	Si-APD	– 63 dBm	
32 Mbit/s	1.27 μm	InGaAsP/InP-LD	53.3 km graded index	Ge-APD	– 43.1 dBm	87
50 Mbit/s	0.85 μm	GaAs-LED or		Si-PIN-diode	– 41.5 dBm	88
50 Mbit/s	0.85 μm	GaAs/GaAlAs-LD		Si-APD	– 56.6 dBm	
100 Mbit/s	0.83 μm	GaAs/GaAlAs-LD	12 km graded index	Si-APD	– 50 dBm	89
400 Mbit/s	0.83 μm	GaAs/GaAlAs-LD	8 km graded index	Si-APD	– 38 dBm	
159 Mbit/s	0.85 μm	GaAs/GaAlAs-LD	6 km graded index	Si-APD	– 47 dBm	86
159 Mbit/s	0.85 μm	GaAs/GaAlAs-LD	8 km graded index	Si-APD	– 44 dBm	
400 Mbit/s	0.85 μm	GaAs/GaAlAs-LD	5.9 km single mode	Si-APD	– 38 dBm	90
800 Mbit/s	0.85 μm	GaAs/GaAlAs-LD	7.3 km single mode	Si-APD	– 35.5 dBm	91
800 Mbit/s	1.05 μm	$LiNdP_4O_{12}$-laser $LiNbO_3$-modulator	0.8 km single mode	Ge-APD	– 32 dBm	92
1 Gbit/s	0.83 μm	GaAs/GaAlAs-LD	1.6 km single mode	Si-APD	– 30.8 dBm	85,93
1.12 Gbit/s	0.813 μm	GaAs/GaAlAs-LD	3 km graded index	Si-APD		94
100 Mbit/s	1.293 μm	GaInAsP/InP-LD	11 km single mode	Ge-APD	– 39.9 dBm	95
400 Mbit/s	1.293 μm	GaInAsP/InP-LD	11 km single mode	Ge-APD	– 36 dBm	
800 Mbit/s	1.293 μm	GaInAsP/InP-LD	11 km single mode	Ge-APD	– 33.3 dBm	
1.2 Gbit/s	1.293 μm	GaInAsP/InP-LD	11 km single mode	Ge-APD	– 29.1 dBm	

LD laser diode
LED light emitting diode

8 to 280 Mbit/s are already sufficiently developed and will soon be able to compete economically with coaxial cables. A Japanese study by the Nippon Telegraph and Telephone Public Corporation also comes to the conclusion that as a first step 32 and 100 Mbit/s digital fibre-optic links using graded-index fibres will be introduced for short- and medium-haul trunks with heavy traffic.[100] Large-capacity, long-haul digital transmission systems, for example at 400 Mbit/s and using graded-index or monomode fibres, will follow.

Field trials have been performed in order to evaluate lightwave technology and to test cabling techniques, splicing techniques and fibre-optic equipment under field conditions. A 44.7 Mbit/s fibre-optic digital transmission system was put into operation by the Western Electric and Bell Laboratories in Atlanta in 1976.[101] Similar field trials are being performed in England at 8 and 140 Mbit/s by the British Post Office[86] and in Berlin, Germany, at 34 Mbit/s by the Deutsche Bundespost.[102,103]

Besides the introduction of fibre-optic links in existing telephone networks plans exist also for fibre-optic digital wide-band networks with a full integration of data, voice, video telephone, and broadcasting services including radio and television. A model of such an integrated network, comprising fibre-optic links from 140 to 560 Mbit/s, is now being built in the Heinrich Hertz Institute in Berlin.[104]

In the near future, fibre-optic analog systems will find application in radio and television broadcast distribution systems. In analog systems the subscriber terminals are simple and inexpensive. Since there are problems at present with the linearity of optical sources, analog systems operate at low bandwidths and over short distances. In the Japanese Hi–OVIS project an individual fibre is used for every television channel. The subscriber is connected to the network by two fibres (one for upstream and one for downstream video transmission).[105] In a Canadian project, two television channels and one audio channel are transmitted over a single fibre by analog intensity modulation with frequency-division multiplexed signal. The programmes can be selected via a return line.[106]

A further application for fibre-optic communication links is for high-reliability information transmission within electric power systems.[107] The insensitivity of optical links to electromagnetic interferences in this case is advantageous. For the same reason, optical fibres are also of interest for inter-module and inter-system wiring in electronic systems. In complex electronic circuits, ground loops can be avoided by the use of fibre links. For lower bit rates, monolithic integrated receiver and transmitter modules can be mounted directly on printed-circuit boards.[98] A data bus, that is a single transmission line carrying a multiplexed signal stream fed into the line by different transmitters and distributed over different receivers, can also be realized with fibre optics.[108–110] Coupling of the optical transmitters and receivers to the fibre can be performed by optical star couplers[110] or optical T-couplers.[111] Transparent photodiodes can be inserted into the transmission path to tap off a signal from a fibre.[112]

1.2 PHYSICAL ASPECTS OF OPTICAL COMMUNICATIONS

Electromagnetic radiation in the optical waveband differs from the electromagnetic radiation in the radio-frequency band not only in frequency but also in its statistical properties. The reason for this is that the quantum nature of the electromagnetic radiation plays an important role in the optical region. The information carried by a light wave is in general limited by quantum noise and not by thermal noise. In this section, therefore, we shall briefly discuss the implications of the statistical properties of coherent and incoherent radiation as carriers of information.

When Planck derived his formula for black-body radiation in 1900 he assumed that only integer multiples of discrete energy quanta can be exchanged when radiation and matter interact.[113] The energy quantum ϵ is related to the radiation frequency f by

$$\epsilon = hf \tag{1.4}$$

where h is Planck's constant. Using heuristic arguments Einstein suggested in 1905 that radiation really consists of independent energy quanta.[114] By 1927, the development of modern quantum theory was largely completed. In quantum theory the concept of quanta includes radiation as well as matter. Although quantum theory cannot be explained on the basis of classical physics, analogies to classical physics are helpful in order to develop a clear concept of the phenonoma. For example, an electromagnetic wave confined in a resonator can exhibit discrete frequency values only. This quantization of frequency values is a classical phenomenon. Now in quantum theory the electromagnetic field undergoes a second quantization, namely the quantization of the energy in each mode. Each resonator mode is occupied by a discrete number of radiation quanta, called photons, having an energy ϵ according to Equation 1.4.[115] Matter, on the other hand, also exhibits wave properties according to quantum theory. If a particle is spatially bounded, the matter-wave assigned to it can also have discrete frequency values only, and therefore, according to Equation 1.4, only discrete energy values are possible. To sum up, it can be said that the first quantization, i.e. the quantization of frequency and energy values, is the contribution from the wave picture to the quantum picture whereas the second quantization, i.e. the particle quantization of wave fields, is the contribution from the particle picture to the quantum picture of physics.

The quantum behaviour of radiation must be taken into consideration when $hf > kT$, since in this case the quantum fluctuations dominate over the thermal fluctuations. For a vacuum wavelength of 0.85 μm for example, $hf/kT = 56.5$ at $T = 300$ K, whereas in the radio-frequency region at a wavelength of 3 cm we obtain $hf/kT = 1.6 \times 10^{-3}$. The detection of light by a photodiode is a discrete process since the creation of an electron–hole pair is effected by the absorption of a photon. If I is the light intensity incident on the photodiode, and η is the quantum efficiency (i.e. is the ratio of the number of generated electron–hole pairs to the number of incident photons), then within a period T the average number of electron–hole pairs $\langle n \rangle$ generated by the incident light is given by

$$\langle n \rangle = \frac{\eta I T}{hf} \tag{1.5}$$

The number of photons detected in a certain period of time is discrete, whereas the light intensity is a continuous quantity. According to quantum theory, the light intensity is a measure for the probability of detecting a photon within a small interval of time. Now let us consider a light beam of constant intensity incident on the photodiode. We would expect a constant photon-detection probability for such a light beam. Since no interaction between photons occurs due to the linearity of the electromagnetic wave equation, the detection probability for a photon is statistically independent of the number of photons previously detected. We would therefore expect that the probability $p(n)$ of detecting n photons in a time T obeys the Poisson distribution[116]

$$p(n) = \frac{\langle n \rangle^n \exp(-\langle n \rangle)}{n!} \tag{1.6}$$

Figures 1.10a and 1.10b show the Poisson distributions for $\langle n \rangle = 10$ and $\langle n \rangle = 1000$. The analogue to the classical electromagnetic sine wave in quantum theory is the single-mode coherent state of the light wave.[117,118] From Glauber's theory of optical coherence it follows that the photon-detection process obeys Poisson statistics for a monochromatic coherent light wave and an arbitrary counting interval. The fluctuations in a light wave of constant intensity are called 'particle fluctuations'. The Poisson distribution exhibits the mean-square deviation

$$\delta \overline{n^2} \equiv \langle n^2 \rangle - \langle n \rangle^2 = \langle n \rangle \tag{1.7}$$

Since the particle fluctuation is proportional to the square root of the light intensity, we would expect the signal-to-noise ratio caused by the particle fluctuations to be inversely proportional to the light intensity.

Incoherent light is emitted by independent atoms and there is no phase correlation between the emission processes. Incoherent light is the optical analogue to noise in the radio-frequency band; like noise, incoherent light has an exponential intensity distribution

$$p(I(t)) = \frac{1}{\langle I \rangle} \exp(-I(t)/\langle I \rangle) \tag{1.8}$$

where $I(t)$ is the instantaneous intensity and $\langle I \rangle$ the average intensity.[118,119] By instantaneous intensity we mean the light intensity averaged over only a few cycles of the light oscillations. Averaging the Poisson distribution over the distribution $p(I(t))$ yields

$$p(n) = \frac{1}{\langle I \rangle} \int \exp\left(-\frac{I}{\langle I \rangle}\right) \frac{\left(\frac{\eta I T^{n}}{hf}\right) \exp\left(-\frac{\eta I T}{hf}\right)}{n!} \, \mathrm{d}I = \frac{\langle n \rangle^n}{(1 + \langle n \rangle)^{n+1}} \tag{1.9}$$

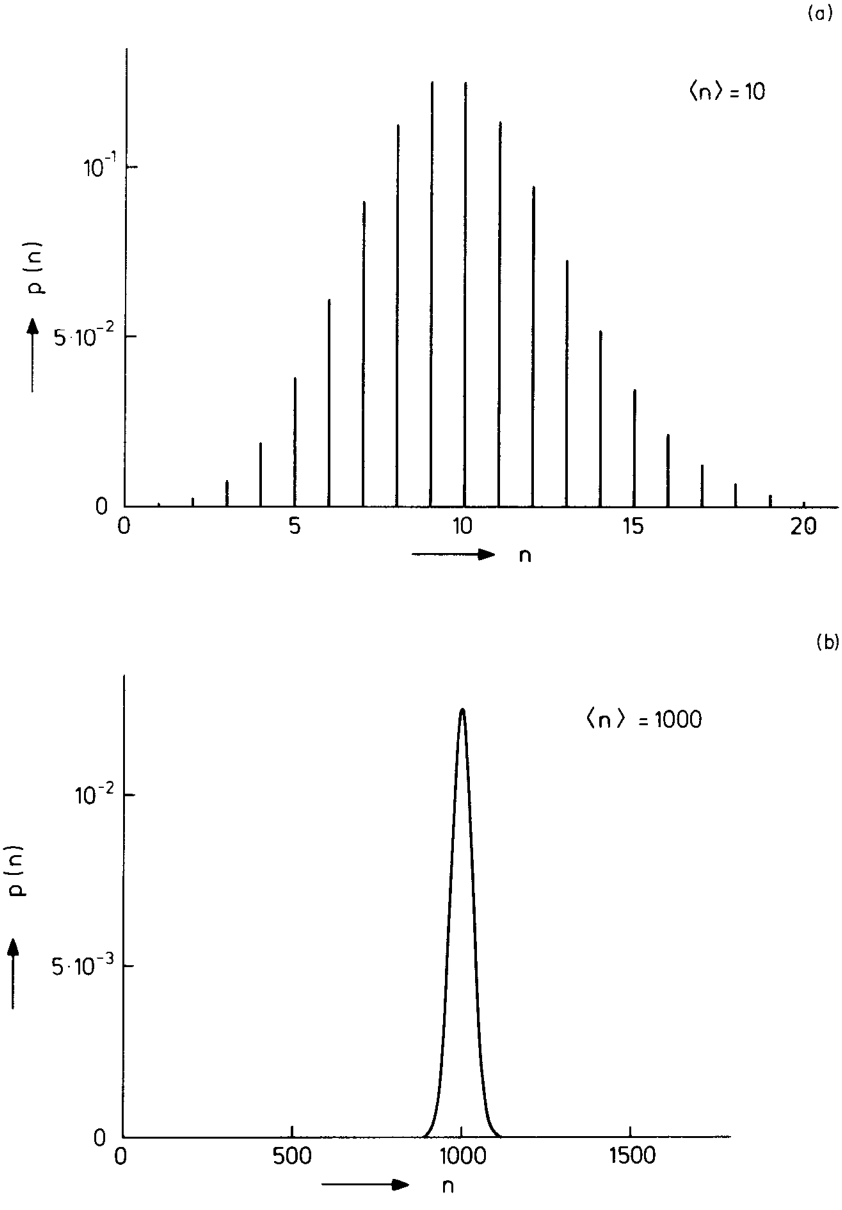

Figure 1.10. Poisson distributions $p(n)$ for: (a) $\langle n \rangle = 10$; (b) $\langle n \rangle = 1000$

where we have used Equations 1.5, 1.6 and 1.8. This probability distribution is identical with the probability distribution for the Bose–Einstein distribution for thermal light. The corresponding mean-square deviation is

$$\delta\overline{n^2} = \langle n\rangle + \langle n\rangle^2 \tag{1.10}$$

The instantaneous fluctuations of incoherent light are proportional to the light intensity and are of the same magnitude. Figure 1.11 shows the photon-count probability distributions for incoherent light for $\langle n\rangle = 10$ and $\langle n\rangle = 1000$. However, if the light intensity is averaged over a certain interval of time, the fluctuations of this averaged intensity are smaller than the fluctuations of the instantaneous intensity. This can be compared with the measurement of Gaussian noise intensity

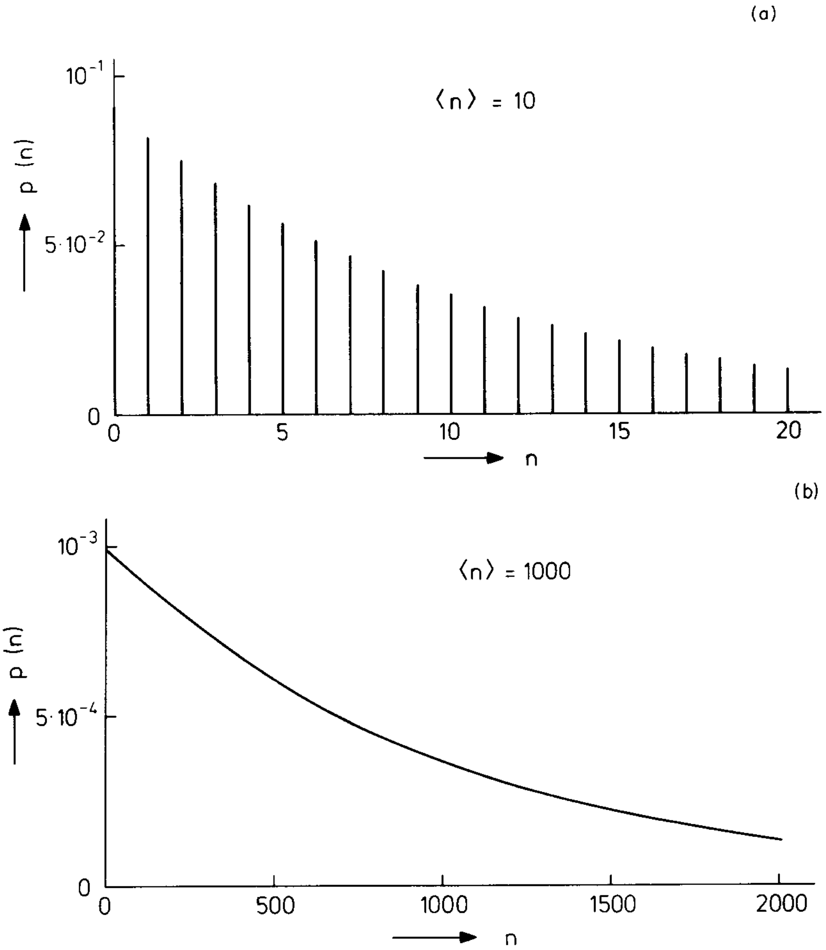

Figure 1.11. Probability distributions $p(n)$ for the instantaneous fluctuations of incoherent light for: (a) $\langle n\rangle = 10$; (b) $\langle n\rangle = 1000$

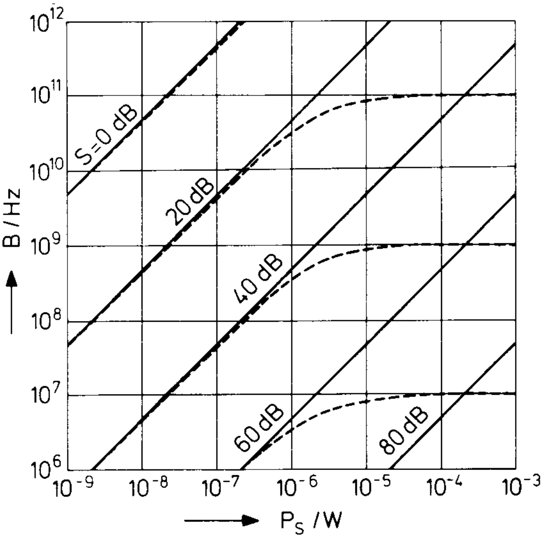

Figure 1.12. Achievable signal bandwidth B as a function of the signal power P_S for a given signal-to-noise ratio S. The solid line represents coherent light, and the dashed line incoherent light[10]

in the radio-frequency band. In addition, the fluctuations decrease with increasing averaging time of the square-law detector. The determining factor for the reduction of the fluctuations is the ratio of the coherence time τ_c of the light wave to the time of observation T. The coherence time is given by $\tau_c = 1/B$ where B is the bandwidth of the incoherent light wave. The observation time T corresponds to half of the inverse post detection bandwidth. For $\tau_c \ll T$ the mean-square deviation of the photon-count statistics is given by[118,119]

$$\delta \overline{n^2} = \langle n \rangle + \frac{\tau_c}{T} \langle n \rangle^2 \tag{1.11}$$

Thus incoherent light is appropriate as a carrier for optical communications only if the signal bandwidth is lower by orders of magnitude than the optical carrier bandwidth. Figure 1.12 shows the achievable signal bandwidth B as a function of the signal power P_S for a given signal-to-noise ratio S using coherent and incoherent light sources, as calculated by Grau.[10] Optical communication theory is treated in great detail in the books by Helstrom[120] and by Saleh.[121]

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