The Physical Fundamentals of Electro-Optics

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By

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CONTENTS

PREFACE

This book is intended to appeal to any practicing optical scientist and optical engineer who is concerned with the design, operation, and service of wired (fiberoptic) and wireless optical systems for resolving both the direct and the inverse problems of optical communication and optical location, namely of LIDAR. It will be very useful for students of all three degree levels, B.Sc., M.Sc., and Ph.D., who are concerned with the performance of mathematical algorithms, theoretical and applied models, as well as with the design, construction, and servicing of different optical devices: from various kinds of laser, photodetectors, light emitters and diodes, and optical amplifiers, wired waveguide optical structures, such as fiberoptic structures – 2D and 3D – with applications in wireless (atmospheric) networks, to LIDAR applications.

It should be mentioned that during the last 20–30 years a lot of optical elements, devices, and systems have been developed and constructed to satisfy the continually increasing demands of modern optical engineering and photonics for wired and wireless communications and LIDAR applications, including wide spectra – visual, infrared (IR) ultraviolet (UV) – sensors, devices, and systems. And, if for wireless (atmospheric) communication systems numerous excellent monographs have been published (see bibliography in Refs. [1-4]), the role of fiberoptic communication has been weakly illuminated. Moreover, the foundational books regarding photonics, physical aspects of laser and optical detectors operation, and photodiodes were published twenty to thirty years ago and paid attention only to some specific fields of wide spectra optical physics applications [5–8], accounting mostly either for a wide description of solid materials, such as dielectrics and semiconductors and their role in different optical sources and detectors operation, or fiberoptic communication, ignoring basic aspects of such elements as optical emitters (lasers) and detectors. During recent decades, many articles about all of these aspects have been published, including articles by the authors of this book, but general views on the problems of fiberoptic communication and lasers and detectors as basic terminals of any wireless and wired optical communication system or network were absent. Moreover, even such books and papers that were recently published mostly paid attention to aspects of signal coding and decoding and signal modulation, and less so the physical layers of devices, transmitters, and receivers of optical information [9–11].

We created this book to bring together all layers, where the first "layer" deals with a wide spectrum of electronic devices and circuits, which needs a careful and very transparent explanation of the physical processes occurring in the basic elements of optical emitters; lasers, detectors of optical radiation, various amplifiers, and so forth. The second "layer" illuminated in our book regards the presentation of optical signals in the channels and elements of their modulation during signal processing of the information passing through fiberoptic and wireless channels. The last "layer" deals with the physical nature of all kinds of noise occurring in each element of wired and wireless communication links – from the light emitter consisting of optical lasers to detectors consisting of laser and photodiodes. To unify all these "layers" and to create a "bridge" between them, it is important to introduce an additional layer, which the authors call the "physical and mathematical layer." Therefore all aspects described in this book regarding electro-optic engineering start from the physical explanation of the matter and then, by entering into other engineering problems of these three "layers" mentioned above, where each engineering aspect is accompanied by corresponding examples, give the reader the chance to use the obtained information for application in the performance and design of modern devices and systems for optical communication and optical location (LIDAR) applications.

At the same time, the book does not enter into technical details of how to produce different kinds of lasers, emitters, diodes, amplifiers, and optical waveguides, nor how to design different kinds of electronic devices based on semiconducting materials, assuming that for the reader it is more important to obtain fundamental knowledge about all above-mentioned elements of electro-optical engineering based on the common and joint physical "layers" on whole spectra of these elements, without entering into individual technical details and schemes.

The main goal of this book is to illuminate those questions and aspects of modern electro-optical engineering and optical physics, which were only partly illuminated in the existing literature. The authors enjoyed sharing their knowledge of teaching undergraduate and postgraduate students the physical fundamentals of classical and applied optics and photonics, optical emitters and detectors fundamentals, different aspects of wired (fiber optic) and wireless engineering, and fundamentals in optical waves propagation in fiberoptic 2-D and 3-D structures.

The book comprises ten chapters. Chapter 1 presents an introduction to the subjects that will be discussed and explained in chapters 2 to 10. It gives the reader information on optical spectra, from UV to IR, as a part of the full electromagnetic spectra, with a general explanation of the similarity of optical and radio waves. This fundamental similarity of radio and optical waves allows Chapter 2 to present all electromagnetic aspects of optical wave propagation via the general laws of Maxwell, of optical waves via plane electromagnetic waves, their propagation in free space, the intersection between two media, and finally, in various kinds of media – from dielectric to conductive. In Chapter 3, the main laws of classical and quantum physics based on corpuscular theory and on wave-corpuscular dualism are discussed using a simple explanation of the subject with clearly presented illustrations. In this manner, the structure of a simple atom, molecules, and crystals are described based on elements of quantum mechanics and wave theory in such a manner so as not to complicate the text of the book with mathematical descriptions of differential equations and integral presentation of the basic characteristics and functions describing each element's own structure. Then, Chapter 4 describes the basic physical principles of photonics, optical emitters, and laser operation based on the quantum presentation of their structure via linearly distributed discrete spectra of each element, emitter, or detector, and based on the interaction between holes and electrons inside various kinds of semiconductors as materials of such optical elements. In Chapter 5, laser diodes (LDs), *p-n-* and *p-i-n*-type photodiodes, and the avalanche photodiode (APD) are described, acting as emitted sources (e.g., lasers) or receiving detectors, which have found importance in electronics, photonics, and in optoelectronic diodes, as well as in solar cells. Their operational parameters and characteristics were described in a unified manner based on the physical knowledge illustrated in Chapters 3 and 4. Chapters 3 and 5 are filled with corresponding examples to aid the reader in understanding the matter and using the obtained knowledge in practice.

In Chapter 6, different types of noise occurring in light sources (lasers) and detectors (diodes), as the initial and the later terminals of any optical communication link, whether wired (fiber optic) or wireless (atmospheric), are described in a unified manner. Chapter 7 explains the principles of operation of optical amplifiers based on various kinds of emission – stimulated and spontaneous – which compete with absorption in any semiconducting material. It is shown what type of emission gives the main impact in terms of noise and plays a positive role in the amplification of optical signals with data transmission along the link. An example of an optical amplifier based on an Erbium fiberoptic amplifier is fully described, with estimations of its full noise interference via the corresponding examples having practical meaning. In Chapter 8, types of optical signals –

continuous and discrete – are fully described with their mathematical explanation for practical applications. Chapter 9 deals with the types of modulation, analog and discrete, most practically used in optical communications. Here, more precisely, is given the relationship between the spectral presentation of analog signals after amplitude and frequency modulation to show the reader advantages of angular-frequency and phase modulation with respect to amplitude. At the end of this chapter, the corresponding examples are shown to prove these advantages. In Chapter 10, which is short but informative, the basic types and characteristics of optical waveguides – 2D and 3D – as well as of fiber optic cylindrical structures are presented, and the propagation of optical wave modes in various kinds of optical guiding structures is fully analyzed with illustrations and computing plots. Then, the main factors of dispersion – waveguide, modal, material, and polarization – are described in a unified manner accounting for the specific impact of each of these factors on noises and fading occurring in optical communication links, both wired and wireless. At the end of this chapter, the examples, having practical meaning, will be important for the reader to accumulate the knowledge obtained in previous chapters and introduce them in practice.

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LIST OF ABBREVIATIONS

2-D – two dimensional

3-D – three dimensional

PDF – probability density function

CDF – cumulative distribution function

UV – ultraviolet

VIS – visible light

THz – terahertz-band wave

MW – microwaves

RW – radiowaves

IR – Infrared spectrum

IRA – near infrared

IRB – middle infrared

IRC – far infrared

ASK – amplitude shift keying

FSK – frequency shift keying

PSK – phase shift keying

RZ – return to zero

NRZ – non return to zero

$\mathbf{A}(\mathbf{r}, t)$ – vector of any electromagnetic component

$\mathbf{D}(\mathbf{r}, t)$ – electric flux induced in the medium by the electric field, in coulombs/m^3

$\mathbf{E}(\mathbf{r}, t)$ – electric field strength vector, in volts per meter (V/m)

$\mathbf{B}(\mathbf{r}, t)$ – magnetic flux induced by the magnetic field, in Webers/m^2

$\mathbf{H}(\mathbf{r}, t)$ – magnetic field strength vector, in amperes per meter (A/m)

k – vector of electromagnetic field propagation

$\mathbf{j}(\mathbf{r}, t)$ – vector of electric current density, in Amperes/m^2

$\rho(\mathbf{r}, t)$ – charge density in Coulombs/m^2

S = **E** x **H** – vector of density of wave power flow, the absolute value of which is in Watt/m^2

$\nabla \times$ – curl operator, as a measure of field rotation

$\varepsilon(\mathbf{r})$ – permittivity

$\mu(\mathbf{r})$ – permeability

$\sigma(\mathbf{r})$ – conductivity

$\varepsilon_0 = 8.854 \bullet 10^{-12} = \dfrac{1}{36\pi} 10^{-9}$, in Farad/meter (F/m) – permittivity in free space

$\mu_0 = 4\pi \bullet 10^{-7}$, in Henry/meter (H/m) – permeability of free space

$c = \dfrac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3 \bullet 10^8$, in m/c – light velocity in free space

$\varepsilon = \varepsilon' - j\varepsilon''$ – complex form of permittivity presentation; ε' – its real part, ε'' – its imaginary part.

$n = n' - jn''$ – complex refractive index; $n' = \sqrt{\varepsilon' / \varepsilon_0}$ – its real part, $n'' = \sqrt{\varepsilon'' / \varepsilon_0}$ – its imaginary part

$\lambda = c / f$, f - wave frequency in Hz=s^{-1}

$\omega = 2\pi f$ – angular frequency of wave

$\Psi(\mathbf{r})$ – scalar component of electromagnetic field

$\gamma = \alpha + j\beta$ – propagation parameter of wave

α – attenuation factor, in Neper/km

β – phase velocity factor in Radian/m

$v_{ph} = v_{ph}(\omega)$ – wave phase velocity

1 eV – electron-volt = $1.6 \bullet 10^{-19}$ Joule

$h = 6.625 \cdot 10^{-34}\, J \cdot s$ – Planck's constant

$P_n = h/\lambda \cdot n$ – impulse of electron of number n inside atom; λ – wavelength

$Ekn = (1/2)Pn^2 / m_0$ – kinetic energy of electron of number n inside atom

$m_0 = 9.11 \cdot 10^{-31}$ kg – mass of electron in free space

n = 1, 2, 3, …., N – main number, related to radius of the orbit r

l = 0, 1, 2, …, n-1 – orbital number related to the longitudinal angle θ

m_l – momentum of rotation number related to the azimuthal angle φ

s = -1/2 and s = +1/2 – left-hand and right-hand orbital spin momentum, respectively

(r, θ, φ) – spherical system of coordinate

Si – silicon

GaAs – gallium-arsenide

GaN – gallium-nitrogen

Sb – stibium

Ge – germanium

SbGe – stibium-germanium

In – indium

InGe – indium-germanium

p-n – positive-negative junction

A_{ji}, B_{ij} and B_{ji} – Einstein coefficients

D_n and τ_n – coefficient of diffusion and life-time of n-type particles (electrons), respectively

D_p and τ_p – coefficient of diffusion and life-time of p-type particles (holes), respectively

σ_n and σ_p – conductivity of electrons and holes, respectively

ρ_n and ρ_p – resistivity of electrons and holes, respectively

μ_n and μ_p – mobility of electrons and holes, respectively

e – 1.6 10^{-19} C – charge of electron (the same with + for hole)

η_i – quantum efficiency

LED – light emitting diode

LD – laser diode

E_g – depletion zone energy (energetic width of gap)

λ_g – cutoff frequency

k_B – 1.38 · 10^{-23} J/K - Boltzmann constant

$\acute{R}$ – coefficient of reflection

α_r – total attenuation coefficient

P-N – positive-negative diode

Φ – flux of photons entering into the diode

R – photodetector responsivity, in Ampere per Watt (A/W)

ζ – fraction of electron-hole pairs that successfully contribute to the detector current

PiN – positive-intrinsic-negative diode

W_j – width of junction

v_e and v_h – velocities of electrons and holes

i_{ph} – photocurrent

R_L – load resistance of detector

B_ω – bandwidth of detector

APD – Avalanche photodiode

α_e and α_h – ionization coefficients for electrons and holes, respectively, as ionization probabilities per unit length, in cm^{-1}

M – multiplication factor

SAM APD – separate-absorption-multiplication APD

G – gain of APD

InGaAs APD – indium-gallium-arsenide APD

σ_I^2 – standard deviation of wave intensity

SNR (S/R) – signal-to-noise ratio

σ_i^2 – standard deviation of photocurrent noise

N_T – thermal noise

σ_q – circuit-noise parameter

m – Poisson random variable

q – Gaussian random variable

$<m>$ – mean square variance of Poisson noise

σ_q^2 – mean square variable of Gaussian noise

F – excess – noise factor

B – bandwidth of receiver (detector)

$<i_{nd}^2> / B$ – noise current spectral density for PiN detector

$<e_{nd}^2> / B$ – noise voltage spectral density for PiN detector

$<i_{nd}^2> / B$ – noise current spectral density for avalanche photodiode

$<e_{nd}^2> / B$ – noise voltage spectral density for avalanche photodiode

$<i_{nd}^2> / B$ – noise current spectral density for photoconductor

$<I_c^2>$ – preamplifier noise contribution

I_b and I_c – basic and collector current inside bipolar transistor

FET – field-effect transistor

EDFA – erbium doped fiber amplifier

σ_{SE} – stimulated emission cross-section

$\gamma(v)$ – signal gain of amplifier

ASE – amplified spontaneous emission

dΩ – solid angle

PASE – power of Amplified Spontaneous Emission (ASE)

ρ_{ASE} – spectral power density of the Amplified Spontaneous Emission (ASE)

B_o – optical bandwidth of amplifier

$<i^2>$ – mean square current fluctuations

σ_S – thermal noise

σ_{ASE} – ASE short noise

$\sigma_{S\text{-}ASE}$ – signal-ASE beat noise

$\sigma_{ASE\text{-}ASE}$ – ASE-ASE beat noise

η_{ASE} – quantum efficiency of ASE amplifier

$PASE^{B0}$ – single polarized signal optical power at the optical bandwidth

Bo – optical bandwidth

B_e – receiver bandwidth

$PASE^{Be}$ – single polarized signal power at the receiver bandwidth

SNR_{out} – signal to noise ratio of optical amplifier

NF – noise figure

$\gamma_o(\upsilon)$ –- small signal gain coefficient

$G_0(\upsilon)$ – overall gain of erbium doped fiber amplifier (EDFA)

CW – continuous narrowband (NB) signals

WB – wideband signals

AM – amplitude modulation

FM – frequency modulation

PM – phase modulation

OF – optical frequency

km – amplitude modulation index

β_f – frequency modulation index

k_θ – phase sensitivity

β_θ – phase modulation index

$(SNR)_{in}$ – signal to noise ratio at the input of receiver

$(SNR)_{out,FM}$ – signal to noise ratio at the output of receiver for FM

$(SNR)_{out,AM}$ – signal to noise ratio at the output of receiver for AM

BPSK – binary phase shift keying

QPSK – quadrature phase shift keying

MSK – minimum shift keying

GMSK – Gaussian minimum shift keying

FSK – frequency shift keying

NA – numerical aperture

2-D – two-dimensional fiber optic structure (slab)

3-D – three-dimensional fiber optic structure (cylindrical cable)

TE – transverse electric field (vertical polarization)

TM – transverse magnetic field (horizontal polarization)

LHS – left-hand-side

RHS – right-hand-side

V – normalized frequency parameter

$J_l(hr)$ – Bessel function of the first kind

$K_l(hr)$ – modified Hankel function

LP – linearly polarized (mode)

D_M – material dispersion parameter

$\Delta\tau_g$ – time spread between two modes

$\Delta\omega$ – spectral range of the total signal

n_g – index of transmission of energy via cable

D_W – waveguide dispersion parameter

Dp – polarization mode dispersion (PMD) parameter

TIR – total intrinsic reflection

CHAPTER 1

FUNDAMENTAL ASPECTS OF ELECTRO-OPTICS

Electro-optical engineering, as a subject of analysis and discussion, covers many basic aspects which should be understood and explained to the reader, such as [1–16]:

- electromagnetic nature of light,
- similarity of optical and electromagnetic waves,
- corpuscular nature of light,
- electromagnetic aspects of optical wave propagation in various environments,
- elements of photonics,
- optical lasers – emitters of light,
- optical detectors of light – laser diodes and photo diodes,
- optical amplifiers,
- optical signals presentation – analog and digital,
- types of modulation of optical signals,
- types of noise occurring in optical elements and devices,
- optical guiding structures and fiber optic engineering aspects,
- dispersion and noises, occurring in optical guiding structures, etc.

In this chapter, we will try to introduce the reader to the most important aspects of electro-optical engineering, including the technical and technological aspects of optical elements and component fabrication, their material description, applied aspects of optical links fabrication, basic aspects of optical radar (called LIDAR) operation, and so forth, since the fine details are out of the scope of this book. The main goal of this book is to introduce the reader to fundamental aspects of electro-optical engineering based on basic physical fundamental questions which future engineers, technicians and researchers will meet during the design and development of basic elements and devices for optical communication and LIDAR.

1.1 Spectrum of Optical Waves

An optical communication system, either wired (i.e., fiber optics) or wireless (i.e., atmospheric or LIDAR), transmits analog and digital information from one place to another, using high carrier frequencies in the range of 100 THz to 1000 THz in the visible and infrared (IR) region of the electromagnetic spectrum [1–16]. As for microwave systems, they operate at carrier frequencies that are five orders of magnitude smaller, from 1 GHz to 50 GHz.

As a narrow band of the whole electromagnetic spectrum, the light wavelength band spreads from the ultraviolet spectral band to the far infrared (IR) spectral band, passing through the visible band, to the middle- and far infrared bands, as illustrated in Fig. 1.1, since most fiber optic cables, optical detectors and sources operate in these spectral bands.

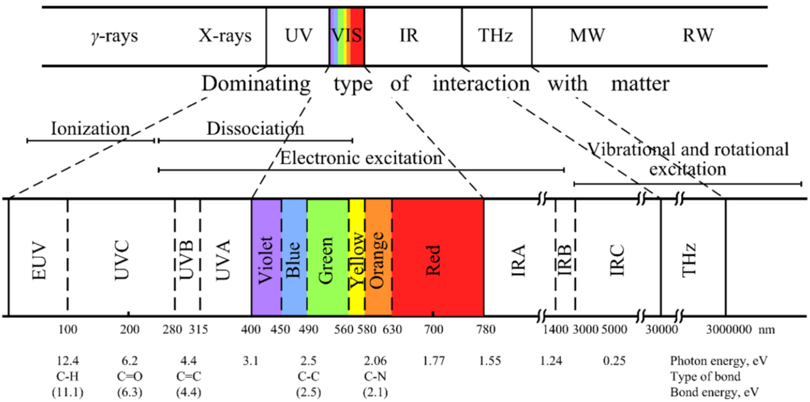

Figure 1.1. Electromagnetic spectrum and types of interaction with matter, indicated in the top panel by: UV – ultraviolet, VIS– visible light, IR – infrared, THz – terahertz-band wave, MW – microwaves, RW – radio waves (modified from [12-16]).

In electro-optics the large spectrum usually used – from the UV-band to the THz–band (see middle panel), which can be divided for practical applications into: UV, with UVC – far, UVB – middle, and UVA – near ultraviolet; VIS, divided from violet to red, as vividly shown by the corresponding color; and IR, with IRA – near, IRB – middle, and IRC – far infrared, as illustrated by the middle panel. The bottom panel presents along the horizontal axis the corresponding wavelengths for each narrow band [in nanometers, 1nm = 10^{-9} m], the type of light and the band energy [in eV, 1 eV = 1.6 • 10^{-19} J].

We notice that the relationship between wavelength (λ) and frequency (*f*) is: $\lambda = c / f$, where $c = 3 \cdot 10^8\, m/s$ is the velocity of light in free space. As an example, a wavelength of light from the near IR band equals $\lambda = 1.5 \mu m$; it corresponds to a frequency of *f* = $2 \cdot 10^{14}\, Hz = 2 \cdot 10^2\, THz$ (with a period of oscillation equal to $T = 0.5 \cdot 10^{-14}\, s$).

The main goal of modern electro-optical engineering, photonics and optical electronics is to find the lowest energy and bandwidth losses of the corresponding materials during fabrication of the optical elements and devices [1–7, 11–16]. Thus, optical fiber systems operating in the 0.65–0.67 µm bandwidth with a plastic intrinsic surface have losses of 120–160 dB/km, whereas those operating in the 0.8–0.9 µm bandwidth have losses of 3–5 dB/km, and those operating in the 1.25–1.35 µm and 1.5–1.6 µm bandwidths, based on a glass surface, have losses of 0.5 to 0.25 dB/km, respectively [13]. We notice that the decibel [dB] is a measure called “path loss” denoted by *L* and defined as *L* = 10log*E*, where *E* is the energy of the optical wave in Joules [J].

Sufficiently wide frequency bands of light have allowed the increase of the bit rate (in bit/second, bps) – distance (in km) ratio during a period of about 150 years from $\sim 10^2$ *bps/km* to $\sim 10^{15}$ *bps/km* (summarized from [7, 12, 14–16]).

1.2 Fiber Optic Links

Below, we will give a definition of the optical link, both for a fiber optical link, as a "wire" communication link, and for an atmospheric link, a "wireless" communication link. The atmospheric links are outside of the scope of this book because they are fully presented in [15, 16].

As for wired optical communication links via fiber optics, they can be considered as a finishing optical communication mono-network, consisting of one fiber optic link, as shown in Fig. 1.2 rearranged from [16]. The message passing such a link is assumed to be available in electronic form, usually as a current. The transmitter is a light source that is modulated so that the optical beam carries the message.

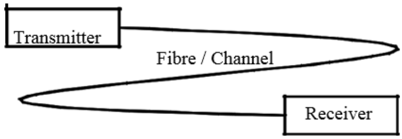

Figure 1.2. Scheme of optical communication link connected by fiber optics.

As an example, for a digital signal, the light beam is electronically turned on (for binary ones) and off (for binary zeros). Here, the optical beam is the carrier of the digital message. As a source fiber optic links usually take the light emitting diode and the laser diode. Several characteristics of the light source determine the behavior of the propagating optical waves [1–6]. The corresponding modulated light beam (i.e., the message with the carrier) is coupled into the transmission fiber.

1.3. Main Elements and Devices in Electro-Optics

The input to each optical channel is the optical signal from the optical transmitter, which emits optical signals, and the output of the channel is the input to the receiver, which detects optical signals. The receiver amplifies these optical signals, converts them to an electronic signal, and extracts the information. At the receiver, the signals are collected by a photodetector, which converts the information back into electrical form.

The photodetectors do not affect the propagation properties of the optical wave but certainly must be compatible with the rest of the optical system (Chapter 5). The transmitter includes a modulator, a driver, a light source, and optics (Fig. 1.3). The modulator converts the information bits to an analog signal that represents a symbol stream. The driver provides the required current to the light source based on the analog signal from the output of the modulator. The light sources are a light emitting diode (LED) and a pure laser, which is a coherent source and the subject of Chapter 5.

The source converts the electronic signal to an optical signal [6, 12]. The optics focuses and directs the light from the output of the source in the direction of the receiver.

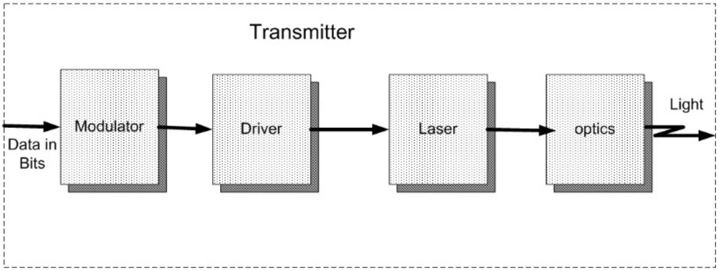

Fig. 1.3. The light source (transmitter) scheme.

The receiver includes optics, a filter, a polarizer, a detector, a trans-impedance amplifier, a clock recovery unit, and a decision device (see Fig. 1.4). The optics concentrate the received signal power onto the filter. Only light at the required wavelength propagates through the filter to the polarizer. The polarizer only enables light at the required polarization to propagate through to the detector. The detector, in most cases, is a semiconductor device such as a positive-negative (PN) or positive-intrinsic-negative (PiN) photodiode, which converts the optical signal to an electronic signal (see Chapter 5).

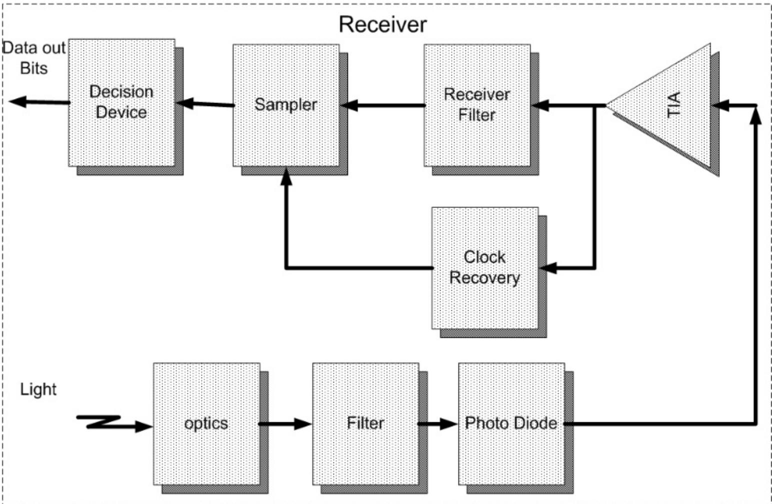

Figure 1.4. The light detector (receiver) scheme.

The amplifier increases the amplitude of the electronic signal from the detector. The clock recovery unit provides a synchronization signal to the decision device based on the signal from the output of the trans-impedance amplifier. The decision device estimates the received information based on the electronic signal from the trans-impedance amplifier and synchronization signal.

1.4. Noise in Optical Emitters and Detectors

In wired fiber optic and wireless (atmospheric) links, when the data stream is guided through them, they can be affected by noise occurring in each element of the optical emitters and detectors; the corresponding types of noise are discussed in Chapter 6.

1.5. Presentation of Signals in Electro-Optics

In electro-optics, the information carried by the optical signal can be presented both in analog and digital form, as shown in Figure 1.5. The analog form is a harmonically presented form of the signal in the time and frequency domains

$$s(t) = a(t)\exp\{j[\phi(\mathrm{t}) + 2\pi f t]\} \tag{1.1}$$

via its amplitude $a(t)$, phase ϕ(t) and frequency f (see Chapter 8).

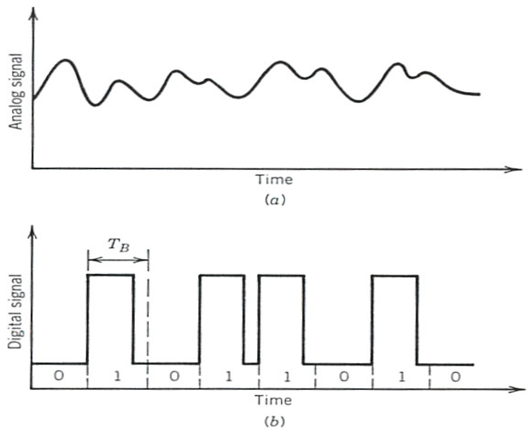

Figure 1.5. Presentation of information in optical communication links in the form of a) analog signal and b) digital (e.g., pulse) signal.

So, the upper set of blocks shown in Fig. 1.4 operate with a set of digital signals that were obtained by converting an analog signal, presented in harmonic form [see Eq. (1.1) above], into a digital signal via quantization of the analog optical signal and presentation of the flux of optical quants as a discrete sequence of codes, 0 and/or 1, as shown in Figure 1.6.

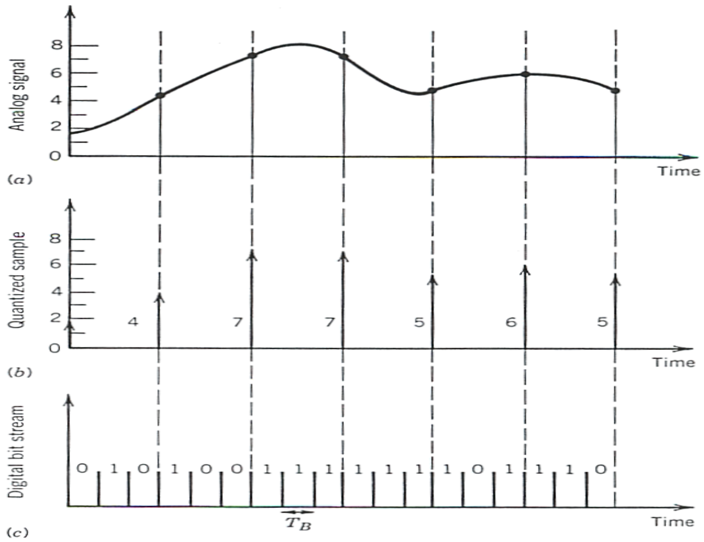

Figure 1.6. a) Sampling, b) quantization, and c) coding.

1.6. Types of Modulation of Optical Signals

As for types of modulation, it also depends on the type of optical signal – analog (or continuous wave (CW)) or digital. To understand the further presented material, we refer the reader to a simple explanation of CW modulation usually used in optical devices to obey different kinds of signals.

For such kinds of optical signals, we deal with three kinds of modulation/demodulation: *amplitude* or *intensity*, *phase* and *frequency*. Thus, each CW signal can be presented in exponential form (1.1). As follows from (1.1), there are three possible kinds of modulation/demodulation of CW optical signals:

a) via changes of carrier optical signal amplitude or intensity by the influence of the modulating signal (usually called the *message*),

b) via changes in phase of the modulated carrier optical signal by mixing it with modulating signal, and

c) via changes in frequency of the modulated carrier optical signal by mixing it with modulating signal frequency.

All these aspects will be discussed in Chapter 9, where some examples of practical application will also be presented.

As for digital modulation/demodulation [10, 16], this also can be divided into three types according to changes of amplitude (called amplitude shift keying, ASK), phase (phase shift keying, PSK), and frequency (frequency shift keying, FSK), as shown schematically in Fig. 1.7.

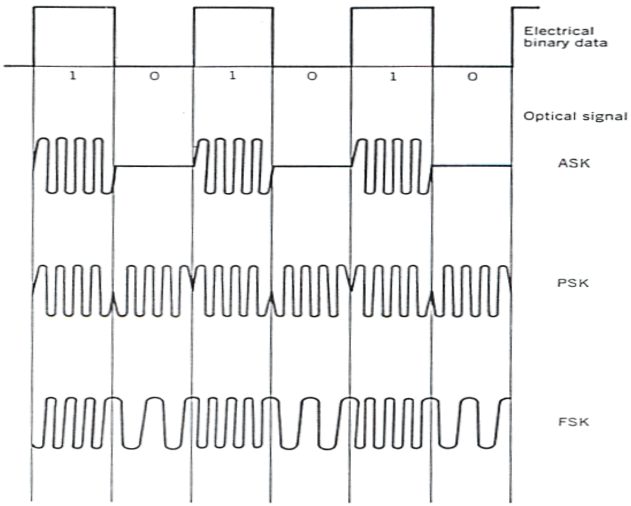

Figure 1.7. Three types of modulation of digital (pulse) optical signal: amplitude (ASK), phase (PSK), and frequency (FSK).

The most common type of digital coding and encoding is On-Off Keying (OOK) [10]. This can be presented in two basic formats (see Fig. 1.8): a) Return-to-Zero (RZ), and b) Non-Return-to-Zero (NRZ) [10, 16].